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Development of a Cost and Impact Assessment Tool for Floating Wind Turbines

MASTER'S THESIS

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ABSTRACT

The offshore wind energy industry is working towards a transition from fixed bed support structures to floating wind turbine substructures. These structures will allow the installation of offshore wind turbines in waters deeper than 60 meter and further away from the shore. Although floating offshore wind turbines have reached a high technology readiness level, the full commercialization of offshore floating wind turbines is still under way. To enable a benchmarking of concepts, this thesis develops an integrated framework for the cost and impact assessment of floating wind turbines. The developed parametric cost model considers all life cycle phases and also incorporates a simulation based approach for the performance assessment of the operation and maintenance phase.

The performance of multi-component systems, such as wind turbines, is heavily dependent on the maintenance strategy applied on each subsystem. Related costs and the impact of subsystem failures on the performance of the overall system must be considered.

The performance assessment is carried out by dividing single wind turbines into major subsystems, applying different maintenance strategies and evaluating the produced electricity and the Levelized Cost of Electricity (LCoE) of the entire wind farm. Investigated scenarios include corrective, time based and reliability centred maintenance strategies. Thereby, limits concerning minimum and maximum performance, as well as the impact of a realistic application of condition based maintenance on the performance are identified.

The developed cost model is directly linked to a Life Cycle Assessment model which allows to estimate the environmental impact of an offshore floating wind project. The impact assessment is based on ISO 14040 and models impact categories through the consideration of used materials and processes. Included impact categories and indicators are the energy payback period, energy yield ratio, cumulated energy demand and global warming potential.

KURZFASSUNG

Die Offshore Wind Industrie befindet sich in einer Entwicklung von fest gegründeten, hin zu schwimmenden Fundamenten für Offshore Windturbinen. Schwimmende Fundamente werden die Installation von Windturbinen in Gewässern von mehr als 60 Meter Tiefe erlauben. Trotz des hohen Technologie-Reifegrads, den schwimmende Windkraftanlagen erreicht haben, ist eine breite Kommerzialisierung noch nicht erfolgt. Um ein Benchmarking verschiedener Konzepte zu ermöglichen, wird im Rahmen dieser Arbeit ein Framework für die integrierte Bewertung von Kosten und Umwelteinflüssen schwimmender Windkraftanlagen entwickelt. Dieses Framework berücksichtigt alle Lebenszyklusphasen einer Windkraftanlage und enthält darüber hinaus eine simulationsbasierte Bewertung der Betriebs- und Wartungsphase.
Die Leistungsfähigkeit eines Mehrkomponentensystems, wie einer Windkraftanlage, ist stark beeinflusst von der auf die Komponenten angewandten Instandhaltungsstrategie, deren Kosten sowie dem Einfluss eines Komponentenfehlers auf die Leistung des Gesamtsystems. Für die Bewertung der Leistung wurde die Windkraftanlage in wesentliche Subsysteme unterteilt. Unter Annahme verschiedener, geeigneter Instandhaltungsstrategien wurde die über die Laufzeit produzierte Elektrizität sowie die Stromgestehungskosten ermittelt. Die betrachteten Instandhaltungsszenarien beinhalten korrektive, vorrausschauende und risikobasierte Instandhaltung. Hierbei wurden Grenzen für die minimale und maximale Leistungsfähigkeit, sowie der Einfluss einer realistischen Anwendung von risikobasierter Instandhaltung auf einzelne Komponenten identifiziert.

Das entwickelte Kostenmodell ist direkt mit einer Lebenszyklusanalyse verknüpft, welche die Abschätzung von Umwelteinflüssen, die ein schwimmender Windpark verursacht, ermöglicht. Die Lebenszyklusanalyse, basierend auf ISO 14040, modelliert relevante Einflusskategorien durch die Berücksichtigung von Materialkonsum und eingesetzten Prozessen. Betrachtete Einflusskategorien und Kenngrößen sind das Energieertragsverhältnis, die Energie-amortisationszeit, der kumulierte Energiebedarf sowie der CO2-Ausstoß.

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LIST OF ABBREVIATIONS

AC	Acidification Potential
AHTS	Anchor Handling Tug Supply
CAPEX	Capital Expenditures
CED	Cumulative Energy demand
CIAT	Cost and Impact Assessment Tool
CMS	Condition Monitoring System
D&C	Development & Consenting
D&D	Decommissioning & Disposal
EEIOA	Environmental extended input-output analysis
EF	Equivalence Factor
EP	Effect Potential
EPB	Energy payback period
EYR	Energy yield ratio
FINEX	Financial Expenditures
GHG	Greenhouse Gas
GWP	Global Warming Potential
I&C	Installation & Commissioning
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
MTBF	Mean Time between Failures
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
O&M	Operation & Maintenance
ODP	Ozone Depletion Potential
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditures
OW	Operational Weather Window
P&A	Production & Acquisition
POCP	Photochemical Ozone Creation Potential
PSV	Platform Supply Vessel
SCADA	Supervisory Control and Data Acquisition
WACC	Weighted Average Cost of Capital

1 Introduction

Driven by European climate and energy policies wind energy has become one of the key sources for renewable energy. In 2018 wind power has reached a total installed capacity of 189GW while onshore wind accounts for 170GW and offshore wind accounts for 19GW [1]. This represents 18.8% of the total installed electricity production capacity in Europe [1]. Levelized Cost of Electricity (LCoE) ranges from 39.9€/MWh to 83.3€/MWh for onshore wind [2]. Due to the use of more resistant materials and higher efforts for installation and maintenance offshore wind LCoE is significantly higher and ranges between 74.9€/MWh and 137.9€/MWh [2]. Main components of LCoE in wind energy are capital costs, financing costs and operation and maintenance costs [3]. Typically Operation and Maintenance (O&M) costs account for 20%-25% of total LCoE [4]. Considering total expected wind energy investments of €239bn [5] until 2030 in Europe the importance of cost saving O&M strategies for wind energy is evident.

At present the vast majority of offshore windfarms employ bottom fixed foundation concepts whereby monopile and jacket foundations are under the most common. Bottom fixed foundation concepts are viable up to maximum water depths of around 50m due to economic and technical limitations [6]. As stated by [7], 80% of the European offshore wind energy potential is located in waters of 60m and deeper. In those locations the deployment of floating offshore wind turbines can be a viable and economic attractive option. While offshore floating wind was in research and development stage in the last years, it is now reaching the transition to a broad industrial scale deployment. As depicted in Figure 1-1 the four main types of floating substructures have reached or will reach technology readiness levels of 9 in the next years.

Semi-submersible floating substructures are buoyancy stabilized floaters, which are hold in place by mooring lines and anchors. Spar type floaters are ballast stabilized due to their centre of gravity and centre of buoyancy. Tension Leg Platforms (TLP) are stabilized by mooring lines, which pull the structure to the seabed against the buoyancy force. Barge type floating substructures, similar to semi-submersible substructures, are stabilized by buoyancy forces but float on the water surface [8].

Floating offshore wind turbines promise to have several advantages. They can be installed in areas with higher wind speed and more stable weather conditions which might lead to a higher utilization. Furthermore, environmental impacts such as noise and visual pollution can be reduced with installation sites far from shore.

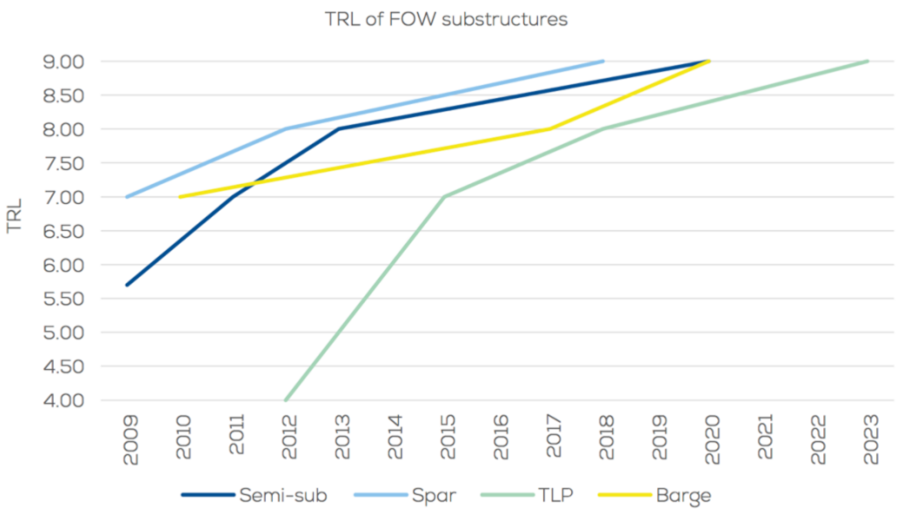

Figure 1-1: Technology Readiness Level (TLR) Floating Wind Concepts [7]

However, the understanding of project costs of different concepts over all life cycle phases is a prerequisite for the full commercialization of floating offshore wind turbines. On the other hand the understanding of associated environmental impacts such as global warming potential is necessary for the holistic assessment of floating wind projects. This work addresses this needs with the development of an integrated cost and impact tool for floating wind turbines.

1.1 Aims and Objectives

This work aims to develop a framework for the integrated cost and impact assessment of floating wind turbines. The developed framework shall be implemented in a software tool. This software tool is intended to provide the following key functions:

- Identification of key cost components in each life cycle phase

- Estimation key performance indicators, such as LCoE, Energy Yield Ratio (EYR), Energy payback Period (EBP)
- Simulation and quantification of operation and maintenance activities
- Estimation of cumulated energy demand in each life cycle phase
- Estimation of environmental impact indicators such as global warming potential

1.2 Methodology and Structure

Starting point for this work were recent research activities at Cranfield University. The cost model (chapter 3) is based on an existing framework for the cost assessment of fixed bed wind turbines. To transfer this framework into a cost model for floating wind turbines, a comprehensive review on cost assessments for floating wind turbines has been conducted. Based on this information parametric equations has been derived and implemented in a software code. For the assessment of operation and maintenance phase an O&M simulation tool has been developed and integrated.

For the development of the impact model in chapter 4, first a comprehensive review on Life Cycle Assessments (LCA) of floating wind turbine projects has been conducted. The parametric model has been developed based the guidelines provided in ISO 14040.

In order to evaluate the cost and impact model a comprehensive case study has been conducted. In this case study a wind farm, consisting of 100 floating wind turbines has been modelled and different maintenance strategy scenarios have been applied. In chapter 6 and 7 a discussion of results and limitations takes place.

2 Integrated Cost and Impact Assessment Tool (CIAT)

The lifetime costs of an offshore wind farm are composed of capital expenditures (CAPEX), financial expenditures (FINEX) and operational expenditures (OPEX). Considering the total produced electricity the LCoE can be calculated [21].

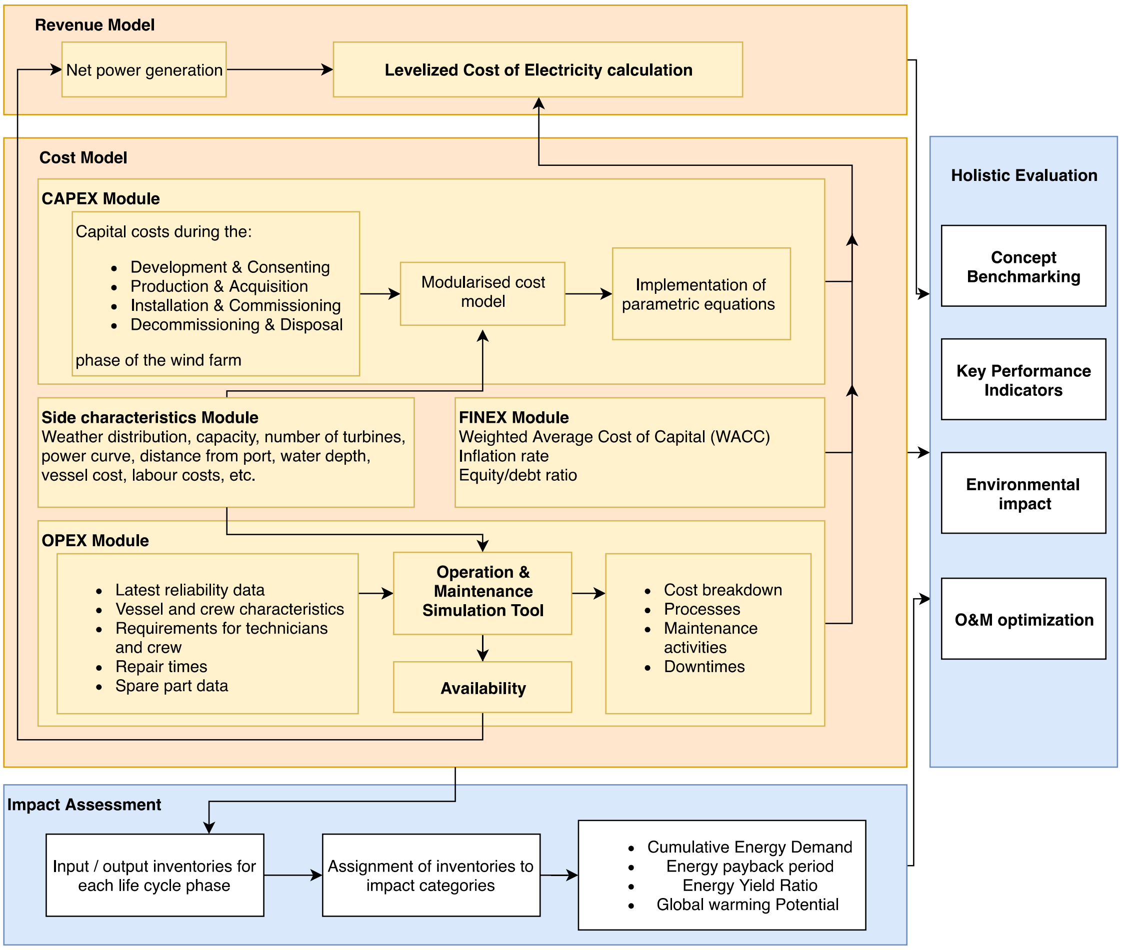

Figure 2-1: Methodological framework CIAT (adapted from [9]**)**

Figure 2-1 depicts the methodological framework of the Cost and Impact Assessment Tool (CIAT). The model developed in this work is based on the work of [9] who developed a technoeconomic framework (depicted in orange) for the valuation of an offshore wind energy project across the entire life cycle. Although the framework of CIAT based on previous work, CIAT is developed for the specific requirements of floating wind projects. Therefore, the underlying calculation methods, which are developed in this work differ significantly from the calculations in [9]. Furthermore, the novelty of this work lies in the integration of a LCA model which incorporates data from the cost model. The output of this holistic tool allows not only the analysis of concepts from a technoeconomic point of view but also the estimation and benchmarking of environmental impacts.

The CAPEX module considers the capital expenditures occurring in the Development and Consenting (D&C), Production and Acquisition (P&A), Installation and Commissioning (I&C) and Decommissioning and Disposal (D&D) life cycle phase through a modularised cost model. The site characteristics module contains general information of the project like details on the weather distribution, type of turbines including power curves, and distance to the service port. The FINEX module incorporates parameters related to financial expenditures such as Weighted Average Cost of Capital (WACC) and equity debt ratio. The OPEX module models operational expenditures during the O&M phase. It simulates the O&M phase by incorporating reliability data, cost for materials and personnel related to the maintenance process. While [9] implemented the industry standard O&M tool, developed by the energy research centre of the Netherlands, to predict O&M cost, in CIAT an O&M simulation tool was developed as part of this work. The output of the OPEX module is besides the cost breakdown of associated processes the availability of the wind farm. Availability is a key performance indicator of every wind farm, and enables the calculation of net power generation. Finally the revenue module of CIAT calculates the LCoE for the wind farm project.

CIAT aims to offer a generic framework which can be used for the cost and impact estimation of a wide range of different concepts. Therefore, it is not based on prescribed input parameters which are specific for an individual concept but on modelling material consumptions and associated activities. This approach allows the modelling of the project to the desired level of detail. However, this approach also requires an in depth understanding of concept and project characteristics to deliver accurate results.

The realization of the developed framework is based on MS EXCEL and MATLAB. In general EXCEL spreadsheets are used for the definition of input parameters while the data processing realized by means of MATLAB codes. The general architecture of CIAT is depicted in Figure 2-2.

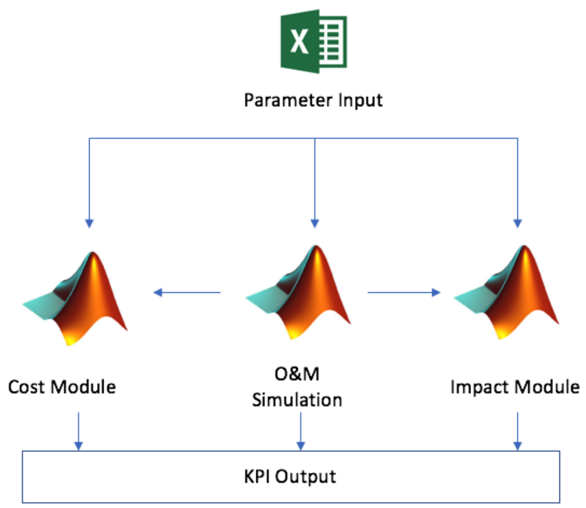

Figure 2-2: CIAT Architecture

The development of the MATLAB codes for cost module, O&M simulation tool and impact module are an integral part of this thesis project.

3 Cost modelling

Developers and researchers working on the exploitation of floating offshore wind energy need a clear picture of project life cycle cost to optimize concepts and to assess the economic feasibility. Uncertainties in the economic feasibility assessment of floating offshore wind project occur due to [10]:

- Volatile commodity prices, strongly affecting component cost
- Expenditures arise in different currencies, spread over the live span of the project
- Site characteristics, such as metocean and seabed conditions, are strongly influencing project costs as well as the expected energy yield.
- Operational expenditures are heavily dependent on characteristics such as distance to service port as well as applied maintenance strategy.

The cost model of CIAT aims to address these factors by providing a methodology based on parametric inputs for all key costs components related to an floating offshore wind farm project in each life cycle phase. As described before cost modelling in CIAT is structured in three different modules, covering financial expenditures, capital expenditures and operational expenditures. The relation between cost modules and life cycle phases is depicted in Figure 3-1 based on the findings of [11], [6] and [9].

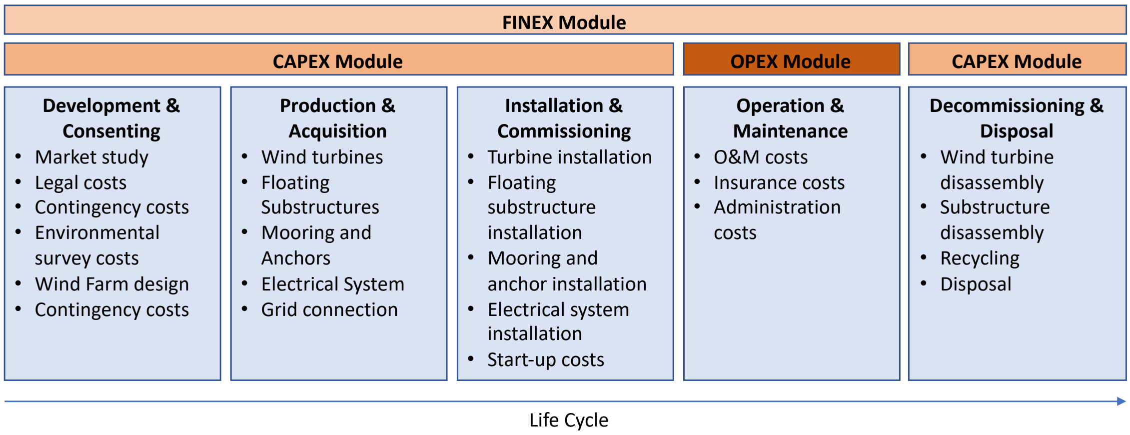

Figure 3-1: Cost Modules and Life Cycle Phases

The three different cost modules are discussed in detail in chapter 3.1, 3.2 and 3.3.

3.1 FINEX

Expenditures and revenues occur at different times during the timespan of the project. Due to different factors like interest rates, inflation rates and risk acceptance of investors, the value of the same amount of money will be different at different points in time. To be able to evaluate cash flows throughout the project, the present value of each cost component is calculated in CIAT based on [12] by

$$Present\ Value = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t}$$

Equation 1: Present Value

Where C_t is a cash flow occurring at time t, and r is the interest rate. The interest rate is represented by the WACC. In CIAT the WACC is calculated by incorporating the method suggested by [9]. In this method the WACC is adjusted to the loss of purchasing power of a unit currency:

$$WACC_{real} = \frac{1 + WACC}{1 + R_{inf}} - 1$$

Equation 2: Real WACC

Where R_{inf} represents the inflation rate.

The WACC itself is calculated based on [9] by

$$WACC = \frac{VE}{V} * RoE + \frac{VD}{V} * Rd * (1 - t_C) \ .$$

Equation 3: WACC

Where VE is the market value of equity and VD is the market value of debt. RoE and Rd represent the return on equity respectively the interest rate on debt. t_C denotes the asset tax rate and V is the sum of VE and VD.

3.2 CAPEX

The CAPEX module aims to model all cost occurring during the D&C, P&A, I&C and D&D life cycle phase of a floating offshore wind farm. Cost during the O&M phase are considered separately in the OPEX module.

3.2.1 Development & Consenting

The D&C phase considers all activities related to the project that take place before the production and acquisition of components starts. As suggested by [13] and [14] the D&C life cycle phase can be subdivided in two parts. The first part includes costs for activities carried out up to the point of the final investment decision while the second part includes the cost for the detailed engineering of the floating offshore windfarm. Different studies like [15] and [16] describe slightly different breakdowns of cost components in the D&C phases. Cost components commonly considered in D&C phase of offshore wind energy projects are:

- Costs for project management
- Legal costs
- Survey costs
- Engineering costs
- Contingency costs

CIAT calculates the costs by the following equation, adapted from [16]:

$$C_{D\&C} = C_{Proj.Man.} + C_{legal} + C_{Survey} + C_{Eng} + C_{Contingency}$$

Equation 4: Cost D&D

The costs for project management $C_{Proj.Man.}$ includes activities like administrative services, pre-feasibility studies, tendering process and negotiation activities. CIAT considers $C_{Proj.Man.}$ as a predefined value. However, as suggested by [16] it can be estimated as a percentage of around 3% of total CAPEX.

Legal authorization costs C_{legal} include costs which occur due to the need for project authorization by the government or regulatory body. [14] suggests to estimate legal cost as a function of the number of wind turbines while [16] suggest an estimation as a percentage (0.13%) of total CAPEX. CIAT considers C_{legal} as a predefined value. This allows for a estimation based on the information available.

Different types of surveys are conducted prior to the final investment decision of an offshore wind project. In [15] environmental surveys, coastal process surveys, met station survey and sea bed surveys are distinguished. CIAT calculates the survey costs as follows:

$$C_{Survey} = C_{EN} + C_{CP} + C_{MS} + C_{SB}$$

Equation 5: Cost Survey

Where C_{EN} represents the costs for environmental surveys, C_{CP} represents the costs for coastal process survey, C_{MS} represents the costs for met station survey and C_{SB} represents the cost for sea bed surveys. As noted by [16] the costs for meteorological surveys will be constant while the other ones will depend on the desired capacity of the wind farm.

C_{Eng} refers to costs arising after the final investment decision and related to the detailed engineering of the floating offshore wind farm. Dependent on the results of the survey carried out before, activities in this cost category include the structural design, selection of suitable foundation concept and the design of the electrical system. As suggested by [16], in CIAT C_{Eng} is divided in main engineering costs $C_{Eng-main}$ and engineering verification costs $C_{Eng-ver}$. Estimation of main engineering costs is a complex task as it depends on a variety of parameters. While [14] suggests to calculate engineering costs as a function of the number of wind turbines and their power rating in CIAT the approach of [16] is inherited:

$$C_{Eng-main} = C_{Eng-base} + C_{Eng-unit} * IC$$

Equation 6: Engineering Costs

This approach assumes that main engineering costs can be modelled by a linear function composed of constant base costs ($C_{Eng-base}$) and variable costs increasing with the installed capacity (IC).

