D4.3
Condition Monitoring Strategies for Floating Wind O&M

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Authors

Name	Organisation
Debora Cevasco	RAMBOLL
Jannis Tautz-Weinert	RAMBOLL
Marie-Antoinette Schwarzkopf	RAMBOLL
Friedemann Borisade	RAMBOLL
Moritz Häckell	RAMBOLL
Qi Pan	USTUTT
Mohammad Youssef Mahfouz	USTUTT

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1 Nomenclature

Abbreviation	Description
AHV	Anchor Handling Vessel
CAPEX	Capital Expenditures
CBM	Condition Based Maintenance
CM	Condition Monitoring
CTV	Crew Transfer Vessel
DAS	Distributed Acoustic Sensing
DSS	Distributed Strain Sensing
DTS	Distributed Temperature Sensing
FBG	Fibre Bragg Grating
FMEA	Failure Mode Effect Analysis
FOWF	Floating Offshore Wind Farm
FOWT	Floating Offshore Wind Turbine
JUV	Jack-Up Vessel
KPI	Key performance indicator
LCOE	Levelized Cost of Electricity
MCE	Major Component Exchange
MRU	Motion Reference Unit
O&G	Oil and Gas
O&M	Operations and Maintenance
OPEX	Operational Expenditures
OSS	Offshore Substation
OSV	Offshore Service (or Support) Vessel
PBA	Production-Based Availability
PPE	Personal Protective Equipment
RCM	Reliability Centred Maintenance
ROV	Remotely Operated Vehicle
SHM(S)	Structural Health Monitoring (System)
SOV	Service Operation Vessel
TBA	Time-Based Availability
TBM	Time Based Maintenance

TEV	Transient Earth Voltage Sensors
TRL	Technology Readiness Levels
TTF	Time-to-failure

2 Executive Summary

The costs which occur during the operation and maintenance (O&M) phase of the offshore wind farms greatly influence the levelized costs of electricity (LCOE). The maintenance of floating offshore wind systems come with additional constrains and challenges due to the more complex accessibility and the likely further distance from shore of the assets. It is thus of high interest to investigate if the use of monitoring technologies can contribute to a reduction in overall operating costs.

This study analyses the effect of structural health monitoring technologies on the O&M cost and availabilities figure of a reference wind farm. A Ramboll's in-house O&M model is extended to be capable of considering the maintenance actions in response to alarms and floating offshore wind O&M strategies. The focus is on floating specific components, for which the most promising monitoring technologies are presented and ranked according to a Failure Mode Effect Analysis (FMEA). Following, an investigation is conducted to determine the most critical hotspots.

The presence of the selected monitoring system is then modelled into the O&M cost model by updating the maintenance logistics and scheduling of actions from a baseline scenario. By comparing the results of the baseline scenario to the one applying the condition-based maintenance strategy, the benefits of the deployment of the monitoring systems are evident. The operational expenditures (OPEX) per MW and year are shown to be reduced of 15% of the baseline ones. This seems to be additionally associated to an increase of the wind farm availability figures, resulting in a further potential increase in the revenue.

3 Introduction

The COREWIND project investigates the influence of different O&M strategies and new requirements on the operational expenditures (OPEX) in the prospect of future floating offshore wind farms The O&M of floating wind farms is a major cost driver and motivates the assessment of new strategic opportunities and developments to reduce the O&M costs.

A comprehensive overview of floating wind specific O&M requirements as well as a review of state-of-the-art inspection and maintenance strategies and monitoring techniques was published in deliverable D4.1 [1], of August 2020. This deliverable concluded with general recommendations on O&M strategies for floating wind farms and a reflection on required studies to be performed for a detailed OPEX assessment.

Deliverable D4.2 [2], progressed on these considerations and summarised the activities undertaken to assess O&M strategies specific to floating wind. The lifetime OPEX and availability figures of a commercial-scale floating wind farm were evaluated for several O&M scenarios. COREWIND's reference wind farm - consisting of 80 units at 15 MW rating per unit - was modelled using a combination of the reference floater designs – i.e. Windcrete (spar) and ActiveFloat (semi-submersible) – and the reference site conditions – i.e. West of Barra (Scotland), Gran Canaria (Spain) and Morro Bay (USA).

This deliverable D4.3 contributes to the objectives and the exploitable results of the COREWIND project regarding the development of an O&M planning and strategy tool landscape. **The aim is to assess the potential benefits in terms of O&M expenditure (OPEX) reduction and production-based availability increase related to the implementation of traditional and innovative monitoring technologies for floating wind turbine systems.** To achieve this, a pre-analysis of the most promising technologies, and a model for the simulation of the availability and cost outcomes of an O&M scenario are suggested and presented in this deliverable.

3.1 Maintenance Strategies and the Impact of Monitoring

The deployment of monitoring systems and remote sensing technologies unlocks the possibility of fewer access occurrences to the offshore wind assets by the establishment of a condition-based maintenance (CBM) strategy. The different maintenance strategies are illustrated in a simplified and conceptual manner in Figure 3-1.

A corrective maintenance strategy is based on the full utilisation of an asset until this leads to its failure – defined as the 'inability of a system or component to perform its required functions within specified performance requirements' [3]. Although this approach avoids the underutilisation of an asset, its drawbacks are associated to the need for a fast response to avoid high costs for the rectification of the assets. The threat of a significant financial loss is associated with the potentially long downtime, due to offshore weather-dependent accessibility limitations; this pushed the offshore wind industry increasingly toward the implementation of preventive maintenance strategies.

A preventive maintenance strategy relies on the planning and performance of time-based maintenance actions. It has the advantage of ensuring a reliable and predictable delivery of electricity, thus allowing an optimised financial return. Drawbacks include the possibility of over-maintaining the assets, by replacing components well before the end of their nominal life and/or by inspecting them at the wrong moment in time – i.e. just shortly before a failure mechanism becomes visible and/or quantifiable by in-situ inspections. In addition, time-based maintenance of all turbines in a wind farm would lead to extremely high costs if not combined with a Reliability Centred Maintenance (RCM) approach that aims to find a workable balance between the effort required for a preventive maintenance campaign and the risk of component failure.

