Logistic Efficiencies And Naval architecture for Wind Installations with Novel Developments

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Definitions

ALWC	Accelerated Low Water Corrosion	OEE	Overall Equipment Effectiveness
BOP	Balance of Plant	OEM	Original Equipment Manufacturer
CAPEX	CAPital EXpenditures	OFTO	OFfshore Transmission Owner
CBM	Condition Based Maintenance	OLPD	On-Line Partial Discharge
CM	Corrective Maintenance	OMS	Operation & Maintenance Service
CMMS	Computerized Maintenance Management Systems	OMSP	O&M Service Provider
CMS	Condition Monitoring Systems	OPEX	OPerating EXpenses
DECC	Department of Energy and Climate Change (UK)	OWDIN	Offshore Wind Drivetrain INnovation
DOW	Description of Work	PD	Partial Discharge
ERP	Enterprise Resource Planning	PLB	People Locator Beacons
ETTF	Estimated Time To Failure	PM	Preventive Maintenance
FBG	Fibre Bragg Grating	PO	Project Owner

FMEA	Failure Mode Effect Analysis	PTO	People – Technology – Organization
FMECA	Failure Mode Effect and Criticality Analysis	RBI	Risk Based Inspection
FTA	Fault Tree Analysis	RCM	Reliability Centred Maintenance
GBS	Gravity Based Structure	RDS-PP	Reference Designation System for Power Plants
HAZOP	HAZardous OPerations	ROV	Remotely Operated Vehicle
H_S	Significant Wave Height	RUL	Remaining Useful Life
HSE	Health, Safety and Environment	SCADA	Supervisory Control and Data Acquisition
HV	High Voltage	SoA	State-of-Art
IEC	International Electro technical Committee	SRB	Sulphate Reducing Bacteria
ISO	International Standardization Organization	SW	Software
IR	Infrared	SWA	Service & Warranty Agreement
KPI	Key Performance Indicator	TCM	Turbine Conditioning

			Monitoring
LCoE	Levelised Cost of Energy	TDR	Time Domain Refraction
MIC	Microbial Induced Corrosion	TPM	Total Productive Maintenance
MTBF	Mean Time Between Failures	WP	Work Package
MV	Medium Voltage	WPS	Wind Power Supervisor
NDT	Non Destructive Testing	WT	Wind Turbine
O&M	Operations & Maintenance	WTG	Wind Turbine Generator

Executive Summary

This document outlines the main challenges for operation and maintenance of offshore wind farms. The following key areas are covered:

- Technical integrity
- Operational integrity
- Tools and methodologies
- Standardization
- Lifetime extension
- Climate change

The recommendations are given as a background for the further work to be performed in WP4.

Technical integrity

The technical integrity of an offshore wind farm can to a large extent be assessed through use of condition monitoring. A major challenge today is how condition monitoring data is systemised and coupled to relevant models that may support the continuous improvement processes inherent in maintenance strategies. Automation of data capture should be expanded to cover potentially all activities related to inspection, surveillance and monitoring. The use of automation, robotics and autonomous units will help address the necessary reduction in manned interventions, directly influencing the LCOE for offshore wind. Manned interventions should be confined to heavy maintenance work.

In addition to information from condition monitoring, information from inspections can be important to assess the technical integrity. Compared to condition monitoring which typically provides indirect information on the deterioration / damage level of the components, inspections can provide direct information with less uncertainty. Since the cost of inspections are generally larger than costs of condition monitoring a cost-benefit or risk-based approach is needed for cost-optimal decision making.

Operational integrity

Operational integrity is about the challenges to keeping the wind turbines operational that are not directly related to the technical integrity of the wind turbine. Among the various factors that are relevant, a logistics strategy allowing the accessibility that is necessary for the maintenance strategy is crucial for the operational integrity of the wind farm. The requirements for the logistic solution and vessel fleet (as well as the rest of the maintenance strategy) will increase as wind farms are deployed on sites further from shore and in harsher wave climates. Both topics are interdependent on other aspects of O&M. The use of methods such as Reliability Centred Maintenance and Total Productive Maintenance ultimately requires a maintenance organisation to acquire a culture which cultivates the ability to change and adapt throughout the life of the installation. Concepts such as the People-Technology-Organisation (PTO) from the oil & gas industry should be explored to exploit the value of increased collaboration, both within individual companies as well as between suppliers and operators. Such collaboration is crucial to bring down the LCoE.

Support by:

Risk-based approaches for planning of O&M activities provide a consistent approach for optimal decision making.

Tools and methodologies

Examples of challenges and developments include

- the improvement in availability expected from improved condition monitoring systems or novel concepts such as remote presence
- the effect of weather conditions and sea sickness on the maintenance work to be done by technicians
- the effect of improved scheduling, grouping and routing on the overall operation of the wind farm
- the interaction between the strategy for spare parts and the strategy for vessel logistics
- the best strategies for chartering of heavy-lift vessels

Standardisation

The wind power industry should adopt international standards for data capture, storage, communication and presentation. The use of open data protocols encourage development of new and innovative solutions.

Standardization could have two implications. One is standardization of O&M activities / operations used for many different wind farms / wind turbines. This could in some cases imply that that a more optimal site specific process / operation is not used because it is not part of the standardized tools.

The other aspect of standardization is to develop standards / regulations that specifies minimum requirements e.g. to secure a sufficient safety level for personnel. Both types of standardization should be investigated and the potentials for cost savings identified without compromising the requirements to personnel safety.

Lifetime extension

The same tools as used for decision making related to planning of O&M can equally be used for decision making related to lifetime extension (or shortening). Information from condition monitoring provides very useful information for this decision making.

Climate change

Climate change is inherently a slow process on a global scale (climate is defined as average weather patterns over an arbitrarily selected 30 year period), but regional and local changes may occur faster. The industry should undertake actions to ensure that changes in wind patterns and other relevant environmental factors are monitored for the purpose of detecting changes that may impact load factors, energy yield and survivability of a wind farm.

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1. Introduction and background

"LEANWIND" (Logistic Efficiencies And Naval architecture for Wind Installations with Novel Developments) is an EU funded project under FP7 which aims to provide cost reductions across the offshore wind farm lifecycle and supply chain. This will be achieved through the application of lean principles and the development of state of the art technologies and tools. The project is a collaboration of industry and academic partners from 11 countries to provide most opportunity for this to be achieved.

1.1 Project Description

The Levelised Cost of Energy (LCoE) produced by the offshore wind power in the end of 2013 has been estimated to be between 0.119 and 0.194 Euro/kWh. The cost of offshore wind power is significantly higher than that produced onshore, mainly due to the more expensive installation procedure, and the higher associated operation and maintenance costs.

It is expected that in the short-term, improved logistics infrastructure for installing wind power plants will reduce the costs. However, in the long run, the application of larger turbines and the improvement of efficient manufacturing and installation processes determine the trends.

Operation and maintenance accounts for approximately 25% of the LCoE for offshore wind. The reason for this high percentage is found in several factors:

- Offshore wind has traditionally been based on moving onshore technology offshore
- Using onshore technology has led to use of inherent O&M procedures, leading to a high number of manned interventions per turbine per year
- Access is limited by metocean conditions and HSE considerations
- The lack of dedicated offshore technology focusing on robust solutions, automation, instrumentation and robotics

The main objective of the LEANWIND project is to contribute to reducing the overall cost of offshore wind energy, through modification of the current state of foundation design, logistics, transportation, installation, and operation and maintenance of the wind farms as part of an integrated framework. LEAN as a methodology focuses on reducing waste in the form of unnecessary procedures, organizational issues and other issues. Focus is placed on an organization's ability and capacity to carry out its task while cultivating improvement through change originating at any level in the organization.

1.2 Scope of Work

Deliverable 4.1 shall provide a brief state-of-the-art (SoA) within the scope of work package 4, and point to the main challenges that the industry faces within operations and maintenance of offshore wind turbines.

The report covers the areas of technical integrity and operational integrity, tools and methods and finally strategies for implementing optimized logistics and operations and maintenance. There is also a chapter outlining the framework of work package 4.

LEANWIND has decided on a design basis as a foundation for the first deliverables in WP2, WP3 and WP4, shown in Figure 1.

Case	Water depth (m)	Distance to port (km)	Likely substructure types
0	20	30	Monopiles Gravity based foundations
1	40	30	Jackets and tripods (piled or suction based) Gravity based foundations
2	60	100	Jackets and tripods (piled or suction based)
3	100	30	Floating turbines

Figure 1 Design basis for LEANWIND

The design basis has its primary impact on the logistics issues in strategies for operation and maintenance. This relates to transport of personnel, spare parts and utilities to the wind farm. This is the focus of work package 5, thus a comprehensive analysis on these issues will not be covered by deliverable D4.1.

One of the important issues that need to be addressed to bring down the LCoE is the need for manned interventions. This challenge remains regardless of water depth and distance to shore. Work package 4 will address this issue through studies on design and use of comprehensive, advanced systems for condition monitoring, condition based and predictive maintenance. The use of robotics and automated systems will also be addressed by work package 4.

Deliverable 4.1 is the first in work package 4 and will be used by other work packages (WP5, WP6) to coordinate the work performed throughout the LEANWIND project. Deliverable 4.1 is not intended to provide details on specific methodologies, but may do so where it is found appropriate for the readability of the document.

2. Concepts and definitions

In this project the European standard EN 13306:2010 specifies generic terms and definitions for the technical, administrative and managerial areas of maintenance.

Maintenance is defined in paragraph 2.1 of EN 13306:2010 as: "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.

Annex A of EN 13306:2010.gives us this Maintenance – Overall view

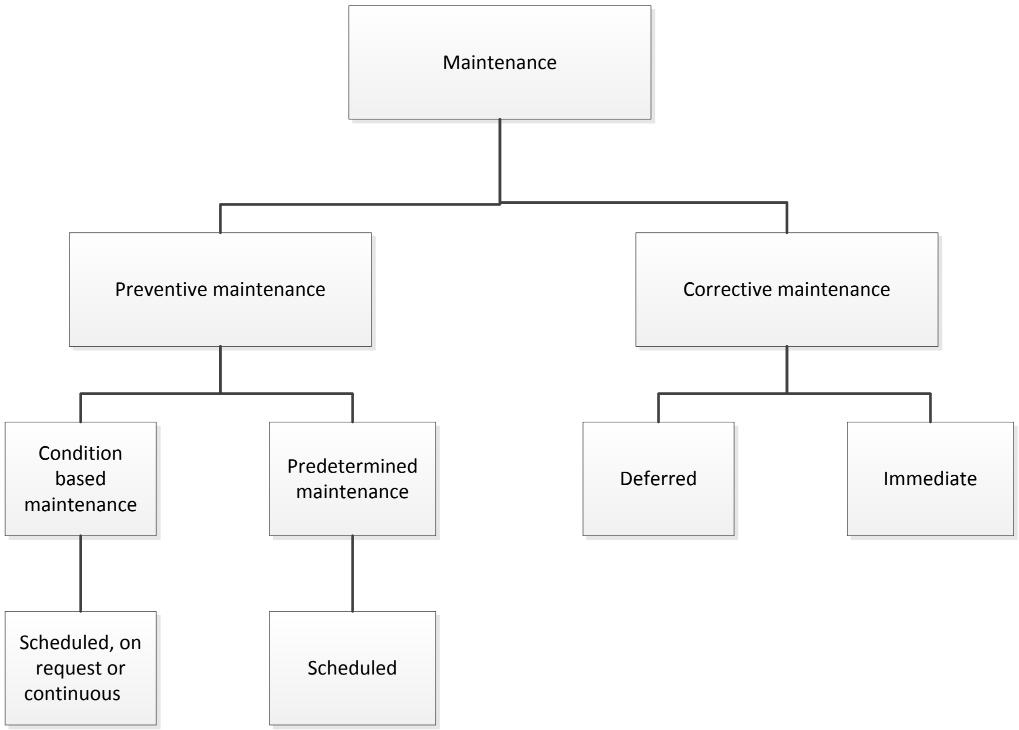

Figure 2 Maintenance overall view taken from Annex A of EN 13306:2010

2.1 LEAN philosophy

Ref. [1][2][3][4]

Proactive thinking from the early stage of concept evaluation until decommissioning of a wind turbine is a key success factor in lean maintenance philosophy. The entire life cycle of the item in question must be observed and subject to lean evaluation and cost evaluation.

Lean seeks to eliminate all forms of waste in a life cycle of an item – including waste in the maintenance process. [1] Maintenance management is a key factor in the setting up an efficient maintenance program. This involves all activities of the management that determine the maintenance objectives, strategies and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and the improvement of maintenance activities and economics. (Paragraph 2.2 of EN 13306:2010)

The foundation of Lean Maintenance is TPM (Total Productive Maintenance). TPM is team based proactive methodology focused on optimising maintenance and involves every level and function in the organization, from top executive to the shop floor. TPM addresses the entire production system life cycle. [1]The organizational culture is of utmost importance in the transformation to a lean organisation. Thus lean transformation is a journey not a destination. [1]Key components in lean organisations are teamwork, employee involvement, continuous improvement, communication, and self-direction. [1]Maintenance management should be at the same organisational level as production management. Maintenance should thus be regarded as a supportive service and not a subordinate one.

Optimizing the hardware is part of the road to lean maintenance implementation. Reliability of wind turbines depends on design and maintenance. A bad design or using components of low reliability will influence maintenance activities and the amount of maintenance required. RCM (Reliability Centred Maintenance) is often used to determine which components are critical to the availability of the wind turbine. The RCM concept is a structured analyses methodology used to achieve an optimal maintenance programme.

In order to achieve a maintenance strategy for items and systems the following questions have to be answered:

1. What is the function of the item and which precision standard is required for its function?
2. How can an item fail in fulfilling its function?
3. What is the reason for each individual failure?
4. What is the consequence of each individual failure?
5. What can be done to prevent each individual failure?
6. What can be done if no acceptable preventive action is exist?

The process of answering these questions is done by systematic analysis of the items/systems functions, failure mode, failure cause, consequences, possible preventive actions and whether these preventive maintenance measures are cost-effective.

The RCM concept can be divided into 4 separate activities

1. Functionality analysis
2. Error and criticality analysis
3. Identification of maintenance activities decision logic
4. Continuous improvement of the maintenance program

FMEA / FMECA (Failure Mode and Effect Analysis – FMEA and Failure Mode, Effect and Criticality Analysis) are used to analyse failures in technical systems. By ranking criticality of the different effects of failure in a failure mode and failure effect analysis you go from FMEA to FMECA.

The goal of the analysis is:

1. Identify possible failure modes of every component in a technical system
2. Determine the cause of the failure modes
3. Determine the failure modes impact on the system as a whole
4. Determine the severity of the different failure effects

An FMECA analysis is often a required part of system documentation.

It is very important to be aware of the fact that an FMECA analysis focuses on one item at a time, assuming the other items in a system will fulfil their required function. An FMECA analysis will thus not reveal critical combinations of component failure.

FTA (Fault tree analysis) can be used in many contexts both in risk analysis and reliability analysis. In a design phase, the FTA can be used to discover hidden failure modes due to combinations of item failure. The analysis can also be used to optimize the reliability of a system or verify that an acceptable reliability can be achieved. An FTA analysis can be qualitative, quantitative or both depending the analysis scope and aim.

HAZOP (HAZardous Operations) analysis is a systematic analysis of how deviation from design condition can appear, and whether these deviations can cause risks. It is done in an interdisciplinary team, composed of experienced personnel. HAZOP analysis is an effective way to determine possible safety and/or operational problems that can occur during operation and maintenance of primarily process plants. It is, however, also used on different systems and plants.
An event tree is a logical diagram showing possible event chains as a result of an initial critical event. This methodology is often part of a risk analysis on technical systems. The aim of the analysis is to identify chains of events following a specified initial event that can result in accidents. If relevant reliability data is available the event tree can be used to calculate the probability of the different events identified.

RBI (Risk based Inspection) is a qualitative methodology that is based on RCM, but used primarily towards inspection of static equipment (pipes, valves, tanks, separators etc.). The methodology is used for setting up the optimal inspection programme, based on material properties, operating conditions and findings from previous inspections. It advises on the extent and frequency of inspections based on updated information on the significant contributing factors to integrity.

Fine tuning TPM through integration with elements of Reliability Centred Maintenance (RCM) require among other things:

- Assessing equipment criticality
- Prioritising Maintenance tasks

When planning maintenance work the equipment with the highest criticality is scheduled first and maintenance tasks are scheduled in order of priority. Reliability engineering can help in tuning the maintenance further by the use of probabilities and reliability calculations and the use of historical data.

Using the results from Predictive Maintenance and Condition Monitoring and Preventive Maintenance (PM) task analysis, the job of Maintenance Engineering is to eliminate unnecessary maintenance activity.

TPM activities should focus on results. One of the fundamental measures used in TPM is Overall Equipment Effectiveness or OEE.

- OEE = Equipment availability X Performance Efficiency X Rate of quality [%]

World Class levels of OEE start at 85% based on the following values:

- 90% (Equipment Availability) X 95% (Performance Efficiency) X 99 % (Rate of quality) = 84,6 % OEE

Smith et. al. [4] suggest that the first focus on TPM should be on major equipment effectiveness losses, because this is where the largest gains can be realized in the shortest time. The losses can be divided in 11 major areas and furthermore into four categories.