The contingency costs $C_{Contingency}$ account for unpredictable expenses that may arise related to an offshore wind farm project. In this way negative events which are not covered by insurances are considered in the financial planning. The inclusion of contingency costs in LCoE calculations is controversial. As stated by [6] contingency costs can be seen as a tool supporting tool for the final investment decision rather than basis for LCoE calculations. [16] and [9] suggest the inclusion in CAPEX calculation. A commonly used approach for the estimation of $C_{Contingency}$ is the consideration as a percentage ($\cong 10\ \%$, [16]) of total CAPEX. CIAT offers the consideration of $C_{Contingency}$ as a fixed value.

3.2.2 Production & Acquisition

In this section a framework aiming to consider all expenditures arising in the P&A phase is developed. Main components considered in CIAT are the wind turbine, the floating substructure, moorings and anchors and the transmission system. CIAT calculates the cost for production and acquisition accordingly:

$$C_{P\&A} = C_{Wind\ Turbine} + C_{Substructure} + C_{Mooring} + C_{Anchor} + C_{Tramission} + C_{Monitor}$$

Equation 7: Cost P&A

3.2.2.1 Wind Turbine

Obviously, the wind turbine is one of the main cost components of a floating offshore wind farm. The cost for the turbine will depend on various parameters and on the technologies employed. However, as suggested by different authors ([10], [9], [14]) the costs can be represented as a function of the power rating in a simplified model. These functions are created based on the evaluation of cost data from existing wind farms. CIAT makes use of the wind turbine cost function suggested by [16]:

$$C_{Wind\ Turbine} = (3{,}000{,}000 * \ln(P_{WT}) - 662{,}400) + C_{Tower}$$

Equation 8: Cost wind turbine

While $C_{Wind\ Turbine}$ is the cost per turbine in GBP and P_{WT} is the power rating of the wind turbine. Figure 3-2 shows the relation between cost per turbine and power rating which is slightly degressive. This indicates that the cost per power rating is decreasing for higher power ratings.

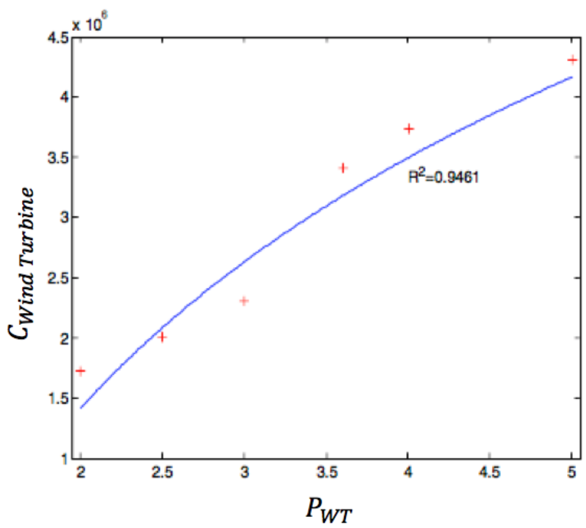

Figure 3-2: Cost function wind turbine, [16]

It is important to note that $C_{Wind\ Turbine}$ includes costs for the tower of the wind turbine C_{Tower}. However, depending on the type of floating substructure the tower may be part of the substructure and costs must not be considered as part of the wind turbine. As stated by [13] and [9] the cost for the tower are in the order of one million GBP for a 5 MW turbine.

3.2.2.2 Substructure

In the literature, there are different approaches for the cost modelling of floating wind turbine substructures available. In general the costs for the floating substructure is dependent on the type of substructure, the associated production processes, the material consumption and labour costs. [14] suggests an elaborated approach where substructure costs are modelled as the sum of material costs, labour costs and activity costs. These are represented as a function of mass, the submerged surface of the structure, the surface out of water, and the internal surface. [6] suggests a more simple approach which is derived from the analysis of existing floating wind farm projects. Costs are modelled through the steel consumption and associated material steel prices. Manufacturing costs are represented by a manufacturing complexity premium on these steel costs. The manufacturing complexity factor ranges between 110% for a tension leg substructure (Tension-Leg-Buoy concept) to 200% (Semi-Sub project, WindFloat).

This approach is adapted for the cost estimation in CIAT because it allows the modelling at different levels of detail. A list of materials with associated price and required masses for the substructure is defined by the user. In addition, the user can define a manufacturing complexity factor. Based on the defined complexity factors, the total production costs will be calculated in CIAT as follows:

$$C_{Substructure} = \sum_{i} m_i * c_{mi} * CF_i$$

Equation 9: Cost substructure

This method is advantageous as it does not require exact geometry parameters and gives a quick estimation of production costs. Economic scale effects due to series production of components can be considered with a discounted manufacturing complexity factor.

3.2.2.3 Mooring

Mooring line consumption is dependent on several parameters like water depth, the anchoring system, seabed conditions, loads and the number of mooring lines per turbine. Detailed information on mooring concepts can be found in [13].

[14] suggests the modelling of mooring P&A costs as a product of mass per meter of mooring line (kg/m), the cost per kilogram, the length and the number of mooring lines. [6] suggests to use the cost per meter and the length of the mooring line as input parameters. This approach is inherited in CIAT because it is likely that mooring lines will be purchased as finished product with a price per meter. In CIAT the user defines the price of mooring lines per length.

CIAT calculates the total costs for mooring lines $C_{Mooring}$ by:

$$C_{Mooring} = \sum_i c_i + l_i + n_i$$

Equation 10: Cost mooring

Where c_i is the unit-length price of mooring lines, l_i refers to the required length and n_i to the required number of mooring lines per turbine.

3.2.2.4 Anchoring

The selection of the anchor system used to fix the mooring lines to the seabed is dependent on the mooring system, the applied loads and the seabed conditions. Detailed Information on anchor concepts can be found in [17]. [6] suggests to model the P&A costs for the anchors similar to the costs for the floating substructure based on the material price with a manufacturing complexity factor to account for the production. [14] suggests to model the costs directly with costs per kilogram anchor weight as an input. However, since advanced anchor systems are complex components which are likely to be supplied as finished components by specialized manufactures, CIAT considers the anchors with total costs per unit as an user defined input.

$$C_{Anchor} = c_i * n_i$$

Equation 11: Cost anchors

Where c_i and n_i represent the cost per unit and required quantity per wind turbine respectively.

3.2.2.5 Transmission system

The transmission system of a floating offshore wind park conducts the electricity produced by the wind turbines to the onshore grid connection point. Usually wind turbines in an offshore wind farm are arranged in several arrays which are connected to an offshore substation. The electricity is then transmitted through an offshore export cable to an onshore substation. From there the electricity is further transmitted to the grid connection point via onshore export cable. In CIAT cost for the transmission system $C_{Transmission}$ are calculated by:

$$C_{Transmission} = C_{cables} + C_{Offsub} + C_{Onsub}$$

Equation 12: Cost transmission

Where C_{cables} expresses costs for all cables in the transmission system, C_{Offsub} refers to the offshore substation and C_{Onsub} refers to the onshore substation. The configuration of the transmission system is depicted in Figure 3-3.

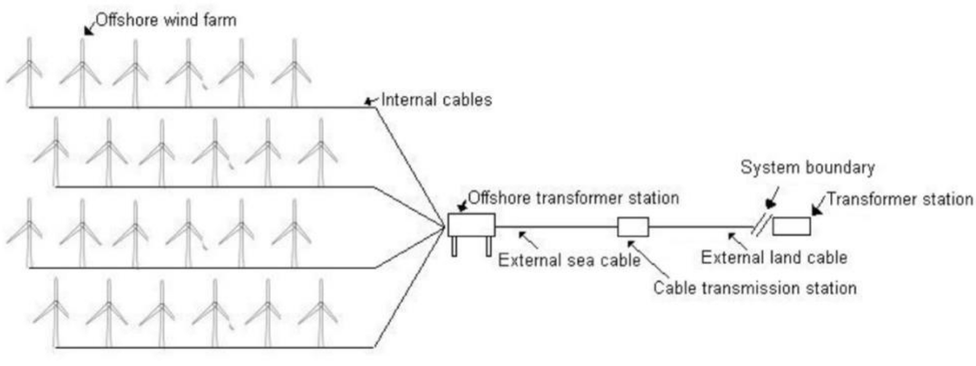

Figure 3-3: Transmission System [18]

It is evident, that the calculation of costs related to transmission cables with a price per unit-length is reasonable. However, different types of cables and site specific characteristics of floating wind farms need to be considered. In the cost model developed by [9] for fixed bed wind farms, it is suggested to distinguish between mean voltage cables, frequently used as array cables, and high voltage cables used as offshore and onshore export cables. This approach seems to be too simplistic for floating wind turbines. Due to different requirements for floating offshore wind farms especially in terms of structural integrity, five different cable sections are defined as suggested by [14]:

- Off1a refers to the cable from the wind turbine to the sea bed. The length of this section depends on the site specific water depth
- Off1b refers to the cable on the seabed connecting the turbines in an array.
- Off1c refers to the cable from the seabed to the substation
- Off2 refers to the offshore export cable
- On refers to the cable from the onshore substation to the grid connection point.

These sections as shown in Figure 3-4 are considered separately in CIAT. However, it must be noted that this allocation of cable section might not be suitable for every floating wind farm project.

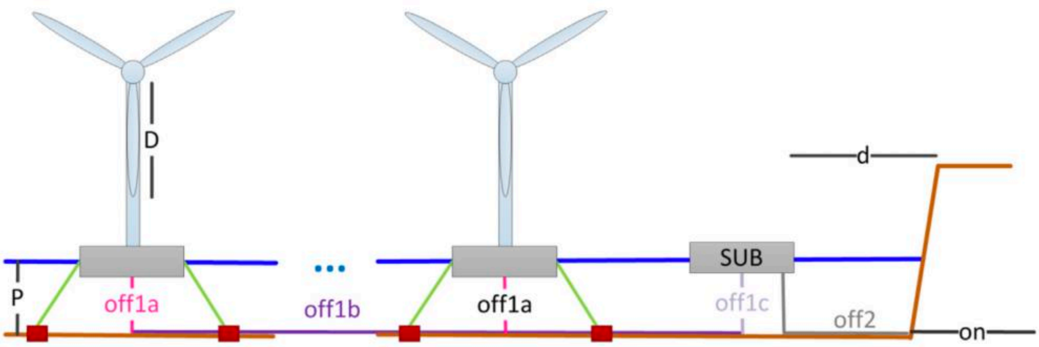

Figure 3-4: Offshore cable sections [14]

CIAT calculates the total costs for offshore and onshore cables C_{Cables} by

$$C_{Cables} = \sum_i (c_i * n_i * d_i) + C_{Protective}.$$

Equation 13: Cost cables

Where c_i refers to the price of cable per unit-length, n_i refers to the number required cables and d_i refers to the associated lengths. This calculation also considers costs for protective equipment $C_{Protective}$ such as bend restrictors or seals. In CIAT $C_{Protective}$ is considered as an user defined fixed value while in practice it will be a function of the number of installed wind turbines or the installed capacity respectively. The estimation of $C_{Protective}$ as a percentage of total cable costs is a reasonable approach as well.

In order to maximize the efficiency and thus minimize electrical losses most offshore wind farms employ an offshore substation. Exception are small wind farms with an installed capacity smaller 100MW and near shore wind farms with a distance to shore below 15 km [13]. The electrical losses of an current carrying conductor are given by $P = I^2R$. With this correlation it is comprehensible, that it is desirable to transport electricity over long distances at high voltage and low currents. Thus, offshore substations are used to step up the voltage of the array cables. In some cases the offshore substation will also convert the current from alternating current to direct current. The costs for the offshore substation are not expected to differ for the case of floating offshore wind. However, deviating costs for floating substructures, mooring and anchors must be considered. In CIAT the parametric cost model suggested by [9] is adapted for the calculation of substation production costs C_{Offsub}:

$$C_{Offsub} = C_{TR} + C_{SGMV} + n_{TR} * (2 * c_{SGHV} + c_{BB}) + C_{DG}$$

Equation 14: Cost offshore substation

Where C_{TR} refers to the mean voltage high voltage transformer an is calculated as a function of the rated power of the transformer A_{TR} by

$$\mathrm{C_{TR}} = \mathrm{n_{TR}} * (42.688 * \mathrm{A_{TR}^{0.7513}}).$$

Equation 15: Cost transformer

C_{SGMV} refers to the mean voltage switchgear cost and is calculated as a function of the nominal transformer voltage V_n:

$$C_{SGMV} = 40.543 + 0.76 * V_n$$

Equation 16: Cost switch gear

n_{TR} refers to the number of transformers, c_{SGHV} refers to the high voltage switch gear costs and c_{BB} refers to the high voltage bus bar costs.

C_{DG} refers to the diesel generator cost which is needed for electricity generation in case the wind farm is not operative. It is calculated as a function of the installed capacity in MW by:

$$C_{DG} = 21.242 + 2.069 * IC$$

Equation 17: Cost diesel generator

The costs for the floating substructure, moorings and anchors must be considered in the respective sections before.

As suggested by [11] and [16] the cost for the onshore substation C_{Onsub} can be calculated as a percentage of the offshore substation costs C_{Offsub}, since the environmental conditions onshore are less harsh:

$$C_{Onsub} = C_{Offsub} * f_{sub}$$

Equation 18: Cost onshore substation

The discount factor f_{sub} in CIAT is user defined. [15] suggest a discount factor of approximately 0.5 for a fixed bed wind farm.

3.2.2.6 Monitoring System

Some studies like [16] and [9] suggest to include costs for condition monitoring and SCADA systems in the cost calculation. These system allow the collection and processing of sensor data which gives the operator information about the condition of the wind turbines and helps to organize inspection and maintenance tasks. CIAT calculates the costs for the monitoring system $C_{Monitor}$ as suggested by [16]:

$$C_{Monitor} = (C_{SCADA} + C_{CMS}) * n_{WT}$$

Equation 19: Cost monitoring

However, it must be noted that modern wind turbines are often already equipped with comprehensive monitoring systems by the Original Equipment Manufacturer (OEM). In this case costs for the monitoring system might be already covered by the wind turbine costs.

3.2.3 Installation & Commissioning

In the I&C phase all activities related to the commissioning of components in the port, transportation of wind turbines and foundations to the site and the offshore installation are considered. Essential input parameters for the I&C cost modelling are vessel day rates, site characteristics such as distance to port and expenditures for time and labour. [9] developed a cost model for fixed bed offshore wind turbines which is based on the estimation of durations for emerging installation activities, personnel costs and vessel day rates. This general approach is adapted for the cost model in CIAT. Hereby, the objective is to develop a modular framework which gives the user guidance in cost calculation without predetermining project specific procedures.

CIAT calculates the installation cost by the following expression adapted from [14]:

$$C_{Installation} = C_{Inst.\ WT} + C_{Inst.\ Floater} + C_{Inst.\ Mooring} + C_{Inst.cables} + C_{start\ up}$$

Equation 20: Cost installation

While $C_{Inst.\ WT}$ refers to the installation costs of the wind turbine depending on the installation strategy. $C_{Inst.\ Floater}$ refers to the installation costs of the floating substructure. $C_{Inst.\ Mooring}$ refers to installation of the mooring system and anchors. $C_{Inst.cables}$ includes the installation costs for the electrical system including subsea cables and offshore substation. $C_{start\ up}$ refers to estimated cost for the start-up of the wind farm including test runs and grid connection.

3.2.3.1 Wind turbine and floating substructure installation

For the estimation of $C_{Inst.\ WT}$ and $C_{Inst.Floater}$ it is essential to consider different installation strategies. The installation strategy determines the activities that must be carried out in the ship yard and at the offshore site as well as the transportation of components between these locations. [14] and [13] identify different installation strategies for floating wind turbine installation. In CIAT the most relevant cases are considered:

- Onshore or near shore installation of wind turbine and substructure. Towing of the complete assembly to the offshore site. This scenario assumes that the floating platform is built in a shipyard while the turbine is built at different location onshore or in a shipyard. The assembly takes place in a port. Therefore, the transportation of floater and turbine to the port and the towing of the assembled turbines to the site must be considered.

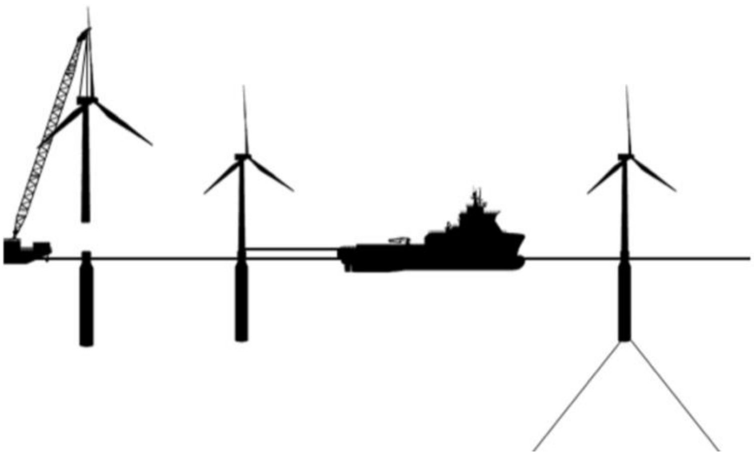

Figure 3-5: Installation Strategy 1 [13]

- Dry transportation of onshore preassembled wind turbines and towing of floating substructure to the site. In this case the installation of the wind turbines including the tower takes place in the port. Onshore facilities with potentially bigger OWs can be used for lifting activities. A offshore crane is required to lift the entire wind turbine onto the floater.

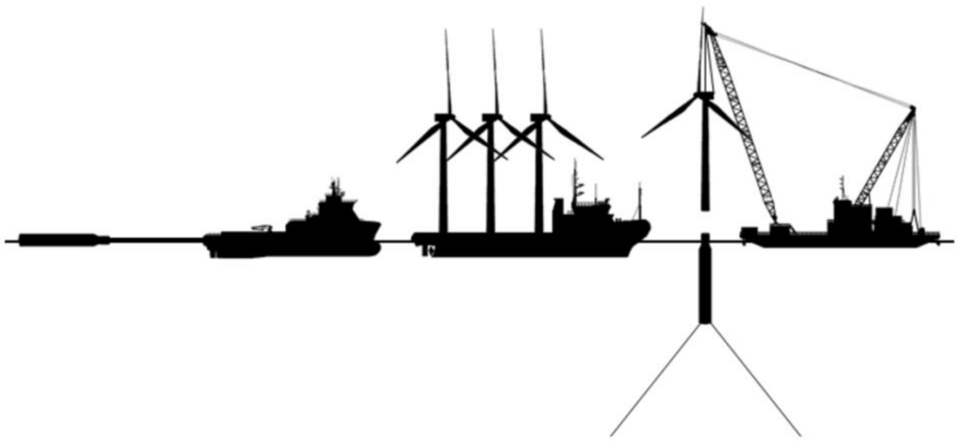

Figure 3-6: Installation Strategy 2 [13]

- Towing of floating substructure-tower configuration and dry transport of turbine components. This case assumes that the floating substructure and the turbine are pre-assembled in the port or build as one structure in the shipyard. A offshore crane vessel is required to lift the nacelle and rotor onto the tower offshore.

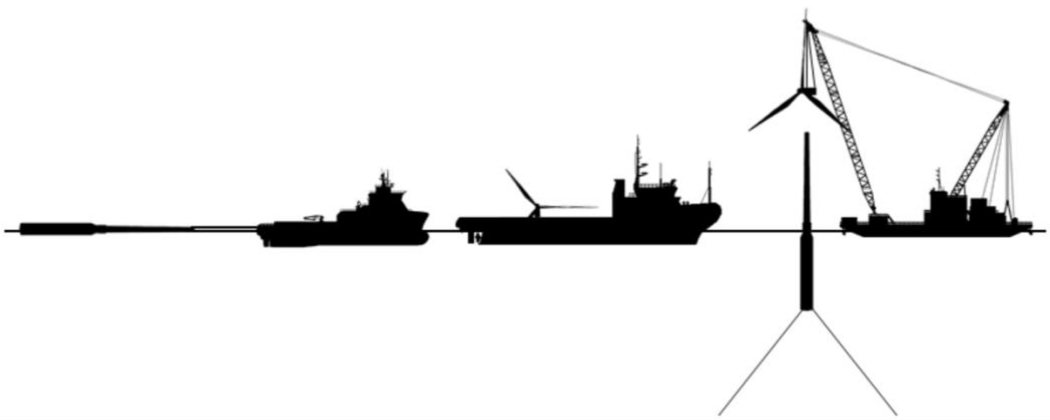

Figure 3-7: Installation Strategy 3 [13]

- Dry transport of floater, tower and turbine components to the site. In this scenario all (pre-assembled) components are transported on a PSV to the offshore site. All Lifting activities must be carried out by an offshore crane. Taking into account potentially small operational weather windows and extensive costs for offshore crane vessels, this scenario might lead to high installation costs.

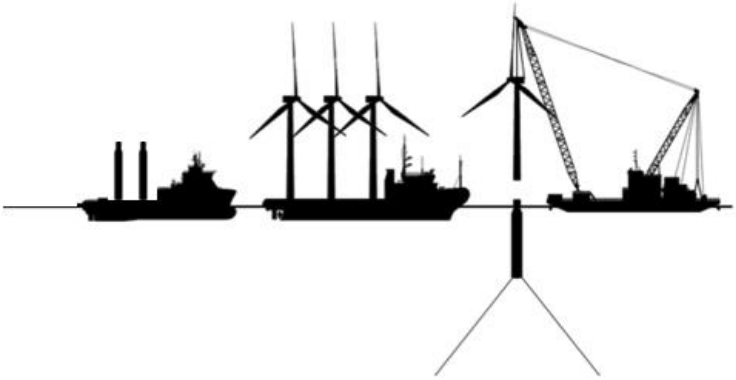

Figure 3-8: Installation strategy 4 (adapted from [13]**)**

Cost calculation for $C_{Inst.\ WT}$ and $C_{Inst.\ Floater}$ is divided in four calculation categories:

- Transportation to port
- Port installation and loading activities
- Transportation to offshore site
- Offshore installation activities

The activities taking place in the previously mentioned categories are represented in CIAT in a standard format which allows for a high degree of modularity:

$$Cost_{activity} = Value * Duration * Unit\ Cost * OW$$

Equation 21: Cost activity

While $Cost_{activity}$ refers to the costs for a specific activity, e.g. quayside lifts. $Value$ refers to a quantity, associated to the activity, e.g. number of lifts. $Duration$ refers to the time in days needed for the activity. $Unit\ Cost$ refers to the day rate of the technical equipment or personnel costs per day. Operational weather window (OW) is a statistical value between zero and one that takes into account the share of time, in which the activity can be carried out due to weather conditions. An OW of 0.6 for instance means that in 40% of the time the activity cannot be carried out due to adverse weather conditions.

The advantage of this approach is, that it allows to model the installation costs at different levels of detail. On the other hand it requires detailed knowledge of specific vessel data to deliver accurate results.

Wind turbines and floating structures are usually not constructed at the same place. Floating structures may be constructed in a shipyard, while the wind turbines may be constructed at a different shipyard or site on land. Thus, turbines and floating structures needs to be transported by sea or by land to the port where preassembly may take place.

Costs for road transport of wind turbine components are calculated by CIAT by following the above mentioned format:

$$C_{roadtrans\,WT} = n_{rt} * t_{rt} * c_{rt} * OW_{rt}$$

Equation 22: Cost road transport

While n_{rt} describes the number of required transport units. The duration t_{rt} will usually be a function of the distance between the construction site and the port d_{rt}. In case of road transport the OW can be assumed to be close to one.

Costs for sea transport of wind turbine components and floating substructures are calculated by:

$$C_{seatrans} = n_{st} * t_{st} * c_{st} * OW_{st}$$

Equation 23: Cost sea transport

While n_{st} describes the number of required transport units. The transport duration t_{st} will usually be a function of the distance between port and shipyard d_{st}. The vessel day rate c_{st} is depending on the vessel type in use. OWs are determined by the operational limits of vessel and weather data of the region.