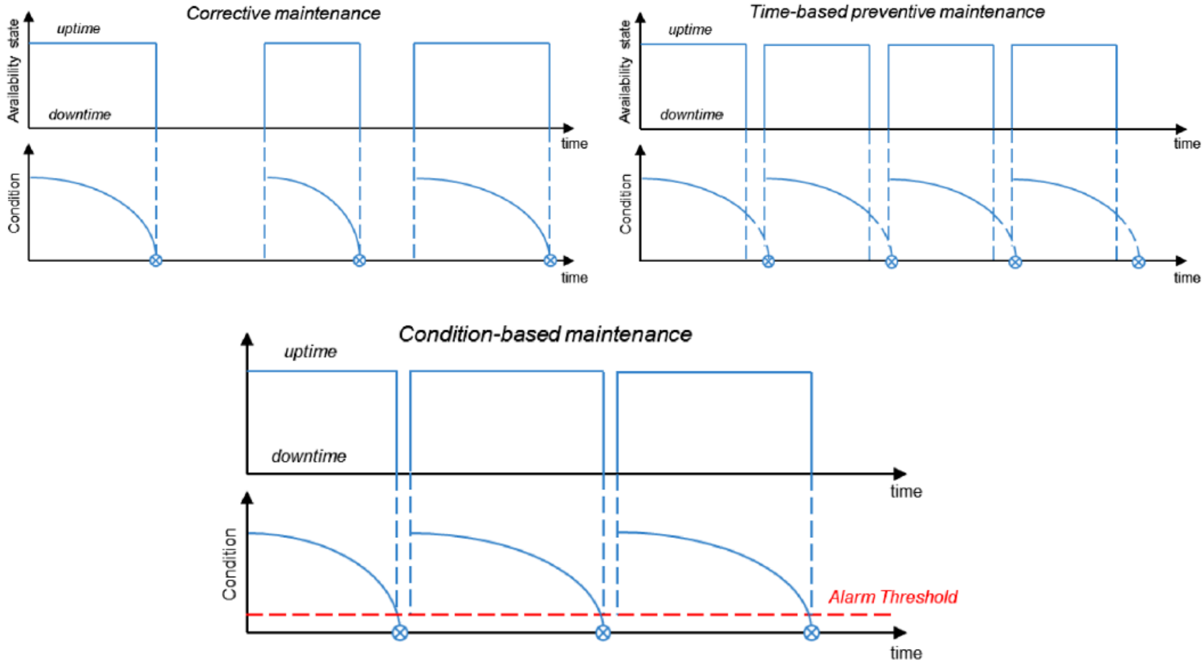

Figure 3-1: Overview of the maintenance strategy - corrective, preventive and condition-based (or predictive) - on the condition vs. time, and uptime vs. downtime plots, from [4]

The CBM, or predictive maintenance strategy, has the potential to: (i) **mitigates against risks and costs of unplanned activities** as all the interventions – which are also likely to can be planned in advance and conducted at the earliest suitable weather window, (ii) **challenge the performance of preventive maintenance action** if no alarms are raised as indication of the development of a failure.

This is achieved by knowing the condition of the asset based on data collected by continuous or periodic, online or offline sensing systems, which can be monitored remotely or accessed at regularly planned intervals). These actions maximise the potential asset usage life in service, while serving to provide advanced warning of a developing failure mechanism.

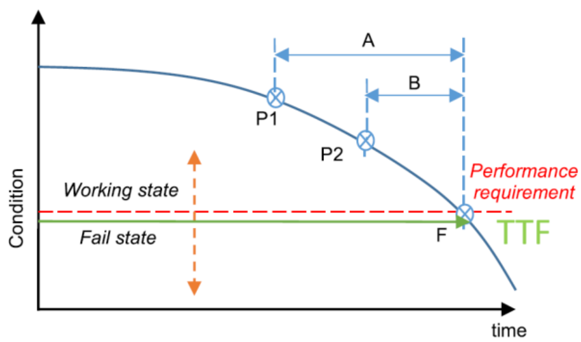

Figure 3-2: Schematic representation of a P-F interval, from [4]

To apply a CBM strategy, the physics of failure of the component must be known. This strategy is indeed most efficient if it is possible to detect, well in advance, the development of a failure; this concept is usually referred as P-F interval [5]. As it can be seen in Figure 3-2, it describes the interval between the point in time when a developing failure can be detected (potential failure, P) until the (functional) failure occurrence (F). Any P-F interval is smaller than the lead time to failure (TTF), and it is used as a performance indicator for the monitoring technology. For example, the monitoring system A is capable of detecting the failure development at time P1, while B is capable of detecting the failure development at time P2. In this case, system A offers an earlier warning to enable a better-informed intervention to restore the asset's operational capability.

3.2 Scope of the Analysis and Outline

The scope of this analysis is to identify and prioritize monitoring systems which are suitable and beneficial to the emerging offshore floating wind industry. The return on investment (quantification of the impact of monitoring technologies on OPEX) of the most promising monitoring technologies is assessed for one of the optimal O&M scenarios of D4.2 [2].

In Chapter 4, the analysis for the prioritization of the monitoring systems is performed following a Failure Mode Effect Analysis (FMEA) approach. The FMEA criteria and the rankings are introduced in Section 0. It should be noted that the focus of this analysis is on the investigation of the systems – both in term of monitored systems, and monitoring technologies – specific to the floating offshore wind structures. Some of the main systems of a floating wind turbine which differ from a bottom fixed are:

- the station keeping system (i.e. mooring lines and anchoring system),
- the dynamic cables – which become exposed and affected to the metocean conditions for floating wind systems , and
- the floating support structure.

The dynamic cables are affected by greater water movement higher in the water column, platform offsets and platform imparted dynamic motion induced by metocean conditions on floating wind systems. An in-depth study of the Structural Health Monitoring System (SHMS) suitable for the above mentioned components is carried out in Section 4.20 of this deliverable. The information relative to the modes of failure, their occurrence, and the severity of the maintenance actions required for their restoration are retrieved in Section 4.2.1 from D4.2 [2]. As concerns the monitoring systems, the technologies identified in D4.1 [1] are classified in Section 4.2.2 according to several key performance indicators, being representative of their reliability, detection capabilities, capital cost, and maturity. Finally Section 4.3 presents and discusses the results of the FMEA.

The reader is referred to the research performed in the field of offshore bottom fixed structures concerning the SHMS of wind turbine generators (i.e. towers and blades), and of the condition monitoring system (CMS) of the components of the drivetrain [6]. Regarding the analysis of the impact of the deployment of these technologies on the operational expenditure (OPEX) and availability figures, the reader is referred to the research of Koukoura et al. [4] and Vieira et al. [7]. Koukoura et al. [4] investigated the positive impact that longer warning time of potential-to-functional failure of the drivetrain components has on the availability of an offshore wind farm. Vieira et al. [7] used a stochastic approach (based on Monte Carlo simulations) to evaluate the benefits of the application of SHMS to the monopile support structure of an offshore wind turbine. They concluded that structural health monitoring systems may indeed be beneficial for offshore wind operation, however other parameters influence their potential and attractiveness to the wind farm owners.

In chapter 5 the selected monitoring technologies are then incorporated into the O&M cost model which was extended by specific functionalities to meet this purpose. A baseline and a benchmark scenario are then established, where the baseline scenario does not include a monitoring system in the O&M strategy and represents the strategy outlined in D4.2 [2]. The benchmark scenario represents the same strategy with the difference that the selected monitoring technologies from chapter 4 have been included into the model. By benchmarking both scenarios against each other it is assessed how the technologies affect the KPIs of the operation phase. The benefits of the selected monitoring systems on the OPEX, availability and power production are presented thereafter.

4 Prioritisation of Monitoring Technologies for Floating Offshore Wind

Based on the technologies identified in subtask 4.1.2 (presented in D4.1 [1]), a set of optimal monitoring systems is selected in this chapter. The prioritisation of such systems is done by deploying a FMEA approach. In a FMEA, the potential failure modes of one or more systems are identified at first, to then proceed with the recognition of their likelihood, their effects, and the feasibility of their timely detection. This qualitative analysis is transformed into a quantitative assessment by assigning a rank to the:

- occurrence (O),
- severity (S), and
- detection (D)

of each of the failure modes. A visualisation of the workflow of the analysis is presented in Figure 4-1.