PLANNED SHUTDOWN LOSSES
1 No production, breaks, and /or shift changes
2 Planned maintenance

DOWNTIME LOSSES
3 Equipment failure or breakdowns
4 Setups - waiting for spares
5 Part changes
7 Start – up and adjustment

PERFORMANCE EFFICIENCY LOSSES
8 Minor stops – they add up
9 Reduced speed or output

QUALITY LOSSES
9 Scrap – losing operation time due to wrong output
10 Defects on product – supply frequency problems etc.
11 Yield or process transition losses – run in time, warm up time

Optimizing the inspection interval and thus costs is a key contribution to lean inspection. Failures do not occur instantaneously, and it is often possible to detect the fact that the failure is occurring during the final stages of deterioration.

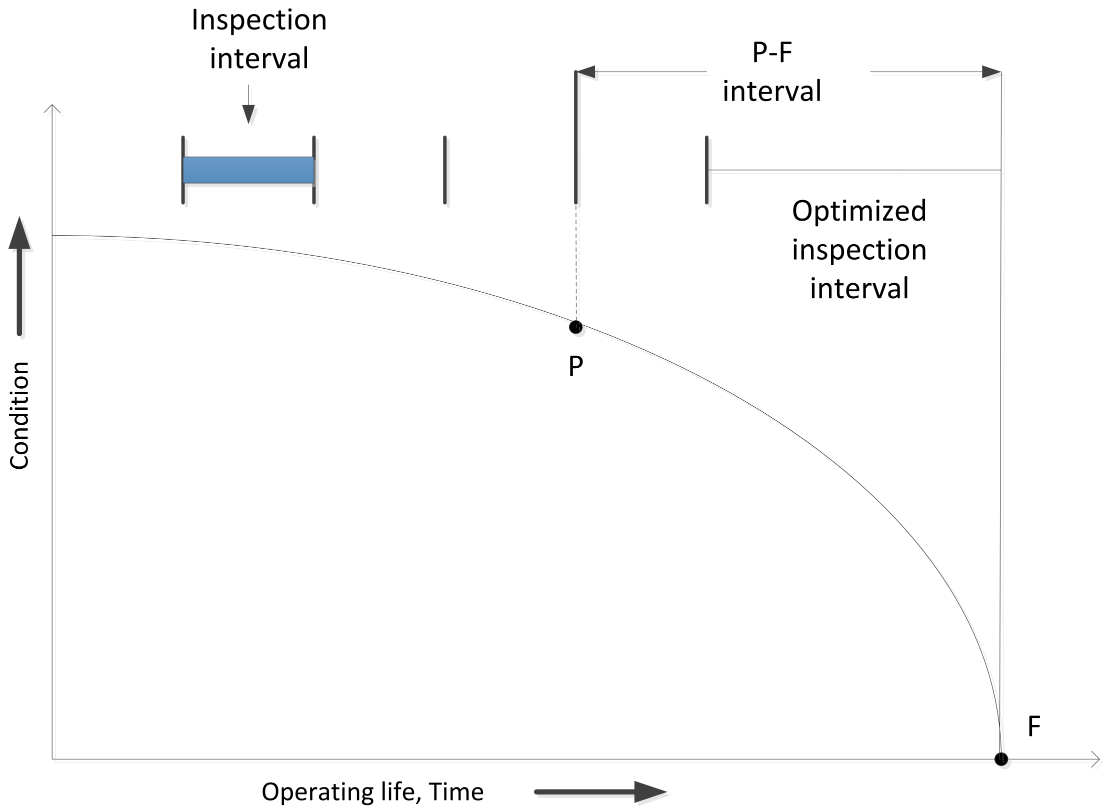

Figure 3 P-F interval and determination of optimized inspection interval based on periodic inspections [1]

The potential failure point P is the point where deterioration is possible to detect. At point F the functional failure is a fact. Selecting the right monitoring approach is of utmost importance as the main objective is to get an early warning on an item approaching failure. Probability and reliability calculations can be used to further determine the need for maintenance activities.

2.2 Corrective maintenance (CM)

CM is defined in paragraph 7.5 of EN 13306:2010 as:
"Maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function."

A fault is defined in paragraph 6.1 of EN 13306:2010 as:
"State of an item characterized by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources."

Maintenance activities carried out after fault recognition is as we can see covered by the term corrective maintenance. Planned activities or preventive maintenance is normally not to be considered as part of corrective maintenance.

Corrective maintenance is subdivided depending on the criticality of the fault.

Deferred corrective maintenance is defined in paragraph 7.6 of NS-EN 13306:2010 as: "corrective maintenance which is not immediately carried out after fault detection but is delayed in accordance with given rules"

The given rules determine if run to failure is acceptable. The effect of the fault is of importance when determining the rules.

Immediate corrective maintenance is defined in paragraph 7.7 of EN 13306:2010 as: "corrective maintenance that is carried out without delay after a fault has been detected to avoid unacceptable consequences"

In this case the effect of the fault is of such a character that immediate action is required.

Further sub division of corrective maintenance is not done in this project.

2.3 Preventive maintenance (PM)

PM is defined in paragraph 7.1 of EN 13306:2010 as: "maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the function of an item"

A failure is defined in paragraph 5.1 of EN 13306:2010 as: "termination of the ability of an item to perform a required function."
Maintenance activities carried out in order to prevent failure or degradation of an item is as we can see covered by the term preventive maintenance.

An item is defined in paragraph 5.1 of EN 13306:2010 as:
"...part, component, device, subsystem, functional unit, equipment or system that can be individually described and considered."

Preventive maintenance is subdivided into time based maintenance and condition based maintenance.

Predetermined maintenance is defined in paragraph 7.2 of EN 13306:2010 as: "preventive maintenance carried out in accordance with established intervals of time or number of units of use but without previous condition investigation"
In this case established intervals of time or number of units of use determine maintenance activities not the condition of the item in question.

Condition based maintenance is defined in paragraph 7.3 of EN 13306:2010 as: "preventive maintenance which includes a combination of condition monitoring and/or inspection and/or testing, analysis and the ensuring maintenance actions"

In this case the condition of the item in question is a major factor in determining maintenance to be carried out.

Further subdivision of preventive maintenance than in figure A.1 of EN 13306:2010 is not done in this project.

2.4 Condition based maintenance (CBM)

CBM is as was determined in paragraph 2.3 to be considered as a subdivision of the preventive maintenance term.

The main component of CBM is the monitoring of the condition of the item in question.

Hameed et al. [5] list the monitoring techniques used on wind turbines:
Vibration analysis, oil analysis, thermography, physical conditions of materials, strain measurements, acoustic monitoring, electrical effects, process parameters, and performance monitoring.

In a note to paragraph 7.3 of EN 13306:2010 it is stated: "The condition monitoring and/or inspection and/or testing may be scheduled, on request or continuous."

CBM is used to provide an early indication of item damage, allowing for planned item repair prior to failure.

Tavner [6] suggests that Monitoring of modern wind turbines (WT) may include a variety of systems as follows:

- Supervisory Control and Data Acquisition (SCADA) system, to provide low resolution monitoring to supervise the operation of the WT and provide a channel for data and alarms from the WT.
- Condition Monitoring system (CMS), to provide high-resolution monitoring of high-risk sub-assemblies of the WT for the diagnosis and prognosis of faults.
- Structural Health Monitoring (SHM), to provide low-resolution signals for the monitoring of key items on the WT structures.

2.5 Predictive maintenance

Ref. [7][8][9]

Predictive maintenance is defined in paragraph 7.4 of EN 13306:2010 as:
"Condition based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item."

The basic idea behind predictive maintenance is to combine knowledge of design, characteristics, operating conditions and observations of the system (e.g. inspections, maintenance records, measurements) with models of the system in order to arrive at an understanding of the current condition of the system and how long time is remaining until it can no longer perform its desired function.

Tavner [6] suggests that the unreliability of a repairable system can be modelled in terms of failure intensity by the bathtub curve, which represents different phases of a population life. Figure 4 shows three different phases.

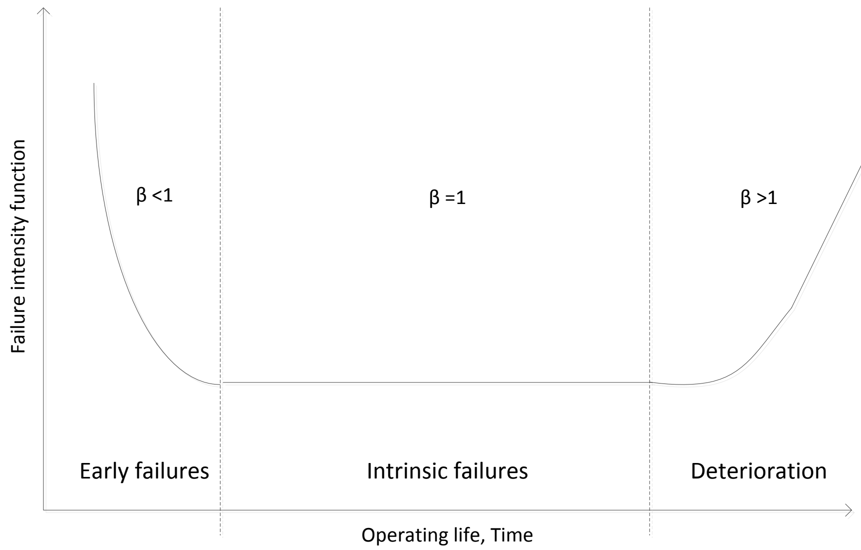

Figure 4 The bathtub curve for the intensity function showing how the reliability varies throughout the life of repairable machinery, Bye [10].

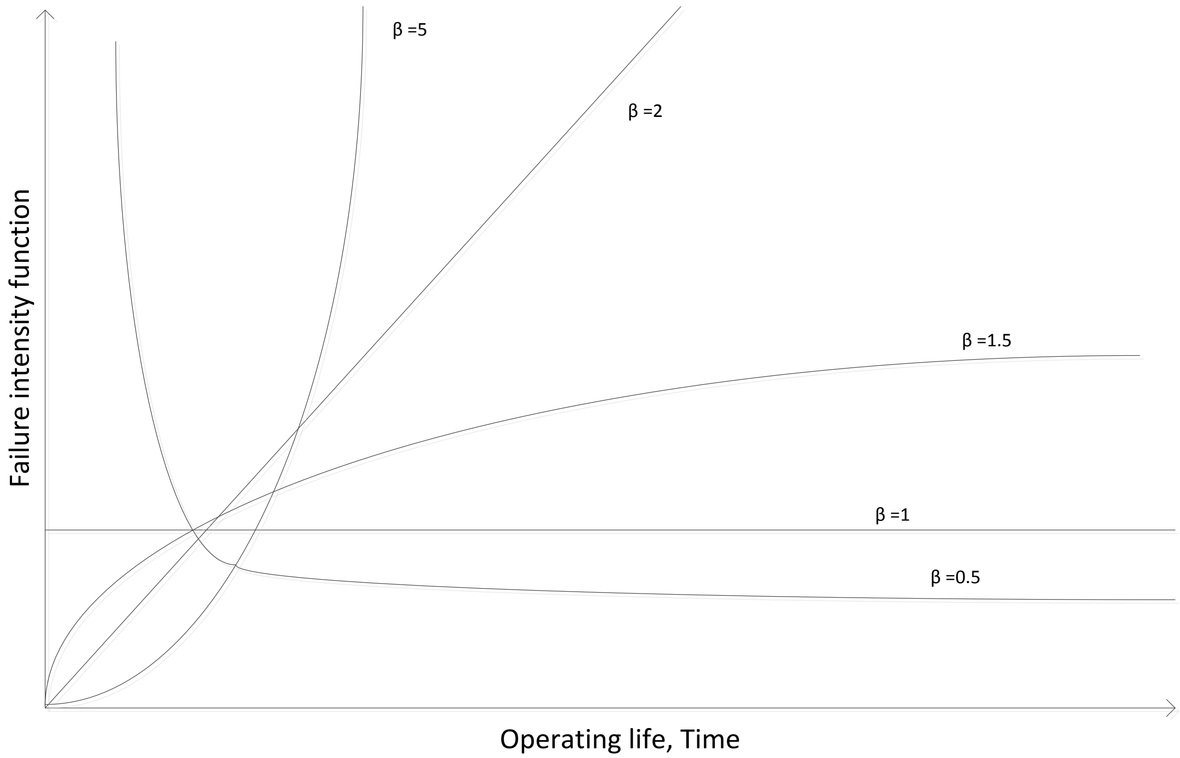

Figure 5 The power law function showing how the failure intensity varies with the shape parameter, Bye [10].

The Weibull distribution can be used to describe the failure intensity function.

Z(t) = $\frac{\beta}{\eta^{\beta}} = (t - t_0)^{\beta - 1}$

β = determines the shape of the curve, and some examples are given in Figure 5.

η = time interval from the time t_0 to the time where probability suggests that 63% of the components have failed –37 % have survived.

t_0= minimum time to failure

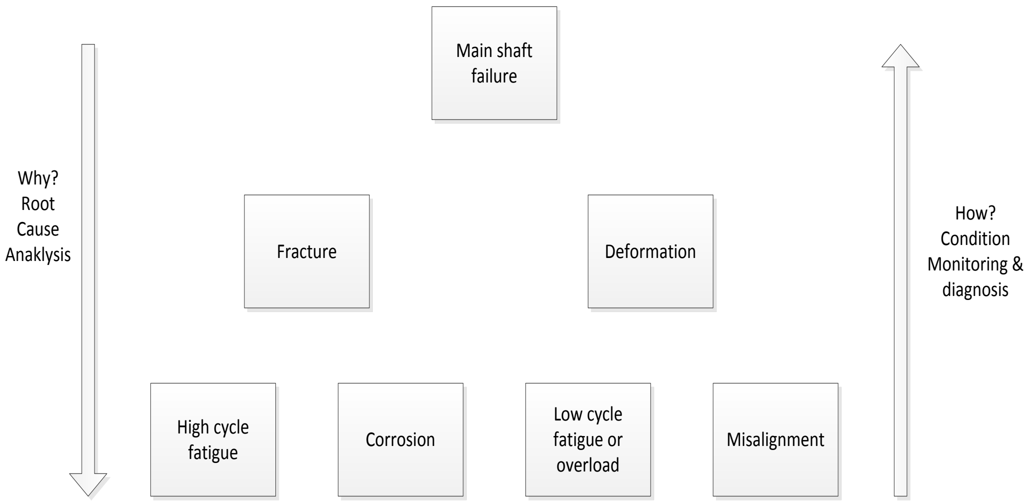

Figure 6 Relationship between failure mode and root cause of a WT main shaft failure

Failure prognosis is aimed at anticipating the time of the failure. The difference between diagnosis and prognosis is that diagnosis is performed after the occurrence of a failure, while prognosis is performed prior to occurrence of a failure.

Several definitions related to prognostics have been reported in the literature [10][12][14]. The International Standardization Organization defines failure prognostics as “the estimation of the Time to Failure (ETTF) and the risk of existence or later appearance of one or more failure modes.” In literature, it is common for the terminology Remaining Useful Life (RUL) to be used instead of ETTF.

2.6 O&M strategy mix - consequences and opportunities

The aim of operation & maintenance (O&M) activities related to the use of offshore wind energy is to achieve high availability of wind turbines while at the same time keeping costs as low as possible. Unplanned outages should be avoided.

The maintenance organisation can basically be distinguished in corrective and preventive strategies as described in the previous sections. These basic strategies are illustrated in Figure 6 to describe their different approaches. The curves show the dependency of the remaining component life time related to the operational time of the component in an idealised way. The operational time is related to the mean time between failures (MTBF) of the respective components.

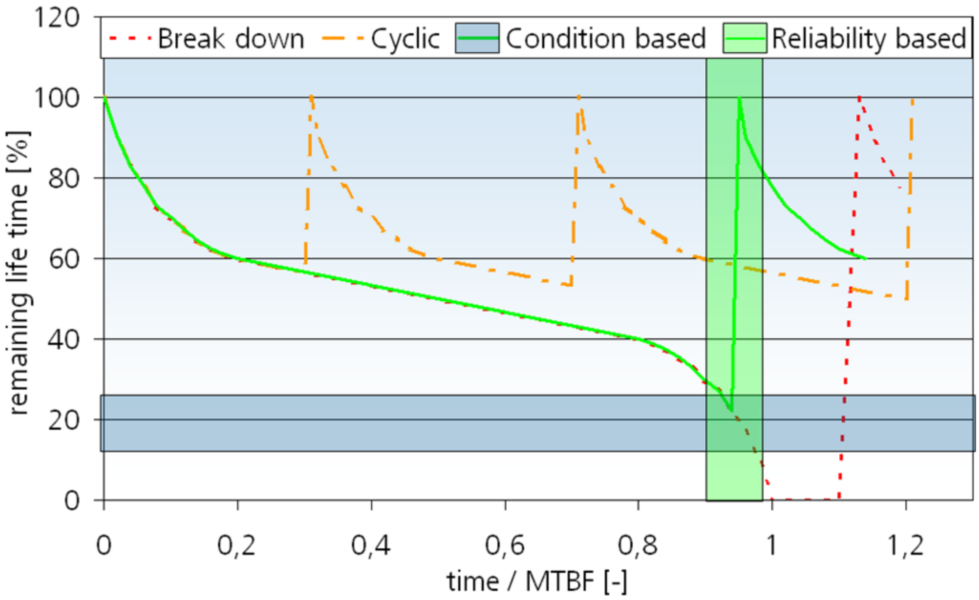

Figure 7 Comparison of several O&M strategies [16]

As a corrective strategy, the break down O&M approach is also reflected in the figure (red dashed line). This method differs strongly from the preventive strategies, because the system will be operated until a major failure of a component results in a shut down: in the particular case of an offshore wind turbine, this will result in intolerable downtimes and possible consequential damages. Therefore, this strategy is not used in the offshore wind sector.