Costs for port installation and loading activities are depending on the installation strategy chosen for the and the assembly procedure. This strategy determines which activities are carried out in the port or near shore and which installation activities will take place offshore. Main cost components occur due to time consuming lifting activities and associated use of personnel and equipment such as quayside cranes, crane barges and tug boats. As analysed by [13] different lifting procedures are conceivable which result in different time consumption. Examples for different lifting procedures are:

- Tower, nacelle, individual blades
- Tower, nacelle, pre-assembled rotor
- Pre-assembled floater- tower configuration, nacelle individual blades
- Lifting of complete turbine

To account for this various deviating options CIAT calculates the costs occurring in the port incorporating an individual list of activities defined by the user. The actual calculation follows the format given in Equation 21. As a guideline the list should contain but is not limited to:

- Personnel expenditure
- Quayside lifts (quayside crane)
- Near shore lifts (crane barge)
- Assistance (tug boats)
- Expenditures for storage of components on grounds of the port

Table 3-1 provides some indicative values for duration of lifting operation and associated wind speed limits.

Component lift	Time consumption	Maximum operational wind speed
Individual rotor blade	4 *hrs.*	8 *m/s*
Assembled rotor	5 *hrs.*	8 *m/s*
Nacelle	4 *hrs.*	10 *m/s*
Tower	6 *hrs.*	12 *m/s*
Complete turbine	12 *hrs.*	7 *m/s*

Table 3-1: Time consumption lifting operations [13]

Expenditures for the transportation of components to the offshore site are again mainly determined by the installation strategy. Travel and towing speeds as well as OWs of Anchor Handling Tug Supply (AHTS) vessels, Platform Service Vessels (PSV) and Tug boats will be different for activities like own transport, towing complete turbines, towing floater-tower configurations or towing floaters.

Travel times will be a function of the distance between the offshore site and the port $d_{port-site}$.

In CIAT transportation costs are calculated incorporating an individual list of activities based on Equation 21. As a guideline this list should contain but is not limited to:

- Transportation (Tug boats, AHTS, PSV)
- Up-ending of floater (Tug boats, AHTS)
- Loading (PSV)

The last calculation category for the installation of wind turbines and floating substructures estimates the costs occurring due to installation activities carried out offshore. If an installation strategy is chosen which makes offshore lifting activities necessary, extensive costs for offshore crane vessels operating in small OWs must be considered. The list of activities should include but is not limited to:

- Assistance (tug boats, AHTS, PSV)
- Mooring (tug boats, AHTS)
- Offshore lifts (Offshore crane vessel)

3.2.3.2 Installation of Moorings and Anchors

The installation costs of the anchors and moorings are mainly dependent on the installation time and the vessel costs. As stated by [6] and [14] the installation of anchors is carried out by a special AHTS Vessel.

As described by [19] two basic methods for mooring system can be distinguished:

- In the **pre-set** installation method, anchors and mooring lines are laid out before the actual installation of the wind turbines takes place. At the time of wind turbine installation the mooring lines are hooked up by the supply vessels. This method provides the advantage of bigger OWs for the installation of anchors and mooring alone. A drawback might be the overall extended installation time.
- In the **concurrent** installation method, the anchors and mooring lines are laid out at the same time with the installation of the wind turbines and

directly connected to the floaters. An advantage of this strategy might be that all activities are carried out at the same time which can lead to reduced expenditures for transports and transfers. However, there is a risk of interference of vessels involved in the different operation. This can lead to logistical problems and uncertainties.

Although these considerations are not modelled in the rather simple cost estimation implemented in CIAT it is important to be aware of possible consequences, occurring due to a specific installation strategy. Uncertainties could be met with the implementation of a risk factor.

CIAT calculates the costs for installation of anchors and moorings $C_{Inst.\ Mooring}$ by the following expression:

$$C_{Inst.\ Mooring} = c_{vessel} * n_{anchor}(t_{inst} * OW_{inst} + t_{transit} * OW_{transit})$$

Equation 24: Cost mooring installation

While c_{vessel} refers to the cost of the installation vessel per time unit, t_{inst} is the average installation time required for the installation of one anchor and n_{anchor} is the number of anchors per turbine.

Transit times per anchor $t_{transit}$ are calculated by considering the anchor type specific deck capacity $n_{capacity}$ of the AHTS vessel:

$$t_{transit} = t_{transit\_total}/n_{capacity}$$

Equation 25: Transit time

When determining the deck capacity of the vessel it should be considered that a free area for handling the anchors during installations must remain free. The deck area occupied by one floating wind turbine anchor will be around 30 m^2. Detailed information on anchor geometries and installation procedures can be found in [17]. Although, water depth is not directly considered as an parameter for anchor installation in CIAT, it should be noted that installation in deeper water will also increase the required storage capacity for mooring lines. As suggested by [13] the deck capacity will decrease by one unit per 200m increase of water depth. In addition, an increase of installation time per anchor should be considered for increasing water depth. [13] suggest to consider 30 minutes additional installation time for additional 100m water depth.

3.2.3.3 Installation of electrical system

The installation of offshore cables requires the employment of a dedicated cable laying vessel (CLV). The costs for the offshore cable installation can be calculated as function of the installation time and day rates of CLVs. However, this method requires an accurate estimation of installation times which are dependent on installation rates in [km/day]. Installation rates reported in literature vary in wide range from 0.6 km/day [9] to 10 km/day [13] and will also be dependent on seabed conditions and cable laying procedures. To offer a generic estimation of costs CIAT calculates the cable installation costs $C_{cable\ installation}$ as a function of installation costs per km of cable type:

$$C_{cable\ installation} = \sum_i l_i * n_i * c_i$$

Equation 26: Cost cable installation

Where l_i refers to the length of each cable type and n_i to the required number of cables of this type. These input parameters are inherited from the P&A section. c_i refers to the installation costs per km of cable type. These values are user defined and must be estimated based on the information available.

Although it allows an accurate cost estimation, the limitation of this method is that it requires detailed data of the cable laying process.

The substation installation costs are largely depending on the foundation concept and the related installation activities. For a floating substructure the costs are again depending on the anchor and mooring system and the water depth. CIAT calculates the installation costs in the same way as described in chapter 3.2.3.1

3.2.3.4 Start-up cost

As suggested by [14] start-up costs $C_{start\ up}$ including expenditures for grid connection and test runs are considered by a user defined value.

3.2.4 Decommissioning & Disposal

The Life Cycle of an offshore wind turbine does not end with its end of operation. When the wind turbines have reached their operational lifetime the D&D of components takes place. Decommissioning is usually referred to as all activities performed to return a site as close as reasonable practicable to its original state [20]. In general, the decommissioning process is a reversed installation process including all components of wind turbines, substructure, moorings, cables and substations. In practice, a detailed decommissioning strategy and related obligations should be defined in the planning phase of a project. This strategy will also vary based on site specific legislations and stakeholders involved.

The costly removal of fixed foundations is obviously not required for floating wind turbines. Depending on site and technical characteristics floating wind turbines can be decommissioned on site or completely towed into a port or shipyard.

As these different options are considered in the installation costs it is reasonable to estimate the decommissioning costs as a percentage of the installation costs. This Method is also suggested by [6]. In general it can be assumed that the effort for decommissioning will be lower than for the installation, since the process requires less accuracy and cautiousness due to the fact that most components will be recycled or scrapped [13].

CIAT calculates the decommissioning costs $C_{D\&D}$ as function of $C_{I\&C}$ cost components and discount factors.

$$C_{D\&D} = \sum_{i} C_i * f_{discount\ i}$$

Equation 27: Cost D&D

Where C_i refers to the cost components considered in the I&C phase and $f_{discount\ i}$ is the discount factor for each cost component. For the disposal CIAT considers a user defined fixed value for the scrap value and for landfill costs per wind turbine.

3.3 OPEX

Operational expenditures, usually referred to as O&M costs, include fixed and variable cost components including insurance cost, maintenance costs, spare parts and administration costs [4]. Total O&M do typically account for 20% to 25% of overall LCoE and are therefore a significant cost component [3]. Considering total expected wind energy investments of €239bn [5] until 2030 in Europe the importance of cost saving O&M strategies for wind energy is evident. While estimation of fixed cost components is relatively easy, the estimation of maintenance efforts and spare parts cots comes with a variety of uncertainties. Estimations for total O&M costs in offshore wind per MWh are in the range from 20.17 to 36.7 $€_{2010}$ [21]. The wide range of cost estimations shows the relevance of an accurate O&M cost model which incorporates the specific characteristics of the wind farm project including the applied maintenance strategy.

In the OPEX module of CIAT the expenditures associated with the operation and maintenance phase of the wind farm project are considered. Core of this module is an O&M simulation tool which models all maintenance activities taking place during the O&M life cycle phase. The essential requirement for this simulation tool is to provide the necessary input data for both the environmental impact model of CIAT as well the cost model.

To serve this requirement a simulation tool has been developed as a part of this work. This tool is an advancement of the O3M simulation tool, originally developed at Cranfield University [22]. It incorporates the modelling of:

- Weather forecast
- Failure occurrence
- Maintenance strategies
- Vessel, crew and spare part availability
- Maintenance activities
- Key performance indicators

3.3.1 Theoretical background

Reliability is a characteristic of a system or a system component, describing its ability to fulfil its required function under certain operating conditions. Mathematically, it is the probability that an item will run without occurrence of a failure for a stated time interval. Thus, for numerical statements of reliability the required function, the operating conditions as well as the time interval has to be considered. This applies for repairable as well as nonrepairable items [23].

A failure is an occurrence which stops an item from fulfilling its required function. Failures are described by a failure mode which is defines the visible symptom of a failure and a failure cause which defines the reason for occurrence of a failure. Additionally, failures may have further effects or consequences [23].

An important parameter is the failure rate $\lambda(t)$ as describe by [24]**.** The failure rate is defined as

$$\lambda(t) = \frac{-\frac{d}{dt} * R(t)}{R(t)}.$$

Equation 28: Failure rate

While $R(t)$ describes the time dependent reliability function, it is possible to determine the failure rate with empirical experiments. In many cases the shape of the failure rate will look like the bathtub curve depicted in Figure 3-9.

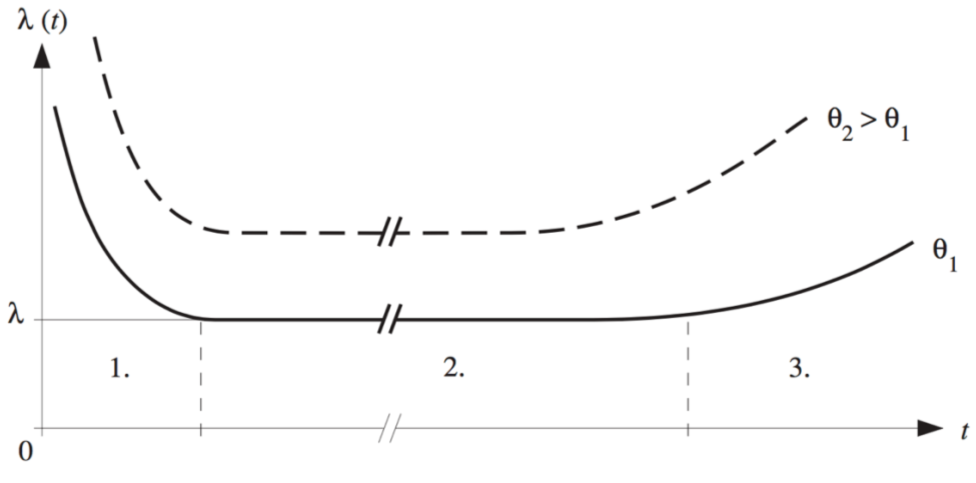

Figure 3-9: Bathtub Curve [23]

This behaviour can be explained with the characteristics of three lifetime phases[24]:

1. Burn in: Failures in this phase are often caused by weaknesses in the production process or material. The failure rate is decreasing rapidly.
2. Useful life: The failure rate is nearly constant. Failures occur randomly or due to human error or misuse.
3. Wear out: The failure rate is increasing due to aging processes such as high cycle fatigue.

However, since in many cases the exact shape of the failure rate function is not known it is reasonable to assume a constant failure rate $\lambda(t) = \lambda$ for practical application. In this case the reliability function can be modelled with a exponential distribution [24]:

$$R(t) = 1 - F(t) = e^{-\lambda * t}$$

Equation 29: Reliability function

Figure 3-10 illustrates the temporal sequence of a failure occurrence. The Mean Time Between Failure (MTBF) is used as a measure for reliability of repairable systems. For an exponential distributed reliability function MTBF is given by [9]:

$$MTBF = 1/\lambda$$

Equation 30: MTBF

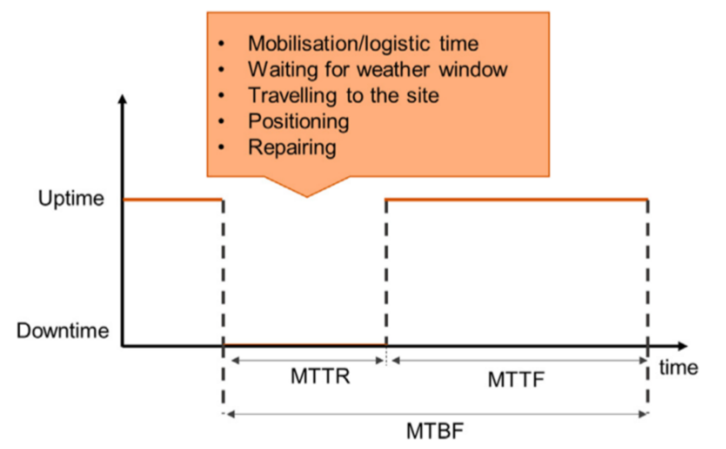

Figure 3-10: Illustration MTTR, MTTF and MTBF [9]

The connection between Mean Time To Repair (MTTR), Mean Time To Failure (MTTF) and MTBF is given by:

$$MTBF = MTTR + MTTF$$

Equation 31: MTBF

Maintenance is referred to as all activities which are performed in order to retain a system in or restore a system to a specific state [23]. Related to wind turbines the general goal is to keep the system in an operational state or restore it to a operational state, thus reducing downtimes. Downtimes caused by planned or unplanned maintenance activities are directly affecting the profitability and the LCoE of a wind farm project. Therefore, the selection of a suitable maintenance strategy is of great importance.

Figure 3-11 shows a classification of maintenance strategies which are in place in modern wind farm operations.

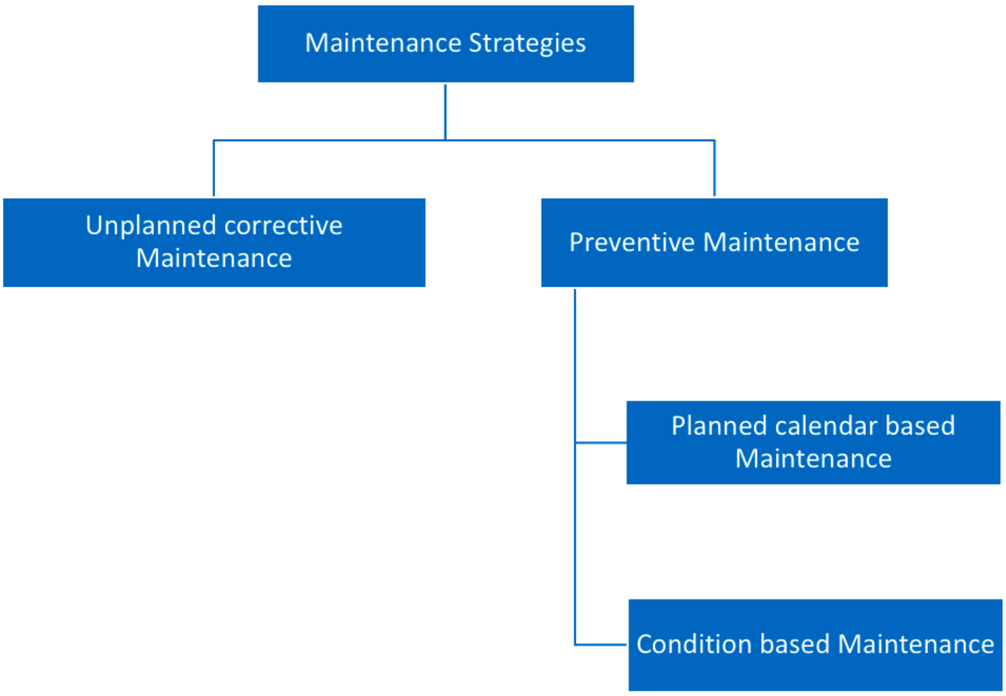

Figure 3-11: Maintenance Strategies

Unplanned corrective maintenance refers to a method, which makes use of the total possible lifetime of a system or system component which is an essential advantage of this maintenance strategy. The maintenance intervention takes place after the failure has occurred. Usually, the turbine will not be in an operative state until the affected part has been repaired or replaced, which will result in a production loss. Another aspect to consider is that the failure of one component might have severe consequences and cause damage or failure of other components. Some failure modes also depend on the load condition of the turbines which means that failures will occur more likely in periods with high load. Especially in offshore wind this can lead to longer downtimes due to adverse weather conditions during phases with high wind speeds. On the other hand there are low investment costs for monitoring systems required [25].

The preventive branch describes a group of maintenance strategies where the maintenance intervention takes place before the actual occurrence of a failure.

Planned or calendar based maintenance activities take place after a defined operational time which might depend on the individual component. The goal of planned preventive maintenance actions is to reduce the probability of failure occurrence and connected downtimes. This strategy is characterized by easy logistics, easy activity planning and scheduling and low operational downtimes [25]. However, in a planned maintenance strategy the system or single components are maintained disregarding their actual functional condition. In general components are not used for their maximum lifetime. This approach leads to an increased use of resources such as maintenance crews, vessels and spare parts.

Condition based maintenance aims at the determination of the actual condition of a component in operation. Maintenance activity are carried based on the actual condition of the component but before the occurrence of a functional failure. Thus, in theory the total lifetime of a component is used efficiently. Concepts for the determination of a components condition often assume an accumulation of damage over its lifetime due to operating conditions. Damaged components are assumed to have a remaining functional potential. A maintenance activity can be triggered for a certain level of functional potential.

Approaches for the determination of the actual component condition are usually based on the evaluation of measurement data like vibrations or temperature [26]. If a measurement value exceeds predefined threshold value a certain degradation of the component is assumed. Other approaches are based on comprehensive data analysis aiming on the identification of patterns which predict the occurrence of a failure.

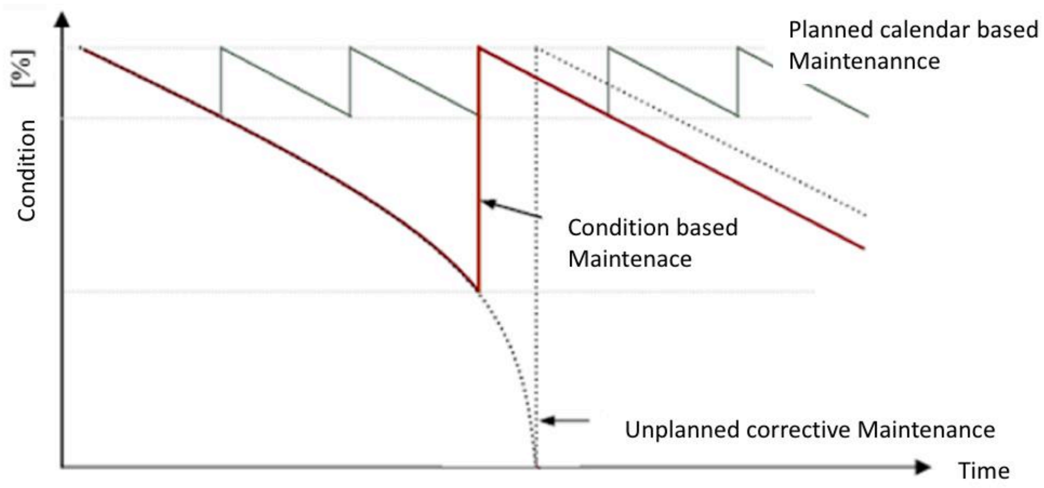

Figure 3-12: Maintenance strategy characteristics [27]

Figure 3-12 depicts the characteristics of the three different maintenance strategies in a schematic way.

One essential advantage of preventive maintenance strategies is the reduced downtime compared to corrective maintenance interventions. While in corrective maintenance the downtime from occurrence to restoration includes logistic times, waiting times and travel times in preventive maintenance the downtime only includes the actual repair time. As a consequence the production loss for preventive maintenance activities is significantly smaller. This relationship is depicted in Figure 3-13.

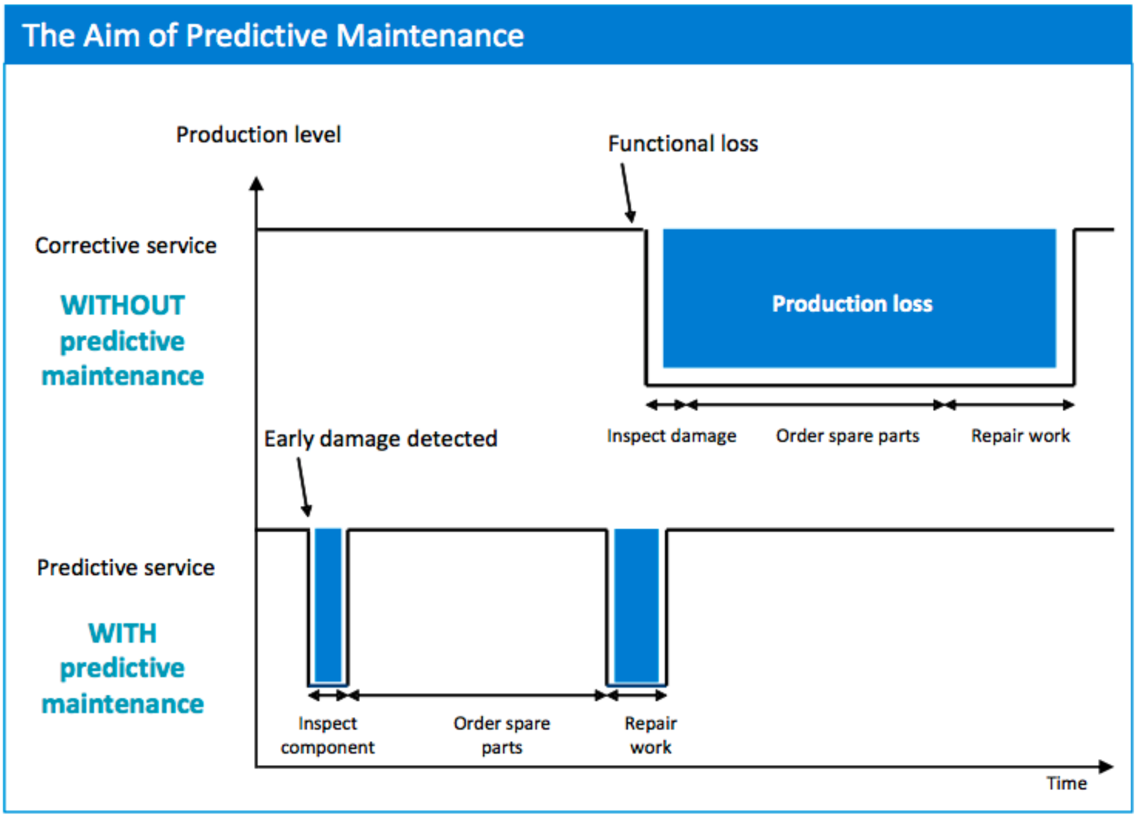

Figure 3-13: Predictive Maintenance [28]

However, condition monitoring systems are not available for all components of a wind turbine and require significant investments and operational expenditures. In addition there is a risk that the condition monitoring system may not be reliable itself. Thus, the monitored component may fail before the system indicates a degradation. This would result in a corrective maintenance activity with potentially high downtimes.

Considering the above mentioned, there is a need for optimizing the overall maintenance strategy regarding the relation between the reduction of production loss due to downtimes, and maintenance efforts in the form of investments for monitoring systems or resources like vessels, crew and spare parts.