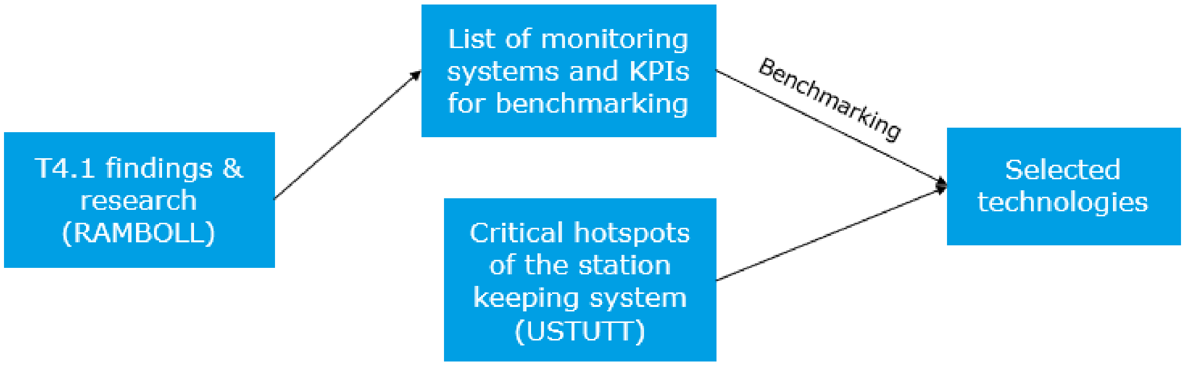

Figure 4-1:Workflow for the identification of the most promising monitoring systems

The FMEA criteria and rankings are introduced in Section 0. by explaining the reasons and the details of the breakdown of the severity and the detection criteria into multiple KPIs. In Section 4.2 the systems to be monitored and the monitoring technologies are described. Finally, in Section 4.3, the FMEA results are presented and discussed. The most promising monitoring technologies for some of the most critical maintenance events – in terms of likelihood and maintenance procedures necessary to restore a floating wind turbine system – are identified. The discussion is extended to identify the most critical hotspots of the floating wind turbine system, which should be given more attention when selecting the setup of the monitoring system.

4.1 FMEA Criteria and Rates

The FMEA ratings are presented in Table 4-1, for the O, S and D parameters. The S and D are additionally broken down into several indicators, to account for the impact of the events on different cost categories (e.g. maintenance units and material cost) in the S, and to rank the technologies base on their reliability and maturity in the D. The resulting criteria for S and D are eventually defined by the arithmetic average of their indicators. To characterize the severity (S) of a maintenance event, the following KPIs are considered: the *maintenance unit cost*, the *manhours*, the *material cost*, and the *impact on production*.

The manhours are associated only with subsequent rectification actions after detection; thus these do not include the running costs and time incurred for analysing the data and identifying the potential failures. The impact to the production accounts for the downtime as a consequence to the failure, including the potential impact of lead times. As concerns the detection (D), the following KPIs, which are associated to the monitoring technologies, are considered:

- *reliability* of the technology, taking into account the reliability of the hardware and of the data collection system;
- *detectability* of the incipiency of the failure, according the first free detection level defined by Rytter in [8]: level 1 for the detection of an out-of-the-normal behaviour, level 2 for the identification of the presence and location of the damage, level 3 for the additional quantification of the severity and progression of the damage;
- *cost* (CAPEX) of hardware required for the monitoring system; and
- *maturity* of the technology classified according to a bundled form of the Technology Readiness Levels (TRL) [9].

In Table 4-1, rates ranging from 1 to 3 are allocated to several criteria following the principle that low ratings are associated to the unfavourable condition (e.g. high cost, low reliability), while high rating are for more suitable conditions (e.g. mature technology, unluckily maintenance events.)

Table 4-1: Occurrence (O) and Severity (S), on the top, and Detection (D), on the bottom, criteria and rates for the FMEA

		O	S			
			Maintenance Units Cost	*Manhours*	*Material Cost*	*Impact on production*
Rank	1	(Maybe) Once or twice in the lifetime ($1/\lambda \geq 15$)	Planned actions requiring CTV (or SOV)	Below 50 h	Below 50k EUR	Small impact (shutdown only during maintenance)
	2	Every 5 years to (maybe) three times in the lifetime ($5 < 1/\lambda < 15$)	Unplanned actions requiring SOV (with extra equipment, such as ROVs)	50 -100 h	50k - 100k EUR	Medium impact (shutdown at failure and small lead times)
	3	Less often than every 5 years ($1/\lambda < 5$)	Unplanned actions requiring an AHV or the turbine's tow-in	Above 100 h	Above 100k EUR	High impact (shutdown at failure and high lead times)

Note: The "λ" indicate the frequency of the access required per asset and year

		D			
		Reliability	*Detectability*	*Cost*	*Maturity*
Rank	1	Low Reliability	Level 1	High	Feasibility - i.e., basic principle, technology concept, experimental proof of concept (TRL1 to TRL3)
	2	Medium Reliability	Level 2	Medium	Laboratory validation and prototyping (TRL4 to TRL7)
	3	High Reliability	Level 3	Low	Full scale applications and technology commercialization (TRL8 and TRL9)

Note: The cost (CAPEX) of the monitoring technologies as a contributor to the detection criteria is here considered only qualitatively. This cost is indeed vastly dependent on the type of deployment of the technology and the size of the windfarm, and thus difficult to quantify and/or provide hard boundaries. For similar reason, the O&M cost of the monitoring technologies is not accounted for this FMEA.

4.2 Monitoring of Floating Wind Systems

This section briefly recaps on the technologies identified in D4.1 [1], which can be implemented to support the structural health monitoring of a floating wind turbine. The monitoring technologies not fitting to the purpose of a condition-based maintenance are exclude from the FMEA analysis, as it is discussed in Section 4.2.2. As regards the failure modes and the respective maintenance events, the most critical components to the OPEX and/or availability of the floating wind farm are retrieved from D4.2 [2], classifying them in term of occurrence and severity in Section 4.2.1.

4.2.1 Monitored System (Structures)

Because a detailed failure mode analysis is not in the scope of this deliverable, only a high-level identification of the possible and planned events requiring an offshore maintenance intervention is performed in this subsection. To continue on the findings of D4.2 [2], the failure events and the inspections accounted for the floating wind specific systems only are collected in Table 4-2.

This table reports the occurrence – statistically possible for corrective tasks, and recursively planned for preventive inspections – of each of the selected events. Additionally, their impact to the O&M strategy is described by taking note, from D4.2, on:

- the type of maintenance units and equipment,
- the manhours and the number of technicians,
- the possible lead times, and
- the cost of the material,

required to restore the floating system to its operating conditions. It should be noted that the severity of the maintenance action required to rectify these events is not considering the impact on the other assets of the wind farm, but only accounting for the actions required on the assets itself.

Acronyms and a colour coding convention is adopted to distinguish the maintenance events by structural wind turbine system. These are used in the FMEA for a more practical and compact presentation of the results.

4.2.2 Monitoring Systems (Technologies)

The technologies which have been identified and described in D4.1 [1] are critically assessed in this subsection, with respect to evaluating the most relevant systems for an effective monitoring of a floating wind turbine structure. As defined by [10], the SHMS considered in this analysis are only the ones which allow the implementation of processes for a system-targeted damage detection and/or prognostic monitoring strategy. Their objective is to monitor the integrity status of the structures, and/or detect - possibly pinpoint the locations - of damages.

Thus, the technologies that can directly or indirectly help to evaluate the structural integrity and/or one or more indicators of the presence of a structural failure are accounted for in the FMEA of Section 4.3. These include local monitoring systems (e.g., acoustic emission systems) and global monitoring systems (e.g., standard SHMS). On the contrary, sensors raising alarms but not informing the user on the system that have failed are excluded from this analysis - e.g. an inclinometer installed on the floating support structure, or a load cell measuring the load on a mooring line.

Table 4-3 summarises the SHM technologies identified, by taking notes on their intent, the hardware required, and the type of monitoring. A difference is made if the technologies aim to monitor either local phenomena by directly recording indicators of a structural failure (i.e. local SHMS), or if they indirectly monitor the incipiency of a failure from structural global properties (i.e. global SHMS).

Table 4-2: Qualitative and descriptive table of the failure events and inspections accounted for in the FMEA, based on the inputs of the baseline case in D4.2 [2].

