D4.6

Final report on best practice guidelines for future WF structural condition monitoring using low-cost monitoring

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List of abbreviations

API	American Petroleum Institute
AR	Augmented Reality
CAPEX	Capital expenditure
CMS	Condition monitoring system
FBG	Fibre bragg grating
FE	Finite element
FEMU	Finite element model update
FM	Failure mode
FMD	Flooded member detection
FMECA	Failure mode, effect and criticality assessment
GPS	Global positioning system
HSE	Health, safety and environment
ISO	International standardisation organisation
KPI	Key performance indicator
MAC	Modal assurance criterion
MP	Monopile
NDT	Non-destructive testing
NFA	Natural frequency analysis
NPV	Net present value
O&M	Operation and maintenance
OEM	Original equipment manufacturer
OMA	Operational modal analysis
OPEX	Operational expenditure
OSS	Offshore substation
RAM	Reliability, availability and maintainability
RBI	Risk-based inspection
RDS-PP	Reference Designation System for Power Plants
ROI	Return on investment
ROSAP	Ramboll Offshore Structural Analysis Package
RP	Recommended practice
SCADA	Supervisory control and data acquisition
SCM	Structural condition monitoring
SEAMAC	Sensor elimination algorithm using modal assurance criterion
SSI	Stochastic Subspace Identification
TP	Transition piece
TRL	Technology readiness level
VBDD	Vibration-based damage detection
VR	Virtual Reality
WTG	Wind turbine generator

1. Executive Summary

This deliverable reports work executed within the Task 4.5 'Final report on best practice guidelines for existing (T4.5.3) and future WFs structural condition monitoring using low-cost monitoring', building on work completed in Tasks T4.1-T4.4, and reported in Deliverables D4.1 to D4.5 [1]–[5].

This report discusses best practice guidelines for low-cost monitoring of offshore structures. It provides information into the main definitions and practices of low-cost monitoring. These include hierarchal insights and costing structure for maintenance, and documents how low-cost maintenance does not directly equate to the technical capabilities of the installed hardware.

The second aspect of this report addresses how appropriate and sufficient the current standards for offshore structures are for the application of mature operation and maintenance (O&M) technologies. A brief overview of some relevant standards is provided.

Lastly, a guide to conducting low-cost monitoring is included. Based on the proof-of-concept work and demonstrations performed as part of ROMEO, key aspects of relevant risk-based approaches, risk strategies and monitoring objectives, requirements for cost-effective maintenance, modelling and analysis for structural health monitoring, and visualization of a digital enabled asset management tool are explained.

2. Introduction

Operators of offshore assets for the oil and gas sector in the North Sea, have accumulated experience of around half a century. The experience was used to optimise operation of fixed and floating platforms, regularly extending their nominal service life through appropriate integrity evaluation and maintenance plans. Although this practice has served as an important basis for the offshore wind energy industry, it remains important to evaluate both the present and past approaches to structural condition monitoring (SCM) with their accompanying inspection techniques. This evaluation is needed throughout the entire supply chain of the industry, from suppliers and consultants to the operators and regulatory entities. All these entities are equally important when considering the optimisation for the operation and maintenance of offshore wind structures. Whereby the special nature of the application must be taken in account when multiple units are exposed to different environmental conditions and subjected to highly dynamic loads.

Optimising operations and maintenance (O&M) heavily rely on available reliability, availability and maintainability (RAM) data as well as a confident assessment of the integrity of each asset, while balancing requirements imposed by regulators and the need for cost reduction. Plans to optimize O&M need to be adequately documented, followed and updated, ensuring a smooth operation during the normal and extended service life of the asset as well as across different operators, where relevant. Typically, operators and asset owners are responsible, and the accountable entities ensure the effective structural integrity management system is put in place and implemented accordingly. These systems are developed evaluating appropriate technological options against relevant key performance indicators (KPIs), including cost and others related to organisational objectives, ultimately aiming to maximise the return in any capital investment in condition monitoring system (CMS) and alleviate the impact of a potential consequence in the case of an unplanned failure.