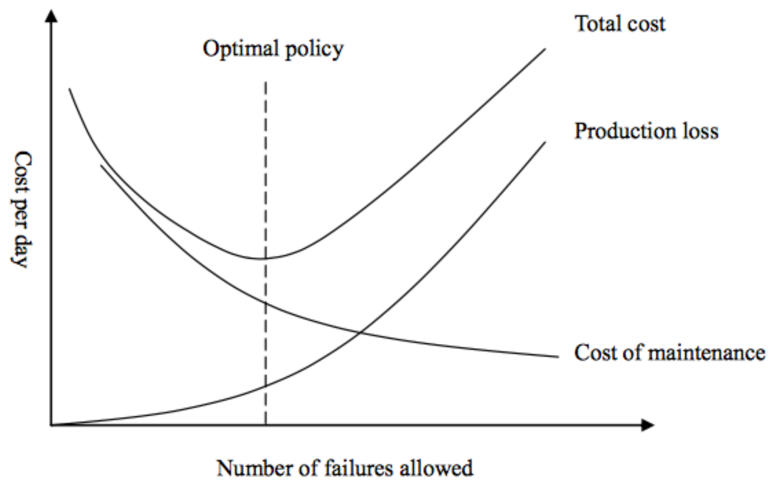

Figure 3-14: Optimal maintenance strategy [25]

In Figure 3-14 this optimization problem is depicted. In this concept, the costs for maintenance activities are related to number of failure allowed by the maintenance strategy. A low number of allowed failures or a low allowed production loss will result in high maintenance efforts and thus in high cost. Allowing a higher number of failures and thus downtime, will result in high production loss and rise overall costs. The ideal maintenance strategy will represent the point of lowest overall costs by making use of an ideal mix of maintenance strategies.

3.3.2 O&M Simulation Tool

In the following section the O&M simulation tool developed as part of this work is described by making use of the Hierarchical Control Conceptual Model (HCCM) framework introduced by [29]. HCCM is a structured approach used to model the problem situation and to report the resulting simulation.

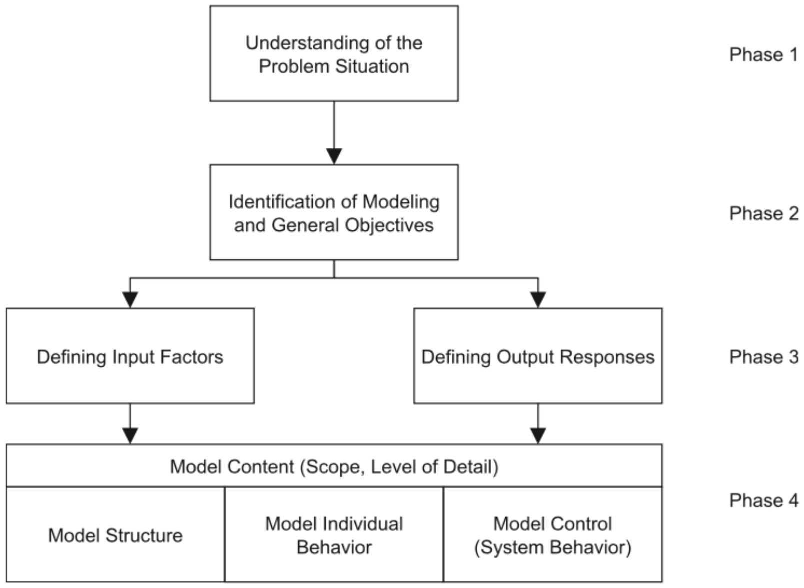

Figure 3-15: Structure of the HCCM framework [29]

As depicted in Figure 3-15 in a first step it describes the general problem addressed with the simulation. In a second step the objectives of the simulation are defined. From that, the necessary input and output parameters are derived. In the model content layer of the HCCM model the structure and behaviour of the simulation is described. The model structure defines the structure of elements which are part of the simulation. The model individual behaviour section describes the processes which determine how the elements in the simulation behave. Finally, the model control section describes the rules and processes which are responsible for the overall behaviour of the system.

3.3.2.1 Problem description

The economic feasibility of a wind farm project is highly depending on the cost efficiency of the operation and maintenance phase. In order to estimate resulting efforts for operation and maintenance as well as the energy yield of the wind farm, a model which considers all relevant influencing parameters is needed.

However, the model developed in this work is intended to serve as a generic framework rather than an exact replication of a specific wind farm. The system under consideration is a wind farm with 100 wind turbines arranged in arrays at a certain distance from a service port (Figure 3-16). It is assumed, that all maintenance activities are operated from this service port. Consequently, service vessels and maintenance crew are based in this port. All travel activities take place between the service port and the wind farm. Travel times are estimated based on vessel travel speed and distance. The spare part stock keeping is also located in the service port. Besides order waiting times, there are no further waiting times connected to the spare part supply.

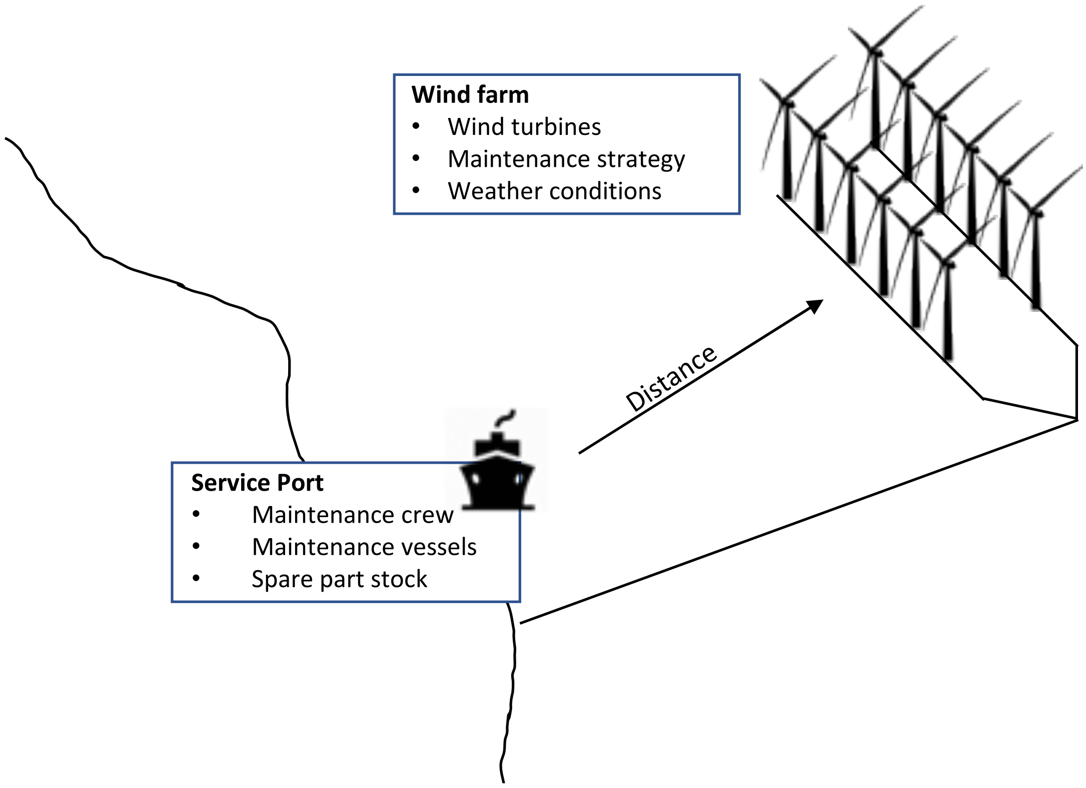

Figure 3-16: Offshore wind farm and service port

Wind turbines are multi component systems which require repair and maintenance activities over their lifetime. Overall goal of these activities is to keep the wind turbines in an available, operative state and maximize total availability over time. Downtimes caused by planned or unplanned maintenance activities are directly affecting the profitability and the LCoE of a wind farm project. Therefore, the selection of a suitable maintenance strategy is of great importance. To enable a realistic cost estimation the simulation must be capable to represent different maintenance strategies.

Weather conditions are affecting the wind farm operations in two ways. The wind speed defines the turbines energy yield dependent on the turbine specific power curve. Significant wave heights influence the maintenance process, since safe operations are only possible up to a maximum wave height which is defined for each maintenance vessel type.

3.3.2.2 Objective

The simulation is intended to answer the following main questions:

- What is the overall wind farm performance under a particular maintenance strategy?
- What is the influence of different maintenance strategies on the overall wind farm performance?
- What is the ideal mix of maintenance strategies in order to achieve a maximum overall wind farm performance?

Overall wind farm performance is an complex measure and has multiple dimensions to be considered. The first objective of a wind farm operator is to maximize the electricity output while minimizing the operational costs. Minimizing downtime by applying a preventive maintenance strategy will increase the total electricity output of the turbine. However, operational costs will increase due to more maintenance activities and increased use of spare parts. Furthermore, increasing the number of maintenance activities may add bottlenecks to the maintenance process chain due to limited resources like technicians and vessels. Thus, there is a target conflict between minimizing the efforts for operation and maintenance and maximizing the availability of the wind farm. The simulation must be able to address this conflict and find the ideal solution.

Another aspect to consider when evaluating wind farm performance is the influence on environmental impact of the wind farm project over its lifecycle. The simulation must therefore be able to deliver relevant inputs for life cycle impact assessment. Although, the contribution to environmental impact categories from the O&M phase is rather small [30], transportation activities are a main contributors to marine eutrophication and photochemical oxidant formation [31] and should be considered.

3.3.2.3 Input / output

Input parameters of the O&M simulation tool can be grouped in variable and fixed parameters. Fixed model parameters are used to define the model independent from different scenarios described in chapter 5.1. Variable input parameters are used to define the different maintenance scenarios.

Fixed Inputs

Essential part of the model is the simulation of the failure behaviour of wind turbine components. This behaviour is modelled using empirical reliability data from offshore wind farms from previous studies [9]. Each wind turbine is divided into 19 subsystems, with each subsystem having three possible failure modes (minor repair, major repair, major replacement). For each possible subsystem and failure mode a failure rate is defined in a failure per year per turbine format which results in a total input of 57 failure rates. For each of these possible failure modes, additional parameters describing the number of required technicians, the average repair time and the material costs for this particular failure mode are defined. The behaviour of the maintenance process is further determined by parameters describing the number of available vessels per vessel type, a mission organisational time, the number of available maintenance crew members and travel times from the service port to the wind farm. It is assumed, that the travel time to the wind turbine as well as the mission organisational time is a constant averaged value only depending on the vessel type. The process of spare part procurement is determined by an initial number of spare parts per type as an input value.

For components which are maintained by applying a preventive maintenance strategy a reliability threshold value for each failure mode is defined which controls the time, an intervention is triggered.

The weather forecast module is based on a Markov-chain approach and uses a historic set of weather data including wind speed, significant wave height and wind direction as an input. This weather prediction serves the calculation of wind turbine power production which has a wind turbine type specific power curve as an input. The power curve defines the electricity production as a function of wind speed including cut in and cut out speed. The weather information also determines if a specific vessel type is able to operate. Therefore, each vessel type has a maximum significant wave height assigned.

Variable inputs

The variable input parameters in this model are used to define the three different scenarios investigated. Since the scenarios are characterized by different combinations of maintenance strategy the input parameters are values, defining if a corrective or a preventive maintenance strategy is applied for each subsystem.

Outputs

Output parameters are aggregated key performance indicators which are collected and calculated during the runtime of the simulation in order to describe relevant system characteristics. The output parameters are finally used to answer the questions defined in the objectives of the simulation study. Core of the questions to be answered is the assessment of wind farm performance considering the different dimensions of performance.

To assess the total effort for maintenance activities all workorders processed during the simulation period are counted and relevant information is evaluated. This includes the total number of workorders in the maintenance categories, corrective, reliability based and calendar based. For each workorder the downtimes due to waiting and repair times are accessible for analysis. This information is used for cost assessment and final calculation of LCoE in the post processing modules. Another direct output is the average downtime per workorder which is a measure for the performance of the maintenance process. A breakdown which shows the downtime caused by each subsystem is also available.

An important measure which is commonly used to assess wind farm performance is technical availability as defined by IEC 61400-26:

$$Availability = \frac{Available\ hours}{Available\ hours + unavailable\ hours}$$

Equation 32: Availability

It provides the percentage of time in which the wind turbine was technically available disregarding if electricity was actually produced.

Based on operational status information of each turbine and actual wind conditions per time step the total amount of total produced electricity during the simulation period is calculated as an output. This output serves as an input for calculation of LCoE in the post processing.

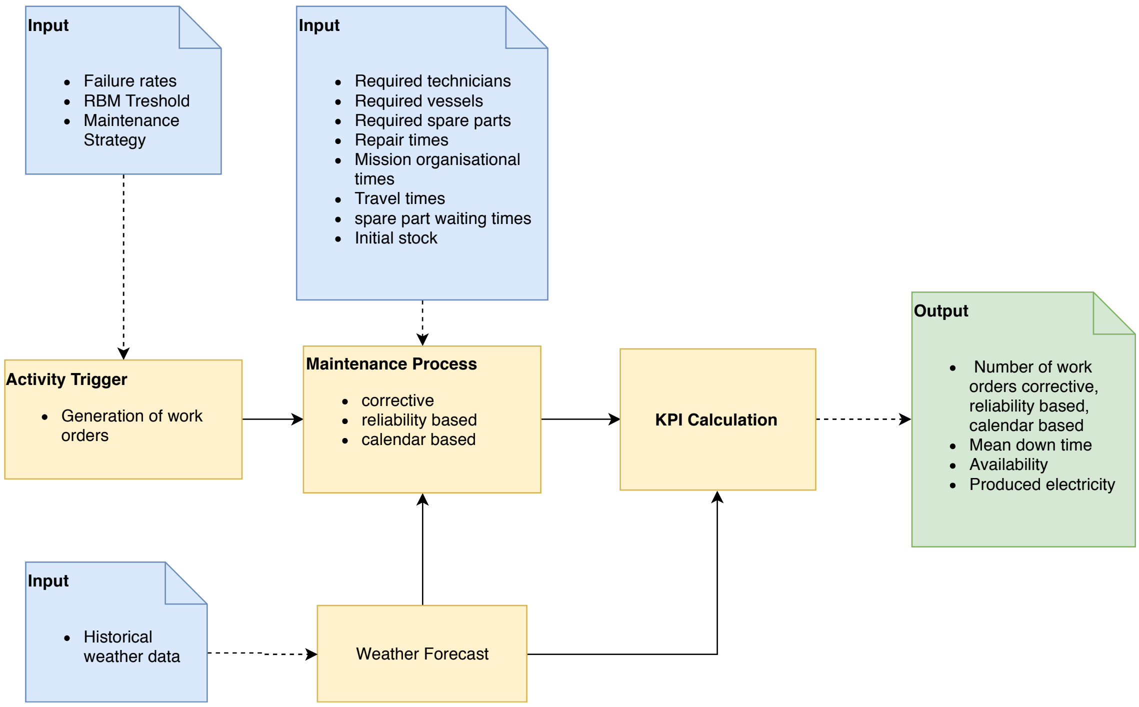

Figure 3-17: O&M simulation inputs and outputs

In Figure 3-17 the most relevant inputs and outputs of the O&M simulation are summarized.

3.3.2.4 Process Entities

Table 3-2summarizes the entities acting together in the O&M simulation. To each entity a set of attributes is assigned which describes the state of the entity.

Entity	Attribute	Description
Wind turbine	Subsystem structure	Each wind turbine is composed of 19 subsystems which can fail separately
	Failure mode	Each subsystem has three different failure modes which can occur. (Minor repair, major repair, major replacement)
	Operational state	The operational state of a turbine defines if the turbine currently available or not
	Power Curve	The wind turbine power curves provides the relation between actual wind speed and power output including cut in and cut out wind speed
Vessel	type	Defines the type of vessel. Different failures require different vessel types for maintenance activities
	total number	Total number of vessels for each type
	Availability	Each vessel can be available for a new activity or unavailable if it is in operation
Crew	total number	Total number of maintenance crew
	Availability	Each crew member can be available for a new activity or unavailable if it still on mission
Spare part	type	Defines the spare part needed for each possible failure
	initial stock	Defines the total number of initially available spare parts per type

	stock	Defines the number of currently available spare parts per type

Table 3-2: Process entities

3.3.2.5 Individual behaviour

In this section the individual behaviour of the entities defined before is described in detail.

Starting point of the simulated process is the individual failure behaviour of the wind turbines. A main assumption in this simulation is that the subsystems are either be maintained according to corrective maintenance strategy or to a preventive, reliability based maintenance strategy. This means that subcomponents which are maintained with the reliability based strategy will not fail and cause a corrective maintenance activity. Calendar based maintenance is assumed to take place after a constant time period of one year independent from the chosen maintenance strategy for all subcomponents.

Based on the occurrence of corrective, reliability based and calendar based workorders, the behaviour of the other active entities in the process is determined.

To model the occurrence of failures which cause the generation of a corrective workorder, all subcomponents which are maintained according to corrective maintenance strategy are pooled to a serial overall system without redundancy. The occurrence of a failure is modelled using an exponential distributed reliability function with a constant failure rate for the overall system.

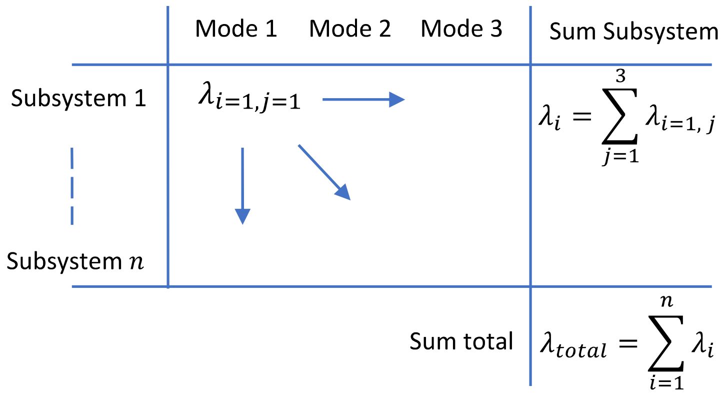

Figure 3-18: Failure rate aggregation for subsystems and failure modes

As depicted in Figure 3-18, the total failure rate λ_{total} is the sum of all subsystem failure rates λ_i. The subsystem failure rate λ_i is the sum of the failure rates of the failure modes $\lambda_{i,j}$.

The reliability function of this system is given by

$$R = e^{-\lambda_{total} * t}.$$

Equation 33: Reliability function

Accordingly the distribution function of the system is given by

$$F = 1 - e^{-\lambda_{total} * t}.$$

Equation 34: Distribution function

To simulate the time to failure with a statistical range of variation a Monte Carlo experiment is conducted using a random number between zero and one. Accordingly, the time to failure is given by

$$t_{failure} = -\ln(1 - rand) * \frac{1}{\lambda_{total}}.$$

Equation 35: Time to failure

Here, the random number represents the probability of failure occurrence.

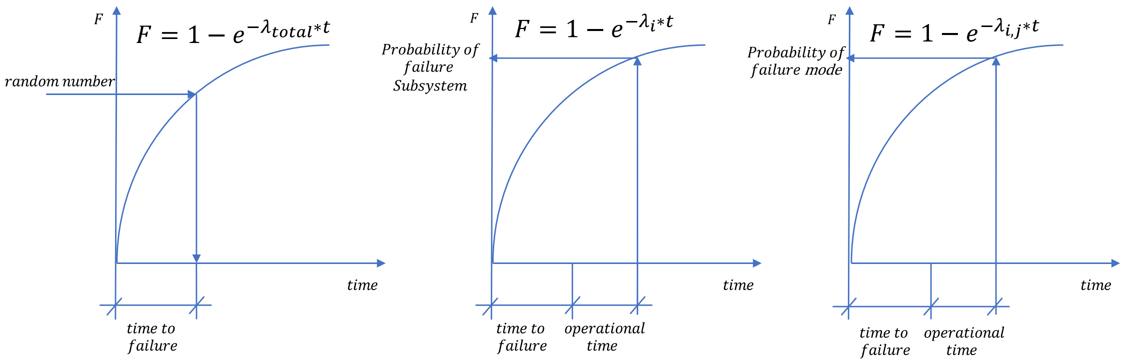

Figure 3-19: Subsystem and failure mode sampling procedure

After the determination of time to failure of the overall system, the failure probability of each subsystem is calculated considering the time to next failure and the time the subsystem was in operation before. With the failure probability of each subsystem known, the failed subsystem is sampled. The failure mode of the chosen subsystem is chosen, using the same approach. The failure probability of each failure mode is calculated and the failure mode is sampled. This procedure is depicted in Figure 3-19. The occurrence of a failure triggers the change of the operational status of the wind turbine from available to unavailable. It also triggers the generation of a workorder which defines the activities to be carried out in order to restore the turbine to an operational state again. This workorder includes all relevant information which is needed for the maintenance process.

The occurrence of a reliability based, preventive maintenance action is triggered by modelling the reliability function of each failure mode of the affected subsystem and calculating the time, a defined reliability threshold is fallen short (Figure 3-20). The statistical variation of a threshold shortfall is modelled by adding a uniform distributed proportion between -0.5 and 0.5 of MTTF:

$$t = \frac{\ln(R_{threshold})}{\lambda} + \Delta t \text{ with } R_{threshold} = 0.4 \text{ and } \Delta t \in (-\frac{0.5}{\lambda}, \frac{0.5}{\lambda})$$

Equation 36: Time to threshold

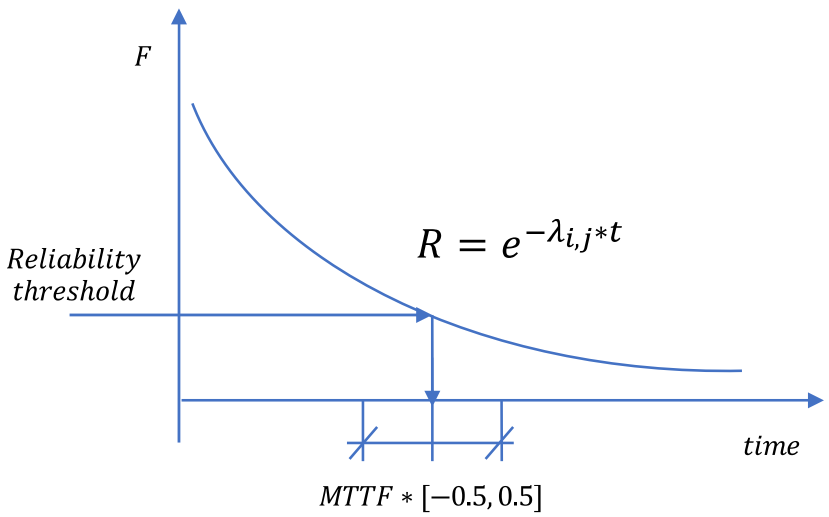

Figure 3-20: Reliability threshold

As soon as the simulation time has reached the calculated time for a reliability shortfall, the generation of a workorder is triggered which defines the activities to be carried out in order to reset the reliability of the affected subcomponent. In this case the wind turbine remains in its available operational state.

Calendar based maintenance workorders are generated according to the maintenance schedule. The turbine remains in its available operational state until the actual repair activity begins.

In all cases, workorders contain all relevant information to specify the maintenance process. This includes the affected subsystem and failure mode as well as crew, vessel and spare part requirements. Figure 3-21 shows the processes for different maintenance strategies and the operational states of the wind turbines which is either set by the occurrence of a failure or the maintenance process itself.