Event Acron.	System	Maintenance event required	Maintenance Strategy	Maintenance Intervention Rate [1/y]	Severity of Maintenance Action
a1	Station Keeping System (a)	Mooring lines twisting/ breakage requiring major repairs and/or replacements	Corrective	0.0275	- AHV (with a support CTV) - Man hours between 240-360 h, with 10 technicians required - Possible delays from lead time of about 2 weeks - Material cost ranging from 20,000 to 135,000 EUR
a2	Station Keeping System (a)	Displacement/loss of anchor requiring major repairs and/or replacements	Corrective	0.0275	- AHV (with a support CTV) - Man hours between 240-360 h, with 10 technicians required - Possible delays from lead time of about 2 weeks - Material cost ranging from 75,000 to 512,000 EUR
a3	Station Keeping System (a)	Buoyancy modules dislocation requiring a replacement	Corrective	0.033	- SOV (carrying and launching ROVs) - Man hours 40 h, with 5 technicians required - Possible delays from lead time of about 1 weeks - Material cost of approx. 100,000 EUR
b1	Power Cables (b)	IA / Dynamic cable failures requiring major repairs and/or replacements	Corrective	0.041	- SOV (carrying and launching ROVs) - Man hours between 240-360 h, with 10 technicians required - Possible delays from lead time of about 2 weeks - Material cost ranging from 30,000 to 220,000 EUR
c1	Floating Sub-structure (c)	Marine growth requiring a minor intervention for removal	Corrective	0.12	- SOV (carrying and launching ROVs) - Man hours 40 h, with 5 technicians required - Possible delays from lead time of equipment of about 2 days - Material cost of approx. 1,500 EUR
c2	Floating Sub-structure (c)	Broken/blocked pumps of active ballast system requiring minor intervention	Corrective	0.01	- access to the turbine via CTV or SOV (see D4.2 scenario) - Man hours 8 h, with 2 technicians required - Material cost of approx. 1,000 EUR
c3	Floating Sub-structure (c)	Structural integrity inspections of above-water elements (e.g., floater compartments/TP visual inspections and NDT)	Preventive	1	- access to the turbine via CTV or SOV (see D4.2 scenario) - Man hours 96 h, with 4 technicians required - Material cost 600 EUR
a4 b2 c4	(a) (b) (c)	Sub-sea inspections for the integrity of mooring lines, dynamic cables, and floater hull	Preventive	0.5	- SOV (carrying and launching ROVs) - Man hours 60 h, with 5 technicians required - Material cost 500 EUR

Table 4-3: Qualitative and descriptive table of the technologies available, to date, to be applied for the SHM of floating wind turbine systems

Tech.#	Monitoring Technology	Monitored System	Intent	Hardware Type	Monitoring Type	Maturity	Pros and Cons
1	Standard Structural Health Monitoring (SHMS) [6]	Floating Substructure	Monitoring modal properties and/or loads (in terms of strain) variation from the normal and expected behaviour.	- Accelerometers, Inclinometers, gyroscopes, strain gauges (*)	Global	TRL9	+ Reliable, depending on the type of sensors installed + Extensively implemented for SHM of bottom-fixed offshore wind turbines – Detectability of structural anomalies be challenged by the varying environmental conditions
2.1	Digital Twin (DT)	Station Keeping System [11]	Using a combination of sensors and monitoring technologies together with (numerical) models and data analysis tools to support the decision making, in: - lifetime management - anomaly detection	- (*) - AIS, and/or GPS - MRU installed in the nacelle and/or on the turbine tower - Load cells	Global/Local[1]	TRL7	+ Provides a more contextualize, deeper, and potentially holistic, understanding of the simple alarm raise by the sensors + Reliable and informative monitoring of fatigue and anomalies in the systems – Potentially expensive setup of the monitoring technologies – Complex calibration of the models and complex validation of the predictive and diagnostic capabilities – Complex and not proven scalability at the farm level
2.2		Floating Substructure [12]		- SCADA and MRU systems - (*)		TRL6 (bottom-fixed OW)	
3	Acoustic Emissions (AE) sensing system	Station Keeping System [13]–[15]	High-frequency vibration-based sensors measure the energy and the amplitude of the signal returning from the material. Detects any defects and/or initiation of structural failures.	High frequency accelerometers	Local	TRL4	+ Promising for localised and not (effective within a range depending on – Not deployed yet in the offshore environment and for wind applications – Effectiveness might be affected by OFW operating and environmental conditions
		Floating Substructure [16]					

Tech.#	Monitoring Technology	Monitored System	Intent	Hardware Type	Monitoring Type	Maturity	Pros and Cons
4	Contouring of floater positions [17]	Station Keeping System	Recording the floater motions in contour lines, and monitoring eventual offset related to mooring lines and/or anchor failures.	- GPS tracker on floating substructure - AIS for drifting alarms - Gyroscope	Global	TRL2	+ Easy to install and maintain + Relatively cheap setup – Effectiveness depends on mooring system, water depth, monitoring of environmental conditions, and reliability of GPS and Gyro
5	Indirect in-line tension monitoring [1]	Station Keeping System	Continuous monitoring and measuring mooring line angles and subsequent prediction of the tension based on line angles or direct measurement of tension.	Inclinometer and load cell installed on each mooring line	Global	TRL8 (O&G)	+ Measured angle is periodically transmitted to hull-mounted receivers e.g. using hydro-acoustic data link + Installation and retrieval by ROV – Careful calibration of the detection model and setting of the alarm criteria is required
6	Integrated Monitoring and Advisory Systems (IMAS) [1]	Station Keeping System	Monitoring metocean condition and floater motion forecasting mooring lines loads. Provide operation advisory and prognostics by comparing the predicted to the measured tension.	- GPS (or AIS) - Inertial Measurement Unit (IMU) - Acoustic Doppler Current Profilers (ADCP) - Inclinometers, - Accelerometers	Global	TRL8 (O&G)	+ Comprehensive system for real time monitoring – Relatively expensive due to the high number of sensors installed and measurements recorded – This technology is relatively new, and the effectiveness of the advisory system is not yet known.
7	Sonar probe [18]	Station Keeping System	If permanently deployed, the sonar reflections are processed in real time to detect if a line is missing or has moved outside its maximum allowable design envelope, triggering alarms.	Horizontal scanning single beam or multi-beam sonars	Local	TRL8 (O&G)	+ Easy to install and repair + Can be retrofitted – This technology is relatively new, and the effectiveness of the advisory system is not yet known – Possible problems detecting failure on seabed if it does not result in significant mooring line angle change at turret – No mooring line tension data collection

Tech.#	Monitoring Technology	Monitored System	Intent	Hardware Type	Monitoring Type	Maturity	Pros and Cons
8.1	Distributed vibration sensing (DVS) systems [19]	Dynamic Cables	Optical fibre (pre-installed in the cable) detects the presence of anomalies, based either on Brillouin or Rayleigh scattering.	Distributed Acoustic Sensing (DAS) [20], [21]	Local[2]	TRL9	+ The optical fibres are integrated within the cable, making this monitoring more reliable and less prone to failures + Monitoring of strain and fatigue can be used to inform preventative maintenance actions – Detection effectiveness might be affected by the offshore environment and varying loadings
8.2				Distributed Strain Sensing (DSS) [22], [23]		TRL4 (for static export cables)[3]	
9	Real Time Thermal Rating (RTTR) [24], [25]	Dynamic Cables	Monitoring the cables integrity by checking temperature distribution of fibre cable and calculating temperature distribution along power cable.	Distributed Temperature Sensing (DTS) and/or DAS	Local[2]	TRL9	+ The optical fibres are integrated within the cable, making this monitoring more reliable and less prone to failures + This method is especially useful for cables with a dynamic rating + DTS systems are immune against EMC interferences – Sensors of DTS are FBGs, which do not give the precision needed over distances required in a typical windfarm – Raman technique often shows dead spots at the connections in areas of interest – Challenge with the Brillouin backscatter is to isolate the fiber from strain to get accurate temperature information