In addition to corrective maintenance, the above mentioned preventive strategies are applicable. With the cyclic maintenance strategy, which is shown by the orange dashed line, components will get maintained after fixed periods of time independent of their actual condition.

More sophisticated preventive strategies are the condition based and the reliability centred maintenance (RCM). Both aim at finding the optimum point in time for carrying out the required maintenance actions. Condition based maintenance tries to find that point by monitoring the real current status of the components. This is illustrated by the blue shaded area, which shows the attempt to find the point where the remaining life time is getting below a significant tolerance criteria. The main task of this strategy is to find out the propagation of degradation over the time of operation, i.e. the most important stressing parameter and their influence on the life time curve.

RCM tries to find the right time for maintenance measures through analysing a broad database filled with experience from the past regarding the reliability function. It is shown in Figure 7 by the green shaded area that the RCM strategy tries to identify the MTBF and by that, the probability for failure occurrence.

A RCM strategy can transform unscheduled outages into planned maintenance activities and reduce or even avoid downtimes as well as maintenance costs. For the future offshore wind energy, these two strategies (condition based and reliability based) may be combined to get the necessary information for preventive and planned measures to reduce maintenance costs.

However, for RCM a detailed documentation of all maintenance measures of a large population of plants and a purposeful structured data base are necessary to extract sound conclusions out of the operational experience. After a certain period and with adequate statistical basis some reliability characteristics such as failure rates, repair times, etc. with respect to technical concepts (e.g. generator or gearbox-type), the operating conditions (e.g. wind conditions or ambient temperatures) or the plant ages can be determined with such a documentation. This provides a number of possibilities for optimising availability of wind turbines both in design & construction and in operation & maintenance.

In reality, the O&M strategy for large offshore wind farms will be a mixture of the condition based and reliability based approach. Some components, such as the rotating electro-mechanical drive train elements, can be monitored quite well with industrial standard condition monitoring systems. Vibration measurement will provide information on e.g. damages in the surfaces of rollers elements in bearings, particle detectors for the lubricant oil can identify wear of bearing cages, etc. Analysis of the 1st, 2nd and higher order harmonics of shaft rotating frequencies can point to misalignment and cracks.

Other main components, such as fibre reinforced plastic materials; tend to show no significant signs of wear or a modification of modal frequencies before failure. For those components, a reliability based approach in combination with a monitoring or accumulation of actual loading can define the optimum time for repairing or replacing the component.

2.7 Logistics and overall O&M strategy

Following the definition of maintenance introduced in earlier in Section 2, aspects of logistics are also included within the scope of the term. Logistics is defined in EN 14943 [15] as "planning, execution and control of the movement and placement of people and/or goods and the supporting activities related to such movement and placement, within a system organized to achieve specific objectives". These are some of the technical, administrative and managerial actions referred to in paragraph 2.1 of EN 13306:2010, and the "specific objectives" are to retain items in or restore them to a state in which it can perform the required function.

Furthermore, maintenance time is defined in paragraph 9.7 of EN 13306:2010 as "time interval when maintenance is carried out on an item including technical and logistic delays", logistic delays in turn being defined as "accumulated time when maintenance cannot be carried out due to the need to acquire maintenance resources, excluding any administrative delays" in paragraph 9.13. For corrective maintenance of offshore wind farms, logistic delays can form a major part of the maintenance time due to harsh offshore weather conditions when access to the wind turbines by sea is required.

It follows from the terminology that the logistics strategy can be regarded as a part of an overall maintenance strategy, together with the strategy for the mix and intensity of different maintenance types described in the preceding sections. Although being an integral part of maintenance, logistics aspects will not be described in detail in this report in cases where the state of the art or industry challenges are more naturally described in the corresponding first deliverable for other work packages in the project.

Logistics terminology as used in this report shall comply with and be understood in conjunction with EN 14943 when no corresponding definition can be found in EN 13306:2010.

3. State-of-the-art

This chapter looks at issues related to technical and operation integrity, tools and methods, standardization and life time extension.

3.1 Technical integrity

By technical integrity we mean the condition, capabilities and performance of systems, structures and components. The technical integrity is monitored by various methods, e.g. inspections and permanent monitoring by sensors. This chapter briefly describes the most common approaches that are used today.

The main objective of the inspection and condition monitoring is to ensure the integrity of the structure during the design lifetime. Activities of in-service inspection, maintenance and condition monitoring shall be planned in the design stage considering safety and environmental requirements and ensuring its feasibility in terms of costs.

The condition monitoring and maintenance activities' purpose is to reflect the need for repair works and should include the latest developments, knowledge and experience available. [16]

Maintenance shall be carried out according to a plan based on the expected life of the structure or component or when the specified inspection or monitoring efforts detect unpredicted happenings. [16]

3.1.1 Inspection

Ref. [16][17]

Periodic inspection

The following elements shall be periodically inspected in order to evaluate the condition of the offshore wind farm during its design lifetime:

1- Wind turbines
2- Structural and electrical systems above water
3- Structures below water
4- Submerged power cables.

A specific program for inspection must be planned to cover the in-service life time. The periodical inspection consists of three levels of inspection: general visual inspection, close visual inspection and non-destructive examination. General visual underwater inspections can be carried out using an ROV (Remotely Operated Vehicle), whereas close visual underwater inspections require inspections carried out by a diver.

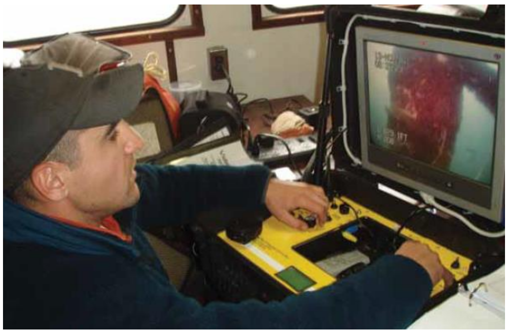
Figure 8 Remotely Operated Vehicle. [18]

In-service inspection program of turbines and their support structures should be planned taking into account the number of units comprising the wind farm. They also depend on the design and the specific environmental conditions.

With single wind turbines, or wind farms with a small number of turbines, the inspection program should require inspection of each turbine.

In wind farms with a large number of turbines it may be possible to perform inspection on a subset of the turbines, provided that they are exposed to similar environmental loads and that they have identical (or close to identical) designs. This type of inspection is known as a risk based approach, where one addresses the risk as the product of the probability of a failure and the consequence of that failure. [17] Recommends that for large wind farms one may limit inspection to one structure for every 20 to 50 installed structures.

Some issues to consider in this respect is the relative positioning and distances between the turbines, that can be exposed to different environmental conditions or the different times of installation of the structures. In large wind farms the installation period may span more than one year.

Preparation

The inspection will typically consist of an onshore part and an offshore part [17]. The onshore part relates to preparations for inspection, including creation and updating of inspections plans, follow up of outstanding issues from previous inspection and preparatory interviews with relevant personnel. The offshore part relates to execution and reporting of inspection. This includes an assessment of the findings in order to distinguish between random failures and systematic failures.

Inspection of wind turbines

Inspection is currently based on the recommendations given by the turbine manufacturer, found in the turbine service manual. Normal inspection routines give inspection intervals at 6 to 12 months, [17] recommends at least annual inspections.
The items of the wind turbine to be covered by the inspection are: blades, gear boxes, electrical systems, transformers and generators, lifting appliances, fatigue cracks, dents and deformations, bolt pre-tension and status on outstanding issues from previous periodical inspections of wind turbines.

Inspection of structural and electrical systems above water

The items considered here are: electrical systems, transformers and generators, tower structures, transition pieces, grouted connections, lifting appliances, access platforms, upper part of J-tubes, upper part of ladders, upper part of fenders, heli-hoist platforms, corrosion protection systems, marine growth, fatigue cracks, dents, deformations, bolt pre-tension and status on outstanding issues from previous periodical inspections above water.

The inspection interval for fatigue cracks depends on the structural detail in question and the inspection method and may be determined based on the magnitude of the safety factor applied in design. In general, the smaller the safety factor, the shorter is the interval between consecutive inspections. Therefore, inspection for fatigue cracks should take place at least every year as required for wind turbines and structural and electrical systems above the water may be waived.

Inspection of structures below water

In the case of structures that remain below water, five-year inspection intervals are common; however, more frequent inspections during the first few years after installation are recommended.

The following items shall be covered by the inspection: support structures, lower part of J-tubes, lower part of ladders, lower part of fenders, corrosion protection systems (anodes, coating etc.), marine growth, fatigue cracks, scour and scour protection, damages and dents, deformations, debris, status on outstanding issues from previous periodical inspections below water.

The program for inspection and condition monitoring shall cover the whole support structure, which might be partially emerged, and comprise the use of instrumentation data.

Concrete GBS

Concrete durability is an important aspect concerning structural integrity of gravity bases and shall be assessed during the lifetime. Important factors to assess are:

- Those factors that are important but are unlikely to change significantly with time, such as permeability and cover to reinforcement.

- Those factors that will change with time and need to be assessed regularly, such as chloride profiles or corrosion.

Chloride profiles should be measured in order to establish the rate of chloride ingress through the concrete cover. Either total chloride ion content or water-soluble chloride content should be measured. However, the method chosen should be consistent throughout the life of the structure.

These profiles can be used for estimating the time to initiation of reinforcement corrosion attack in the structure.

Figure 9. Chloride damage on a concrete structure. [19]

Inspection of concrete offshore installations normally includes a survey of the different parts of the structure, including the **atmospheric zone**, the **splash and the tidal zones** and the large amounts of **immersed concrete.** It is generally recognized that the splash zone is the most vulnerable to corrosion. The submerged zone is also recognized as important because most of the structure is underwater.

- Atmospheric zone

Inspection and condition monitoring of the atmospheric zone should focus on detecting possible damage or defects caused by structural design and construction imperfections, environmental loads, mechanical loads, static and dynamic operational loads, altered operational conditions, chloride ingress, geometric anomalies, such as construction joints, penetrations, embedment, subsidence and impact loads.

Figure 10. Ship impact in concrete structure. [20]

The typical defects are: deformation/structural imperfections, cracks, reinforcement, corrosion, damaged coatings, freeze/thaw damage, spalls and de-laminations and local impact damage.

- Splash zone

The inspection and condition monitoring of the splash zone should focus on the effects due to alternating wetting and drying of the surface and the development of marine growth.

Figure 11 Damage of the splash zone. [19]

- Submerged zone

In addition to the aspects listed for the atmospheric and splash zones, the inspection and condition monitoring of the submerged zone should focus on scouring of the seabed under or in the immediate vicinity of the installation, current conditions, movement in bottom sediments, mechanical loads, tension cable anchor points, debris, settlement and cathodic protection system (anodes).

Figure 12 Inspection of seabed and scour protection. [20]

The inspection of the internal parts shall focus especially on detecting any leakage, detecting any reinforcement corrosion and concrete cracking.

Inspection methods

The methods and extent should be chosen depending on the location and function of the actual structure/structural part considering the possibility to reduce the risk associated with the inspection activity itself. The main techniques for use underwater depend on visual inspection by divers or by ROVs. In some cases, it is necessary to clean off marine growth to examine potential defects in more detail.

The methods shall be chosen with a focus on discovering serious damage or defects on the structures. The methods shall reveal results suitable for detection and characteristic description of any damage/defect. Areas with limited accessibility should preferably be monitored through instrumentation.

The following type of inspection may be used:

a) Global visual inspection

Global visual inspection is an examination of the total structure to detect obvious or extensive damage such as impact damage, wide cracks, settlements, tilting, etc. The inspection can be performed at a distance, without direct access to the inspected areas, for instance by use of binoculars. Prior cleaning of inspection item is not needed. The inspection should include a survey to determine if the structure is suffering from uniform or differential settlement.

b) Close visual inspection

Close visual inspection is a visual examination of specific surface area, structural part or total structure to detect incipient or minor damage. The inspection method requires direct access to the inspected area. Prior cleaning of the inspected item might be needed.

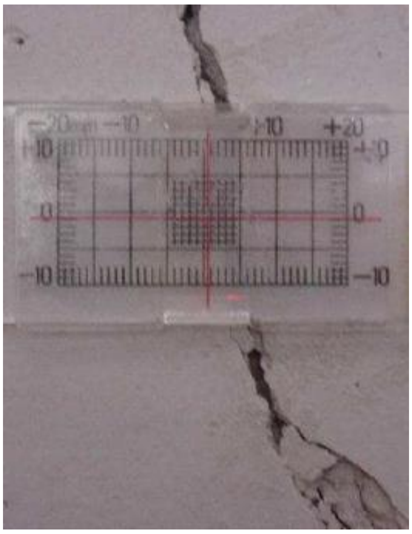

Figure 13 Close inspection of crack width. [19]

c) Non-destructive inspection/testing

Non-destructive inspection/testing are a close inspection by electrical, electrochemical or other methods to detect hidden damage. The inspection method requires direct access to the inspected area. Prior cleaning of the inspection item is normally required.

d) Destructive testing

Destructive testing is an examination by destructive methods such as core drilling, to detect hidden damage or to assess the mechanical strength or parameters influencing concrete durability.

Inspection of special areas

In addition to the above, [16] and [17] set out criteria for inspection of special areas of interest. These cover issues such as (list is not exhaustive):

- Overstressing of structural members
- Creep and shrinkage
- Crushing and spalling of concrete structures
- Delamination
- Non-characteristic cracking patterns
- Interfaces, load transfers, flexible members
- Joints, penetrations and vertical intersections
- Splash zone
- Repaired areas
- Scouring
- Post-tensioning, relaxation of tension

Inspection of submerged power cables

A risk assessment can be carried out for determination of the appropriate inspection interval, such that export cables will be inspected frequently and array cables less frequently. Furthermore, subsea cables buried in very stable seabed may not need as much monitoring as subsea cables buried in less stable sediments or in areas with significant tide. The interval between inspections of submerged power cables should not exceed five years.

Array cables between the wind turbines and the transformer station as well as export cables to the shore shall be inspected, unless they are buried.

To the extent that submerged power cables are to be buried is determined by design depth.

3.1.2 Instrumented systems

Ref.[16][17]

Wind turbines are fitted with a number of sensors (100-200), most being temperature sensors. The sensors are often part of e.g. the step-up gear, generator, converters or other equipment. The primary purpose of such instrumentation is to provide machine protection and operator alarms when certain threshold values are exceeded. Some instrumentation is provided for monitoring performance and the energy production of the turbine.

The use of instrumentation dedicated to monitor and document the evolving technical condition of structures, systems and components of wind turbines has been the realm of turbine manufacturers. The wind energy industry, especially in Europe, has set up operations where the turbine manufacturer takes responsibility for operation and maintenance of turbines during the first 2-5 years, with an optional take-over by the operator at the end of this period. The operator can thus keep a smaller organization than if they took full responsibility for operations from the start. The tendency has thus been for operators to outsource the main O&M activities to third parties.

Continuous monitoring should be carried out to detect and give warnings regarding damage and serious defects, which significantly reduce the stability and load carrying capacity. The goal of forecasting the occurrence of significant events, i.e. those that represent significant risk to people or the environment or those having large economic consequences, is to allow sufficient lead-time for repairing actions.

Monitoring should be used to detect small damages and defects, which can develop to a critical situation. Particular emphasis should be placed on identifying the likelihood of small failures, which can lead to progressive collapse. The type and extent of monitoring on this level should be handled as a risk minimization problem, which includes the probability of damage/defect occurrence, detection probability, monitoring costs and cost savings by repairing the damage/defect at an early stage.

If values for loads, load effects, erosion or foundation behaviour are highly uncertain, the installation shall be equipped with instrumentation for measurement of environmental condition, dynamic motion, strain, etc. to confirm the applicability of governing design assumptions.

Monitoring activities depend on the geometry, materials of construction and design in general of the support structure. Typical condition monitoring system for wind turbines can be vibration and oil condition monitoring of the drive train of wind turbine is common practice for offshore wind turbines. It can provide useful information on the deterioration condition of the different components of the drive train, which can help scheduling and clustering major replacements. In this respect, the efficiency of the condition monitoring system can have a major impact on the availability. Another approach to condition monitoring is to make use of existing measurements from the Supervisory Control And Data Acquisition (SCADA) system in order to detect and determine faults.