CMSs rely heavily on data. Specifically for offshore wind farms, sufficient data need to be collected to cover both the complexity of the structural/mechanical/civil systems as well as the distributed nature of the installation in multiple units. The aspects of quantity, quality, and confidence of information becomes pertinent, also considering the remote location and unfavourable environment offshore. The example of sensors stopping to record data during extreme weather conditions has been faced a number of times in the first-generation installations. Basing our understanding of an asset's integrity on data collected from a network of sensors and potentially in combination with inspection reports, is a complex problem. In order to develop an effective plan, hardware specifications (sensors and connectivity) have to be optimized with appropriate numerical analysis (soft sensing) that can maximize the value of the data while minimising the number of sensors (and hence the capital investment) required.

Considering the complexity of the structural systems, it is important to allocate most of the available resources in components/subsystems/locations of highest criticality. This requires developing an appropriate risk prioritisation framework that captures organisational priorities and objectives, and establishing a clear plan to ensure a clear and transparent approach to assigning the most appropriate maintenance decisions. Each maintenance decision should focus directly on the failure modes relevant to each subsystem/component. Failure modes capture structural changes due to degradation mechanisms, structural damage or changes in operation and environmental loading.

For selection of an appropriate monitoring strategy, it is beneficial to also assign realistic confidence levels to the capabilities of monitoring systems.

CMS systems can continually gather information from offshore structures through instrumentation and corresponding data acquisition systems. Formally, CMS is referred to ‘the process of implementing an automated online strategy for damage detection in a structure’ [6], [7], which ‘can bring some context to the current state of the structural condition’ [8]. A detailed review of monitoring technologies and a clear specification of the support structure monitoring problem for offshore wind farms, can be found in a previous deliverable of this WP [9]. Traditional inspections, visual inspections, non-destructive testing (NDT), and flooded member detection (FMD) are often used to obtain information about the condition of the structure. The frequency of the inspection intervals of these methods depends on the risk level of the components. The motivation for introducing CMS is to identify structural damage and obtain information to mitigate risk, optimize maintenance, extend service life, reduce inspection costs, and increase structural safety. Moreover, there is an argument for the potential increased use of CMS systems to move towards condition-based inspection. However, a systematic approach should be followed to ensure that the required capital investments indeed add value and plans should follow the aforementioned risk-based approach.

This concluding report of WP4 discusses the development of effective monitoring for offshore wind farms, summarising findings, and proposing best practices. Several aspects are covered, including an overview of monitoring definitions and systems, an overview of monitoring guidelines and standards, and a guideline for selecting risk-based maintenance strategies and monitoring concept optimisation.

3. Overview of condition monitoring definitions and systems

This section presents an overview of the existing definitions, systems, key functions, and relevant technologies in CMS. More specifically it will reference the pre-existing work carried out in ROMEO and highlight the main observations taken from these sections.

The motivation behind the concept of CMS is to determine a process that provides evidence for the relevant stakeholders and the operator that the structure is indeed fit for purpose. The fundamental aspect of this process includes collection of data both from periodic inspection reports, post-failure reports, and data from continuous monitoring systems. Processed into damage related KPIs, this data can form the basis for decision-making.

In the offshore sector, the difference between monitoring and inspection is unfortunately not strong. Often the terms are used interchangeably. Monitoring can be translated from Latin as, to warn or to remind. Conversely inspection means to observe, or to watch. Several monitoring campaigns fall into both categories such as data acquisition. The data is both monitored and observed simultaneously.