Tech.#	Monitoring Technology	Monitored System	Intent	Hardware Type	Monitoring Type	Maturity	Pros and Cons
10	Partial Discharge (PD) monitoring [26]	Dynamic Cables	Identify failure of part of the insulation system to withstand the electrical field applied to it.	– high frequency current transformers (HFCT's) on the cables outside of the switchgear to detect PD in the cables and switchgear – transient earth voltage sensors (TEV) for detection of electromagnetic radiation from 'local' PD activity nearby the sensor from sources in the cable termination or switchgear	Local	TRL7 (in case of continuous monitoring)	+ This monitoring technology can detect defect before they develop into failures requiring maintenance actions – The high voltage required to identify minor damages, may damage itself the cable – Measurements are highly susceptible to noise sources – External transformers and sensors necessary, observable area usually limits around those

[1] Global to local monitoring capabilities depending on the sensors deployed

[2] Distributed sensing technologies which can globally monitor the cable looking for functional failure and possibly locate it

[3] Technology applied for straight laid products such as ridged pipelines on the seabed and potentially useful for static export cables. Application to dynamic power cables seen less beneficial as they are designed to minimise strain on the components and due to practical implications on ancillaries (e.g. attachment of buoyancy elements).

4.3 FMEA Results and Discussion

4.3.1 Results

This section collects the results from the FMEA ranking, and the prioritisation on the maintenance events and monitoring systems. The O and S are reported in Table 4-4, while the scores for D are given in Table 4-5. The ranking scores are given according to Table 4-1.

In Table 4-4, it can be observed that the highest score is for the maintenance event associated to the displacement and/or loss of connection of the station keeping system to the anchors (event a2), followed by the maintenance required for the breakage and twisting of the mooring lines (event a1). Both these events are relatively unlikely, though, if they happen, they require the deployment of an expensive anchor handling vessel (AHV) and long repair times. The cost of the material for the restoration of the anchoring system is generally higher than the one of the mooring lines. Regarding the unforeseen failure of the dynamic cable (event b1), the potential high impact to energy production - caused also by the relatively long manhours for the restoration of the operating conditions – classify this event as the third one for criticality despite of the low likelihood.

Table 4-4: FMEA rankings for O and S of the maintenance events. The S breaks down this into the several KPIs, and is averaged into single values.

Monitored Event		O	S					O x S
			Maintenance Units Cost	*Manhours*	*Material Cost*	*Impact on production*[1]	Average	
a1	Mooring line twisting/breakage	1	3	3	2	3	2.75	2.75
a2	Anchor loss	1	3	3	3	3	3.00	3.00
a3	Buoyancy module dislocation	1	2	1	2	2	1.75	1.75
b1	Dynamic cable failure	1	2	3	2	3[2]	2.50	2.50
c1	Marine growth removal	2	1	1	1	1	1.00	2.00
c2	Blocked pumps of active ballast system	1	1	1	1	2	1.25	1.25
c3	Structural integrity inspections	3	1	2	1	1	1.25	3.75
a4	Subsea inspection mooring lines	3	2	2	1	1	1.50	4.50
b2	Subsea inspection dynamic cables							
c4	Subsea inspection floater hull							

[1] Referring to a single WTG, not a full wind farm consisting of multiple WTG

[2] Rating referring to a single WTG. In general, the severity and impact on production depend on where the failure occurs in the windfarm, the windfarm layout, and the redundancy of included links. In the context of a full wind farm, the severity from a failure of the static export cable is very high. Considering that some dynamic (inter-array) cables in the wind farm matter more than others a rating of 1-2 could be chosen for the dynamic cable. A failure of a dynamic cable involves costs and downtime depending on the axial length of the cable or the possibility to use repair joints or replacement cables, but generally at a lower level than for a static cable.

Table 4-5 presents the rankings of the detection capabilities of the monitoring technologies. The top ranked systems share a very high level of maturity. The distributed vibration sensing system – in the specific by implementing acoustic-based technologies (DAS, number 8.1) – ranks first for its high reliability, detectability and maturity. This monitoring system for dynamic cables is currently deployed at the fixed-bottom wind farm Horns Rev. 3 in Denmark [27]. The standard SHMS of the floating substructure (number 1), the indirect in-line tension monitoring system (number 5), and the simple sonar probe (number 7) equally rank seconds. The standard SHMS scores low in reliability and detectability but high in the cost criteria. In contrast, the other two technologies improve on the first two aspect by being requiring an higher investment.

Table 4-5: FMEA rankings for D, breaking it down into the several KPIs for the monitoring technologies. These are eventually averaged into single values.

Monitoring Technologies			Detection (D)				
			Reliability	*Detectability*	*Cost*	*Maturity*	Average
1		Standard SHMS	2	1	3	3	2.25
2	2.1	DT - station keeping system	3	2	1	2	2.00
	2.2	DT - floater substructure	3	2	1	2	2.00
3		AE sensing system	2	3	1	2	2.00
4		Contouring of floater positions	3	1	3	1	2.00
5		Indirect in-line tension monitoring	2	2	2	3	2.25
6		IMAS	2	2	1	3	2.00
7		Sonar probe	3	2	2	3	2.50
8	8.1	DVS - DAS	3	3	1	3	2.50
	8.2	DVS - DSS	3	3	1	1	2.00
9		RTTR	2	2	1	3	2.00
10		PD	2	2	1	2	1.75

Finally, the FMEA prioritisation numbers are reported in Table 4-6. A matrix format is used to combine the maintenance events with the technologies capable to detect the incipiency of the failures. Colour coding is used to visualise the most promising combinations, by highlighting them with a more saturated colour. Whether the monitoring system cannot be applied for detecting the failures, the cells are left blank. The last columns finally sums up the rankings per technologies, indicating the overall capability to detect any of the events considered in this analysis. These sums are used to identify and discuss the most promising technologies for the impact assessment of Section 5.

It can be observed that the digital twin technology for the prognosis of the mooring lines fatigue and the diagnosis of their integrity status (technology 2.1) has the highest sum score and second highest sum-of-squares score (i.e. 24 and 159.5 respectively). Its employment is especially beneficial for the monitoring of the integrity of the connection and of the position of the anchors (event a2), and of the mooring lines (events a1 and a3). Additionally the implementation of this monitoring system has the potential to support the setup of a condition-based maintenance strategy for the station keeping system (event a4) which would lead to a possible reduction of the scheduled inspection – e.g. from every 2 year as simulated in D4.2 to every 5 years as suggested by the standards [28].

The method for the continuous monitoring and measuring of mooring line angles to predict the line tension (technology 5) ranks third, with an overall score of 20.25. This method has slightly higher diagnostic capabilities than technology 2.1, with lower costs and a more advanced maturity.

As concerns the most promising technology (with the highest score on the sum-of-squared), the distributed vibration (acoustic-based) sensing (technology 8.1) should be accounted for the detection of failures of the dynamic cables.