In areas with limited accessibility, or for monitoring of load effects, corrosion development, etc., additional information can be provided by use of instrumentation based condition monitoring. The instrumentation can be temporary or permanent. Sensors shall preferably be fitted during fabrication. The sensors will be such as strain gauges, pressure sensors, accelerometers, corrosion probes, etc. [16]

The structure itself may be instrumental in order to record data relevant to pore pressure, earth pressure, settlements, subsidence, dynamic motions, strain, inclination, reinforcement corrosion, etc. [16] In the case where the structure is equipped with active systems which are important to the structural integrity, e.g. pore pressure, water pressure under the base, drawdown (reduced water level internally in the structure to increase the external hydrostatic pre-stressing of the structural member) in case of storms, etc., these monitoring systems shall be inspected regularly.

3.2 Operational integrity

By operational integrity we mean the organizational capabilities and performance, including maintenance strategies and plans.

The measures needed to maintain the operational integrity of the wind farm can be divided in those that are done remotely and those that can are done on site. Unless or until the maintenance strategy becomes purely remote, maintenance is dependent on accessibility to the wind turbine, and a strategy for logistics and accessibility will be driven by the maintenance strategy. Conversely, the choice of maintenance strategy (e.g. investment in condition monitoring systems or remote inspection) for a wind farm may be driven by the accessibility at the site.

3.3 Tools and methodologies

Planned maintenance is currently being carried out on turbines and balance of plant via inspections. Planned inspections of turbines are generally scheduled once or twice a year, depending on the wind turbine manufacturer.

Turbines are monitored using SCADA systems, which process data from the turbine controller, switchgear in the tower base and, in some cases, condition monitoring systems. When using a combination of SCADA and condition monitoring data, some proactive service can be carried out, for example, the replacement of a gearbox final stage prior to failure or the exchange of a complete generator.

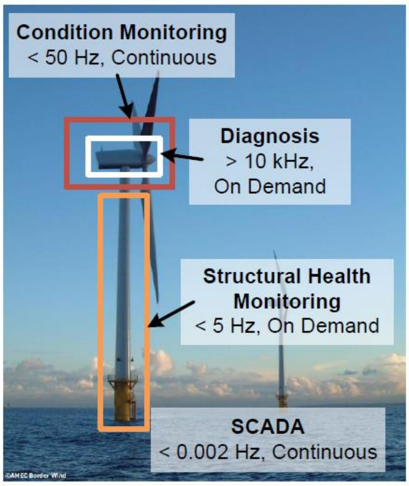

Figure 14 SCADA, Structural Health and Condition Monitoring of a Turbine [21]

Today, all offshore turbines are equipped with mainly drive train condition monitoring systems (CMS) able to provide the following capabilities:

- Status monitoring (routine reporting and operational safety)
- Fault detection (finding problem)
- Diagnosis (finding cause of problem)
- Prognosis (predicting future failure)

These current CMS focus on the following turbine components:

- Blades
- Main bearing
- Gearbox internals

- Gearbox bearings
- Generator

As the majority of CMS are based on monitoring methods coming from other traditional rotating machinery industries, the current CMS use mainly vibration monitoring data via several accelerometers so as to monitor key components of the drive train such as the gearbox and main bearing. Additional sensors can also be installed to monitor other part of the drive train including oil debris (gearbox), the nacelle structure, the blades (vibration analysis, strain measurement via fibre optic), the tower and the foundation structure.

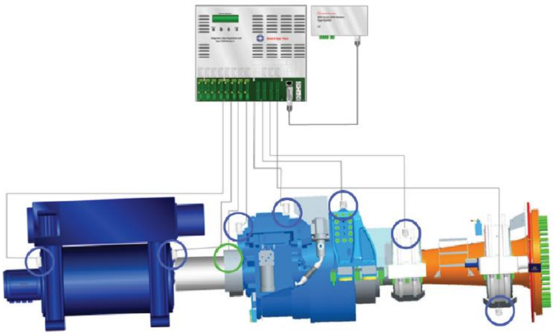

Figure 15 CMS for Offshore Wind Turbine [22]

CMS can also be installed on electrical cables (array and export cables) so as to detect cable joint or termination failures which are considered to be the weakest points.

Most CMS are independent “add on” systems (e.g. Vestas, Gamesa, Siemens...) but some wind turbine manufacturers have developed in house systems (e.g. Areva who has sold it to ACOEM)

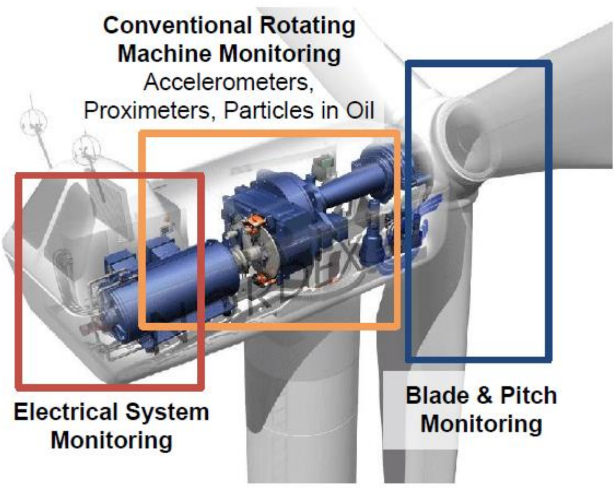

Figure 16 General layouts of areas for condition monitoring within the turbine nacelle [21]

Condition monitoring: What is measured

Company	System	Temperature	Humidity	Pressure	Acoustic emission	Cleanliness (oil)	Electrical	Strain	Accelerometer	Displacement	Tachometer	Video	Rotor	Drivetrain	Tower
Areva/01db-Metravib Drivetrain	*OneProD*	✓				✓			✓		✓			✓	
Bently Nevada (GE)	*WT-CMS Adapt.wind*						✓		✓		✓			✓	
Beran Instruments	*PlantProtech*					✓			✓		✓		✓		✓
Brüel & Kjær Vibro	*WTAS - Type 3651*	✓			✓	✓			✓		✓		✓	✓	✓
Eickhoff	*E-GOMS*					✓			✓		✓			✓	
Emerson Process Management	*epro MMS*	✓							✓					✓	
FAG	*FAG WiPro*	✓				✓			✓		✓		✓	✓	✓
Gamesa	*SMP-8C*								✓		✓			✓	
Global Maintenance Technologies	*E-Sentry System*	✓	✓	✓					✓					✓	
Gram & Juhl	*TCM®*								✓		✓	✓	✓	✓	✓
Holroyd Instruments	*AE Systems*				✓						✓			✓	
IGUS ITS	*BLADEcontrol®*								✓				✓		
Insensys	*RMS*							✓			✓		✓		
Prüfteknik Condition Monitoring	*VibroWeb XP*	✓				✓			✓	✓				✓	
Rovsing Dynamics	*Winergy CDS*					✓			✓		✓			✓	
Siemens Wind Power AS	*FLENDER CM*							✓			✓		✓	✓	✓
SKF	*WindCon*				✓	✓							✓	✓	
Vatron	*DriveMon Wind*	✓					✓							✓	
WindSL	*WT-HUMS*	✓			✓	✓			✓		✓			✓	✓
μ-SEN	*Ω-Guard®*				✓						✓			✓	

(excludes single-sensor type systems based on accelerometers AE, US, oil cleanliness sensing; also analytics only suppliers)

Figure 17 Condition Monitoring Systems on the market [23]

To date, current CMS only provide partial solutions with limited diagnosis/prognosis capabilities and the main drawbacks are as follows:

- Too many different and independent CMS solutions installed within the turbine
- Difficulty in evaluating the overall state of the system
- Training and operating issues due to the different system architectures
- Lack of cost optimization due to too many different CMS

Specificities of offshore wind such as variable speed, load conditions and low rotor speeds keep on challenging traditional diagnostic techniques developed and used for other applications. Despite success stories in other industries, CMS for offshore wind has not yet been widely implemented and does not meet all the requirements.

3.3.1 Computer models, tools and software

A number of different computer tools and software are used in the operation and maintenance of offshore wind farms. Other tools and models may have been developed in research institutes but may only be applied to a limited degree in the industry. These tools differ in the time scales they are designed to be used for, ranging from strategic tools for long-term planning to operational tools for day-to-day planning. One way of categorising different tools is as follows.

<u>Strategic decision support tools:</u>
These tools, also referred to as O&M tools or O&M models, are intended to aid in the process of deciding on the maintenance and logistics strategy. As an example, one typical decision is what kind of crew transfer vessels one should use for a given offshore wind farm. Such tools are also used in analysing different strategies and study the sensitivities in such metrics as the wind farm availability and O&M costs to see how they may depend on different aspects of the O&M strategy [1].There exist many different tools, both spreadsheet calculation models and event-based simulation models, but many are either commercial software products by consultancies or in-house tools

developed by developers and operators of offshore wind farms [24]. For an up-to-date review of some of the most relevant models and related challenges, see [25].

Maintenance management and planning:
Commercial software exists for implementing maintenance management strategies such as RCM (as described above). Computerized Maintenance Management Systems (CMMS) are used to manage scheduled preventive maintenance tasks and registered faults, often for use in the long-term to intermediate-term maintenance planning. These systems may be an integrated part of the Enterprise Resource Planning (ERP) system used for the wind farm project.

Scheduling of maintenance tasks:
There exist models for optimising the scheduling and grouping of maintenance tasks (including opportunistic maintenance) and the routing of maintenance vessels. Such formal decision support tools for operational application (on a day-to-day basis) do, however, seem to mostly be on an academic level, and may not at present be widely applied in the O&M of offshore wind farms.

Spare part management:
Management of spare parts stock is an integral part of the logistics planning. In addition to software for managing spare parts that is a part of the ERP system used for the project, dedicated tools exist for finding the optimal spare part stock and logistics strategy.

Cost models:
Models for estimating OPEX can exist in different forms, from spreadsheet models to being a part of O&M models described above to being done as a part of the budget management system or the ERP system used for the offshore wind project.

3.4 Standardization

The following section contains a listing (partly with comments) of existing standards and technical guidelines with respect to Offshore Wind Farm O&M.

3.4.1 Technical Guideline VDI3834

The VDI3834 will define standards for the measurement of vibration in the drive train of wind turbines as well as for the oscillation amplitudes of structural elements (tower, blades, etc.). It is split into two parts:

- Part 1: Wind turbines with gearbox: Published in March 2009 (with scope on onshore WTs with<= 3MW only), currently under revision and extension (to offshore, without any power limitation)
- Part 2: Wind turbines without gearbox: not yet published, requires ongoing data collection to define evaluation criteria

The VDI3834 is designed to support the state of health of a wind turbine by definition of absolute vibration / oscillation amplitude levels, gained in ad hoc measurement campaigns, rather than for the definition of warning and alarm limits for online condition monitoring systems (CMS). Nevertheless, most of the main providers of online CMS for wind turbines have included measurement modes with full conformity to the VDI3834 in their systems to obtain additional relevant data for the interpretation of the wind turbine's overall condition.

Currently, there are efforts in the ISO/TC108 to include the VDI3834 into a new part of the ISO 10816 "Mechanical vibration — Evaluation of machine vibration by measurements on nonrotating parts". It will become the Part 21: "Onshore wind turbines with gearbox". At the time of preparation of this deliverable, the ISO 10816-21 is in a CD (Committee Draft) status.

3.4.2 Technical Guidelines of DNVGL

Germanischer Lloyd (GL) has published (before its fusion with the Det Norske Veritas) several technical guidelines for the (offshore) wind energy field:

1. Guideline for the Certification of Offshore Wind Turbines [26]
2. Guideline for the Certification of Condition Monitoring Systems for Wind Turbines [27]

The offshore wind turbine guidelines give the user a good overview about what requirements its turbine needs to fulfil to successfully pass the GL certification process.

The CMS guideline defines the technical characteristics (sensor specifications, ADC resolution and sampling frequencies, etc.), which such a system needs to fulfil. Furthermore, recommendations to the data evaluation facilities are defined, e.g., in case of manual data analysis in an O&M centre, that such a centre has to be operational 24/7.

Some insurance companies in Germany have regulations for wind turbines, which mandatorily require the use of CMS (for the drive train). In this context, only GL certified CMS are accepted. Therefore, most suppliers of CMS have performed the GL certification process [28]. In addition, this list gives a very good overview of the CMS market for (offshore) wind turbines.

3.4.3 Standards

The NORSOK standards are mostly relevant to the Oil & Gas offshore industry, but could be used as an information pool for the definition of new standards, which is part of the LEANWIND project challenges.

Terminology:
EN 13306:2010: Maintenance terminology

Documentation:
NS-EN 13460:2009: Maintenance - Documentation for maintenance

NS 5820:1994: Supplier's documentation of equipment

NORSOK Z-018:2013: Supplier's documentation of equipment

Preservation:
NORSOK Z-006: Preservation. Rev. 2, Nov. 2001

Procurement:
NS-EN 45510-5-3:1998 Guide for procurement of power station equipment - Part 5-3: Wind turbines

FMEA/FMECA:
IEC 60812: 2006 Analysis techniques for system reliability - Procedure for failure mode and effects analysis (FMEA)

3.4.4 Series IEC61400

The IEC61400 standard series copes with a lot of different aspects of wind turbines. It will be worked out and revised under the IEC Technical Committee TC88. Most of the parts are originally designed mainly for onshore wind turbines only. Meanwhile, the part 3 has been introduced for the application to offshore wind (refer to Table 1). A complete overview of the published IEC61400 parts, including their sub parts, can be seen at [29].

Where appropriate, the IEC61400 is referencing to existing standards. So, in the case of part 22, no new certification rules will be defined, but it is referenced to the GL/DNV offshore certification guide line [27], refer to [29].

Part	Title
1	Design requirements
2	Small wind turbines
3	Design requirements for offshore wind turbines
4	Design requirements for wind turbine gearboxes
5	Wind turbine rotor blades
11	Acoustic noise measurement techniques
12	Wind turbine power performance testing
13	Measurement of mechanical loads
14	Declaration of apparent sound power level and tonality values
21	Measurement and assessment of power quality characteristics of grid connected wind turbines

22	Conformity testing and certification
23	Full-scale structural testing of rotor blades
24	Lightning protection
25	Communication protocol
26	Time based availability for wind turbines
27	Electrical simulation models for wind power generation (Committee Draft)

Table 1 Overview about parts of the IEC61400 standard series

3.5 Lifetime Extension

Ref.[30][31][32][33]

Wind turbines are typically type-certified for 20-year design life. As many wind farms are approaching this threshold, many wind industry stakeholders are considering the possibility of extending operations by 5 to 20 years. Life extension—the operation of an asset beyond the nominal design life — is ultimately about maximizing the financial return of the assets. Lifetime extension can often be regarded as repowering, upgrading, or uprating a turbine.

Wind farm siting classification and turbine design has developed very much during the past 30-40 years. Older farms have been verified and classified according to guidelines that are very different from current standards. When undertaking a lifetime extension review, the next life period of the turbines will be evaluated in accordance with current standards and regulations. As a result, if the current criteria were used, these machines would be classified in a different type class, likely one subject to higher loads, than that originally assigned.

Lifetime extension relates primarily to the larger parts of the turbine, as smaller parts are constantly handled in a well set up maintenance program. The main components, such as gearboxes, frames, tower, blades, generator and main shaft, will suffer from fatigue – a failure mode that there is no currently available technology to measure directly. The state of fatigue is assessed based on visual and NDT inspections looking for tell-tale deformations, cracks and onset of fracture zones. Fatigue failures can damage some parts of the structure leading to, in some cases, a sudden collapse of the machine. Such failures jeopardize the original business case as the potential solutions are costly and are not covered either by manufacturer's warranties or customers' insurance.

Current undertakings on lifetime extension of turbines is centred on repowering the turbine through upgrades on blades, generators and power electronics. This is done to increase the energy yield, and thus potential financial return. The introduction of SCADA systems and to some extent other CM technologies have increased the potential for extending useful life of turbines based on a better understanding of their actual technical condition and state of fatigue.

Using free public data for of a UK fleet of wind turbines on the actual and theoretical ideal load factors from the UK's 282 wind farms it has been shown that load factors do decline with age, at a similar rate to other rotating machinery. Wind turbines are found to lose 1.6 +/- 0.2% of their output per year, with average load factors declining from 28.5% when new to 21% at age 19. This trend is consistent for different generations of turbine design and individual wind farms. This level of degradation reduces a wind farm's output by 12% over a twenty year lifetime, increasing the levelised cost of electricity by 9%. This seems to be inherent for all types of rotating machinery, and is an expression of an irreversible loss due to a combination of all ageing factors.

In the offshore oil and gas industry, a method has been proposed for evaluation of ageing with regard to extension of operational life of systems, structures and components. The method makes use of 10 major steps to evaluate the suitability of lifetime extension, looking at degradation, inefficiency and obsolescence from the perspectives of technological, organizational and external factors.

In order to make informed decisions regarding life extension, wind project owners and operators need to be able to demonstrate to that the wind turbines can be reliably and safely operated past their design life and that life extension is a financially attractive option.