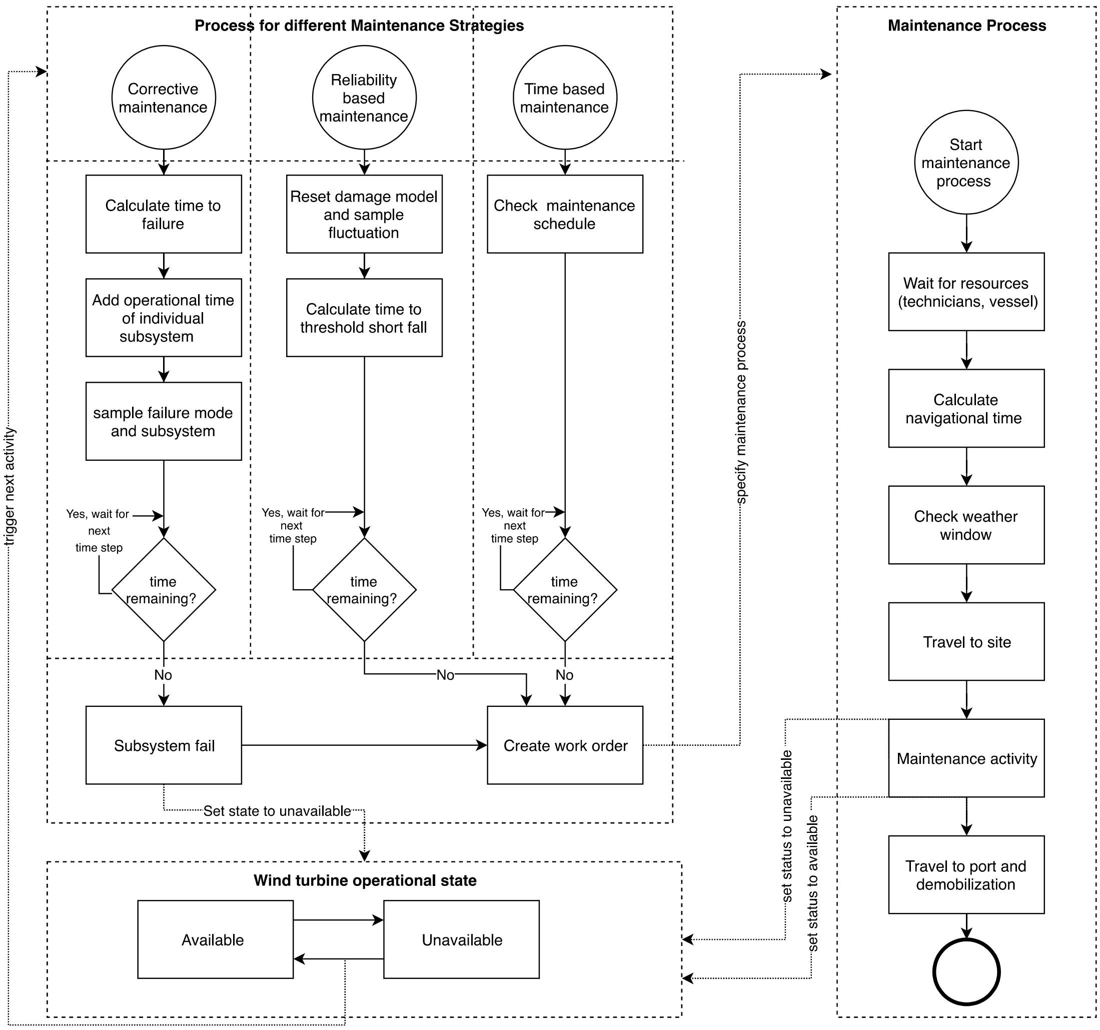

Figure 3-21: Failure simulation process and turbine operational states

Vessels and maintenance crew members and spare parts belong to resources required for the maintenance process. Within the maintenance process their availability is checked. Vessels and maintenance crew members are located in pools of available units. If a maintenance process requires a certain type and number of vessels and an certain number of maintenance crew members the respective units are blocked. Thus, they no longer available for other workorders. In case the maintenance process has reached its end, the respective vessels and maintenance crew members are enabled in the pool of available units.

Spare part behaviour is different for different spare part types. Parts needed for minor and major repairs are hold on stock. They are reordered as soon a defined stock threshold is reached. After an individual waiting time they are available for use. Spare parts needed for major replacements are not hold on stock. They are ordered as soon the specific spare part is needed by a maintenance process. After an individual waiting time they are available for use.

The maintenance process, as detailed depicted in Figure 3-22, is generic for all three types of maintenance activities. After receiving a workorder, the availability of required vessel, crew spare parts is checked. In case resources are not available the process pauses until they are available. If all resources are available the total navigational time is calculated considering mission organisational time, travel times, repair times and demobilisation times. For the calculated navigational time, it is checked if a weather window is available. In case a weather window is not available the process pauses. If the weather window is available the mission takes sea, following the depicted order. Downtimes are counted according to the type of the individual workorder. For corrective maintenance all waiting times and activity durations until the restoring of the turbine are counted. For planned and reliability based maintenance activities only repair times contribute to downtimes.

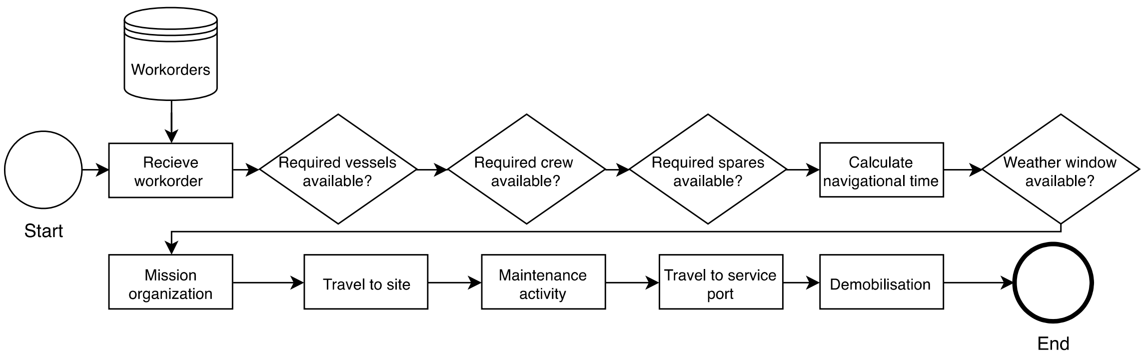

Figure 3-22: Maintenance process

3.3.2.6 System control

The behaviour of the overall system is determined by the workorder dispatching. The dispatching is done in the following way. Priorities, determined by the type of maintenance activity, are assigned to all workorders. Corrective workorders have the highest priority followed by reliability based workorders with medium priority and planned calendar based workorders with the lowest priority. Within one priority category workorders are dispatched following a first in, first out principle. If all resources required for the execution of a workorder are available, they are blocked for the use in other missions and the workorder is closed. After the mission has ended, the blocked resources are enabled for the use in pending workorders.

3.3.2.7 Implementation in CIAT

For the calculation of operational expenditures, in CIAT relevant data on maintenance activities is used in the cost modules. In general, it is distinguished between time based and corrective and reliability based maintenance activities.

For **planned maintenance** activities the simulation tool creates a list of all maintenance missions taking place during the lifetime of the wind farm. This list includes the following information:

- Mission number
- Total mission time
- Required vessel type
- Required maintenance crew
- Time stamp

With this information, combined with defined vessel day rates and personnel costs CIAT calculates the cost of planned maintenance activities by

$$C_{time\ based} = \sum_{i=1}^{n} t_{mission\ i} * (c_{vessel\ i} + n_{crew\ i} * c_{crew}) \ .$$

Equation 37: Cost time based activities

For **corrective** and preventive, **reliability based** maintenance activities the simulation tool also creates a list of all missions taking place during the wind farm project lifetime. This list includes the following information:

- Mission number
- Affected subsystem
- Failure Category (minor repair, major repair, replacement)
- Required Crew

- Required vessel type
- Number of vessel required
- Required special vessel
- Total mission time
- Time stamp

This information is supplemented by spare part cost data for each subsystem and failure category as well as vessel and personnel costs.

Combining this information CIAT calculates the cost of unplanned maintenance activities by:

$$C_{corrective/RbM} = \sum_{i=1}^{n} t_{mission\ i} * \left(c_{vessel\ i} + n_{crew\ i} * c_{crew} + c_{vessel\ special\ i}\right) + c_{spare\ i}$$

Equation 38: Costs corrective and reliability based activities

In this approach, it is assumed that only travel times and maintenance times contribute to the mission time, mobilization and demobilization times are excluded. Another main assumption is that each mission takes place separately.

3.4 Revenue Module

The revenue module in CIAT calculates the LCoE of the modelled wind farm project. LCoE are commonly used to compare the electricity costs of different energy generation concepts. LCoE in CIAT is calculated based on [13] by

$$LCoE = \frac{\sum_t \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_t \frac{E_t}{(1+r)^t}} .$$

Equation 39: LCoE

Where $CAPEX_t$ and $OPEX_t$ represents the capital respectively operational expenditures at time t. E_t is the amount of Electricity produced at time t.

The capital costs of the project are represented by:

$$r = WACC$$

In the present version of CIAT the total Energy yield over the total lifetime is imported from the simulation tool. Therefore, it is assumed that the produced electricity is equally distributed over the project lifetime.

4 Life cycle impact assessment

Life cycle assessment (LCA) as defined by [32] is method for assessing the environmental aspects and potential impacts associated with a specific product or service over its life cycle. This is achieved by creating an inventory of relevant inputs and outputs related to the life cycle of a product or service and evaluating potential environmental impacts of those inputs and outputs. The results of an LCA can help to identify improvement potentials for environmental aspects and assist in decision making processes in the industry. Furthermore, it can help to justify environmental claims or environmental product declaration.

[32] provides a general framework of phases a LCA should include as shown in Figure 4-1.

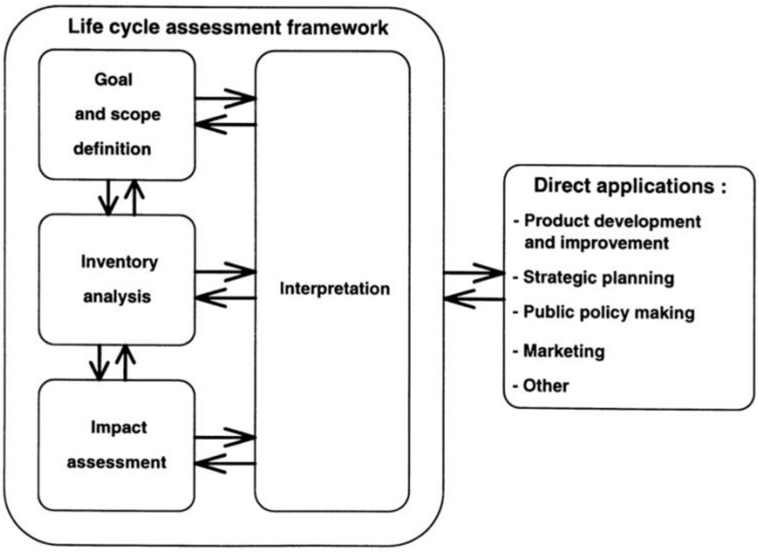

Figure 4-1: LCA Phases

The **goal and scope definition** aims to define the intended application, the reasons for carrying out the study and the indented addressees. The scope of the study aims to define the functions of the system, the functional units and the system boundaries. Another important aspect is the description of any assumptions made in the study and limitations of the study.

The **Inventory analysis** includes the collection and quantification of relevant inputs and outputs. These will typically include the use of resources, raw materials and energy inputs as well as releases to air, water, and land.

The **impact assessment** phase links the defined input and output inventory to specific environmental impact categories and evaluates their significance.

The **interpretation** phase combines the findings from inventory analysis and impact assessment to achieve the previous defined goals. Outputs of this phase may be conclusions or recommendations for decision makers.

This work and the development of the life cycle impact tool follows the framework proposed by [32] in general. However, the scope of this work is not to conduct a LCA for a specific offshore floating wind project but to develop a parametric model which gives researchers and developers assistance in understanding and benchmarking the environmental and ecological impacts of their floating wind concepts. Therefore, the model does not predetermine a specific goal and scope definition to allow a wide scope of application for the user. The main objective of the model is to give the user guidance and to simplify the phase of inventory analysis and impact assessment.

The interpretation of results and derivation of specific recommendations for action is not part of the model and must be conducted by the user according to the requirements of the specific use case.

4.1 Goal and Scope

Although, the specific definition of goal and scope of the LCA is determined by the practitioner , the LCA module in CIAT is developed for LCA of floating offshore wind turbine concepts. In this respect, general assumptions and system boundaries are defined in this chapter.

Figure 4-2 shows the life cycle of an offshore wind farm and its components from the extraction of raw materials to the decommissioning and recycling. Each phase of the life cycle is characterized in by inputs, such as energy use and transportation needs, and outputs in the form of emissions. During the O&M

phase, the offshore wind farm delivers electricity to the grid. CIAT models all processes related to these life cycle phases and links them to relevant inputs and outputs. Processes which might occur outside the life cycle phases shown in Figure 4-2 are not considered in this model.

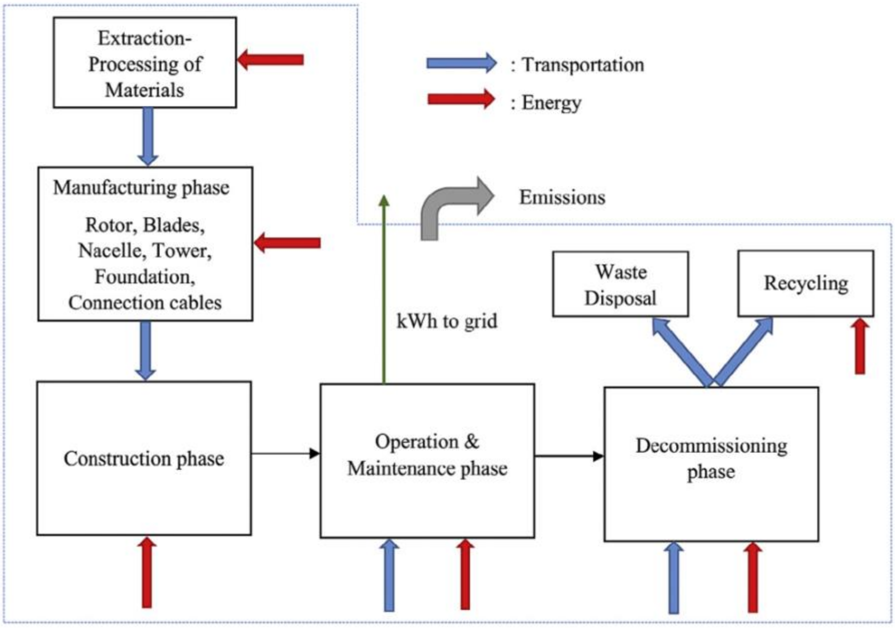

Figure 4-2: Life cycle flow chart of a wind farm [33]

The definition of technical system boundaries is another important characteristic of the LCA model. CIAT includes all components of the floating offshore wind farm which are necessary for the offshore power generation and the transportation of the electricity to the onshore grid connection point. Main components are the offshore wind turbines including the floating substructures, moorings and anchors and the electric system including cable and the offshore substation. The technical system boundary is shown in Figure 4-3.

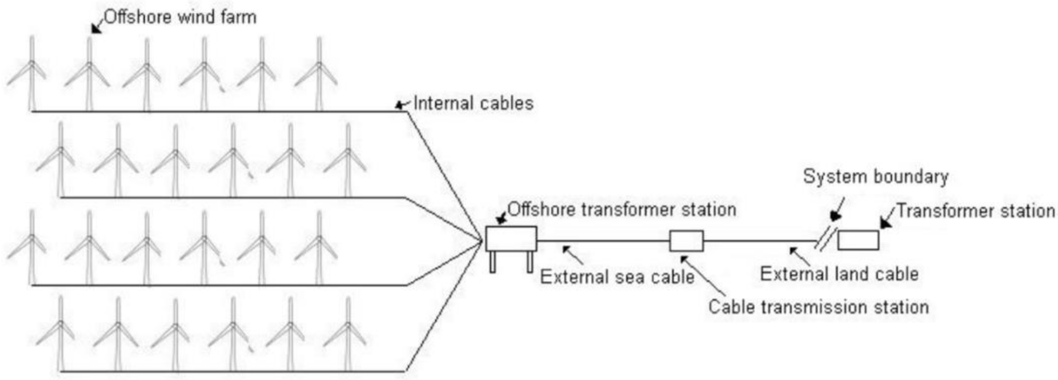

Figure 4-3: Offshore wind power plant system boundary [18]

4.2 Inventory Analysis

Two approaches for inventory analysis can be found in recent LCA studies of offshore wind farms. A process-LCA is a bottom up approach which models the life cycle processes in physical terms [30]. In this case specific process data is used to model to model the physical inputs and outputs for each process step. As stated by [30] this approach provides a high level of accuracy and detail in theory. Practically, cut off criteria must be introduced to exclude processes with insignificant contribution and to limit the modelling effort in terms of labour and time to a reasonable level. Typically, the process LCA considers only a limited number of main materials and key production processes while excluding support processes like production of installation tools and machinery [34]. This general problem of inaccurate system boundary definition in process LCA can lead to significant deviation in the LCA results and systematically underestimated environmental impacts [35]. This needs to be considered in the interpretation phase of the LCA.

Another approach in use is the environmental extended input-output analysis (EEIOA). EEIOA is a top down approach which uses monetary data of economy sectors to quantify inventories [30]. In this case the system is not described on a technical level. Instead, the system is described by monetary flows between the industry sectors involved. The environmental impact of the system is then derived by the aggregated environmental impact data of each industry sector. This approach does not have the same problem of inaccurate system boundaries as the process LCA since it can model the entire economy involved. However, EEIOA is dependent on aggregated industry data which is too coarse to model specific processes [35].

Researchers and developers of offshore floating wind concepts are most likely interested in understanding the environmental impact of concepts on a detailed process level. Furthermore they are likely to have a detailed knowledge about the processes involved in the life cycle which makes a process-LCA on a reasonable level of accuracy possible. Therefore, CIAT follows the process-LCA approach for modelling inventories.

In CIAT inventories for the life cycle assessment are created in the same categories used in the capital expenditures module in the cost model. One exception is the D&C phase which is not considered in the LCA since its contribution is assumed to be neglectable.

4.2.1 Production & Acquisition

The production and acquisition phase is expected to be by far the biggest contributor to energy demand and impact indicators such as global warming potential. As analysed by [30] the contribution is in the order of 90% of the total values across the entire life cycle. This emphasizes the need of an accurate and detailed modelling of this phase. CIAT aims to offer a generic framework for the inventory analysis of produced components.

In CIAT the production and acquisition process is modelled by breaking down the wind farm functional groups. These may include but are not limited to:

- Nacelle
- Rotor
- Tower
- Floating Substructure
- Moorings
- Electrical System

For each of these functional groups the user defines the contained components. In case of the Nacelle group for instance these may include but are not limited to:

- Nacelle (housing)
- Generator
- Main shaft
- Main bearing
- Yaw system

When the components are defined to the desired level of detail, for each component a list of materials and a list of associated production processes is created in CIAT. The materials are quantified in [kg] while the unit for the production processes depends on the process.

The result of this step is a quantified list of contained materials and production processes for each group and component. This is the basis for the quantification of impact indicators later on. The advantage of this method is that the depth and the level of detail of the analysis can be chosen by the user according to the specific goals of the LCA and the available information.

The CIAT Impact module in MATLAB will now calculate the emissions of this phase by:

$$E_j = \sum_{i=1}^{n} m_i * e_{ji} + u_i * e_{u\,ji}$$

Equation 40: Emissions P&A

Where E_j denotes the total emission of category j. m_i is the mass of material i while e_{ji} and $e_{u\,ji}$ are the associated emission per unit.

4.2.2 Installation & Commissioning

Recent LCA studies on wind farms like [36], [34], [37] do not consider activities carried out in I&C phase in detail. Emission emerging from transportation and on-site installation processes are neglected due to their small contribution to the overall emission or modelled through rough estimations. However, as stated by

[31] transportation activities are a main contributor to marine eutrophication and photochemical oxidant formation. Therefore, this work develops a framework to model the airborne emissions from ships resulting from combustion of marine fuels. Other emission that might occur for example due to land based activities are not considered.

The method used for inventory analysis in CIAT is based on the cost modelling procedure of the I&C life cycle phase. The activities taking place in the I&C phase are already documented in the I&C phase of the CAPEX module. Therefore, CIAT imports the data of each cost component considered in the CAPEX module. With the information about duration of activities and associated vessel types CIAT calculates the input and output inventory for this life cycle phase. As described by [38] relevant releases to the atmosphere resulting from ship operations are:

- Carbon Dioxide
- Methane
- Nitrous Oxides
- Sulphur Oxides
- Nitrogen Oxides
- Volatile Organic Compounds
- Ozone depleting Substances

The CIAT Impact module in MATLAB will calculate the emissions of this phase by

$$E_j = \sum_{i=1}^{n} h_i * e_{ji}$$

Equation 41: Emissions I&C

Where E_j denotes the total emission of category j. h_i represents the operational hours of vessel i while e_{ji} the associated emission hour.

4.2.3 Operation & Maintenance

In this section the inventory due to the use of different vessel types in the O&M phase is modelled in a similar way as in the I&C phase.

$$E_j = \sum_{i=1}^{n} h_i * e_{ji}$$

Equation 42: Emissions O&M

Where E_j denotes the total emission of category j. h_i represents the operational hours of vessel i while e_{ji} is the associated emission per hour.

4.2.4 Decommissioning & Disposal

The D&D inventory in CIAT is divided in decommissioning and disposal. The decommissioning phase is modelled with an approach similar to the cost calculation of this phase. It is assumed that the activities taking place during decommissioning are similar to the ones in the installation phase. Therefore the emission inventory of I&C is discounted by a factor $f_{DD\ Impact}$.

To estimate the amount of waste produced by D&D phase the sum of used materials from the P&A model is considered. For each material share of landfill and recycling is defined together with the information whether the waste is harmful or not. CIAT then calculates the sum of hazardous and non-hazardous waste.

4.3 Impact Assessment

The impact assessment is the third phase of a LCA and links the input and output inventory defined in the previous phase to their contribution to environmental impacts. It can be structed in five steps as described by [39]:

- Selection of impact categories and category indicators according to the goal and scope of the study (e.g. global warming potential)
- Assignment of the input/output inventory to impact categories defined in the previous step (e.g. CO2 emissions are assigned to the impact category global warming potential) This step is referred to as *classification.*

- Calculation of category indicator results. In this step characterization factors are assigned to each stressor. This factor indicates how much a single stressor contributes to the respective impact category. The contribution of methane would be expressed by a factor indicating its CO2 equivalent for instance.

Impact indicators

The results the life cycle assessment can be presented in the form of single stressors such as the amount of CO2 emissions associated with the life cycle of a product. Although CO2 emissions are an important measure, with this presentation, there is no link to the actual environmental impact of this stressor. Therefore, stressors can be aggregated to specific impact indicators. Midpoint indicators assimilate several stressors to a single impact category such as global warming potential. Endpoint indicators, such as human health or ecosystem health, assimilate stressors a higher level [30]. Figure 4-4 illustrates an impact pathway of specific stressors and their midpoint and endpoint indicators.

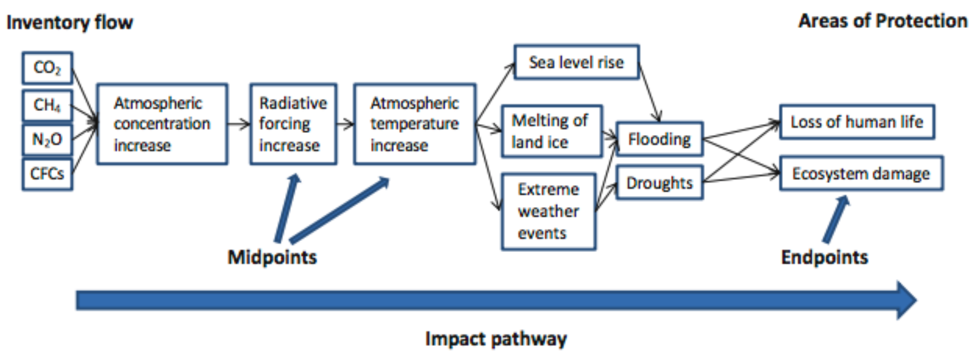

Figure 4-4: Impact pathway example [39]

Each impact indicator can be located along the impact pathway. It is important to note that the impact pathway must be modelled up to the point where the chosen impact indicator is located. Endpoint indicators require the modelling of the whole impact pathway up to areas of protection, such as loss of human life or ecosystem damage [39].

The framework of [32] does not provide an exhaustive list of impact categories and does also not define which impact categories have to be included in a LCA.

Thus, the inclusion and exclusion of specific impact indicators is eventually depending on the individual goals of the LCA and needs to be justified the practitioner. The Danish Ministry of the Environment gives the following general recommendation concerning the selection of impact categories in [40]:

- All impact categories should be included for which international consensus has been reached
- Internationally recognised impact categories should only be excluded if that can be justified scientifically
- Depending on individual goal and scope definition it can be necessary to include also new impact categories for which international consensus has not been reached
- Qualitative assessment of potential environmental impact is acceptable if there is no quantitative method or available data is not sufficiently accurate

In the literature several default lists of impact categories and related default classifications can be found. In practice the use of this default lists reduces the effort of conducting an LCA significantly. Recent LCAs related to wind power like [33], [37] and [36] focus on energy demand and impact categories related to greenhouse gas emissions and global warming potential. CIAT aims to give the user guidance in conducting an individual LCA according to the specific goal and scope definition. Therefore, in this chapter impact categories included modelled in CIAT together with classification and characterization definition are introduced based on the recommendation of [41] and on the review of recent LCA of offshore wind farms.