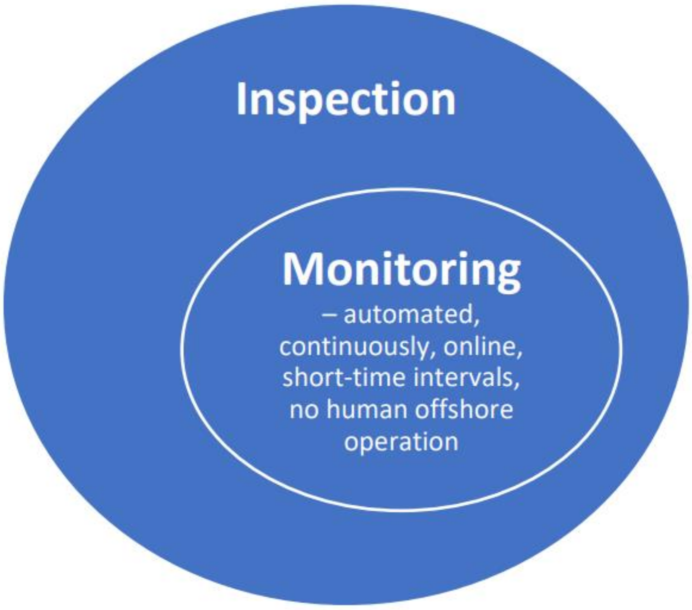

Figure 1 – Classification of monitoring as a subset of inspection

Monitoring is a sub-category of inspection, as can be highlighted in Figure 1. A monitoring campaign collects data and stores it automatically and continuously based on a predetermined frequency of a sensor. The sensor information is measuring signals that can be associated to the condition of the offshore structure without the need of human intervention. The term online measurement campaign is often used as the offshore structure information is transferred in real-time onshore for storage and further use.

The semantics of inspection is when human action is required. Inspection can be performed on-site with the use of inspection equipment, and when evaluating the monitoring data. The latter would be further categorised as inspection of monitoring campaign. If the data is not evaluated, it is merely monitoring.

3.1. Approach

To obtain an optimal condition monitoring campaign, one must find the best balance between inspection and monitoring. Monitoring refers to the magnitude of sensing technology deployed on the offshore structure. Inspection refers to the scope of the on-site inspection and the level of inspection during the monitoring campaign.