3.6 O&M strategies, use of LEAN principles

Ref. [6][34]

Madsen et.al. [2] argue in their article wind power at rough sea that in the immature field of offshore wind, TPM and RCM, outlined in Section 2.1, are not beneficial. They suggest that a customized concept is the way to go. A preventive maintenance strategy instead of the current preventive/corrective strategy is suggested.

They further argue that TPM is regarded, by some, more like a management strategy than a maintenance concept. It does not provide clear guidelines or rules that decides which basic maintenance policy should be used. RCM is a very complex maintenance concept and as a consequence is a very expensive concept, which can be difficult to introduce in a rather immature field like the offshore wind energy sector.

In their article a study of current maintenance challenges in a large offshore wind farm, Madsen et al. [35] conclude that focus on O&M of wind parks has been very limited and is currently in its early phases. A comparative study [35] of existing life cycle analysis of offshore wind parks found that the majority of these analyses do not include an O&M aspect in their calculations.

4. Industry challenges

The overall goal for the industry is to reduce LCoE. An important contribution to this can come from improved condition monitoring systems that can

- Reduce the need for manned service trips, both planned and unplanned
- Reduce the risk for consequential damage
- Reduce the downtime associated with each failure and repair

In addition, automation not reduces the cost but also the personnel risks related to service trips to offshore WTG's.
The next stages of the LEANWIND project should address the following questions:

- Are there faults that are not detected before they develop into a failure with the present monitoring systems and service schedules?
- Are there manual inspection methods that preferably should be replaced by online automatic methods?
- What is the cost associated with false alarms? (In worst case there may be a need for manned inspection before the turbine can be safely restarted – how can this be avoided?)
- Which savings can be obtained by automatic remote diagnostics (reduced need for on-site investigations, reduced time to perform a root cause analysis and identify the faulty part etc.)
- What are the benefits of having an early warning CM system?
  - prolonged lifetime by reducing the load (power production)
  - repair before the component is non-reparable instead of replacement
  - reduced consequential damage on other components
  - ordering of spare parts before complete failure occurs will reduce downtime and need for spare part s in stock
  - better time and information for planning of maintenance
  - scheduling of repair on multiple turbines on the same repair mission
  - savings on logistics by better utilization of expensive work vessels
- Can we develop a relation between pre-warning time and savings potential?
- What are the potential savings by changing from periodic to condition based maintenance for an offshore wind farm?
- Is a fleet leader with extra instrumentation sufficiently representative for other turbines in the same wind farm?
- How can the information from the fleet leader be used to limit the condition monitoring system to cover only the "weak spots" in the other turbines?

This will give a background for the evaluation and priority to be given to the monitoring and inspection methods proposed in the following chapters.

4.1 Technical integrity

The technical integrity of the equipment is monitored by various methods, i.e. inspections and permanent monitoring by sensors. The value of the measurements can, as shown below, be significantly improved by a model based approach.

4.1.1 Present inspection and monitoring methods

Standard Wind Turbine Generators are typically equipped with 100-200 sensors for control and alarm monitoring of which the majority are temperature sensors. These sensors provide a lot of information which can be employed by the Condition Monitoring system, provided that the data quality is good enough and that the data are sampled and stored at a sufficiently high rate. The number of sensors fitted purely for the purpose of Condition Monitoring is limited, and includes mainly oil debris analysis and vibration sensors. For offshore WTG's, also corrosion sensors and strain gauges are usually included.

4.1.2 What should be required from the CM system

The purpose of an improved CM system is to reduce the number of both planned and unplanned stops and service trips, and to detect developing failures while the components are still operable and can be repaired. Reduction in the need for manned service trips can be achieved by

- Extension of service intervals by applying condition based maintenance
- Replacing manned inspections by remote online monitoring methods
- Reducing the time for fault identification and thereby also downtime by improved instrumentation and supporting software tools
- Use of remote monitoring/remote presence systems combined with decision support tools that can permit safe restart without manual intervention at site after false alarms and "un-necessary stops"

The CM system should make notifications to the supervisory systems in the following events or upon request

- Indicate the technical state of the components including the degree of normal wear
- Upon failure, give true positive indications of failure as early as possible after initiation and with as low rate of false indications as possible
- Enable root cause analysis, fault diagnostics and exact location of the fault
- Enable estimation of remaining useful lifetime of the monitored components

4.1.3 Manual service and inspection to be considered for automated methods

Inspections or service interventions that are at present performed manually that should be considered for full or partial automation includes:

- Collection of samples and analysis of lubrication oil and grease for quality or particle debris
- Visual inspections for surface cracks
- Ultrasound inspections for subsurface cracks
- Blade integrity inspections
- Thermal imaging with handheld IR camera
- Scouring monitoring by stationary sonars, combined with dynamic soil and structure modelling
- Replacement of operators hear, see and touch inspections by permanent instrumentation

4.1.4 Methods for increased pre-warning time of failures

Increased pre-warning time can be achieved by combining more sensors and measurement techniques to have a better validation of the indication before a warning is issued This is especially important when sensitive methods capable of giving early warnings such as acoustic emission or ultrasound techniques are applied, as they may otherwise generate false indications because of their susceptibility to noise.

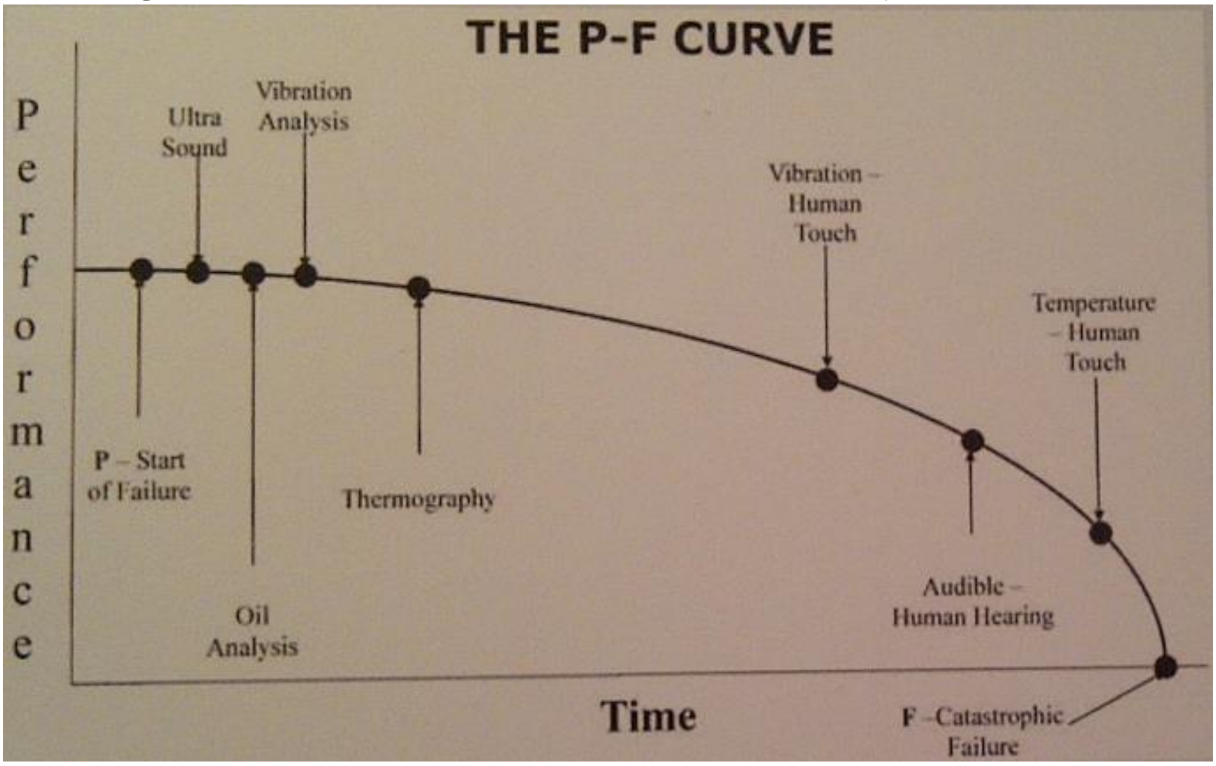

Figure 18 Illustration of how different measurement techniques may give different detection points of failure [34]

Present methods for detection of failures or underperformance often rely on comparison with the situation when the equipment was new, or with similar equipment in the same wind farm or in other wind farms. As the operational conditions varies significantly with time, and between the turbines in the farm and between wind farms, the envelope of "normal operation" must be quite widely defined, and the method is not likely to reveal abnormal behaviour until the failure has developed into a critical or non-repairable fault.

By establishing an online data model that predicts the expected normal value of a chosen Key Performance Indicator (KPI) based on the measurements of all influencing variables, it is possible to compensate for variations in environmental parameters and operational conditions before comparison, and thus get a much more narrow variation area and hence an earlier indication of developing failures.

Such models can be mathematical models based on physical relations or data driven model such as Artificial Neural Networks. Figure 19 below illustrates this method.

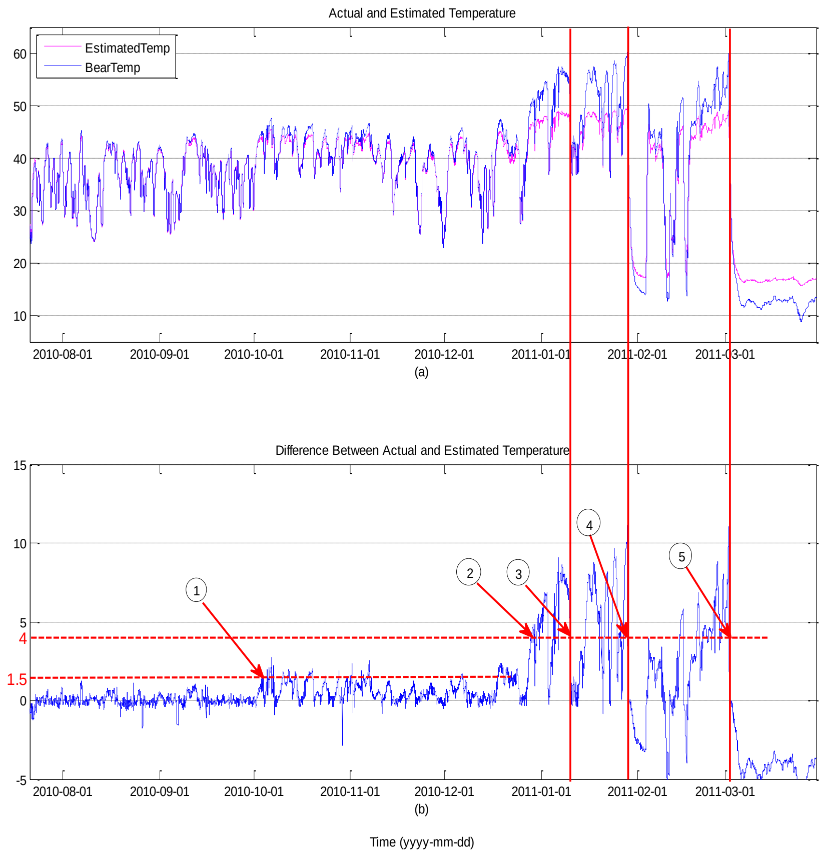

Figure 19 Model based detection of failure in main bearing by use of an Artificial Neural Network. Upper graph: Measured data and predicted data compared. Lower graph: difference of measured and predicted data. It is seen that the abnormal temperature level starts to develop 3 months before the alarm level was reached and the bearing was stopped due to overheating. [36]

4.1.5 Methods for estimation of remaining useful lifetime

For all KPI's that show a gradual change with the development of the failure such as vibration level, temperature or acoustic emission, it is possible to give predictions of remaining useful lifetime based on empirical models. The same type of prediction can be obtained by observing the detection points for various measurement methods as was indicated in Figure 19 above.

Another approach to estimate component lifetime is to monitor actual loads, count load cycles and relate this to the design lifetime of the component or to statistical data from other turbines.

Effective use of empirical data requires a change in the willingness to share data between the different turbine manufacturers and wind farm owners.

4.1.6 CM and the fleet leader concept

The model based approach described above can also be applied to check the representativeness of so-called fleet leaders having more extensive instrumentation than the other turbines in the wind farm. The same applies if a statistical sample of turbines is selected for inspection instead of a total survey of the wind farm at every interval.

4.1.7 The Future of Wind Turbine Condition Monitoring

Due to the need to bring down the O&M cost of offshore wind farms, the introduction of turbine condition-based maintenance is likely to be more widespread. The combination of advanced condition monitoring with risk-based approach to planned maintenance will help operators choose inspection and repair of key components with a higher potential impact on cost reduction.

In order to make the most of CMS, planned maintenance procedures have to be changed and optimised so as to develop better prognosis capabilities. The need to develop and improve prognosis tools is fully admitted by the offshore wind industry. New holistic CMS could provide accurate early warnings of turbine's components failure and should minimise unavailability and corrective maintenance operations.

The possibilities with existing CMS can be significantly improved by increasing the number of sensors to locate, identify and diagnose failures. However, the implementation of new sensors remains a barrier since a deep knowledge of the information about the turbine equipment design is needed (e.g. drive train, gearbox…) but manufacturers are often reluctant to provide it.

Following lessons learned from offshore failure rates and detailed analysis, an adequate offshore-specific CMS would consist of an array of existing (from SCADA) and extra sensors on each turbine as well as data communication capabilities, and analysis software (detection and diagnosis) that can gather and analyse data coming from every critical subsystem of the turbine.

To date, few turbine manufacturers offer systems which can integrate both control and condition monitoring data for the turbine and provide a holistic data set to the operator via the SCADA system. This low level of integration of the control system and condition monitoring data should be improved and the new dedicated offshore wind turbines, which are about to commercialised, already provide automatic integration and interpretation of all turbine operational data. Such systems include low frequency (1Hz) data from the control system and the SCADA system, high frequency (500Hz) condition monitoring data, turbine design data and turbine maintenance histories from technician records.

Holistic CMS would provide accurate, reliable and near real time data and information to wind farm operators. A better knowledge of remaining life estimate of key equipment or components (bearings, pitch actuators...) and consumables (gearbox oil) would improve the planning of planned maintenance in terms of resource, spare parts management. Diagnosis of problems and root cause analysis would be easier to undertake thanks to better information. Ultimately, more sophisticated and offshore wind specific condition monitoring technologies would help reduce the O&M costs and increase the reliability wind turbines.

In order to increase the capability of diagnostic and prognostic, there is a need to combine the data from different sensors with databases of material properties, with service history (both of the farm and of the particular machine), with models of damage progression, and with forecasts of future service conditions. Fusion of these disparate types of information is an area of active research, with some significant successes already achieved. Specifically, the system must present its outputs in such a way as to support the decision-making process of the operator. The system must be reliable and accurate enough for an operator to trust its recommendations.

Condition Monitoring suppliers (e.g. Moog, Bosch-Rexroth...) have already started to commercialise new holistic CMS and some turbine manufacturers (e.g. Siemens, Vestas...) are involved in the development of rotor monitoring technology. Most of the turbine manufacturers are also keen to develop at least integrated control monitoring and SCADA systems, before moving to holistic CMS.

Nevertheless, some specific areas of missing knowledge and future technical challenges can be identified. In particular, the assessment of the potential impact of new CMS on cost reduction is still considered to be a possible show stopper for their implementation. Due to confidentiality issues, publicly available cost justification of CMS are difficult to obtain and therefore the added valued provided by CMS cannot be easily assessed.

For each key turbine component, the most promising CMS systems are as follows:

Rotor (blades):

CMS suitable for blades require the implementation of specific load and damage detection sensors. Operators are keen to detect de-bonding, cracks and weakening on blades and dedicated sensors can measure delamination, kissing bounds and local weakening changes in stiffness via ultrasound techniques, fibre optics...

Fibre Bragg Grating (FBG) sensors are likely to be a promising technology. FBG are specific Optical Fibre Sensors and the concept consists in illuminating the core of a suitable optical fibre with a spatially-varying pattern of intense UV laser light. Some blade manufacturers have already replaced resistive strain gauges with FBG sensors which measure strains and provide inputs to turbine control systems or even for CMS.

Nacelle (drive-train)

The trend towards vibration monitoring of wind turbines will continue but other CMS and diagnostic techniques will be incorporated into existing systems such as oil debris monitoring (e.g. particle counts), temperature and fibre optic strain measurement.

Innovative CMS technologies using electrical data from drive trains are currently being developed and should enable the detection of both mechanical and electrical faults. Vibrations due to mechanical faults and electrical faults in the generator lead to unbalanced magnetic field in the generator, which can be measured. The system is integrated in the converter.

In the UK, the OWDIn (Offshore Wind Drivetrain Innovation) project was launched in November 2013; it is part of the DEC-TSB Offshore Wind Component Technologies Development and Demonstration scheme. The Ricardo-led project takes a broad drive-train approach to improving reliability through the development of sub-systems that will be applicable to a wide range of different drive-train architectures. In particular, the project aims to develop a next-generation condition monitoring and prognostics system targeted at offshore wind farms but capable of retrofit to existing wind farms. This system will use advanced sensors to provide early indications of potential fault development in order to enable preventative measures to be taken, hence avoiding the costs and lost production of enforced downtime through damage.