4.3.1.1 Cumulative energy demand and energy yield ratio

Although Cumulative Energy Demand (CED) and Energy Yield Ratio (EYR) are no direct environmental impact indicators, they are important parameters for the energetic performance of an power generating system. CED comprises the entire energy demand which arises during all life cycle phases of a product. As stated by [42] the total energy demand can be calculated by adding the energy demand of each life cycle phase. CIAT calculates the total energy demand by adding the CED for P&A, I&C, O&M and D&D:

$$CED_{total} = CED_{P\&A} + CED_{I\&C} + CED_{O\&M} + CED_{D\&D}$$

Equation 43: CED

The EYR is the total produced energy by the wind farm during its lifetime W_{total} over CED_{total} [42]:

$$EYR = \frac{W_{total} * g}{CED_{total}}$$

Equation 44: EYR

Another important measure for the sustainability of renewable energy power plants like offshore wind farms is the Energy payback Period (EPB). The EPB determines the time the wind farm has to be in operation and generate energy to compensate the cumulated energy demand of its entire life cycle [37]. Following the method defined in VDI 4661 the EBP is calculated in CIAT by

$$EBP = \frac{CED_{P\&A} + CED_{I\&C} + CED_{D\&D}}{E_{yearly} * g - CED_{O\&M}} .$$

Equation 45: EBP

In this calculation the energy demand of the O&M phase is covered by the yearly electricity production E_{yearly}. The energetic supply factor g is introduced to value the produced electricity as primary energy. It indicates how much kWh of primary energy are used to produce one kWh of electricity in the reference system [37]. The correlation of life cycle phases and EBP is depicted in Figure 4-5.

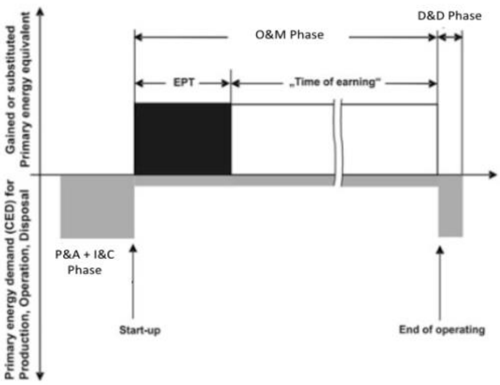

Figure 4-5: Energy payback period, adapted from [43]

4.3.1.2 Global warming potential

Global warming is referred to as the effect of increase of temperature in the lower atmosphere. Incoming solar radiation is partly reflected by the earth surface in the form of infrared radiation. The presence of greenhouse gases such as carbon dioxide or methane in the atmosphere is causing the reflection of infrared radiation (radiative forcing) and is thus causing the greenhouse effect. As a consequence of increasing temperatures in the atmosphere and in the oceans impacts such as melting polar ice caps, sea level rise, extreme meteorological events and other regional climate change effects may occur. Figure 4-6 shows the impact pathway for the emission of greenhouse gases, as defined by the International Reference Life Cycle Data System (ILCD) Handbook.

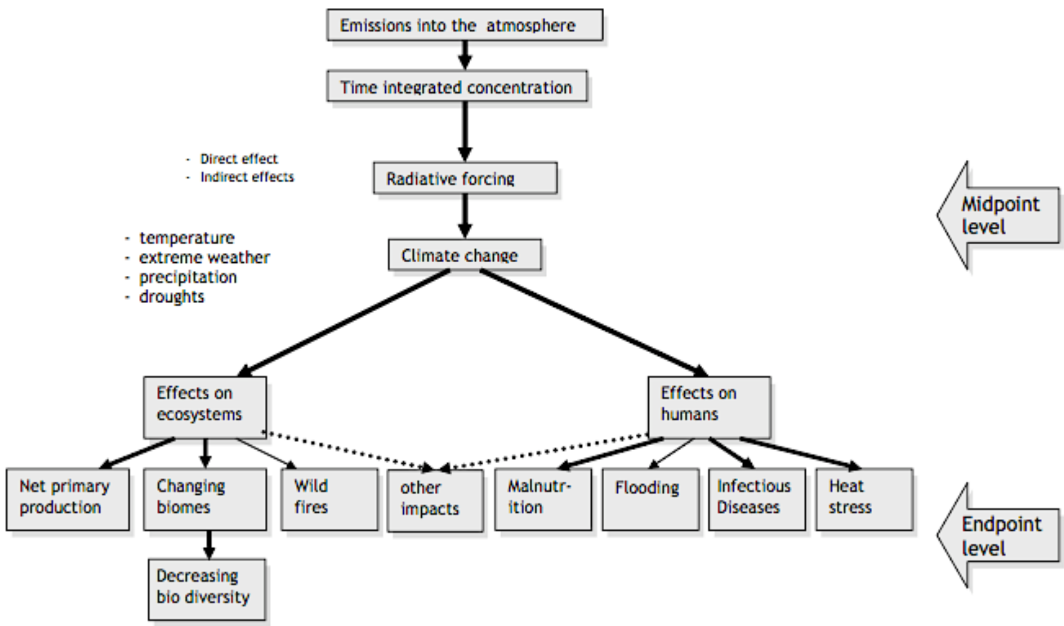

Figure 4-6: Impact pathway climate change [44]

In CIAT the midpoint impact indicator radiative forcing is used for global warming potential impact category. The modelling of endpoint effects is a complex task which is object of recent research activities and is out of the scope of this work. However the results at midpoint level are usable as input for further assessment if required by the practitioner. More detailed information can be found in [45] and [39].

In general substances contributing to global warming are gases which absorb infrared radiation or are degraded to CO2 and have an lifetime in the atmosphere which allows significant contribution [41]. The main greenhouse gases (GHG) resulting from human activities contributing to global warming according to [39] are:

- Carbon dioxide (CO2)
- Nitrous oxide (N2O)
- Methane (CH4)
- Halocarbons

For the LCA of floating offshore wind turbines the most relevant GHG certainly is CO2 which is mainly the result off combustion processes. However, the impact of all GHGs mentioned can be modelled in CIAT using Global Warming Potentials (GWP) as characterization factors. GWP is an index measuring the radiative forcing following an emission of a unit mass of a GHG accumulated over a chosen time horizon, relative to CO2 [45]. With these factors the amount of CO2 emission which would cause the same radiative forcing (CO2-equivalent) are calculated for different GHGs by

$$GWP = \sum_i GWP_i * m_i \ .$$

Equation 46: GWP

GWP values for timespans of 20 and 100 years can be found in appendix A1. The values are abstracted from the most recent assessment report, published by the Intergovernmental Panel on Climate Change (IPCC) [45]. Although, these values represent state of the art research it must be mentioned that the uncertainty of GWP values is estimated to be in the order of 30% [39]. GWPs for contributing substance can be found in appendix A1.

4.3.1.3 Photochemical ozone formation

Unlike the stratospheric ozone, which is vital for life on earth ground level ozone formation has several negative impacts on human health and ecosystems. Negative impacts arise due to the reactive nature of ozone. Ozone is able to oxidise organic molecules on surfaces exposed to it. For humans this can result in tissue damage and respiratory diseases. For vegetation the exposure to elevated ozone concentration can result in oxidative damage on photosynthetic organelles [44].

Although the photochemical ozone formation process is highly complex and depending on many parameters it can be summarized as follows. Ozone is formed under the influence of sunlight and the presence of

- VOC (non-methane volatile organic carbons)
- CO (carbon monoxide)
- NOx (nitrogen oxide)

VOCs or CO react with hydroxyl radical in the troposphere and form peroxy radicals. The peroxy radicals oxidize nitrogen oxide to nitrogen dioxide. Oxygen atoms are formed by splitting of nitrogen oxide under the influence of sunlight. Oxygen atoms react with molecular oxygen in the ambient air to ozone [44]. Detailed information on the ozone formation process and the impact path as shown in Figure 4-7 way can also be found in [39].

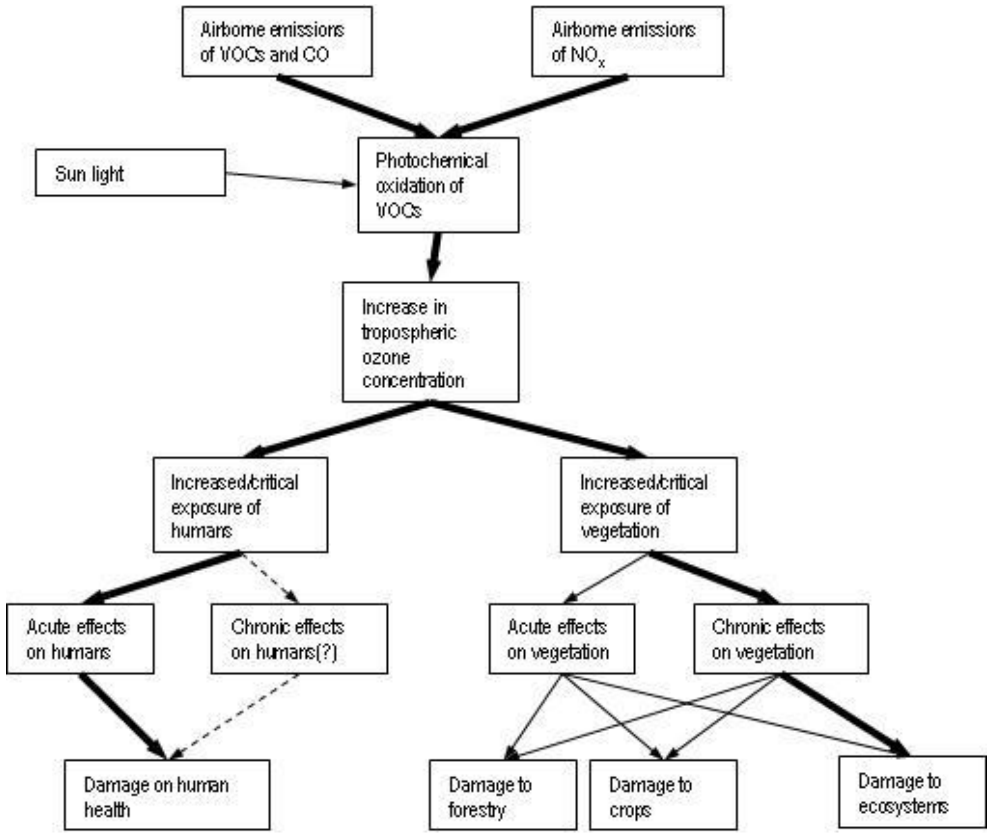

Figure 4-7: Ozone formation impact pathway [44]

The complexity of the ozone formation process leads to a simplification of the characterization models suggested for the use in life cycle assessments. One commonly used characterization method is the use of POCP Photochemical Ozone Creation Potential (POCP). POCPs are relative values which describe the amount of formed ozone from a certain VOC in relation to the amount of ozone produced from an equally large emission of ethene [41]. Similar to global warming potential and ozone depletion potential the POCP is directly used as midpoint impact indicator in CIAT:

$$POCP = \sum_i E_i * POCP_i$$

Equation 47: POCP

Endpoint indicators such as ecosystem damage or damage on human health are not modelled in CIAT. Photochemical ozone formation is considered to be a regional impact category. It is therefore important to note that POCP values are dependent on the specific regional scenarios. The POCP of a specific VOC is depending on the nitrogen oxide concentration in the ambient air for instance. Therefore POCP values can be found for high nitrogen oxide environments and low nitrogen oxide environments. In appendix A2 POCP values from several sources can be found.

4.3.1.4 Acidification

The impact category acidification refers to processes that increase the acidity of terrestrial and aquatic environments caused by hydrogen ion concentration. It is generally caused by the emission airborne acidifying chemicals such as nitrogen oxides, sulphur dioxide and ammonia [44].

Typical consequences of acidification in terrestrial ecosystems are the in inefficient growth and dieback of softwood forests. In aquatic ecosystems clear acid lakes without any wildlife can be observed as a consequence. Also manmade structures like buildings or sculptures can be damaged by the exposure to acid rain [41].

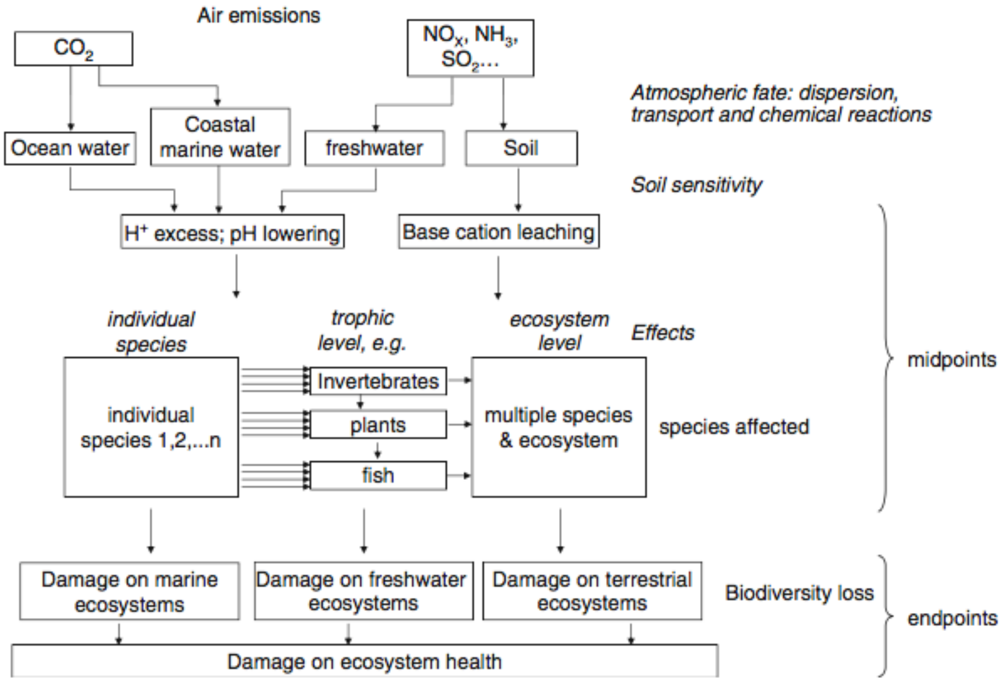

Figure 4-8: Acidification impact pathway [39]

Figure 4-8 shows the impact pathway from airborne emission different endpoint indicators. Further information on the impact pathway and associated chemical reactions can also be found in [46], [39] and [44].

Substances contributing to acidification effects are substances which result in the supply of hydrogen ions in the environment or in leaching of the corresponding anions from the concerned systems such as [41]:

- Sulfur Dioxide
- Sulfur Trioxide
- Nitrogen Oxides
- Hydrogen Chloride
- Nitric Acid
- Sulfuric Acid

For the characterization of different substances contributing to acidification an equivalence factor is used. It describes the Acidification Potential (AP) of each contributor in relation to the AP of sulfur dioxide. In this way APs are given in sulfur dioxide equivalents [41]. In CIAT the sum of APs from all contributing substances is directly used as midpoint impact indicator:

$$AP = \sum_i EF_i * m_i$$

Equation 48: AP

In Appendix A3 a list of equivalence factors for main contributors can be found.

4.3.1.5 Eutrophication

The anthropogenic increase in nitrogen and phosphorus inputs in terrestrial and aquatic ecosystems is referred to as nutrient enrichment or eutrophication [39]. It describes the over-supply of nutrient salts in the environment. Typical consequences of nutrient enrichment for terrestrial ecosystems include effects on vegetation such as changing plant communities and damage to forestry and crops. In aquatic ecosystems the consequences include as a change in communities of animals and plants as well. A typical effect is an increased production of algae and plankton which sinks down to bottom layers of the water body. The algae is the broken down in a oxygen consuming process[40]. This leads to an decreasing oxygen concentration which has adverse effects on the biodiversity in the affected water bodies. Further Information on the impact pathway can be found in [39] and [44].

Characterization is realized by means of the EDIP methodology. In this approach substances contributing to the impact category are characterized by their [41]:

- N-potential, which expresses their nitrogen content
- P-potential, which expresses their phosphorus content
- The equivalence factor for the total nutrient enrichment potential, while an average ratio of 16:1 is assumed between nitrogen and phosphorus contents in aquatic organisms

In CIAT the P-potential is considered by:

$$P_{eq} = \sum_{i} m_i * EF(P)$$

Equation 49: Eutrophication

Effect potential for contributing substance can be found in appendix A4.

5 Case Study

Based on the theoretical framework developed in the previous chapters, a cases study has been developed as part of this work. In this case study the framework is used to model a large offshore floating wind farm consisting of 100 wind turbines. This model is evaluated in terms of costs and environmental impact. The input parameters are based on a spar type floating wind turbine concept (quelle) such as the sway concept. However, some input parameters are estimated based on data from other concepts and projects. Furthermore, not all details of this concept are considered and some details are simplified for the purpose of this study.

In order to assess the influence of applying different maintenance strategies three different scenarios are defined for the O&M phase. The results of these scenarios are evaluated in the cost and impact assessment modules.

The wind farm modelled in this cases study consist of 100 offshore wind turbines with a power rating of 5MW. The power output of the wind turbine is characterized by a power curve with a cut in speed of 5 m/s and a cut out speed of 25 m/s at a hub height of 85 meters. For the cost module it is assumed that all activities and associated costs for the D&C, P&A and I&C phase appear in the first three years of the project. In year three the wind turbines operational lifetime of 20 begins. The D&D phase is assumed to take place in year 23.

For the FINEX module, an equity debt ratio of 0.3 to 0.7 is assumed. It is further assume that the return on investment is 15% while the return on debt is 7%. The inflation rate is assumed to be 2.5% while the asset tax rate is 17%.

5.1 Cost assessment

In this section relevant input parameters for the calculation of capital expenditures and operational expenditures are summarized.

Table 5-1shows estimated costs arising in the D&C phase. Information is based on an estimation for a fixed bed offshore wind farm given in [9]. It is assumed, that costs will not differ significantly for a floating offshore wind farm.

Activity	Cost
Project management	40,000,000.00 €
Legal	15,000,000.00 €
Environmental Survey	5,000,000.00 €
Coastal processes Survey	5,000,000.00 €
Met station Survey	5,000,000.00 €
Sea bed Survey	5,000,000.00 €
Contingency	110,000,000.00 €
C_Base Engineering	500,000.00 €
C_Unit Engineering	5,000.00 €

Table 5-1: D&C cost assumptions

Table 5-2 shows the estimations made for substructures, mooring lines, anchors and cables based on information given in [13]. The cost of the wind turbine itself is calculated using Equation 8, assuming a power rating of 5 MW and tower cost of 1 million € per turbine. Additionally costs for monitoring systems are considered with 75,000€ per turbine.

Substrcuture wind turbine	Cost [€/ton]	mass [tons]	Complexity factor
Steel	1,000.00 €	2000	1.2
Subsstructure Subsation			
Steel	1,000.00 €	4000	1.2
Wire wind turbine	**Cost [€/m]**	**Required length [m]**	**required quantity**
Type 1 Cain	50.00 €	2000	1
Type 2 Wire	250.00 €	150	1
Wire Substation			
Type 3 Cahin	60.00 €	2500	1
Type 4 Wire	300.00 €	200	1
Anchor type	**Cost [€/unit]**	**Quantity / turbine**	
Type 1 Wind turbine	350,000.00 €	3	
Type 2 Substation	400,000.00 €	3	
Cables	**Required length [km]**	**Required quantity**	**Cost [€/km] , [km]**
Offshore 1a	0.2	10	320,000.00 €
Offshore 1b	2	10	320,000.00 €
Offshore 1c	0.2	1	320,000.00 €
Offshore 2	100	1	450,000.00 €
Onshore	20	1	200,000.00 €
Potective equipment			1,000,000.00 €

Table 5-2: P&A Cost assumptions

Table 5-3 shows estimations made for all I&C activities which are calculated using Equation 21. Additionally, costs for cable laying activities are considered to be 50.000€ per km.

Transportation to port	**Value**	**Duration [days]**	**Unit Cost**	**OW**
Road transport	1	1	5,000.00 €	0.95
Sea Transport	1	1	100,000.00 €	0.8
Port installation and loading	**Value**	**Duration [days]**	**Unit Cost**	**OW**
Quayside lifts	5	0.08	6,000.00 €	0.75
Personal usage	30	0.08	370.00 €	0.75
Transportation to offshore site	**Value**	**Duration [days]**	**Unit Cost**	**OW**
Crane Vessel Rigging	1	0.15	530,000.00 €	0.65
Tug boat transportation	1	1	17,000.00 €	0.7
AHTS transportation	0.5	1	90,000.00 €	0.7
PSV Loading	1	0.3	50,000.00 €	0.75
PSV Transportation	0.3	0.5	50,000.00 €	0.7
Offshore installation activities	**Value**	**Duration [days]**	**Unit Cost**	**OW**
Crane Vessel offshore lifts	1	0.7	530,000.00 €	0.6
Crane Vessel ballast	1	0.7	530,000.00 €	0.5
Personell Usage	30	0.7	370.00 €	0.6
Tugboat Mooring	2	1	17,000.00 €	0.6
Tugboat Assistance	2	0.7	17,000.00 €	0.6
AHTS Mooring	1	1	90,000.00 €	0.6
AHTS Assistance	1	0.7	90,000.00 €	0.6
PSV Assistance	1	0.7	50,000.00 €	0.6
Offshore installation activities Substation	**Value**	**Duration [days]**	**Unit Cost**	**OW**
Tugboat Mooring	2	1	17,000.00 €	0.6
Tugboat Assistance	2	0.7	17,000.00 €	0.6
AHTS Mooring	1	1	90,000.00 €	0.6
AHTS Assistance	1	0.7	90,000.00 €	0.6
PSV Assistance	1	0.7	50,000.00 €	0.6
Tug boat transportation	1	1	17,000.00 €	0.7
AHTS transportation	0.5	1	90,000.00 €	0.7
PSV Loading	1	0.3	50,000.00 €	0.75
PSV Transportation	0.3	0.5	50,000.00 €	0.7

Table 5-3: I&C cost assumptions

Table 5-4 summarizes the assumptions made for the anchor installation procedure.

Mooring Installation	Cost Vessel [€/day]	number anchor / turbine	t_inst [days]	OW_inst	t_transit [days]	capacity_deck	OW_transit
Turbine Mooring	50,000.00 €	3	0.3	0.6	0.6	10	0.75
Substation Mooring	50,000.00 €	3	0.3	0.6	0.6	10	0.75

Table 5-4: Assumptions anchor installation

Although, the O&M phase is just one life cycle phase which is considered in cost assessment as well as impact assessment the outputs of the O&M simulation are used as an input for KPI calculation in both modules. In the following section the relevant input parameters as described in chapter 3.3.2.3 as well as the different O&M scenarios are explained.

Table 5-5summarizes the input values for failure rates, repair times and number of required crew members. This information is retrieved from [9].

Subsystems	Minor repair			Major repair			Replacement		
	Failure rate [failures/year]	Repair time [h]	Required Crew [#]	Failure rate [failures/year]	Repair time [h]	Required Crew [#]	Failure rate [failures/year]	Repair time [h]	Required Crew [#]
Pitch	0.824	9	2	0.179	19	3	0.001	25	4
Other compo	0.812	5	2	0.042	21	3	0.001	36	5
Generator	0.485	7	2	0.321	24	3	0.095	81	8
Gearbox	0.395	8	2	0.038	22	3	0.154	231	17
Blades	0.456	9	2	0.01	21	3	0.001	288	21
Oil / grease / other liquid	0.407	4	2	0.006	18	3	0	0.1	0
Electrical compo	0.358	5	2	0.016	14	3	0.002	18	4
Contactor / Circuit breaker	0.326	4	2	0.054	19	3	0.002	150	8
Controls	0.355	8	2	0.054	14	3	0.001	12	2
Safety	0.373	2	2	0.004	7	3	0	0.1	0
Sensors	0.247	8	2	0.07	6	2	0	0.1	0
Pumps / motors	0.278	4	2	0.043	10	3	0	0.1	0
Hub	0.182	10	2	0.038	40	4	0.001	298	10
Heaters / coolers	0.19	5	2	0.007	14	3	0	0.1	0
Yaw system	0.162	5	2	0.006	20	3	0.001	49	5
Tower / fundation	0.092	5	3	0.089	2	1	0	0.1	0
Power supply / converter	0.076	7	2	0.081	14	2	0.005	57	6
Service items	0.108	7	2	0.001	0.1	0	0	0.1	0
Transformer	0.052	7	3	0.003	26	3	0.001	1	1

Table 5-5: Failure rates, repair times, required technicians

The characteristics of the vessels considered in the simulation are summarized in Table 5-6.