Table 4-6: FMEA results presented in the form of a matrix, due to the capability of the monitoring systems - in Table 4-3 - to capture several failure modes. For this reason, the priority numbers are summed up for each technology across the maintenance events (blue coloured column).

		a1	a2	a3	b1	c1	c2	c3	*	Metrics	
	O x S → D ↓	2.75	3.00	1.75	2.50	2.00	1.25	3.75	4.50	Sum	Sum of squares
1	2.25					4.50				4.50	20.25
2.1	2.00	5.50	6.00	3.50					9.00	24.00	159.50
2.2	2.00					4.00	2.50	7.50	9.00	23.00	159.50
3	2.00	5.50							9.00	14.50	111.25
4	2.00	5.50	6.00	3.50						15.00	78.50
5	2.25	6.19		3.94					10.13	20.25	156.30
6	2.00	5.50		3.50					9.00	18.00	123.50
7	2.50	6.88		4.38						11.25	66.41
8.1	2.50				6.25				11.25	17.50	165.63
8.2	2.00				5.00				9.00	14.00	106.00
9	2.00				5.00				9.00	14.00	106.00
10	1.75				4.38				7.88	12.25	81.16

* Scheduled monitoring event involving the sub-sea inspection of the floater, the dynamic cable and the mooring lines: b2, c4, and a4 respectively.

4.3.2 Critical Hotspots of the Station Keeping System

The main task for USTUTT is to identify the hot spot areas for the mooring lines system. This identification is important for operation and maintenance activities. Through dynamic simulations of the floating offshore wind turbine, we can generate the forces along each mooring line and compare the mooring tension forces for points of concerns.

The common locations along the mooring line for the oil and gas field includes the top area called ‘splash zones’, the touch-down point where the friction with seabed would be dangerous for certain mooring materials and the connection parts including fairlead on the top chain and anchor points at seabed. The figure for common hot-spot areas is plot in [29]. It is found that for a semi-submersible structure, the most critical fatigue damage occurs near the touch-down point and at fairleads of the mooring line respectively for low-frequency and wave-frequency tension ranges.

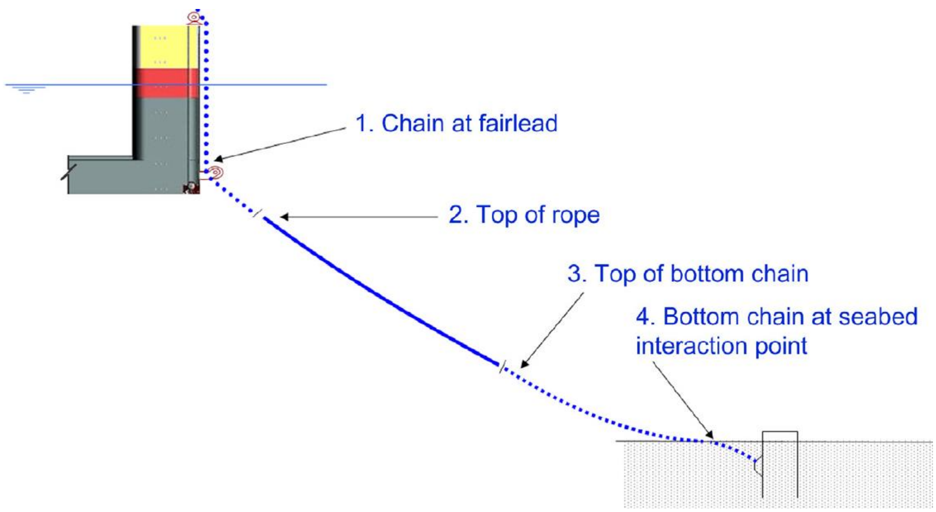

Figure 4-2: Typical critical locations for a mooring line, adapted from [29]

For the ActiveFloat at site C with a water depth of 870m, we conduct the fatigue load analysis for normal operational scenarios DLC1.2. The tested conditions are presented in Table 4-7.

Table 4-7: The environmental conditions for dynamic tests

Load case	Wind speed [m/s]	Wave height [m]	Wave period [s]	Yaw[deg]	Seed	Simulation time [s]
DLC 1.2	[3:2:25]	3	14	[-10,0.10]	3	2400

The time series of mooring tension forces are post-processed by routine fatigue procedures, applying the Rainflow counting method, S-N curves and Palmgren-Miner rule. The damage equivalent loads S_{DEL} are defined in Eq.1 for comparisons of the mooring tension fatigue.

$$S_{DEL} = \sqrt[m]{\frac{1}{N_{ref}} \sum n_i \times S_i^m} \tag{1}$$

where m is the S-N curve slope (set to 3 for chains), N_{ref} is the reference cycle number applied for each time history (set to 1800 for the simulation). By comparing S_{DEL} no details are required for mooring chain fatigue properties, for instance, the intercept values for specific S-N curves, which should be provided by chain manufactures or by experimental tests. We apply three random seeds for winds and run the 40-minute simulations including 10-minute ramp-up time. The reference cycle number of 1800 is used for the 30-minute simulation length, assuming the mooring fatigue load has a frequency of 1 second. The calculated mooring fatigue loads for three mooring lines are presented in Figure 4-3. The S_{DEL} at fairleads and at anchors are very similar for all wind speeds.

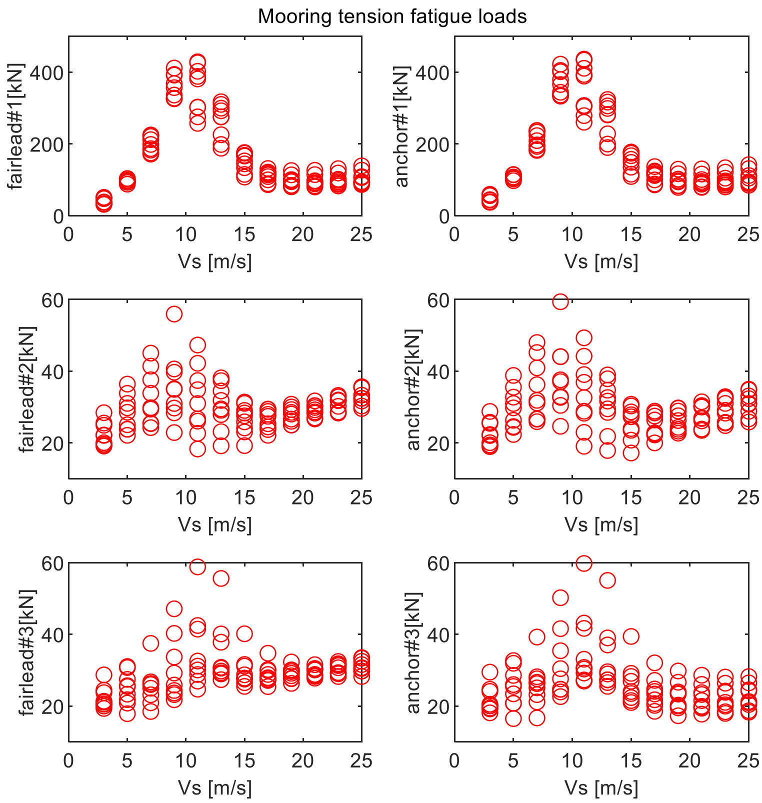

Figure 4-3: The mooring tension fatigue loads

It can be seen that near the rated wind speed of 11 m/s, the mooring tension fatigue loads have peak values. In the following, it was verified how the mooring tension force changes along the most heavily loaded mooring line. In this test, the mooring tension forces are generated for each line segment and the mooring tension fatigue loads along mooring line 1 are illustrated in Figure 4-4.