Substructures

To date, monopile and to a lesser extent gravity base foundations are the most common foundation designs as they are considered to be simple structures. No specific CMS have been developed. Lessons learned have pointed out some issues (Transition Piece grouting, corrosion inside monopile, scour protection…) and therefore, a better monitoring system is expected. The potential use of jackets in deeper water should require more CMS in order to check the impact of fatigue on welded connections, the quality of corrosion protection and to verify the integrity of the whole structure.

The need to continuously monitor load and stress at key critical points of the structure will require the installation of specific sensors. Autonomous and automatic systems able to carry out inspection of the structure including subsea inspection should avoid costly regular visual routine inspection, in particular with divers.

Corrosion and marine fouling could have a significant impact on the lifetime of the substructures due to accelerated ageing process, loss in mechanical properties and additional mechanical stress and fatigue which could lead to damages.

Microbiologically induced corrosion (MIC) could be defined as an abrasion or weakness of a material, metallic or not, initiated directly or indirectly by microorganisms. MIC is not a form of corrosion, but rather is a process that can influence and even initiate corrosion; it can accelerate most forms of corrosion. For example, inside monopile foundation, a common MIC can occur due to sulphate reducing bacteria (SRB) present in the sediment or on the monopile. SRBs produce Hydrogen Sulphide (H2S) and depolarise the steel, hence reducing the effectiveness of cathodic protection. Accelerated low water corrosion (ALWC), a form of concentrated corrosion, is caused by SRBs and can occur on steel maritime structures. Hydrogen Sulphide is highly toxic, flammable and explosive, and is odourless at higher concentrations. It therefore poses a risk to personnel (inspection) and to the turbine itself.

Corrosion mitigation can be accomplished by design considerations, by employing corrosion-resistant materials of construction, by employing cathodic protection, by using protective coatings, or by using inhibitors. The corrosion protection system should be considered as an integrated part of the cycle of design, installation and service of the turbines and structures.

The discovery of corrosion inside monopiles of offshore wind farms after a few years of operation has led to a significant change in DNV standard "Design of offshore wind turbine structures" [17] **(Section 11 for corrosion protection has been restructured and expanded).** This case has pointed out the difficulties in forecasting corrosion and the underestimation of this issue due to water ingress observed inside monopiles, possibly due to malfunctioning J-tube seals or water seeping through the bedrock. For a long time, the interior of wind turbine monopiles were anticipated to be airtight and in principle with a negligible corrosion rate. In connection with the "grout-issue" where the Transition Piece has moved down, it was detected that the design assumption was not fulfilled. Air access from the top (opening hatch) and water ingress at the bottom has changed the conditions and to some extend caused corrosion not accounted for.

Therefore, there is a need for dedicated sensors and CMS which could help operators better understand corrosion rate and check corrosion protection systems. Lessons learned from other industries (oil & gas) or ships should provide relevant inputs.

Cables

Improvements in inter-array and export cable condition monitoring should have applications both in the installation and operational phases. Premature failures of cable insulation are often due to inappropriate handling and inadequate monitoring of cables during the installation phase. The causes of cable insulation faults are numerous and include: thermal, electrical, ambient, mechanical and under designed cable components and installation issues including

- Poor installation producing partial discharge (PD) and tracking in cable joints and terminations.
- Inadequate cables and other equipment design
- Inadequate mechanical protection which leads to external abrasion and ageing
- Mechanical wear and bending caused by movement of subsea cable due to wave or tidal current

Prior to failure, the incipient cable insulation faults can produce both partial discharge activity and localised heating of the cable. Both pre-failures characteristics can be monitored on-line with the cable remaining in service via on-line PD and distributed temperature sensing. These sensors are sufficient to provide the operator with an early warning of the incipient faults to implement condition based maintenance.

Faults on these cables lead to unplanned outages, downtime and loss of revenues.

Two suitable techniques could help to monitor and manage the condition of subsea cables:

- On-Line Partial Discharge (OLPD) testing: detection and location of pre-fault partial discharge and activity tracking
- Use of Time Domain Refractory (TDR) techniques to provide “fingerprint” cable mapping measurements so as to pinpoint any cable fault as soon as they have occurred

For the MV and HV cables, a holistic monitoring system combining a range of power quality and condition monitoring, protection and control technology, requires additional complementary cable condition monitoring devices able to monitor partial discharge, distributed temperature sensing, cable sheath current, power quality monitoring, power flow, overvoltage/overcurrent events as well as sea state parameters (wave, tidal currents…). The success of the implementation of effective condition based maintenance relies on detailed real-time diagnosis intelligence and data on both the state and condition of subsea cables.

A multifunctional, integrated state/condition/performance monitoring system should allow cost effective preventive maintenance.

Data processing

Major innovation is likely to occur as well in the development of signal processing technology so as to manage more operational parameters (loads, speed…). Techniques helping to adapt further to the turbine environment should lead to more reliable CMS, diagnosis and alarm signals.

Due to the increase in offshore wind farms size, operators will require automation of CM, remote data reading, data transmission and diagnosis systems using data processing. Data storage is also key.

The introduction of SCADA monitoring techniques into the system reflects thinking in wind turbine fleets. It enables both monitoring specific parts of an individual turbine and comparing its behaviour against the entire fleet. For example, automated monitoring methods using data from the SCADA could be used to monitor yaw, pitch and power curve to detect deviations from the expected values.

Additional challenges

The following challenges have to be addressed to make the most of CMS
(from Rexroth – Bosch Group)[37]:

- Indirect assessment of desired data and information: the functional chain between measurement and desired information is complex; the realization is largely dependent on experience and knowledge
- Definition of critical states and deduced warning threshold :there is discrepancy between the user expectations and the technical capacities; the margin between false alarms and late detections is narrow

- Distorted perception and appreciation of benefits: benefits are differently perceived amongst OEM and operator; natural opposition still exists (warranty, full-service contracts, insurances…); benefits and added value of CMS is not yet fully accepted in the industry
- Reluctance to disclose and share data: operators still find it difficult to get accurate and comprehensive data from their own turbines

The success of CMS development and implementation at a large scale is also likely to rely on the ability to share data between manufacturers and owners or operators. This is still a key issue as wind turbine manufacturers only share data according to contractual obligations and are reluctant to provide more information. Due to a better competition between turbine manufacturers and the willingness to improve and develop CMS, offshore wind developers are in a better position to ask manufacturers to provide them with all the data required to implement CMS.

4.2 Operational integrity

This section discusses the challenges to keeping the wind turbines operational that are not directly related to the technical integrity of the wind turbine. Among the various factors that are relevant, a logistics strategy allowing the accessibility that is necessary for the maintenance strategy is crucial for the operational integrity of the wind farm. The requirements for the logistic solution and vessel fleet (as well as the rest of the maintenance strategy) will increase as wind farms are deployed on sites further from shore and in harsher wave climates. Although both topics are interdependent on other aspects of O&M, challenges related directly to accessibility and the vessels required for O&M are described in D3.1, and challenges more directly related to logistics will be treated in D5.1. These topics will therefore not be among those given most attention in the following subsections.

4.2.1 Planning and execution

When planning O&M strategy for an offshore wind farm, the following general challenges are usually encountered and have to be evaluated further within the LEANWIND project:

- **Availability maximization.** In contrast to conventional electricity sources, wind turbines power production is variable depending on the resource availability. For this reason planning of schedule maintenance activities should aim to maximize wind turbines' availability. Experiences from the UK round 1 offshore wind farms show availabilities which are significantly lower than for onshore wind farms availabilities. One of the main challenges which are facing the offshore wind industry is to increase farm availability by improving the maintenance planning techniques.
- **Accessibility.** Increasing the access to the wind turbines has a big impact on OPEX. For this reason a cost benefit analysis has to be carried out to determine the target accessibility for a specific offshore wind farm. Vessel operational conditions are limited and in addition, personnel transfer presents some risks that should be analysed to improve accessibility. In addition, remote condition monitoring systems shall be further developed to reduce the need for access.
- **Weather forecasting** for two different applications; to make decisions for offshore coordination (to plan maintenance activities, etc.) and for the purposes of trading

power. This project is interested in further evaluation of the different types of models (statistical and deterministic) that can be used.

- **Offshore wind farm O&M strategy definition.** A techno economic study has to be carried out to make decisions such us: how many O&M vessels will give service to the farm, which is the best location for the maintenance base, etc. Models to carry this kind of studies will be assessed in future tasks of this project.
- **Site organization.** Defining roles and responsibilities of offshore wind farm workers is crucial to optimize the farm operation. Typical roles in an offshore wind farm are head of operations, HSE manager, warehouse coordinator, offshore coordinator, site assistant, etc.
- **Lack of experience in offshore wind farms operation**, in particular for far offshore wind farms.
- **Planning** is key to ensure that the resources i.e. technicians and vessel use is optimised. Decisions prioritising work will be made on daily basis to ensure maximum safety and production from the assets. Once these decisions have been made the teams and their work orders can be allocated. In addition, the parts, tools and any other equipment can be prepared in advance for quick mobilisation the following day.
- **Work shift organization.** Work is organized in shifts which, for offshore wind farms without offshore accommodation vessel, would generally consist of day shifts (12/7). One of the challenging factors to be considered is the correct interaction between shifts in order to organize all maintenance activities. This is to be considered when organising daily maintenance activities as the effective time on the WTG will be reduced and some maintenance activities will last for more than one shift. For wind farms located far from shore, an offshore based maintenance organization (with an accommodation platform or accommodation vessel) enables night work-shifts (24/7) and the ability to respond to failure any time during the day. The main factors that determine the optimal number of technicians and work-shift arrangement is the reliability of the wind turbine, the efficiency of the transportation, the accessibility and weather conditions. Technical and HSE training of technicians has to be planned too. Tools or information that supports, definition of number of shifts and duration of the shifts are required.
- **Performance and condition indicators definition.** To secure continuous focus on the overall operating principles, Key Performance Indicators (KPIs) should be defined, monitored and actively used to improve park performance.

Usually some maintenance activities are outsourced requiring maintenance contracts and creating the following challenges:

- Operators must decide a contract strategy i.e. whether to have a single O&M service provider, multiple O&M service providers or develops in house capacities to carry out the O&M activities avoiding subcontractors.
- The interfaces between the wind farm owner and the O&M service provider have to be clearly defined in the contract specifying which party is responsible for carrying out the task and covering the costs.
- Guarantees and liquidated damages have to be agreed and will determine the feasibility of the project.
- List of spare parts.

Some subsystems require Structural Health Monitoring maintenance techniques, consisting of looking for structural defects, impacts, corrosion etc. These subsystems are:

- The tower and anchoring system
- Blades
- Nacelle

The following subsystems and components require predictive maintenance:

- Mechanical systems
- Electrical systems
- Control systems
- Other systems: Atmospherically variables, lubricant fluids

To apply these maintenance techniques it is necessary to monitor some variables. Choosing the right sensor, defining its right position, guaranteeing signal quality, defining sensor characteristics (signal conditioning; filtering, amplification, etc.), specifying severe ambient conditions that the sensor has to withstand are some of the challenges encountered when designing an offshore wind farm. In addition, considering the limited accessibility, new sensors, may be used to identify possible problems such as structural issues, oil degradation, etc. Remote elements for electrical systems are also to be further developed. Another outstanding challenge is sensors data processing and analysis.

Currently electricity supply problems and signal transmission problems happen in day to day operation of wind farms. These types of problems can only be solved with redundancy. The increase of parks in operation will lead to cost reductions.

Accessibility to the turbine is ultimately limited and it always implies some risks, for this reason, remote inspection technologies would be preferable to avoid sending people out to the turbine. A combination of remote systems for predictive maintenance with O&M planning tools is required to define all activities and reduce costs and risks.

To solve offshore wind O&M challenges, active cooperation, the sharing of information and an environment where everyone is involved and takes responsibility is needed. Today this cooperation is complex, mainly due to the lack of experience, but LEAN principles and tools, such as Kaizen model outlined in Figure 20, are key to facing these challenges.

4. ACT *Make required changes for more effective future and ongoing implementation of improvements*	**1. PLAN** *what is current state, what is future, develop an implementation plan*
3. CHECK *Did the plan execute as expected, are there improvements that can be made*	**2. DO** *Execute the plan*

Figure 20 Kaizen Tools

The figure below illustrates the main contractors and a possible allocation of responsibilities:

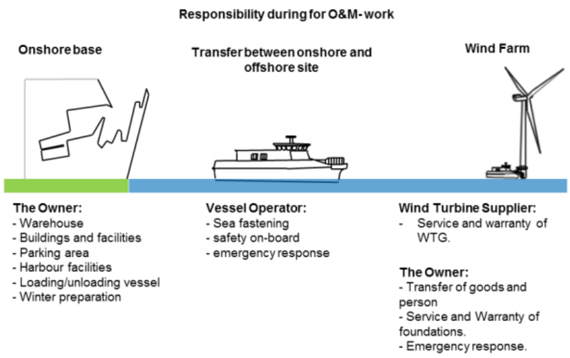

Figure 21 Responsibilities for O&M Work

An important issue for offshore wind farm O&M is logistics. Logistics have to be planned with the aim of maximising the yield and considering the impact on availability of each of the different options. HSE has to be always guaranteed and the goal should be reaching zero harm, which is no accidents, incidents or work related illnesses. The following aspects have been identified as critical for offshore wind farms:

- **Finding an adequate Building and Warehouse.** A sufficient site should be reserved in the nearest suitable harbour with the required services.
- **Spare part stock management** is a key issue for optimal O&M strategy. A spare part strategy consists of choosing the best location of the main storage base, maintenance workshop (for repair of components) and supplier lead time contracts for each component, in order to optimize the availability of the spare parts needed for maintenance at site.
- **Choosing right installation/O&M vessels and number of them** with the right characteristics will increase accessibility to the offshore wind farm at a reasonable cost and reduce technician's sea sickness as much as possible, which can be a big issue. The choice of vessel will depend on sophisticated OMS modelling tools. Key characteristics to be considered include size, speed, limiting Hs, cargo and personnel capacity, cranes capacity, accommodation facilities, distance to shore where they are allowed to operate according to national legislation, capability to launch and recover “daughter” personnel transfer vessels deck specific requirements, fender arrangement to be adapted to boat landing, type of propulsion and manoeuvring, anchoring and mooring equipment, storage, comfort levels, communications, pyrotechnics, rescue equipment, fuel consumption, etc.
- **Vessel supply-chain issues.** Lack of vessels could end up in increased charter costs and longer lead-times. Expected vessel demand is represented in Figure 22.

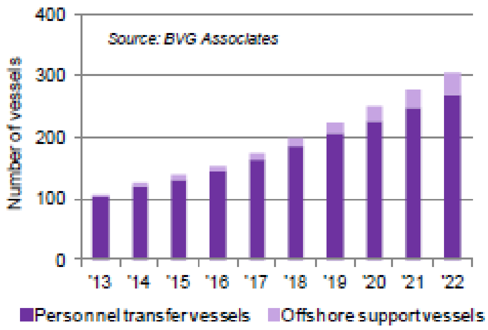

Figure 22 Projected demand for routine maintenance vessels for European offshore wind to 2022 [38]

- **Turbine transfer methods.** New access systems are being developed to increase the operational envelope. The transfer of technicians to a turbine using a personnel transfer vessel can currently only take place with a significant wave height (Hs) at 1.5m or lower, with acceptable swell and wind direction which means that about 30% of the annual working time of a technician is currently spent waiting for weather windows. A challenge for offshore wind farms operators is to increase the turbine access limit to higher Hs and consequently increase availability. These new access systems could be more expensive, and for this reason, a cost benefit analysis must be carried out when planning the logistics of an offshore wind farm to identify the best means for a specific project.
- **Helicopters.** There is uncertainty as to whether helicopters will be widely used. The decision has to be made during the design phase in order to prepare WTGs for the use of helicopters. Weather analysis has to be carried out to assess the benefits of using a helicopter and whether it translates the increased access to the WTG to an increase in availability and therefore yield, which can be quantified in a contribution to the net present value.
- **New logistics solutions for further offshore wind farms.** There is little consensus about what specific vessels, technology and access methodologies should be used for future further offshore projects. The sole use of personnel transfer vessels approach becomes increasingly impractical as technicians must spend a significant proportion of the working day being transported to, from, and around the site. Harsher sea conditions may also mean that a small vessel strategy means technicians are unfit to start complex maintenance work for some time after they have arrived. There is also health and safety implications for long, routine transfers as well as from transporting personnel back to shore should an incident occur. The current fleet of maintenance jack-ups used for major components replacement such us blades or gearboxes may not be suitable for future projects. The market will depend significantly on the reliability of the next generation of turbines.