	Helicopter	Workboat	Jack-up	Divnig
Available Units	1	15	1	1
Mobilisation time [h]	8	0.1	720	360
Demobilisation time [h]	4	0.1	48	0.1
Travel times [h]	0.5	2	3	2
maximum wave height [m]	99	1.80	2	2
maximum wind speed [m/s]	20	16	10	10

Table 5-6: O&M vessel characteristics

All maintenance activities require one or more crew transfer vessel (CTV) with a capacity of 12 maintenance crew members. Maintenance activities on the foundation require a special diving vessel while major replacement on the transformer system require a jack up vessel. The wind farm is assumed to be in a distance of 40 nautical miles from the service port which results in a travel time of two hours for Crew transfer vessels and diving vessel and three hours for a jack up vessel. It is assumed that there are 80 maintenance crew members and 15 CTV available for use. Additional there is one jack up vessel and one diving vessel available. For all vessels type a fixed hourly rate is assumed (CTV:135€, Diving: 2500€, Jack-up: 4700€). The maintenance crew members are assumed to cause total cost of 250€ per mission hour. It is assumed, that all indirect fixed costs, such as management of workforce or the use of port facilities, are covered by the hourly rates. Spare part cost data used in this case study can be found in 8Appendix B. It is assumed that these costs cover possible fixed costs such as stock keeping or procurement costs.

For the scenarios evaluated in this study three different maintenance strategies are applied. In the first scenario (SI) a **corrective only** strategy is applied. In this case all subcomponents of the wind turbines are maintained with a corrective maintenance strategy. Thus, repair takes place after a failure occurred and the turbine is in an unavailable state until it is restored. This scenario is expected to cause the lowest O&M costs. However, there will be higher downtimes which may have an negative impact on total produced electricity.

The second scenario (SII) applies a **reliability based only** strategy. In this case all subcomponents are assumed to be maintained reliability based. Thus, repair takes place before the actual failure. The turbine remains available until the actual repair activities starts, which is expected to cause a higher availability and total produced electricity. However, residual lifetime of components will get lost and a higher number of workorders is expected. This scenario is a rather theoretical consideration, since in reality reliable condition monitoring systems are not available for all subsystems. However, it shows the potential and influence of using preventive maintenance and health monitoring systems.

In the third scenario (SIII) an **optimized** mix of maintenance strategies is simulated. In this case critical components are chosen to be maintained reliability based while the majority of components is maintained with a corrective strategy.

Critically is defined as the product of failure rate and average repair time ($\lambda * ART$). In [26] wind turbine components where condition monitoring is technically possible are listed. Matching this list with high impact subsystems (gearbox: 35.6 at major replacement; generator: 7.7 at major repair and replacement; pitch: 7.4 at minor repair; blades: 4.1 at minor repair) all subsystems with an impact higher than 4.0 are considered as applicable for reliability based maintenance. For simplicity reasons, only components that can be monitored via vibration sensors are considered for scenario three. It is further assumed, that all failure modes of monitored subsystems are detectable. Table 3 summarizes the scenarios. To consider service actions in O&M costs and produced energy calendar based maintenance is applied to all scenarios. For reliability based maintenance a reliability threshold of 40 % is assumed. In case this threshold is exceeded, the creation of a reliability based maintenance workorder is triggered.

Table 5-7 shows the assumed discount factors for decommissioning and site clearance activities. A remaining scrap value of 500.000€ and costs for landfill of 100.000€ are considered per turbine.

Cost Component	discount factor
IC Transport to port	0.8
IC Port installation	0.8
IC Transport offshore	0.8
IC offshore installation	0.8
IC Substation installation	0.8
IC Mooring	0.8
IC Electrical	0.8

Table 5-7: D&D Discount factor

5.2 Impact assessment

In this section relevant input parameters for the calculation of impact indicators are summarized. Table 5-8 shows embodied energy and CO2 emissions for materials and processes considered in production and acquisition of the wind farm components. The values are based on information given in [47]. Of course, for the scope of this study the input and output categories are heavily simplified and do not model the reality conclusively.

Following the estimations of [36] the tower floater combination is assumed to be made of 200 tons steel and 2500 tons gravel ballast. It is further assumed that associated processes are 1000m of welding and 2000m^2 of sandblasting. The nacelle is assumed to be made of 150 tons steel and 10 tons aluminium. Estimations for major turbine components are extracted from the *econinvent* [48] database. For the generator 50 tons of copper and 40 tons of steel are assumed. The turbine blades and the hub are assumed to be made of 13tons epoxy resin, 21.5 tons fibre glass and 30 tons cast iron. Composite prepreg and sandcasting processes are counted according to the material masses. Anchors and mooring lines assumed be made of 270 tons steel per turbine while cables are made of 2800 tons steel, 2800 tons copper and 400 tons aluminium in total. For the floater of the substation 4000 tons of steel are assumed.

Material	Embodied Energy [MJ/kg]	CO2 Emissions [kgCO2/kg]
Steel	30	3
Copper	55	4.38
Aluminum	155	8.24
Cast Iron	37	3.3
Epoxy Resin	137.1	5.7
Concrete	1.4	0.2
Iron	25	1.9
Fibre glass	28	1.5
Process	**Embodied Energy [MJ/unit]**	**CO2 Emissions [kgCO2/unit]**
Comosite pre preg [--/kg]	40	4.8
Flame Cutting [--/m^2]	8.5	1
Sandblasting [--/m^2]	12	1.44
Sand Casting [--/kg]	9.8	1.1
Welding [--/kg]	15.1	1.8

Table 5-8: Material and process embodied energy and CO2 emissions

In Table 5-9 values for sulphur oxides, nitrogen oxides and volatile organic compounds per hour of vessel, extracted from [38] and [49] are summarized. They represent legal limit values for marine diesel engines. For installation activities the use of vessels defined in the cost assessment is considered while for the O&M phase the actual efforts estimated by the O&M simulation are considered.

Type I&C	Fuel Oil Consumption [kg / hour]	Energy/hour [MJ/h]	CO2 [kg/ hour]	Sulphur Oxides [kg / hour]	Nitrogen Oxides [kg / hour]	Volatile Organic Compound [kg / hour]
CTV	62	2790	192.2	0.3	7.4	0.8
Tug Boat	625	28125	1937.5	3.1	74.4	7.8
ATHS	1300	58500	4030	6.5	154.7	16.3
PSV	833	37485	2582.3	4.2	99.1	10.4
Cranevessel	800	36000	2480	4.0	95.2	10.0
Cable laying vessel	2000	90000	6200	10.0	238.0	25.0
Type O&M	**Fuel Oil Consumption [kg / hour]**	**Energy/hour [MJ/h]**	**CO2 [kg/ hour]**	**Sulphur Oxides [kg / hour]**	**Nitrogen Oxides [kg / hour]**	**Volatile Organic Compound [kg / hour]**
Helicopter	80	3600	248	0.4	9.5	1.0
Workboat	62	2790	192.2	0.3	7.4	0.8
Jackup	2000	90000	6200	10.0	238.0	25.0
Diving	62	2790	192.2	0.3	7.4	0.8
Cable Laying	2000	90000	6200	10.0	238.0	25.0
Crane	800	36000	2480	4.0	95.2	10.0

Table 5-9: Vessel fuel oil consumptions and emissions

6 Case study results

CIAT offers a comprehensive framework for the integrated cost and impact assessment of floating offshore wind farms. In general, all variables introduced in chapters 3 and 4 can be accessed in the MATLAB codes of the O&M simulation, as well as the cost and impact module. In this section the results of the cases study introduced in chapter 5 are presented and discussed. Particular attention lies on the comparison of the three maintenance scenarios introduced in chapter 5. The evaluation of results takes place by considering the following key performance indicators.

Operation and Maintenance Simulation

- Availability
- Total Electricity Produced
- Average Downtime
- Workorders

Cost assessment

- Total Expenditures
- Levelized cost of electricity
- O&M Costs per MWh

Impact assessment

- Cumulated Energy Demand (CED)
- Energy Yield Ratio (EYR)
- Energy payback Period (EBP)
- Global Warming Potential (GWP)

Reasonable results of the O&M simulation are highly dependent on the realistic estimation of fixed input parameters. Especially the number of initially available vessels and maintenance crew members affects the behaviour of the O&M simulation as well as the results of the cost and impact module. Therefore, in a first step for scenario SI the downtimes of turbines over their lifetime has been evaluated according to the categorization shown in Figure 6-1.

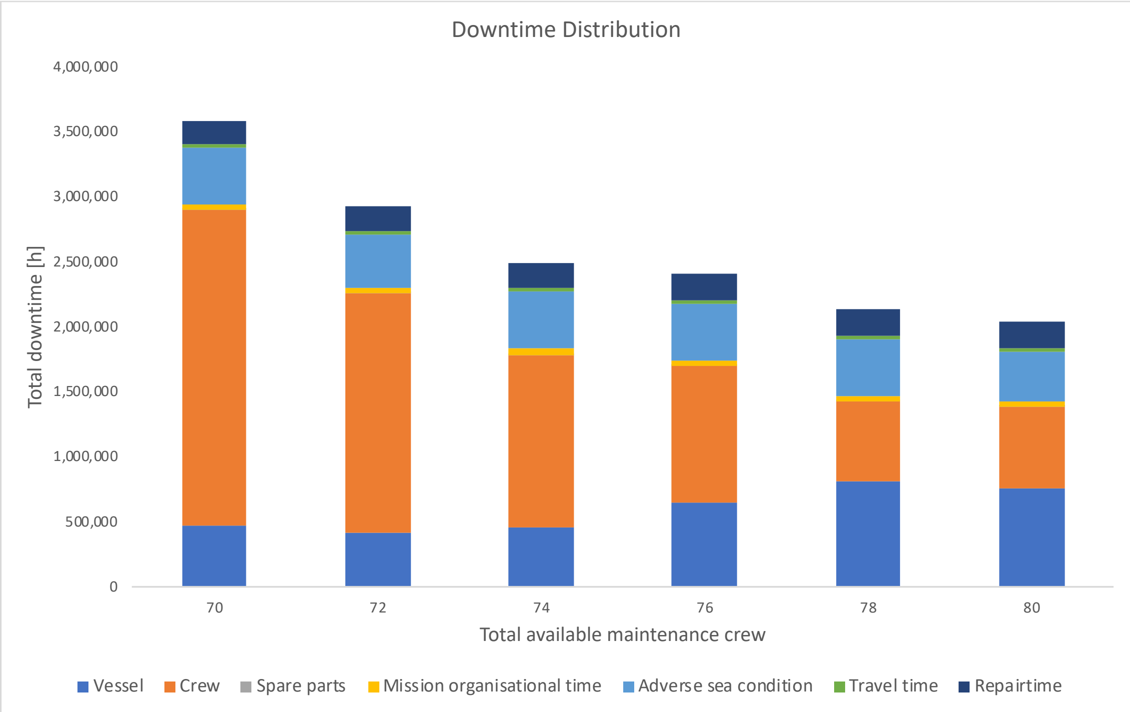

Figure 6-1: Downtime distribution

Downtimes are divided in waiting times, mission organisational times, travel times and actual repair time. Waiting times are consisting of waiting for vessel, waiting for crew, waiting for spare part and waiting for weather window. The distribution of these times has been evaluated for different initial crew and vessel availabilities. Therefore, the number of available maintenance crew members has been increased in steps of two. In this consideration a fixed ratio of one to five between maintenance crew and crew transfer vessel is assumed. This ratio represents the average occupancy of crew transfer vessels under the assumed failure rates and repair times.

With a total number of 80 available maintenance crew members and 15 available crew transfer vessels the distribution of downtimes shows a reasonable result which is in the order of magnitude found by [50]. These values are therefore used as input values in this study.

In order to achieve statistical significant results, each scenario was simulated 100 times. All values discussed in this section are averaged over 100 simulation runs. Table 6-2 illustrates the spread of total number of workorders per scenario. The total number of workorders spreads 4.6% in scenario SI, 3.7% in scenario SIII two and 1.1% in scenario SII. All confidence intervals are within ±1.54% and non-overlapping for all simulation results across each scenario.

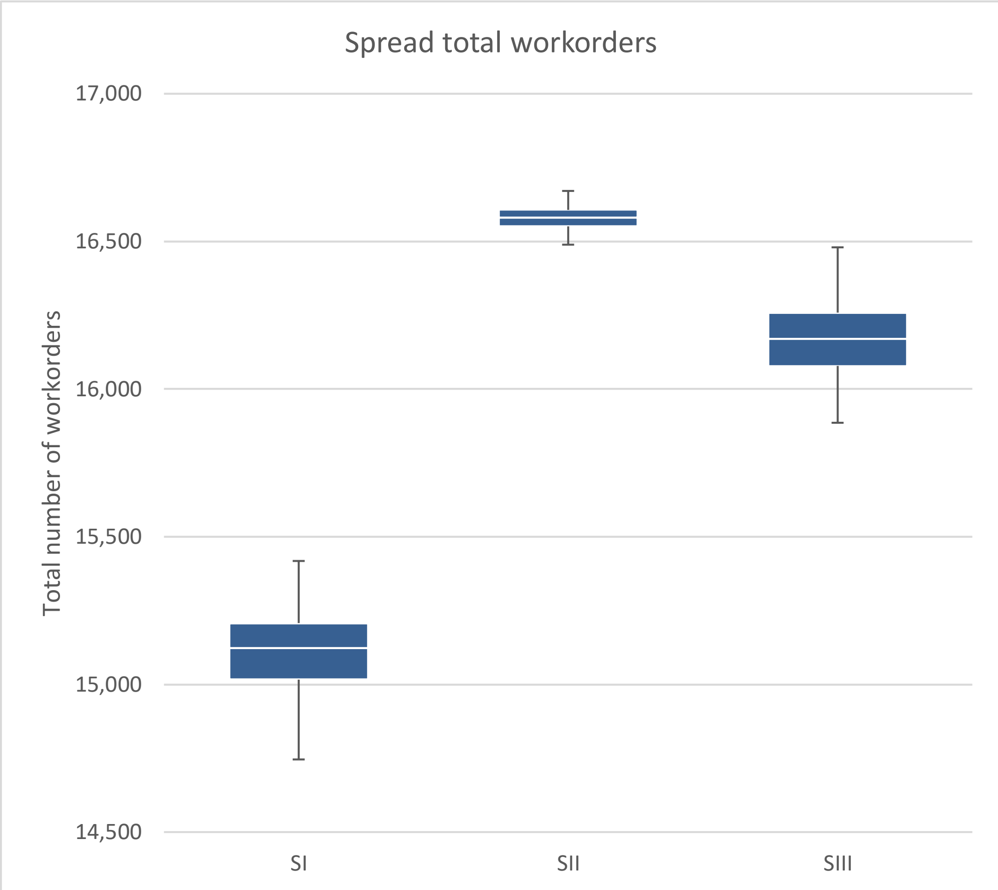

Figure 6-2: Spread of total number of workorders

Figure 6-3 shows the total downtime caused by failures of each subsystem in scenario SI. It can be seen that subsystems 3 and 4 account for the of the downtime. These subsystems represent the generator and the gearbox. As described in chapter 5.1 the application of a condition based maintenance system is technically feasible for these subsystems. Considering these simulation results, subsystems 3 and 4 have the highest potential for reduction of downtime in a condition based maintenance strategy. This results confirms the selection of subsystems simulated with a reliability based maintenance strategy in SIII.

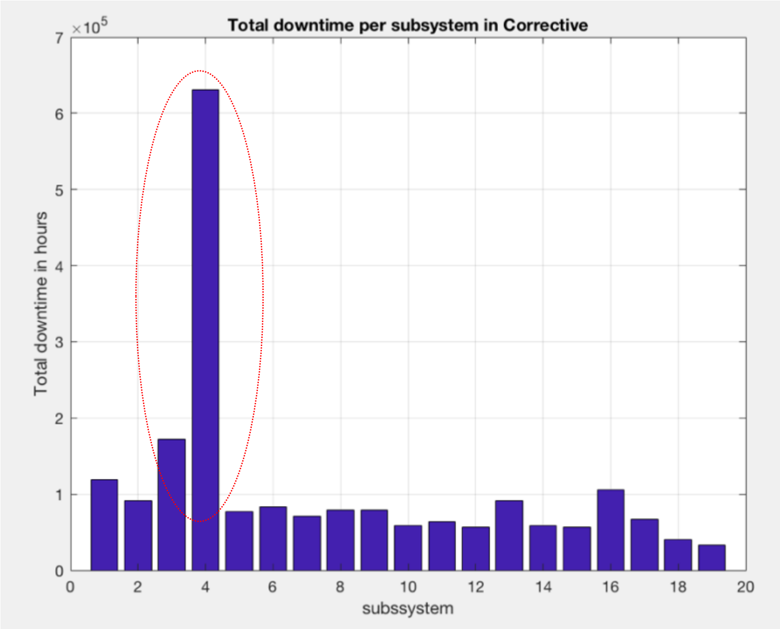

Figure 6-3: Total downtimes per subsystem

Figure 6-4 illustrates the total number of workorders divided per maintenance strategy in the three defined scenarios. It also shows the average downtime in each scenario. In scenario SI an average of 15114 workorders occurred while 1900 are planned maintenance actions. Expectably, the average downtime of 143 hours is the highest value in this comparison, since all waiting times contribute to downtimes of the turbine. In scenario SII, a significantly higher number of 16584 workorders occurred while 1900 are planned maintenance actions. In this scenario subcomponents are maintained before the occurrence of a functional failure, and therefore require a higher number of maintenance actions. The average downtime of 17h is only consisting of actual repair activities and therefore represents the average repair time. In scenario SIII, a total number of 16164 workorders occurred on an average while 1900 workorders are planned 11329 are corrective and 2933 workorders are reliability based activities. The average downtime in this case is 74 hours.

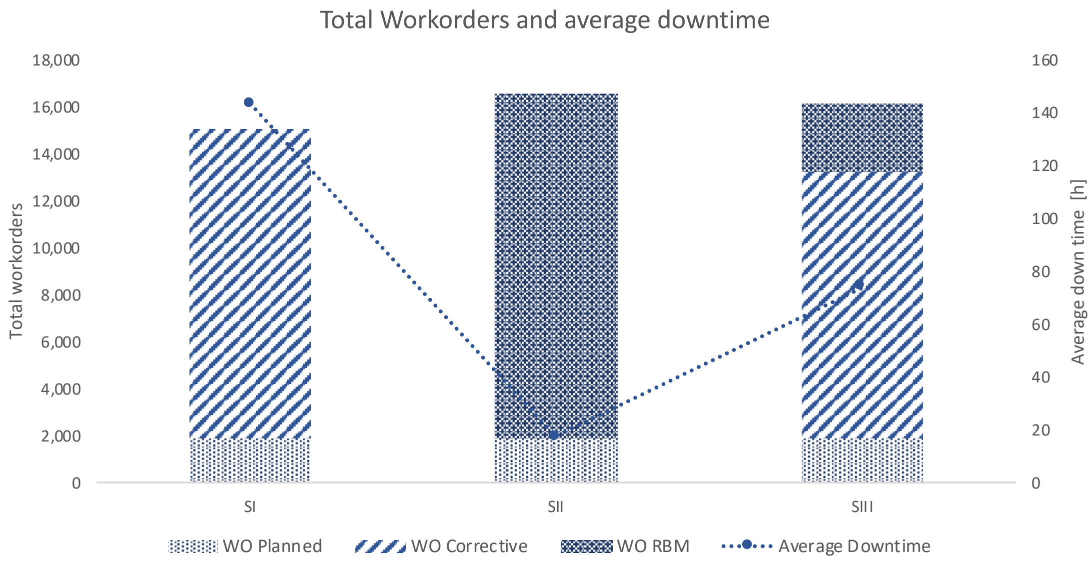

Figure 6-4: Total workorders and average downtime

It is interesting to note, that the increase of total workorders between scenario SI and SIII is 7% while the reduction of average downtime is 48%.

Figure 6-5 illustrates the total produced electricity and the technical availability over all wind turbines in the wind farm. In scenario SI 27453 GWh electricity are produced with an availability 88%. Scenario SII reaches an availability of 98% and 31223 GWh produced electricity. In scenario SIII 29619 GWh electricity are produced with an availability of 94%.

It can be seen, that technical availability correlates with the total energy yield of the wind farm. The application of the reliability based maintenance strategy on only two critical component increases the availability by 6% compared two scenario SI. On the other the application of the reliability based strategy on all components increases availability by only 4% compared two SII. This illustrates the benefit of applying a reliability based maintenance strategy on critical components.

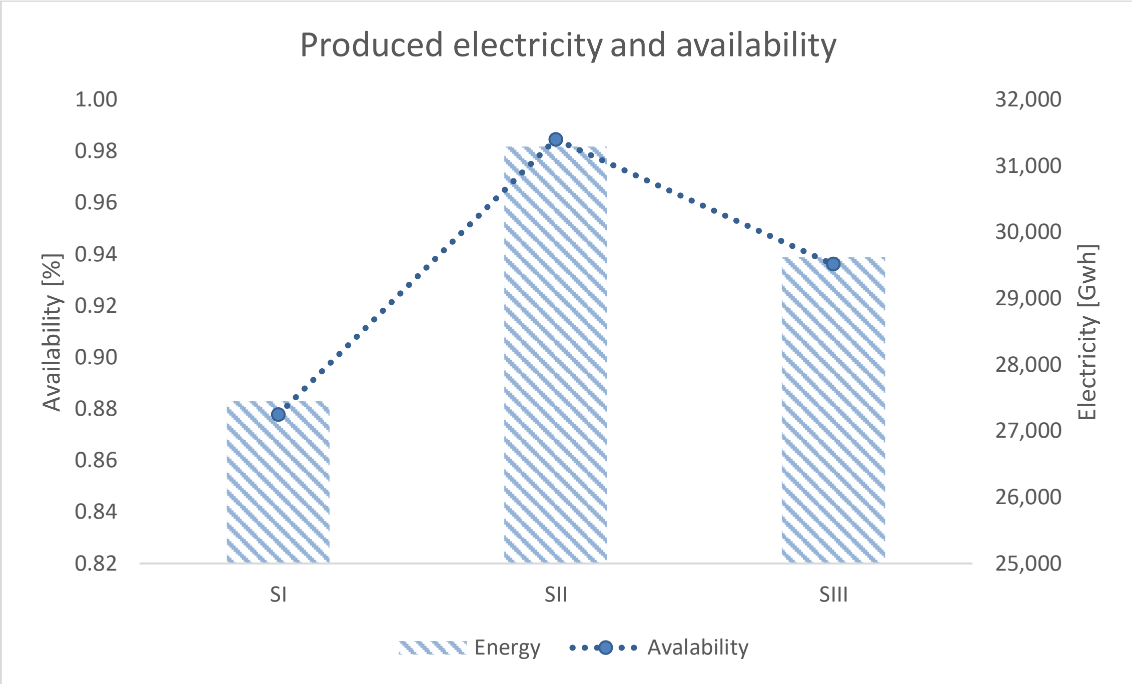

Figure 6-5: Produced electricity and availability

Finally, Figure 6-6 illustrates the LCoE over the three scenarios. In scenario SI the cost of produced electricity is 129 €/MWh. Scenario SII reaches costs of 117€/MWh while in scenario SIII the costs are 122 €/MWh. The O&M costs per produced electricity are in the range of 25.7 €/MWh (SI) to 26.7 €/MWh (SIII). Although the O&M costs per MWh in scenario SIII are slightly higher than in scenario SI, the LCoE are significantly lower due to the increased electricity production.

It is important to note, that these results are theoretical values which do not consider fixed costs arising due to the use of the condition based maintenance strategy. In reality the application of a condition based maintenance strategy will cause significant costs which increase the LCoE eventually.