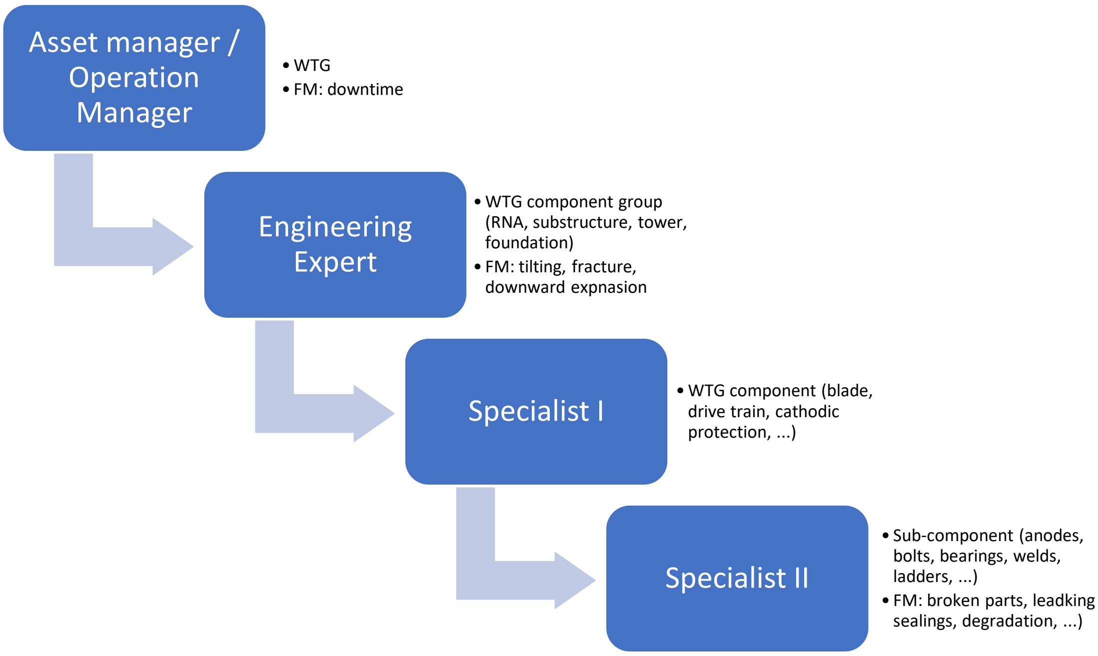

Figure 2 – System hierarchy of impact of failure

The use of a hierarchal approach was presented in Task 4.1. In summary, a monitoring system can be applied in various complexity levels. At the lowest level of complexity only one sensor and one algorithm are applied. For example, converting resistance to temperature. For the higher level of a monitoring campaign, the number of sensors is greatly increased, and must be combined with system knowledge in the form of physical equations when determining the remaining useful life of a particular element in the offshore structure. This hierarchy is displayed in Figure 2. The goal of a monitoring system is to deliver accurate information that can inform the inspector about the structural health status of the structure.

3.2. Direct Sensing technologies

A list of issues and items that should be covered during inspection of a steel structure is given in the DNVGL-ST-0126 [10] standard. This applies to both onshore and offshore assets. This list is an indicator of what should be monitored, while a condensed list includes the following:

- Fatigue cracks
- Dents
- Deformations
- Bolt pre-tension
- Corrosion protection systems
- Anchor points for fall protection
- Lifting appliances
- Marine growth for offshore structure.

To monitor the aforementioned modes, the measurement systems available and the most commonly applied are [11], [12]:

- Strain gauges
- Displacement sensors
- Accelerometers
- Optical fibre sensors
- Inclinometers
- Load cells
- Temperature sensors
- Wind speed and direction sensors
- Wave height sensors.

In an earlier task (T1.2) detailed Failure Mode Effect and Criticality Analysis (FMECA) workshops have taken place and have been documented, associating failure modes with appropriate failure mechanisms and discussing relevant features that can be utilized in order to evaluate damage accumulation [13]. It is important to highlight the link between the failure mode and the associated measurement systems, to justify all decisions for sensors and monitoring. The approach will be briefly presented in section 5 of this report.

3.3. Indirect/Virtual Sensing technologies

The main consideration when implementing indirect measurements is that the technologies may provide valuable information on the state of the offshore structure, but it can be difficult to identify exactly the phenomenon responsible for the deviation from the normal behaviour.

To create the insight needed for value of risk-based monitoring strategies, indirect sensing methods are developed in ROMEO targeting fatigue monitoring and damage detection. These indirect sensing technologies are developed, tested and partially validated with direct measurements in ROMEO. These innovations are presented in chapter 5.4.

3.3.1. Inclination

An inclinometer can provide an indication of the possibility of the structure losing equilibrium. Weinert et al. [7] mention that pile rotation can be measured by an inclinometer at mud line. A 2-axis inclinometer was mentioned by Prendergast and Gavin [8] for monitoring scour on bridges. While such sensors can indicate whether scour is occurring or not, they cannot provide information about the depth of scour. A vibration or modal analysis should therefore be performed.

The inclinometers can also be installed on the TP and on the MP. Evaluating the inclination along the tower at different levels, such as at the mud line, on the TP and on the tower, would allow a comparison and to determine if there is a scour problem affecting the entire structure, or at the grout connection affecting the upper part of the structure. There is also the possibility of both phenomena occurring together, making the interpretation more challenging. Among the different types of inclinometers are optical inclinometers [14] and laser inclinometers.

3.3.2. Vibration Modal Analysis

Vibration-based damage detection (VBDD) and modal-based analysis can estimate changes in dynamic properties and material properties of structures, as well as its response to forces [15] which can be translated to damage accumulation. Using the information provided in [16], such a global monitoring approach based on Operational Modal Analysis (OMA) can be used to detect structural damages. There is no doubt that small and large damages can affect the modes of a structure in the following ways:

- Small damages can be correlated with high frequency local modes;
- Large damages and structural changes can influence global modes.