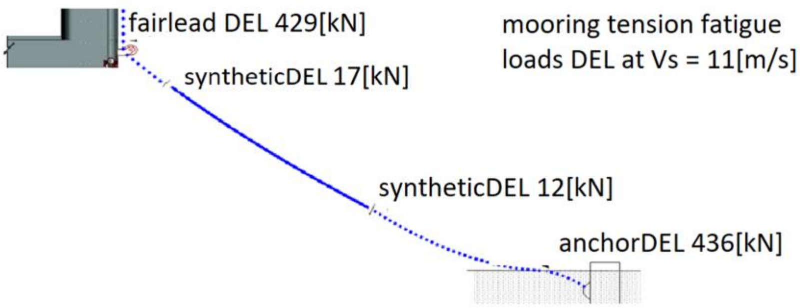

Figure 4-4: At Vs = 11 m/s the mooring tension forces along mooring line 1

4.3.3 Discussion

The findings of Section 4.3.1, identified the mooring lines as the structural system yielding most of the potential for the implementation of digital twin monitoring approach. The highest overall score (in term of sum-of-squares) is actually achieved by the distributed acoustic sensing technology. However, the implementation of this technology would translate into the updating of two tasks only (event b1 and b2) in the impact assessment of Section 5.

To complete the analysis with advices on the sensors setup and locations, the analysis in Section 4.3.2 investigated on the critical hotspots of the station keeping system. Based on this assessment the load cells for the monitoring of the lines tensions could be placed at the fairleads and/or near the touchdown points close to the seabed. However, placing auxiliary equipment or sensors close to connecting components of a mooring system or even close to the seabed comes from a practical perspective with a high risk of damage or loss. For example, a load cell close to the touchdown point could be in contact with the seabed at extreme conditions, which must be prevented from a robustness perspective of the equipment. In addition, it is challenging to maintain a reliable data connection for sensors at larger water depths attached to mooring lines, for instance, to get the signal from the ground to the data logger above the water surface.

Alternatively, the tensions at the fairlead and anchors could be calculated using the time history of floater motion measurements or tension measurements from a top chain, which are feed into a sufficiently detailed digital twin of the asset. However, live monitoring of mooring line tensions comes with the advantage that discontinuous behaviour and anomalies such as tearing or lengthening of fibre ropes indicating moving anchor points can trigger an inspection which would not have been predictable by digital twins. In particular, monitoring of out of plane bending of top chains is seen as an important aspect to consider because of fatigue failures being reported in O&G units.

In the following chapter these considerations are taken forward to the O&M simulations, investigating the potential gain and the return on the investment of such monitoring technology. The analysis includes the assessment of the impact of a PF-interval length on the O&M cost and thoughts on the potential cost for the implementation of the digital twin.

5 O&M Cost Reduction by Condition Monitoring

This chapter presents the approach and the results for the assessment of the impact of the monitoring technologies, identified in Chapter 4, on the O&M cost and availability statistics of one of the COREWIND reference wind farm. The presence of the monitoring system is modelled by updating the maintenance scheme to a CBM strategy, i.e. acting on alarms, and extending the interval between inspections.

The simulations are set up in the Ramboll's PyLCC (Python Life Cycle Cost assessment) tool. The opting for this in-house tool instead of the commercial Shoreline's software, used for the calculation of D4.2 [2], is due the limitations of Shoreline's O&M module in modelling the inputs and logic necessary for this analysis. The Gran Canaria site and its optimized wind farm layout – reported in deliverable D6.1 [30] – are taken as case study. The optimised strategy for the maintenance of the offshore turbines, on ActiveFloat substructures, is rebuilt based on the information reported in D4.2 [2].

A brief introduction to the O&M module of PyLCC is given in Section 5.1.1. The reason behind the selection of this scenario and its optimised maintenance strategy is explained in Section 5.1.2. Details on the modelling assumptions and the setup of the PyLCC simulations are reported in Section 5.2. Finally the results are presented and discussed in Section 5.3.

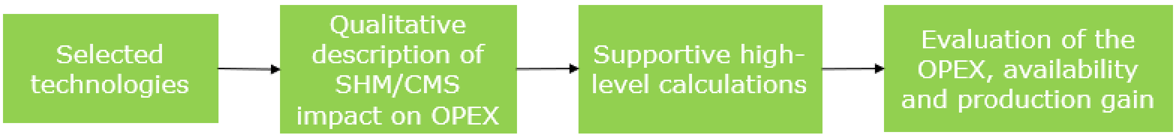

Figure 5-1: Workflow for the identification of the cost reduction potential of the monitoring systems suitable for floating offshore wind

5.1 Impact Assessment Strategy

Due to the often larger distances from shore, the costs for the maintenance of floating offshore wind projects can easily go over budget is not carefully planned in advance. A high-quality O&M strategy targeting a minimum required number of visits to the offshore wind asset has the potential to affect the decision of investment on future projects.

As introduced in Section 3.1, the application of CBM can reduce the number of offshore interventions, by evaluating on the risk of a functional failure based on the assets' monitored conditions. In particular, the application of monitoring systems has a twofold impact on the maintenance planning:

1) It allows to move away from the fixed-time scheduling of the inspections. By gaining knowledge on the actual status of the assets, the necessity of (and interval between) maintenance campaigns can be challenged (and extended) by the support of risk-based judgments.
2) Depending the goodness of the detectability and the correct calibration of the technologies, it allows to act timely on alarms (potential failures) before the occurrence of the functional failure. This might bring the necessity to cope with false alarms of the monitoring system. However, the cost of extra surveys for on-site inspections can be outweighed by the benefits related to the switch to a run-to failure (corrective) to a predictive maintenance. Among some of the advantages are:
    - a reduction of the production losses generally caused by long lead time and delays due to unavailable weather windows;
    - a relieving of the pressure for hurried corrective maintenance, allowing the planning and potentially a better negotiation of the carter rates of the required maintenance units (e.g. vessels) for the maintenance operations.

5.1.1 Implementation in PyLCC

In this analysis, the impact of the switch to a CBM strategy is assessed in the O&M module of the in-house PyLCC tool. This module was originally developed for the O&M cost and availability assessment of offshore wind bottom-fixed project. A Monte Carlo approach is used to capture the stochasticity in the simulation of the environmental conditions – affecting the windowing for the transit and the accessibility to the floating structure – and a Poisson process is implemented for the simulation of unforeseen failure events throughout the lifetime of the wind farm.

Several other commercial O&M tools simulate corrective maintenance actions by triggering them based on random (functional) failure events (F of Figure 3-2). However, the customization and adaption of the simulation logic for the different type of "triggers" is not possible in these black-box tools. Thus, the development has been taken forward in the in-house tool. To fit the purpose of this analysis, the O&M module of PyLCC has been extended to include:

- the modelling of the tow-in procedure, for simulating the towing of the floating asset to shore to perform major component exchange, and its towing back to site at the completion of the repair;
- the constrains of accessibility, workability and transportability matrices dictated by the analysis of the relative motion between the assets and the maintenance units in several metocean states - see Chapter 5 "Operational Limits for Scenarios" of D4.2 [2];
- the triggering the maintenance actions based on potential-to-functional failure intervals, by scheduling activities via a decision gate management of alarms (i.e. acting on potential failure events, e.g. P1 or P2, see Figure 3-2).

5.1.2 Case Study Selection

To investigate the impact of the installation of a monitoring system, and to assess its effects on the cost and availabilities of a floating offshore wind project, the Gran Canaria wind farm with the turbine on the ActiveFloat substructure (i.e. scenario 6A of D6.1 [30]) is taken as a reference. The optimal O&M strategy for this scenario was identified, in D4.2, to be the one deploying:

- 8 crew transfer vessel (CTV) units - 7 owned vessels and 1 charted - for the day-to-day corrective and scheduled maintenance;
- a tug boat to perform the major component exchange is via tow-in, additionally supported by an anchor handling vessel (AHV) for disconnecting, storing and re-connecting the floating structures from the station keeping system and the dynamic cable;
- 2 service operation vessel (SOV) units for transporting and launching the remote operated vehicles (ROVs) for the subsea operations and/or supporting the AHV system on maintenance operations of the station keeping system.