4.3 Tools and methodologies

4.3.1 Tools and methodologies for analysing the O&M strategy

Previous sections have outlined a number of challenges and possible developments (solutions) to address these. Additional challenges are 1) how to estimate the effect of the challenges for different (presently untested) scenarios and 2) how to assess what the impact of these developments will be, i.e. to carry out cost-benefit analyses. O&M models and simulation tools, briefly described in Section 3.3.1, can be used to analyse different aspects of the wind farm O&M (1) and also to analyse the cost and benefit of different developments proposed in this project (2). Examples of challenges and developments described in the preceding sections include:

- the increased availability expected from improved condition monitoring systems or novel concepts such as remote presence [39],
- the effect of weather conditions and sea sickness on the maintenance work to be done by technicians,
- the effect of improved scheduling, grouping and routing on the overall operation of the wind farm,
- the interaction between the strategy for spare parts and the strategy for vessel logistics, and
- the best strategies for the chartering of heavy-lift vessels [40].

Many of these questions can be naturally investigated by dedicated analysis tools or as part of e.g. the scheduling tools and prognosis and prediction tools mentioned in Section 3.3.1. One challenge is, however, to perform the analysis in a more holistic manner so as to assess the costs and benefits for the overall wind farm project as well as how one aspect of O&M being investigated may impact other aspects of the operation of the wind farm. For instance, more robust condition monitoring systems and more accurate failure prediction will reduce the requirement for logistic support for maintenance operations. These kinds of interactions and impacts can in principle be assessed by O&M models and analysis tools. Such questions can also be analysed in a full OPEX cost model, given that it has the outputs and the level of modelling detail necessary to investigate them by cost-benefit analyses.

Just as the maintenance strategy impacts other aspects of the overall operational strategy of the wind farm, aspects of the overall logistics strategy will also impact O&M. To give an example, frameworks for maintenance optimisation such as RCM typically requires one to first assess the criticality of different failure modes. These criticality measures are for offshore wind farms to a large degree determined by the expected waiting time until the required technicians, vessels and spare parts are in place in weather conditions acceptable for carrying out the repair operation. Here, O&M models may be used to estimate inputs to the maintenance optimisation for different scenarios, but new developments in the analysis tools may be necessary to be able to fully capture this and similar interaction effects.

4.3.2 Verification and validation of models and tools

One major challenge in the validation of tools and methodologies is that domain expertise is required to assess the validity of the underlying modelling assumptions [41].

Involvement from industry is therefore crucial. It is also necessary to discuss validation at the very beginning of the development process and determine the level of accuracy required for the purposes of the tool [41]. In general, the level of accuracy required for an operational tool may be less than for a higher-level strategic tool. However, there are indications that aspects of the operational day-to-day-planning may be important to model in some detail in strategic O&M decision support tools [42].

For the verification and validation of different tools, one obvious challenge is the lack of available data for offshore wind farm projects. Partly this may be due to various non-technical industry barriers, and in part it may also be due to the fact that for many scenarios of future wind farms, there simply are no comparable present-day wind farms against which to verify and validate the tools and methodologies. One approach to (partially) overcome this is to verify and validate different comparable models against each other [42]. The approximations assumed in higher-level models can be tested using more detailed models, for instance, mathematical optimisation models (as those to be developed for logistics optimisation within WP 5) may be verified using simulation models.

4.3.3 Standardization

Standardization of CM systems:
The technical standardisation for CMS is pretty well covered by the existing standards and technical/certification guidelines, for example the VDI3834, the IEC61400-25 or the GL CMS certification guideline (see section 3.4 for details).

Standardization of O&M activities/strategies:
From the authors' point of view, the main challenge for standardisation activities in the field of O&M for offshore wind turbines is the generation of a comprehensive fault statistics data base. Fraunhofer IWES is working on several projects to achieve the installation of such a data base [43].

The main challenge for the implementation of such a data base is the data collection. Nowadays, this is mostly done by written maintenance reports, from which the relevant data then needs to be transferred manually in the data base.

An approach to automate the data collection for an O&M fault statistic data base is the implementation the RDS-PP system, which is here described as an example. The RDS-PP is a system to identify components in a complex technical system. Figure 23 gives an example. Every component/part has its unique identification code, which can be applied to it by attaching a barcode or ID-number on a sticker.

The approach with respect to optimised O&M strategies is that a failed component/part, e.g. a relay in the controller cabinet of the wind turbine, will be registered when replaced. The code for this component is given by the attached barcode / ID number and will be scanned by the service personnel (or the code must be typed in manually) in a hand held data collecting device. The data from this device will then read into the O&M management system. There, an entry in the fault statistic data base will be generated, the component will be registered in the spare part logistic data bases so if the stock falls below the critical number, units of the part will be ordered automatically at the manufacturer. This procedure excludes manual personnel efforts as far as possible and also minimises false entries (e.g. by swapping digits) into the data base.

The main challenge for the wind industry with respect to a component identification system (RDS-PP or comparable/compatible) is, in the first place, the acceptance and inclusion of those systems in their wind turbine O&M strategies. This acceptance has two aspects. The first one is the economic implication, since such a system will cause costs (investment as well as operational). A second aspect is the confidentiality of the generated data. One could think that this can be solved by all manufacturers having their own, independent fault statistics data base. But in that case, the full benefit for all manufacturers and for the optimisation of offshore wind technology cannot be achieved. Only a data base with the highest possible data population will yield the maximum benefit.

Therefore, the manufacturers of offshore wind turbines have to be convinced to share the results with competitors. This will require transparency from the turbine manufacturers one the one hand and the fairest possible data anonymity by the evaluating body on the other. In this respect, it is strongly recommended that such an evaluation body is independent from offshore wind turbine manufacturers. Therefore, the main challenge to implement optimised O&M strategies to the offshore wind sector will be to establish such an evaluating body.

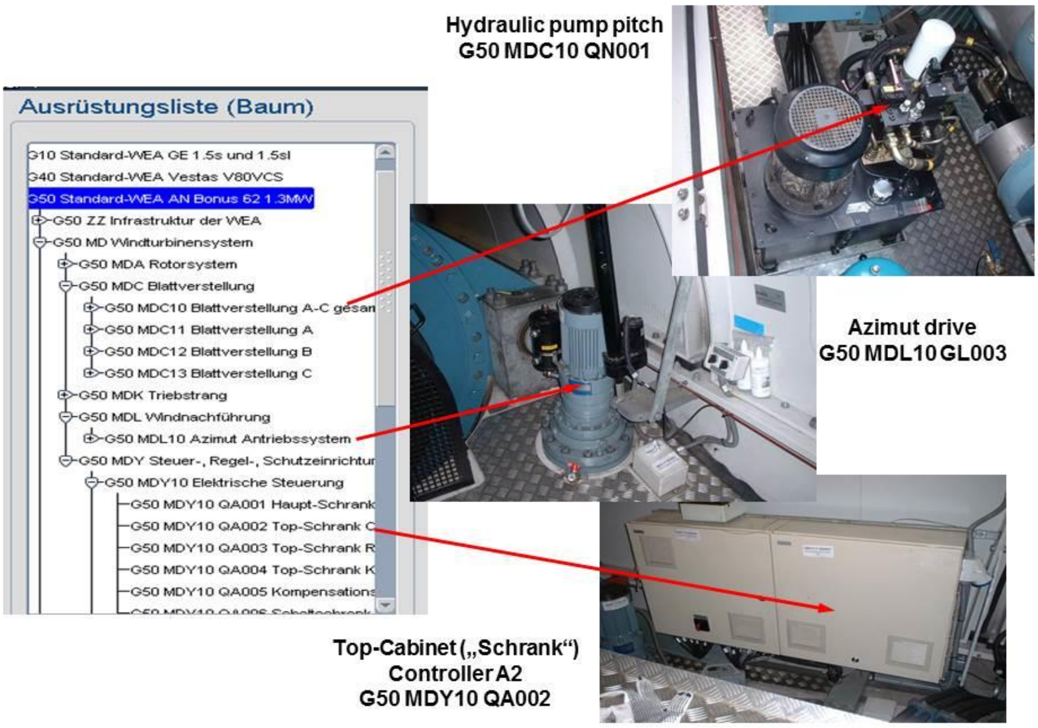

Figure 23 Example for RDS-PP nomenclature [43]

4.4 Lifetime extension

In 2012 a paper [44] was published showing that wind farms in the UK and Denmark have a general tendency towards a reduced load factor over time. In 2014, another paper [32] used a different methodology to arrive at the same general conclusion while also showing that the reduction is in line with known data from other types of rotating machinery, and less than what was shown in the first paper. The reduction is shown to be in the order of 1.6 +/- 0.2% per year. The more disturbing part of these papers is that both attribute this reduction to irreversible processes connected to the overall ageing of turbines. Unfortunately, the papers do not discuss these factors in detail.

From the oil and gas industry it is known [33] that ageing is a challenging issue to detect and document. The practical side of ageing comes down to the issue of whether or not it is financially desirable to extend the operational life of an asset beyond the original design life. In the oil and gas industry, such life extensions are now regularly made due to the technological achievements leading to increasing oil recovery factors beyond that which was assumed at the design stage of older installations. Of note is the Norwegian Ekofisk field which was started in 1973, had its first life extension programme in 1990-1993 and is currently starting the fourth life extension programme with a goal of extending life until 2053, essentially quadrupling the life of the field.

The main obstacle to such life extension efforts is the overall lack of data on operations and environmental loads. From the perspective of ageing, fatigue is one of the dominant factors for any structure. Fatigue in materials cannot be measured directly, the current methods rely on models and inspections looking for cracks, deformations and similar expected failure modes. For existing installations, one thus has to perform what is essentially a conservative estimate of the consumed fatigue life of the installation with a lack of information.

Wind energy is a fast developing technological field, as can be seen by the wide variety of designs and technical solutions being deployed. While the level of, and potential for, standard solutions is higher than e.g. for the offshore oil and gas industry, the rate of technological development renders operational data useless across wind farms, technology providers and operators within only a few years. The move towards high power installations (5 MW and above) will inevitably lead to a number of years with teething problems before the new technology can be regarded as mature.

The challenges facing the industry in light of operational life extension is primarily related to capture and storage of relevant operational data in formats that will be useful over the timeframe of 20-40 years. The primary data of concern are operational loads, environmental loads and particular events (replacement of major parts, changes to structures etc.).

Another challenge is related to the continuous feedback from lessons learned in operations to the design of new turbines and wind farms. This relates both to daily operations and also to ageing.

4.5 Climate change- expected impacts

4.5.1 Changes in the wind resource

Several assessments of future wind resources in northern European areas have been carried out using large-scale climate model projections for the 21st Century, for example, [45][46][47]. The conclusion from many similar types of study around the world is that the potential for change is highly uncertain – partially due to the difficulty in translating large-scale model output to localised wind locations. The magnitude of changes described in the studies for future periods is often similar to the differences between historical records and the climate model representation of the historical conditions, indicating that the future projections fall within the range of model error. This further reduces confidence in the outputs. The three studies mentioned here all have one result in common, which is an indication of strengthening of winter wind speeds.

O&M strategies may need to adapt to future resource changes. For example, a change in the strength of the seasonal signal, as found in [45] could make it much less financially viable to carry out any planned maintenance in winter months. A large proportion of the annual energy is currently produced in winter under current conditions, and downtime for planned maintenance in winter is more expensive due to the larger amount of lost production. Increasing the proportion of the annual energy produced in winter, however, will likely magnify this effect, making it imperative that planned maintenance be scheduled in less windy seasons – this may or may not be possible, given the design requirements of the machines. Stronger resources in winter will themselves have implications for the maintenance requirements during these months, with longer operational periods and higher wind speeds causing more prolonged loading, leading to greater wear, and possibly failures.

4.5.2 Changes in extreme conditions

Changes in the future extreme wind speeds found in [48] varied in space and time, and as with the studies on wind resources, the authors placed little confidence in the results. Overall, the conclusions suggest that there was some indication of increased gust speeds in particular areas of the domain studied (Scandinavia and the Baltic Sea region).

An increase in extreme wind conditions could be particularly relevant to O&M in terms of managing the risk of unscheduled maintenance requirements. Gusty conditions are more likely to cause damage to machinery, whether it is immediate failure, or increased loads that will reduce the MTBF of the machine overall. An important factor to consider is the persistence of extreme winds – in the event that a failure is caused by a storm or extreme gust, continuing high wind speeds will prevent immediate access for repair (see next section). This particular area of study has not been explicitly addressed in the available literature, but could merit investigation.

In the context of investigating the sensitivity of a wave energy device to changes in the wind-driven waves, the authors of [49] present an interesting discussion of several other studies in the literature that show evidence of increasing trends in extreme wave conditions over the last 50-70 years. If this were to be a continuing trend, it would have serious implications for the loading conditions of offshore wind turbine structures and consequently, possibly suggest a need for increased maintenance activity.

4.5.3 Changes in accessibility

The accessibility of offshore wind turbines under conditions of future climate change will be affected by changes in the proportion of time when wind speeds are above the access threshold and by any changes in exceedance of wave thresholds. The effect of inaccessible wind and wave conditions occurring simultaneously is worthy of consideration, although it is more likely that wave conditions will be the limiting factor in determining weather windows.

The issue of maintenance of wave energy devices under future climate change projections is addressed in [50], where it is noted that models predict an increasing range of wave sizes under climate change conditions in an area of southwest England. This implies that whilst there may be increased extreme waves, there is also potentially a compensatory increase in the amount of expected downtime due to smaller waves (in wave energy devices). This would apply equally to O&M scenarios for offshore wind, and would indicate that improved forecasting of weather would be beneficial, in order to take advantage of lower wave conditions as they occur (and corresponding lower wind speed).

4.5.4 Conclusions

There are a range of possible factors related to climate change that could impact on the design and management of O&M strategies for offshore wind developments. The uncertainty associated with future projections of wind speeds and wave conditions is high, but in light of the high cost implications of major changes, it is useful to consider the sensitivity of any O&M plans to future climate change and ensure reasonable adaptations can be applied, if necessary.

5. WP Framework development

This section includes the individual task descriptions as outlined in the approved project Description of Work (DOW) and is updated based on the recent developments in the project.

The objectives:

There is much scope in O&M activities and this WP targets a number of areas that have the potential of making considerable savings over a wind farm life cycle. The objectives of the work package can be summarised as follows:

- Optimise O&M strategies, procedures and scheduling for far-shore/deep water/more exposed locations.
- Reduce OPEX costs by improving condition monitoring and remote presence systems to minimise the need for on-site and corrective maintenance.
- Consider the impact of Structural Health Monitoring on life-cycle performance though minimizing O&M costs.
- Examine the influence of weather conditions, access criteria and access systems, including floating hotels, centralised offshore hubs, etc. and blue-skies strategies (role of helicopters and unmanned aircraft - UAVs). This will interact with access and transfer system concepts examined in WP 3- Novel Wessel's and equipment.
- Provide input to the logistics and cost models in WP5 – Integrated Logistics and WP8 – Economic and market assessment.
- Consider adaptation of Oil & Gas knowledge for the wind energy sector.

5.1 Task 4.1 approach – Industry challenges and work package framework

The objective of Task 4.1 reported in deliverable D4.1 is to describe the targeted key areas of WP4 as those within O&M where innovations will have a positive impact on the LCOE and set out the tasks to achieve cost savings. Further, to precisely define the design constraints and functional requirements related to optimising O&M activities. This will be achieved through the use of lean tools such as value chain mapping. These issues are considered across the range of options and strategies that are available with the aim to describe how the work within the WP will be organised to achieve maximum benefit.

Specifically Task 4.1 will examine personnel transfer scenarios, weather window access requirements, maintenance and service vessels, crane/winch capacities required for major component replacements, reliability/criticality of components for condition monitoring etc. The task will engage with technology developers through direct contact and a stakeholder workshop, to determine the relevant novel technologies under development. A methodology will be developed to assess these technologies for relevance and contribution to the project. Based on this assessment, a number of viable technologies will be selected for more detailed analysis in the WP. The industry advisory group will be consulted for opinion and recommendations as necessary.

5.2 Task 4.2 approach – Strategy optimization

This task will produce a modelling tool to determine the optimal O&M strategy of a farm given site location, distance to port, weather window analysis etc. In addition, it will provide analyses regarding the most effective O&M strategy for different scenarios (shore based, mother ship etc.) and will link with WP8 - Economic and market assessment, to produce a full OPEX tool.

Optimal maintenance strategies will be developed using different approaches incl. risk-based techniques. This task will examine the economic effects of adopting the strategy of using a 100% return trip efficient energy storage system to deliver ongoing guaranteed revenue during scheduled and unscheduled maintenance. It will provide a description of the size and nature of an energy storage system that would be required to deliver such an optimised O&M strategy and an assessment of how this strategy would operate across varying weather windows and how utilisation of labour and marine transport would be affected.

Finally, the effect of weather windows on scheduled and unscheduled maintenance for representative sites will be considered as illustrations of the developed strategies. Also due consideration will be given to right-sizing of man-power requirements in terms of cost and expertise of wind turbines in the marine environment. Representative sites and therefore weather and sea conditions will be chosen based on the locations of existing and planned offshore wind farms. The representative sites will be developed together with WP 2 – Construction, deployment and decommissioning, and WP 3 - Novel Wessel's and equipment as baseline scenarios defining the site conditions relevant for O&M strategy optimization, including water depth, distance to port, wind farm size and wind turbine size.