Martinez-Luengo et al. [17] state that, to date, natural frequency analysis (NFA) is the most commonly used method to detect deviations from the design in wind turbine foundations, due to the high costs, low maturity, and low accuracy of other methods (aside from strain measurements using optical fibre). However, as El-Kafafy et al. [18] notes, it can be difficult to compare datasets recorded at varying moments since the inherent frequencies and damping ratios of the modes can fluctuate due to changes in the operating condition. Additionally, two modes can intersect in terms of natural frequency or damping ratio, providing misinformation about the structure's actual state.

3.4. Low-cost monitoring

Conventionally, there are two main aspects that influence the development of CMSs: the technology for monitoring and the interpretation capacity of the algorithms. In the context of this report, the use of low-cost monitoring concepts does not refer to the procuring ‘cheap’ technology, but rather to a value driven approach that combines the right amount of well-placed equipment with state-of-the-art numerical algorithms for post processing incoming data, maximising the value of corresponding signals.

The operational lifetime of an offshore structure is governed by the accumulation of fatigue damage. To this end, it becomes pertinent to estimate and update the lifetime of structural components as well as the whole system maintaining a time history, also considering unforeseen loading events. Methods to accurately make these predictions, and ideally providing metrics of accuracy of the prediction can effectively support decision making with respect to maintenance decisions. In addition, for existing structures, the outcome of an assessment of fatigue life can indicate the potential for lifetime extension, as demonstrated in T4.3.

4. Overview of monitoring guidelines & standards

This section presents an overview of exiting codes and standards for digital solutions for structural health monitoring. More specifically existing codes and standards are presented for topics that cover inspection and structural monitoring of offshore structures.

4.1. Existing codes and standards

Recognised international standard bodies such the ISO and API, motivated primarily by oil and gas, offshore and marine applications, define the requirements and recommendations relative to in-service inspection, condition monitoring and maintenance. At different levels of depth, recommendations are provided over the different deployment phases of relevant structural systems.

Among the ISO standards, ISO 19900 [19] focuses on the general requirements for the design and assessment of offshore structures. Inspection, monitoring and repair are referred to as conditions to achieve durability of the structure and more specifically inspections during operation are set as a requirement while monitoring is also discussed. Additional standards from the ISO 19900 family of standards, such as ISO 19901-1 [20], discuss more specifically the requirements related to the determination of meteorological and oceanographic (metocean) conditions making reference to monitoring for collection of relevant data as well as methods for data processing such as weather forecasting and statistics. Similarly, ISO 19901-4 [21] provides requirements for inspection and monitoring of geotechnical conditions and other aspects related to the collection of data related to specific failure modes related to foundations. ISO 19901-9 [22] systematically discusses the topic of Structural Integrity Management (SIM) and associates inspection and monitoring with the reduction of risks for the structure and structural components; advanced concepts such as risk based inspection (RBI) are also referenced, while this standard is also referred to in ISO 19902 [23]. Similarly, ISO 19903 [24] introduces requirements for inspection and monitoring of concrete offshore structures, ISO 19904-1 [25] for ship-shaped, semi-submersible, spar and shallow-draught cylindrical structures and ISO 19905-1 [26] for jack-ups.

The standards referenced earlier, focus on the motivation of developing systematic frameworks for data collection from offshore and marine structures, and utilisation of information for the efficient design and operational management of such assets. Standards provide reference to minimum requirements for inspection, and this is associated to the consequence class of the structure. Also considering continuous data collection processes through monitoring, the objective should be to mitigate risks while at the same time maximise availability of the asset.

A detailed review of standards can be found in [27].