This sub-optimal scenario is selected, among all the other of D4.2 [2], because of the potential higher impact of monitoring when deploying the CTV units for scheduled and corrective maintenance. The better optimized scenarios associated to the selection the Morro Bay (US) site (scenario 9A and 9W of D6.1 [30]), and the installation of the turbine on Windcrete supports (scenario 6W of D6.1 [30]) were not preferred due to the following reasons,

- The optimal O&M strategy for the 9A and 9W scenarios accounts for the SOV units to be deployed on site throughout the whole year, to perform above and below water maintenance activities on the wind farm. Thus, the advantage of a reduced number of scheduled inspections cannot be capture in these cases.

- The Windcrete scenario in combination with the tow-in strategy for major component exchange is a more theoretical scenario due to the depth of the spar and possible port restrictions.

5.2 Simulation Setup

5.2.1 Baseline Scenario

Table 4-2 reports the details of maintenance events specific to the floating wind structures, which are accounted for in the FMEA of Section 4.3, and in the simulations of deliverable D4.2 [2]. The same inputs are here used to simulated the unforeseen and scheduled maintenance events, and to setup the logic of the maintenance actions for their rectification.

Due to the inability of the PyLCC-O&M module to represent the detailed scheduling of a return to port of the SOV - required for scheduled subsea maintenance activity - only every 28 days (for refuelling and crew exchange), in the current baseline scenario this unit logistics is modelled as for the CTV units. Therefore, the offshore subsea maintenance inspections are performed by the SOV leaving the port at the scheduled time and returning after completion of the task. No changes are instead introduced in the logistics of the SOV supporting the AHV for corrective maintenance request.

5.2.2 CBM Scenario

For the simulation of the CBM, the inputs and logistics of some of the events of Table 4-2 are modified as shown in Table 5-1. These events are the one deemed to be affected by the installation of a digital twin technology able to monitor the status of a floating turbine station keeping system .

The corrective event are assumed to be detected a year prior the functional failure. Once the alarm is raised, the simulation queues this task in the form of a downgraded corrective maintenance actions (“alarm” in the table) to be resolved at the first chance possible - depending on the resources availability and the weather windowing.

Table 5-1: New assumptions for the CBM scenario for the performance of maintenance actions based on alarms and updated assumptions for the scheduled subsea inspections of the mooring lines.

Event	Kind	Trigger	O&M Strategy	Frequency	Manhours	Number of technicians	Cost of material	Impact on production
Mooring lines twisting and major repair	Corrective	Run-to-repair	AHV with supporting CTV	0.015	240	10	20,000 €	100%
		Alarm					5,000 €	-
Mooring lines breakage and replacement		Run-to-repair		0.0125	360		135,000 €	100%
		Alarm			240		20,000 €	-
Anchor disconnection		Run-to-repair		0.015	240		75,000 €	100%
		Alarm					5,000 €	-
Anchor loss/ replacement		Run-to-repair		0.0125	360		512,000 €	100%
		Alarm			240		75,000 €	-
Buoyancy modules loss/ replacement		Run-to-repair	SOV with ROVs	0.033	40	5	100,000 €	100%
		Alarm					10,000 €	-
Subsea mooring lines inspections	Sched	-		0.2	12		500 €	-

Note: The “impact on production” refers to the necessity to shut down the turbine (100% impact) prior the intervention

As regards the scheduled inspection of the mooring lines, the installation of the digital twin technology has the potential to endorse a longer time period between campaigns based on risk judgments. Therefore the maintenance frequency is updated to every 5 years – maximum allowed period from the classification society perspective [1].

5.3 Simulations Results and Discussion

The results of the baseline and the CBM scenario are reported, to be compared, in Table 5-2. These are presented as the statistics among several random runs (10 per scenario), in terms of mean, minimum and maximum values and 25, 50 and 85 percentiles.

Table 5-2: Results of the baseline and the CBM scenario

	TBA	PBA	OPEX/MW/year
Baseline			
mean	**84.5%**	**82.5%**	**75,280 €**
std	0.9%	1.0%	4,333 €
min	83.4%	81.3%	69,009 €
25%	83.7%	81.7%	72,871 €
50%	84.5%	82.6%	74,377 €
75%	85.0%	83.0%	78,157 €
max	85.8%	83.9%	82,615 €
CBM			
mean	**88.4%**	**86.8%**	**63,816 €**
std	0.6%	0.7%	2,678 €
min	87.5%	85.9%	60,095 €
25%	87.8%	86.2%	62,280 €
50%	88.3%	86.7%	63,627 €
75%	88.8%	87.3%	65,185 €
max	89.3%	87.9%	67,824 €

It can be observed that the figures of the time-based (TBA) and the production-based (PBA) availability are unacceptably low. From a first analysis of the simulation logs, this issue can be associated to excessively long time to restore (of the order of years) of some of the events requiring tow-to-shore of the floating wind assets. The correction of this bug is one of the main objective of the future work on the topic. Despite this shortcoming, the results are deemed to be still informative, due to the fact that the CBM strategy is implemented without acting on maintenance tasks which require a tow-in process.

It is noticeable that the implementation of a CBM approach deploying the digital twin technology to the station keeping system of the assets could have the **potential to reduce the OPEX per MW year of about 15%** of the baseline scenario, while increasing to some extent the revenue – related to the higher PBA.

6 Conclusions

This study presents the findings on the assessment of the impact of the installation of monitoring technologies to the O&M strategy and statistics of a reference floating wind farm. The case study is take to be the 1.2GW offshore wind farm in the Gran Canaria waters, implementing a tow-in and CTV-based O&M strategy for the maintenance of the 80 assets installed on the ActiveFloat foundations.

First, a FMEA is conducted to assess which monitoring technology is the most promising a floating wind turbine. A set of maintenance events of the floating wind structure is characterised with regard to their likelihood and the consequences of their occurrence - in term of the maintenance actions for their rectification, the material costs, the impact on production and the required manhours. A number of monitoring technologies for the floating wind turbine is presented and qualitatively evaluated with regards to reliability, detectability, maturity, and cost of the technology. The maintenance events are then combined to the monitoring systems in a matrix, to identify the technology likely to bring most of the benefit for the purpose of this analysis.

An O&M model is developed to assess the impact of the monitoring system, by benchmarking it against a reference scenario rebuilt from D4.2 [2]. The in-house O&M model is further extended to simulate the floating wind specific O&M strategy and the modelling of alarms triggered by monitoring systems.

The results show possible OPEX savings of about 11.500 €/MW/year throughout the lifetime of the wind farm, which equates to approximately 15% of the original operational expenditures. Improvements seem also to be achieved in the time-based and production-based availability statistics.

The findings of this report help to derive the following main conclusions:

- The benchmarking of the technologies showed that the deployment of a digital twin for monitoring of the station keeping system of the floating wind turbines has the potential to create the most positive impact on the O&M figures;
- The simulation of a maintenance strategy driven by the knowledge on the condition of the monitored system can decrease the OPEX by over 15% the one of the original scenario.
- This condition-based maintenance is additionally associate to an increase availability, and thus an extra gain in the revenue.

Future works will have the following main objectives:

1. A more detailed analysis of the return of the investment for the digital twin technology. For this a market study on the CAPEX needs to be performed.
2. Further debugging of the O&M simulations to increase the availability estimates to an expected range, and validation of the O&M calculations for floating wind system against a multitude of case studies.

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