However, the results show the cost saving potential of condition based maintenance strategies in offshore wind energy. Considering scenario SI and SIII there is a cost difference of 7€/MWh of produced electricity. Assuming a uniform distributed energy production over the wind farm lifetime this results in a yearly cost saving of ca. 10 million €. This yearly cost saving can be seen as potential budget for the implementation of a condition monitoring system. Levelling the produced electricity to project year zero according to Equation 39 this corresponds to a saving potential of ca. 1 million € per wind turbine at t=0.

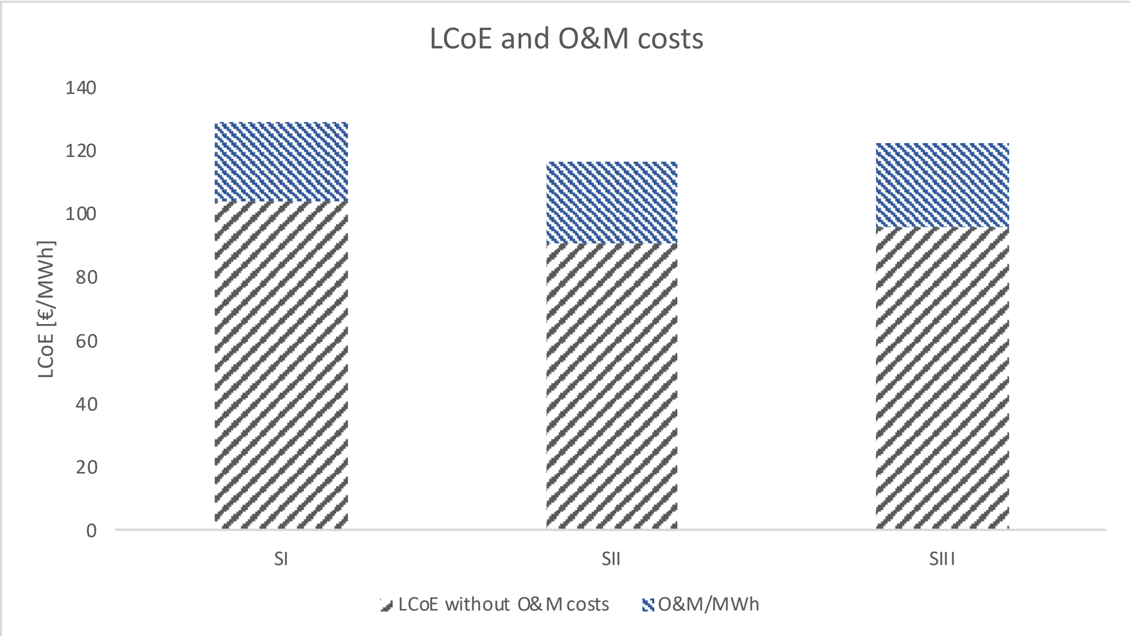

Figure 6-6: LCoE and O&M cost

The LCoE value of 122 €/MWh in scenario SIII is a reasonable result which is close to the findings of [6]. However, also this result must be interpreted with care since it is sensitive to the input parameters of the O&M simulation, such as historical weather data, and to the input parameters of the CIAT cost model such as raw material prices.

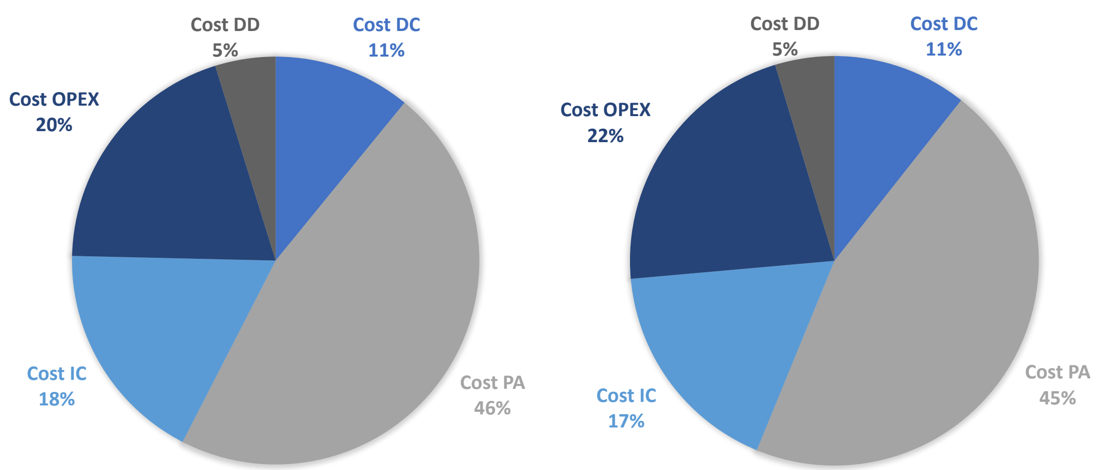

Figure 6-7: Distribution of life cycle cots in scenario SI (left) and SIII (right)

The breakdown of life cycle costs depicted in Figure 6-7 shows a reasonable result compared with [9] and [6]. All cost values show the right order of magnitude for a 100 turbine wind farm. When interpreting the cost breakdown, it is important to note, that all values are shown on a present value basis. Therefore, expenditures occurring at a later life cycle phase contribute less to the overall cost breakdown. A significant deviation from the findings of [9] is the contribution of D&D phase. While [9] estimated a contribution of 1% the simulation results in this study show a contribution of 5%. This is caused by the assumption, that decommissioning effort for floating wind turbines is similar to the installation effort. The contribution of 20% (SI) and 22%(SIII) from the O&M phase is a reasonable result which can be confirmed by the comparison with other studies [9]. However, a very careful interpretation of O&M results is necessary since the integration of the O&M simulation comes with some limitations. The integrated O&M simulation tool is not specifically developed for a floating wind application. Thus, floating wind specific maintenance procedures are not considered at this stage. In addition, floating wind specific reliability data is not included in the simulation. As a consequence, failures on floating wind specific components are not considered. Furthermore, maintenance missions are assumed to take place separately from each other which might lead to an overestimation of O&M effort.

Table 6-1 summarizes all results of the cost assessment.

	Scenario SI	Scenario SII	Scenario SIII
Availability [%]	0.88	0.98	0.94
Total Energy [GWh]	27453.2	31221.9	29619.1
Average Downtime [h]	143	17	74
Total Workorders [#]	15114	16584	16164
Workorders Corrective [#]	13212	0	11329
Workorders RBM [#]	0	14678	2933
Workorders Planned [#]	1902	1905	1902
LCoE [€/MWh]	129.3 €	116.7 €	122.8 €
Cost DC [€]	199,567,961 €	199,567,961 €	199,567,961 €
Cost PA [€]	853,484,173 €	853,484,173 €	853,484,173 €
Cost IC [€]	325,833,883 €	325,833,883 €	325,833,883 €
Cost OPEX [€]	363,011,571 €	411,337,029 €	406,978,716 €
Cost DD [€]	87,719,950 €	87,719,950 €	87,719,950 €
Cost O&M [€/MWh]	25.7 €	25.6 €	26.7 €

Table 6-1: Results cost assessment

As discussed before, a comprehensive evaluation of different maintenance strategies requires the consideration of environmental impact and energetic efficiency. Figure 6-8 shows the results for the overall EYR and the EBP for each maintenance scenario. For scenario SI, a EYR of 25.5 is achieved while the EBP is 0.76 years. For scenario SII, a 12% higher EYR of 28.4 and a 12% lower EBP of 0.67 is achieved. For scenario SIII, compared to scenario SI, a 6% higher EYR of 27.1 and a 7% lower EBP of 0.71 is achieved. This result shows, that the energetic efficiency of the wind farm can be improved significantly by the application a condition based maintenance system for the selected subsystems.

The EBP of around 0.7 years is a reasonable result compared to the results from [37], which are in the range from 7 to 9.5 month.

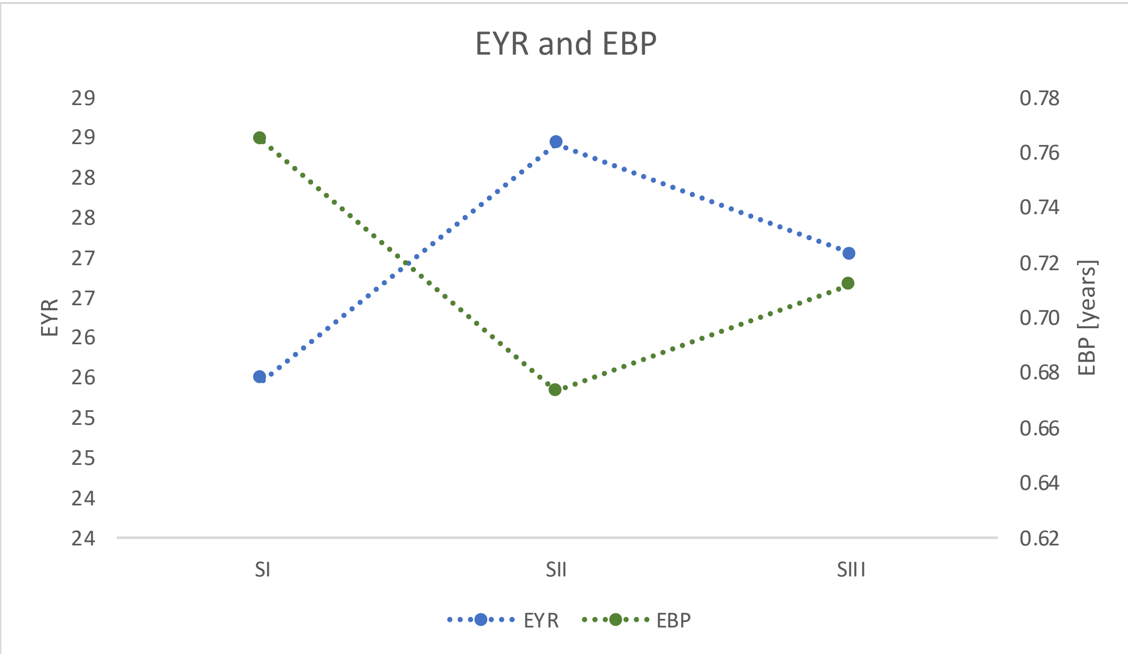

Figure 6-8: Energy yield ratio and energy payback period

The breakdown of CED for the life cycle phases included in the impact assessment shows a reasonable result compared with the distribution found by [37]. With 53% in scenario SIII, the P&A phase is, as expected, by far the biggest contributor to CED. The contribution of I&C phase is the second biggest contributor in this example case, whereas other studies neglect the contribution of this phase. Although this result might be overestimated, it shows the importance of considering this phase. The CED of O&M phase is estimated with 13% (SIII) contribution which is a reasonable value compared with other studies. The decommission is assumed to be similar to the installation phase which is represented by a contribution of around 13%. Although the results show reasonable values, it must be noted that CED is sensitive to variety of parameters from the O&M simulation and CIAT which makes a careful case specific evaluation necessary.

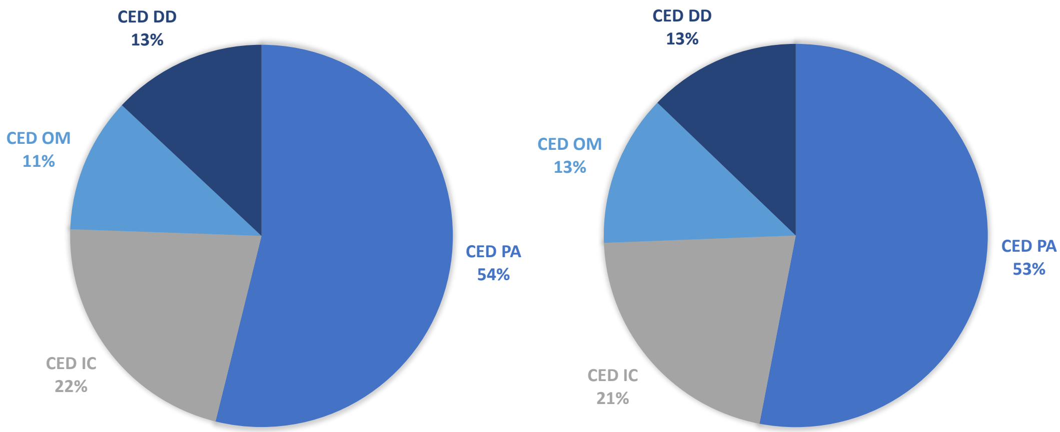

Figure 6-9: Distribution of CED in scenario SI (left) and scenario SIII (right)

The results for GWP show a similar behaviour compared with EYR and EBP. For scenario SI a GWP of 0.0076kg CO_2 eq./MJ produced electricity is achieved. For scenario SII, an approximately 10% lower value and for scenario SIII, an approximately 6% lower value is achieved. This result shows, that the GWP can be reduced significantly by applying a condition based maintenance strategy. Despite a higher number of maintenance missions and associated emissions, the increased energy output results in a lower GWP per produced electricity.

Results (Table 6-2) for GWP, POCP, Acidification Potential and Eutrophication Potential show reasonable values in the right order of magnitude compared with results found by [36].

	Scenario SI	Scenario SII	Scenario SIII
CED PA [MJ]	6,270,251,575	6,270,251,575	6,270,251,575
CED IC [MJ]	2,525,467,680	2,525,467,680	2,525,467,680
CED OM [MJ]	1,330,108,296	1,563,306,320	1,513,588,042
CED DD [MJ]	1,515,280,608	1,515,280,608	1,515,280,608
EYR	25.5	28.4	27.1
EBP [years]	0.76	0.67	0.71
GWP [kg CO2eq./MJ]	0.00767	0.00688	0.00723
Acidification [kg SO2 eq. /MJ]	0.00011	0.00010	0.00010
Ozone formation Potential [kg C2H4 eq./MJ]	0.00001	0.00001	0.00001
Eutrophication [kg P eq./MJ]	0.00004	0.00004	0.00004

Table 6-2: Results impact assessment

Conclusively, it must be noted that the input data for the environmental impact case study is not complete, especially for the emissions related to processes and materials, and therefore results include uncertainties.

7 Discussion

When comparing the developed cost framework with other studies as, [14] and [9], two main differences are evident. First CIAT offers a very generic framework which is not tied to specific concepts concerning modelling of production cost or installation procedures. With one exception, which is the modelling of wind turbine costs, CIAT does not make use of cost estimations estimation functions based on empirical data from historic projects. Instead, costs are modelled based on material consumptions and activities. Especially for floating wind, this approach is advantageous as very few industrial scale projects are already existing to this date. The implementation of cost functions, derived from fixed bed projects, might lead to high uncertainties. The drawback, of the approach implemented in CIAT is the need for detailed product data regarding the main components. Especially weights, material and processes must be available at a very detailed level to obtain accurate results. The second difference is that CIAT, with view exceptions does not use fixed cost values as input parameters, where other frameworks use fixed values for the cost estimation of components. Those have to be estimated based on empirical values. Again, this is an advantage considering the novelty of floating wind turbines, but requires detailed process knowledge.

The O&M simulation tool is based on existing reliability and maintenance process data extracted from literature. Therefore, the functional groups used for cost and impact modelling and the subsystems used in the O&M simulation differ. Due to this approach, especially floating wind specific components, such as mooring lines, are not covered in the O&M simulation. It must also be noted that special maintenance procedures that might apply for floating wind are not modelled in the O&M simulation due to the lack of existing input data. Therefore, the results of the O&M simulation are reasonable estimations but include uncertainties.

The integration of an impact model for a complex system such as wind turbines is a novelty. Therefore, the comparison with similar tools is difficult. Existing LCA studies on offshore wind energy have analysed specific projects but do not provide a transferable framework. The unique characteristic of the impact model in CIAT is that it models all life cycle phases with exception of D&C phase where other LCA studies are limited to the production of components. Furthermore, the present version of CIAT framework covers 6 relevant impact categories while other studies are limited to GWP and CED. The main limitation of the CIAT impact tool is the availability of detailed input data. For accurate and meaningful results detailed inventory data on a variety of materials and processes is required. This data must cover all contributing substances described in chapter 4. Another difficulty is that this data is dependent on regions. For instance, inventory data for steel in Europe will be different from inventory data of steel in China. This can be explained by the different composition of the energy mixes in different regions. Since this energy is used for production of raw material, or components, it will cause different emissions. Conclusively, it must be noted that the LCA of floating offshore wind turbines is, despite the support of the framework developed in this study, a complex task which requires a high level of experience from the practitioner.

8 Conclusions and future work

In accordance with the goals and objectives of this work, a comprehensive integrated framework for the cost and impact assessment of floating offshore wind turbines has been developed and implemented as a software tool.

The cost model of CIAT includes parametric equations modelling key cost components of all life cycle phases. In the CAPEX module the capital expenditures occurring in the D&C, P&A, I&C and D&D life cycle phases are considered. The FINEX module incorporates parameters related to financial expenditures such as WACC and equity debt ratio. The OPEX module models operational expenditures during the O&M phase. It simulates the O&M phase by incorporating reliability data, costs for materials and personnel related to maintenance processes.

All relevant entities of an offshore wind farm were modelled in order to simulate the production of electricity with respect to failure behaviours, maintenance processes, maintenance resources, and sea conditions. The produced electricity and LCoE of offshore wind farms are heavily dependent on availability, downtime and O&M costs. Therefore, different combinations of maintenance strategies were simulated, and optimistic as well as realistic saving potentials were evaluated. The analysis showed that investments in preventive maintenance leads to lower LCoE, which results in a saving potential up to one million Euro over the lifetime of a single wind turbine. The proposed simulation model can be utilized for further research in various directions. These include, but are not limited to: the incorporation of market factors influencing the economic success of a wind farm as well as the design and integration of maintenance planning procedures to further minimize O&M costs.

Summing up, the CIAT cost model provides estimations of key cost components as well as LCoE. The developed O&M simulation tool is also capable of incorporating different maintenance strategies, and thereby measuring the influence of the maintenance strategy on the overall wind farm performance. This output will help to understand real project costs and support the decision making process.

The input parameters used in the cost model have been integrated in a LCA module which is based on the guidelines of ISO 14040. The impact module models a comprehensive inventory of emissions based on material consumptions and activities. This includes all life cycle phases except D&C. These emissions are linked to relevant impact categories. Information on CED and EBP help to understand projects from an energetic point of view and to optimize processes. GWP, POCP, Acidification Potential and Eutrophication Potential are important figures to understand the environmental impact of a project. Conclusively, it can be confirmed that CIAT allows for a comprehensive benchmarking of floating wind projects. Thus, this work is a contribution to the broad deployment of offshore floating wind.

The case study results have shown that floating wind turbines can become an economically viable option in the future exploitation of offshore wind energy. The positive impact and economic potential of applying preventive maintenance strategies to critical wind turbine components has also been demonstrated.

Future work on CIAT should include a more detailed verification of outputs. Therefore, the detailed modelling of example cases and comparison with project data from existing floating wind projects is necessary.

Further development of CIAT should also focus on the following points:

- Integration of a comprehensive material and process database with associated input and output data
- Modelling and integration of spare part impact data
- Modelling and integration of floating wind turbine specific O&M processes with respect to the floater concept

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APPENDICES

Appendix A

A.1 Global warming potential

		GWP	
	Lifetime (yr)	Cumulative forcing over 20 years	Cumulative forcing over 100 years
CO_2	b	1	1
CH_4	12.4	84	28
N_2O	121.0	264	265
CF_4	50,000.0	4880	6630
HFC-152a	1.5	506	138

Figure App 8-1: GWP Values [45]

A.2 Photochemical Ozone Creation Potential

Average POCP values (g C_2H_4/g VOC) for nmVOC mixtures from source categories as used in the EDIP model for calculation of normalisation references for Denmark in 1990 and for EU in 1985 (Hauschild & Wenzel 1998).

Source of nmVOC	POCP (DK 1990) low- NOx	POCP (EU 1985) high- NOx
Petrol-engine car, exhaust	0.5	0.6
Petrol-engine car, vapour	0.4	0.5
Diesel-engine car, exhaust	0.5	0.6
Power plants	0.4	0.5
Burning of woods or twigs	0.6	0.6
Food industry	0.4	0.4
Surface coating	0.5	0.5
Dry cleaning	0.3	0.3
Refining and distribution of oil	0.4	0.5
Natural gas leakage	0.2	0.2
Farming	0.4	0.4
Other substances to be included		
CH4	0.007	0.007
CO	0.04	0.03

Figure App 8-2: POCP Values [41]

A.3 Acidification Potential

Substance	Formula	Reaction	Molar weight g/mole	n	EF kg SO_2/kg
Sulfur dioxide	SO_2	$SO_2+H_2O \rightarrow H_2SO_3 \rightarrow 2H^+ + SO_3^{2-}$	64.06	2	1
Sulfur trioxide	SO_3	$SO_3+H_2O \rightarrow H_2SO_4 \rightarrow 2H^+ + SO_4^{2-}$	80.06	2	0.80
Nitrogen dioxide	NO_2	$NO_2+\frac{1}{2}H_2O+\frac{1}{4}O_2 \rightarrow H^+ + NO_3H^-$	46.01	1	0.70
Nitrogen oxide	NO_x[1]	$NO_2+\frac{1}{2}H_2O+\frac{1}{4}O_2 \rightarrow H^+ + NO_3H^-$	46.01	1	0.70
Nitrogen oxide	NO	$NO+O_3+\frac{1}{2}H_2O \rightarrow H^+ + NO_3^- + \frac{3}{4}O_2$	30.01	1	1.07
Hydrogen chloride	HCl	$HCl \rightarrow H^+ + Cl^-$	36.46	1	0.88
Hydrogen nitrate	HNO_3	$HNO_3 \rightarrow H^+ + NO_3^-$	63.01	1	0.51
Hydrogen sulfate	H_2SO_4	$H_2SO_4 \rightarrow 2H^+ + SO_4^{2+}$	98.07	2	0.65
Hydrogen phosphate	H_3PO_4	$H_3PO_4 \rightarrow 3H^+ + PO_4^{3-}$	98.00	3	0.98
Hydrogen fluoride	HF	$HF \rightarrow H^+ + F^-$	20.01	1	1.60
Hydrogen sulfide	H_2S	$H_2S+3/2O_2+H_2O \rightarrow 2H^+ + SO_3^{2-}$	34.03	2	1.88
Ammonium	NH_3	$NH_3+2O_2 \rightarrow H^+ + NO_3^- + H_2O$	17.03	1	1.88

Figure App 8-3: Acidification Potential [41]

A.4 Nutrient Enrichment Potential

Substance	Formula	1994	EF(N)	EF(P)	Impact potential 1994	
		kt/year	g N-eq./g	g P-eq./g	kt N-eq./year	kt P-eq./year
Airborne emissions						
Nitrogen oxides	NO_x	276	0.30	0	82.8	0
Ammonia	NH_3	94	0.82	0	77.1	0
Waterborne emissions						
Total P	PO_4^{3-}-P	4.016	0	1	0.0	4.0
Total N	N	114.108	1	0	114.1	0
Total					274.0	4.0

NO_x as NO_2

Figure App 8-4: Nutrient Enrichment Potential Values [41]

Appendix B

B.1 Spare part cost data

Subsystem	Minor repair [€]	Major repair [€]	Replacement [€]
Pitch	210,00	1900,00	14000,00
Other compo	110,00	2400,00	10000,00
Generator	160,00	3500,00	60000,00
Gearbox	125,00	2500,00	230000,00
Blades	170,00	1500,00	90000,00
Oil / grease / other liquid	160,00	2000,00	0,00
Electrical compo	100,00	2000,00	12000,00
Contactor / Circuit breaker	260,00	2300,00	13500,00
Controls	200,00	2000,00	13000,00
Safety	130,00	2400,00	0,00
Sensors	150,00	2500,00	0,00
Pumps / motors	330,00	2000,00	0,00
Hub	160,00	1500,00	95000,00
Heaters / coolers	465,00	1300,00	0,00
Yaw system	140,00	3000,00	12500,00
Tower / fundation	140,00	1100,00	0,00
Power supply / converter	240,00	5300,00	13000,00
Service items	80,00	1200,00	0,00
Transformer	95,00	2300,00	70000,00

Figure App 8-5: Spare part cost data [9]