5.3 Task 4.3 approach – Reliability based design implications

This task will develop reliability-based design tools for off-shore wind turbines using existing software tools as well as advanced modelling methodologies for new requisites (e.g. remote presence, design alternatives, O&M integration, redundancy levels, components diversity, physical dispersion, structural integrated modelling, mooring systems, weather windows, time varying parameters, effect of reliability of components on scheduled and unscheduled maintenance, effect of increasing scale on maintenance strategy, etc.). Reliability, Availability, Maintainability and Safety/Security (RAMS) methodologies will be developed for critical components identification and characterization, advanced wind turbine modelling focusing on those most suitable for off-shore wind turbines (e.g. Failure Modes, Effects and Criticality Analysis "FMECA", Root Cause Analysis, Reliability Centred Maintenance, etc.). It will then consider design alternatives and O&M strategies and develop software tools for the simulation and optimization of the wind turbines models derived in the previous tasks.

5.4 Task 4.4 approach – Condition monitoring and remote presence

This task will examine existing and develop novel condition monitoring and remote presence tools considering current market sensors (types and characteristics) and new trends. An initial study will include existing wind turbine data for condition monitoring; the use of Failure Modes and Criticality Analysis (FMECA) to characterize Failure Modes, Failure Mechanisms, degradation patterns and real symptoms expected in wind turbines; Data vs. Symptoms mapping; methodologies for on-line wind turbine Diagnostic and Prognostic (Data driven, Model driven and Mixed Data-Model driven); methodologies for signal analysis (Change Point, Neural Networks, etc.); Diagnostic methodologies (Similarity, Expert Systems, etc.); Prognostic methodologies (Similarity, Expert Fuzzy Systems, etc.) with special attention to Remaining Useful Life; Decision Support Systems (Fusion techniques, Multicriteria Decision Making, etc.) and integrated systems.

Software tools will be developed for Condition Monitoring of the wind turbines based on the conclusions of the previous tasks. A language and protocol compatible with the other project software tools will be selected. Due to the frequent high computational (many signals to be processed in real time), fast programming languages are strongly recommended (C, C++, C#, etc.)

Finally NAAS will develop a prototype for remote presence. The remote presence concept will be a small robot on tracks equipped with different sensors so that different inspection tasks can be performed without the need of accessing the turbine. The possible impact of that concept on the O&M costs due to optimised maintenance strategies will be investigated. The technical feasibility and the operative abilities of the remote presence concept will be validated in close collaboration with WP7 by installing and testing the prototype on a floating research turbine.

The techniques and tools developed in this task will be applied in Task 4.2 and 4.3.

5.5 Task 4.5 approach – O&M access

This task will look at O&M access issues including the number and location of boat landings and the effect on access in various prevailing weather conditions, effect on structure (feed into T4.3) and access by large versus smaller vessels. The skill-set of O&M engineers and technicians with marine domain experience will also be considered and a safety assessment of O&M access with regard to human resources. Analyses of historical met ocean conditions will be used to perform risk analysis for different thresholds of conditions. D4.5 Framework for risk based optimal planning of O&M and inspection will then use this model to investigate how to improve different maintenance strategies and reducing risks associated – using the strategies and reliability assessments developed in Task 4.2 and Task 4.3. A strategy model will be developed including an indication of the cost and logistic implications for the use of flotels, mother ships and helicopter access. This task will require historic, representative data for weather windows, input on substructure designs from WP2 and novel service vessels and access equipment from WP3.

Further information can be found at http://www.leanwind.eu/

6. Closure

The core focus of the LEANWIND project is to implement logistics innovations in the offshore wind energy sector to reduce the LCoE. Operation and maintenance of wind farms represents a substantial fraction of the total OPEX. Reduction of OPEX influences LCoE directly, and there is a need for innovations and improved efficiency in this area.

This document outlines the main challenges for operation and maintenance of offshore wind farms. The following key areas are covered:

- Technical integrity
- Operational integrity
- Tools and methodologies
- Standardization
- Lifetime extension
- Climate change

The recommendations are given as a background for the further work to be performed in WP4. The remaining tasks will be to provide solutions and innovations that in turn will be examined by WP8 to assess the cost-benefit. Figure 24 defines the design basis or site scenarios that will be used in the LEANWIND project.

Case	Water depth (m)	Distance to port (km)	Likely substructure types
0	20	30	Monopiles Gravity based foundations
1	40	30	Jackets and tripods (piled or suction based) Gravity based foundations
2	60	100	Jackets and tripods (piled or suction based)
3	100	30	Floating turbines

Figure 24 Design basis for the LEANWIND project

Work will focus on the topics outlined in this document and summarised as follows:

Technical integrity

The technical integrity of an offshore wind farm can to a large extent be assessed through use of condition monitoring. A major challenge today is how condition monitoring data is systemised and coupled to relevant models that may support the continuous improvement processes inherent in maintenance strategies. Automation of data capture should be expanded to cover potentially all activities related to inspection, surveillance and monitoring. The use of automation, robotics and autonomous units will help address the necessary reduction in manned interventions, directly influencing the LCoE for offshore wind. Manned interventions should be confined to heavy maintenance work.

In addition to information from condition monitoring, information from inspections can also be important to assess the technical integrity. Compared to condition monitoring, which typically provides indirect information on the deterioration / damage level of the components, inspections can provide direct information with less uncertainty. Since the cost of inspections are generally larger than costs of condition monitoring, a cost-benefit or risk-based approach is needed for cost-optimal decision making.

Operational integrity

Operational integrity is about the challenges to keeping the wind turbines operational that are not directly related to the technical integrity of the wind turbine. Among the various factors that are relevant, a logistics strategy allowing the accessibility that is necessary for the maintenance strategy is crucial for the operational integrity of the wind farm. Operation and maintenance of offshore wind farms will always suffer from the constraint on accessibility to the plants due to waves, current and weather conditions. The distance between a shore base and the wind farm is also a constraint, both with regard to connection costs and the time needed to bring people and equipment offshore. The requirements for the logistic solution and vessel fleet (as well as the rest of the maintenance strategy) will increase as wind farms are deployed on sites further from shore and in harsher wave climates. Logistics and accessibility are interdependent on other aspects of O&M.

Risk-based approaches for planning of O&M activities provide a consistent approach for optimal decision making. The use of methods such as Reliability Centred Maintenance and Total Productive Maintenance ultimately requires a maintenance organisation to acquire a culture which cultivates the ability to change and adapt throughout the life of the installation. Concepts such as the People-Technology-Organisation (PTO) from the oil & gas industry should be explored with the aim to exploit the value of increased collaboration both within individual companies as well as between suppliers and operators. Such collaboration is crucial to bring down the LCoE.

Tools and methodologies

Examples of challenges and expected developments include

- the improvement in availability expected from improved condition monitoring systems or novel concepts such as remote presence [3],
- the effect of weather conditions and sea sickness on the maintenance work to be done by technicians,
- the effect of improved scheduling, grouping and routing on the overall operation of the wind farm,
- the interaction between the strategy for spare parts and the strategy for vessel logistics, and
- the best strategies for chartering of heavy-lift vessels

Standardisation

The wind power industry should adopt international standards for data capture, storage, communication and presentation. The use of open data protocols encourages development of new and innovative solutions.

Standardization could have two implications. One is standardization of O&M activities / operations used for many different wind farms / wind turbines. This could in some cases imply that that a more optimal site specific process / operation are not set because it is not part of the standardized tools.

The other aspect of standardization is to develop standards / regulations that specifies minimum requirements e.g. to secure a sufficient safety level for personnel. Both types of standardization should be investigated and the potentials for cost savings identified without compromising the requirements to personnel safety.

Lifetime extension

The same tools as used for decision making related to planning of O&M can equally be used for decision making related to lifetime extension (or shortening). Information from condition monitoring provides very useful information for this decision making.

Climate change

Climate change is inherently a slow process on a global scale (climate is defined as average weather patterns over an arbitrarily selected 30 year period), but regional and local changes may occur faster. The industry should undertake actions to ensure that changes in wind patterns and other relevant environmental factors are monitored for the purpose of detecting changes that may impact load factors, energy yield and survivability of a wind farm.

7. References

[1] Wayenbergh, G., & Pintelon, L. (2002) A framework for maintenance concept development. International Journal of Production Economics, 77 (April 2000)299-313.

[2] Petersen, Kristian R; Madsen, Erik Skov; Bilberg Arne(2013) Offshore Wind Power at Rough Sea: The need for new Maintenance Models, Syddanske Universitet

[3] Andrawus, J.A., Watson, J. Kishk, M., & Adam ,A.(2006) The selection of a suitable Maintenance Strategy for Wind Turbines.Wind engineering,30(6),471-486

[4] Smith, Ricky, Hawkins, Bruce. (2004) Lean maintenance. Elsevier USA/UK 2004, ISBN 075067779-1

[5] Hameed, Z ; Hong,, YS; Cho, YM; Ahn, SH and Song, CK (2009), Condition monitoring and fault detection of wind turbines and related algorithms: A review, Renewable and Sustainable Energy Reviews, 13, 1-39

[6] Tavner, Peter (2012) Offshore wind Turbines: Reliability, availability and maintenance, Renewable Energy Series 13, The Institution of engineering and Technology

[7] Medjaher K., Tobon-Mejia D.A, Zerhouni N. (2012), Remaining useful life estimation of critical components with application to bearings, IEEE Transactions on Reliability 61, 2 (2012) 292-302", DOI : 10.1109/TR.2012.2194175

[8] Venkatasubramanian, V. (2005), “Prognostic and diagnostic monitoring of complex systems for product lifecycle management: Challenges and opportunities", Computers & Chemical Engineering, vol. 29, no. 6, pp. 1253 – 1263.

[9] AFNOR (2005), “Condition monitoring and diagnostics of machines - prognostics - part 1: General guidelines. NF ISO 13381-1,"

[10] Bye, Per I (2009) Vedlikehold og Driftssikkerhet, HiST (Sør-Trøndelag University college)

[11] Lebold, M; Thurston, M (2001), “Open standards for condition-based maintenance and prognostic systems,” Maintenance and Reliability Conference (MARCON)

[12] Wang, W.Q; Golnaraghi, M.F; Ismail, F (2004) “Prognosis of machine health condition using neuro-fuzzy systems,” Mechanical Systems and Signal Processing, vol. 18, no. 4, pp. 813 – 831.

[13] A. Muller, M.-C. Suhner, and B. Iung, (2008) “Formalisation of a new prognosis model for supporting proactive maintenance implementation on industrial system,” Reliability Engineering & System Safety, vol. 93, no. 2, pp. 234 – 253.

[14] S. Faulstich, B. Hahn, S. Pfaffel "Offshore Wind Reliability Database" Proceedings of the EWEA Offshore 2013 in Frankfurt, Germany

[15] Norsk standard NS-EN 14943; 2006

[16] DNV-OS-C502. (September de 2012). Offshore Concrete Structures. Det Norske Veritas

[17] DNV-OS-J101. (January de 2013). Design of Offshore Wind Turbine Structures. Det Norske Veritas.

[18] COWI. (s.f.) (2014), Marine and coastal engineering - Services for terminals, ports, harbours, coastal development and special marine structures. http://www.cowi.com/menu/service/BridgeTunnelandMarineStructures/Documents/021-1700-023e-11e_Marine.pdf

[19] Rodríguez Romero, J. (s.f.) (2014). Workshop of repair and reinforcement of marine structures. Inspection of port structures.

[20] González Sánchez, E. (2014). Workshop of repair and reinforcement of marine structures. Repair and reinforcement of Barcelona Dock.

[21] Crabtree C.J, Zappala D, Tavner P, Survey of commercially available condition monitoring systems for wind turbines, Durham University and Supergen Wind

[22] Elliot Martin, Reducing Cost of offshore wind opportunities for condition monitoring, BVG Associates: http://www.merinnovateproject.eu/wp-content/uploads/martin-elliott-bvg-assoc-mer-innovate-170913.pdf

[23] Maples, B. et al. (2013), Installation, Operation, and Maintenance Strategies to Reduce the Cost of Offshore Wind Energy, NREL/TP-5000-57403, NREL

[24] Hofmann, M. (2011), A Review of Decision Support Models for Offshore Wind Farms with an Emphasis on Operation and Maintenance Strategies, Wind Engineering, 35(1), 1–16.

[25] Martin, R. (2013), State of the Art of Reliability and Availability of Offshore Wind, EDF Energy

[26] Guideline for the Certification of Offshore Wind Turbines, Edition 2012, GL, Hamburg, Germany

[27] Guideline for the Certification of Condition Monitoring Systems for Wind Turbines, Edition 2013, GL, Hamburg, Germany

[28] List of Certifications - Condition Monitoring Systems (CMS) / Monitoring Bodies for CMS , File: PDF [51,70 KB] on GL/DNV web site: http://www.gl-group.com/pdf/Condition_Monitoring_System.pdf

[29] Overview about TC88 publications (web link): http://www.iec.ch/dyn/www/f?p=103:22:0::::FSP_ORG_ID,FSP_LANG_ID:1282,25

[30] EPRI (2012) Report # 1024004

[31] Gamesa Corporation (2014) – " Life Extension Program", http://www.gamesacorp.com/recursos/doc/productos-servicios/operacion-y-mantenimiento/life-extension-eng.pdf

[32] Iain Staffell, Richard Green (2014), " How does wind farm performance decline with age?", Renewable Energy 66 , 775-786

[33] MARINTEK (2011), report # 260052.03.02 Rev.1 "Procedure for ageing evaluations" (restricted)

[34] Høyen Kristine, Kvame Susanne Amalie, Mariathas Tharsika, Powll Daryl and Tranberg Anniken Resvold; Integrating RCM and TPM: Towards a framework for Lean Mainteance, Proceedings of IWAMA 2012 he second international workshop of advanced manufacturing and automation.

[35] Petersen, Kristian R; Madsen, Erik Skov; Bilberg Arne(2013) A study of current maintenance challenges in a large offshore wind farm – A case study, Syddanske Universitet

[36] Zhang, Z-Y, Wang K-S, Wind turbine fault detection based on Scada data analysis using ANN, (2014), Advances in Manufacturing, Springer Verlag

[37] Tilch, Dietmar, Holistic Condition monitoring solutions for wind turbines, Bosch Rexroth, Husum Wind Energy messekongress 2012

[38] BVG Associates. (Nov. 2013). Offshore Wind: A 2013 supply chain health check- A report prepared by BVG for The Crown Estate

[39] Netland, Ø., Sperstad, I. B., Hofmann, M., Skavhaug, (2014) A. Cost-benefit evaluation of remote inspection of offshore wind farms by simulating the operation and maintenance phase. (Submitted for publication.)

[40] Dinwoodie, I. A., McMillan, D., Heavy lift vessel strategy analysis for offshore wind, In: EWEA Annual Wind Energy Event 2013, 2013-02-04 - 2013-02-07, Vienna.

[41] Sargent, R. G. (2013), Verification and validation of simulation models, Journal of Simulation, 7, 12–24.

[42] Dinwoodie, I., Endrerud, O.-E. V., Hofmann, M., Martin, R., Sperstad, I. B., (2014) Reference Cases for Verification of Operation and Maintenance Simulation Models for offshore wind farms. (Submitted for publication; draft version available online athttp://www.sintef.no/uploadpages/330498/Dinwoodie_etal_reference_cases_draft_v_2014-02-06.pdf

[43] A. Ringhandt, B. Bührig (2007) "Datenbankgestützte Inspektion von Windenergieanlagen (Data based inspection of wind turbines"; VGB Meeting "Instandhaltung von Windenergianlagen (Maintenance of wind turbines)", , Hamburg, German

[44] Hughes, G (2012), " The Performance of Wind Farms in the United Kingdom and Denmark", The Renewable Energy foundation, http://www.ref.org.uk/attachments/article/280/ref.hughes.19.12.12.pdf

[45] L. Cradden, G. Harrison, and J. Chick, (2012) “Will climate change impact on wind power development in the UK?,” Climatic Change, vol. 115, no. 3-4, pp. 837-852 LA - English.

[46] S. C. Pryor, R. J. Barthelmie, and E. Kjellström,(2005) “Potential climate change impact on wind energy resources in northern Europe: analyses using a regional climate model,” Climate Dynamics, vol. 25, no. 7-8, pp. 815-835 LA - English.

[47] P. Nolan, P. Lynch, R. McGrath, T. Semmler, and S. Wang, (2012) “Simulating climate change and its effects on the wind energy resource of Ireland,” Wind Energy, vol. 15, no. 4, pp. 593-608.

[48] S. C. Pryor, R. J. Barthelmie, N. E. Clausen, M. Drews, N. MacKellar, and E. Kjellström (2012), “Analyses of possible changes in intense and extreme wind speeds over northern Europe under climate change scenarios,” Climate Dynamics, vol. 38, no. 1-2, pp. 189-208 LA - English.

[49] G. P. Harrison and A. R. Wallace, (2005) “Sensitivity of wave energy to climate change,” Energy Conversion, IEEE Transactions on, vol. 20, no. 4, pp. 870-877.

[50] D. E. Reeve, Y. Chen, S. Pan, V. Magar, D. J. Simmonds, and A. Zacharioudaki (2011), “An investigation of the impacts of climate change on wave energy generation: The Wave Hub, Cornwall, UK,” Renewable Energy, vol. 36, no. 9, pp. 2404-2413.