4.2. Discussion and summary

It is common knowledge that standardisation and knowledge sharing has significantly added value to the offshore oil and gas industry, and it is expected that the offshore wind industry can equally benefit, sharing best practice and further promoting standardisation. To this end, it becomes pertinent to support such initiatives that will operationalise the high-level description of definition of inspection and monitoring from existing standards. In addition to this, new techniques that are proposed need to go through the validation and technology qualification process, so as to increase confidence to end users, highlighting benefits and limitations. With respect to prioritisation of areas for standardisation, industry will benefit significantly from guidance on optimal sensor placement for more advanced types of sensors, as well as guidelines for data processing in order to extract maximum value from data that are collected. More specifically, current recommended practices (RPs) such as those proposed by DNV [28]–[32] and ISO [33], [34], [35], can be beneficial for the latter aim as they can be applicable for CMS, however more specific and advanced frameworks can be suggested taking into account the significant amounts of data that can be collected within a typical offshore wind farm and the distributed nature of such a system [36]. Further, in service inspections and monitoring signals should be integrated into a systematic CMS system, avoiding redundant information and saving relevant costs. Within our work we have already proposed a risk-based framework to stand as a basis for the development of CMS, however it would be beneficial if the process of common failure mode identification is standardised together with their associated monitoring features.

With respect to reported barriers to the implementation of CMS, in the first generation of offshore wind farms, the key obstacle has been the poor assessment of the return on investment and the lack of automation of the decision making process [37]. Implementation of CMS, and especially extrapolation of measurements to non-instrumented units/locations, involve a level of uncertainty and additional technical skills are required in order to effectively inform decisions. Further, the design of a CMS should fit the nature of the plant, and in order to consider its optimisation, should not be generalised in different systems/wind farms, unless key design assumptions are appropriately evaluated.

5. Best practise guidelines

This section presents a recognised state-of-the-art of digital and automated solutions to enhance the structural integrity using data analytics concepts developed and presented in the ROMEO project. More specifically, the section covers a presentation of algorithms for collecting and processing the data from a complete monitoring campaign.

5.1. Risk based monitoring strategies

The first stage in developing such a solution, accounts for the identification of prevailing failure modes, assessment of their criticality, qualification of the most appropriate methods and association of relevant features for future monitoring system development.

5.1.1. Maintenance options for offshore wind farms

Maintaining offshore wind energy assets faces important challenges due to the harsh deployment environment, requirements for specialist vessels and accessibility issues due to weather restrictions and distance from ports. Throughout the 25 years of nominal service life of wind farms, several interventions are expected for inspection and maintenance. For an evolving technology, such as wind energy, failure data are scarce, constituting maintenance planning a non-trivial task with increased uncertainty.

Fundamentally, a number of options are available with respect to maintenance, which can be broadly categorized into three groups: corrective maintenance, preventive maintenance and predictive maintenance, as shown in Figure 3.

- Corrective maintenance assumes that components are running-to-failure with no specific inspection or monitoring taking place. This approach can refer to components of low criticality where spare parts are easy to procure and no special vessels, equipment or personnel are required for the intervention. Corrective maintenance can be planned, where certain failures are corrected during regular maintenance campaigns, and unplanned, following failures occurring during operation or maintenance activities.
- The second strategy refers to preventive maintenance, where operators put effort to avoid failure from occurring through either collecting information from the component (continuous monitoring or periodic inspections) or maintaining the asset after certain time intervals (calendar or operational time) [26]. In addition, opportunistic maintenance occurs during regular maintenance campaigns through ad hoc inspection by trained technicians.
- Finally, predictive maintenance takes a forward-looking approach, collecting information from the asset and, through analytics models, evaluating how damage is accumulated on a component with a view to predicting when certain thresholds will be exceeded, denoting failure, and hence planning the best time to intervene, reducing or potentially avoiding under-utilization of components that would otherwise be substituted earlier. Often predictive maintenance is considered part of preventive maintenance as its objective is also to avoid a failure from occurring.

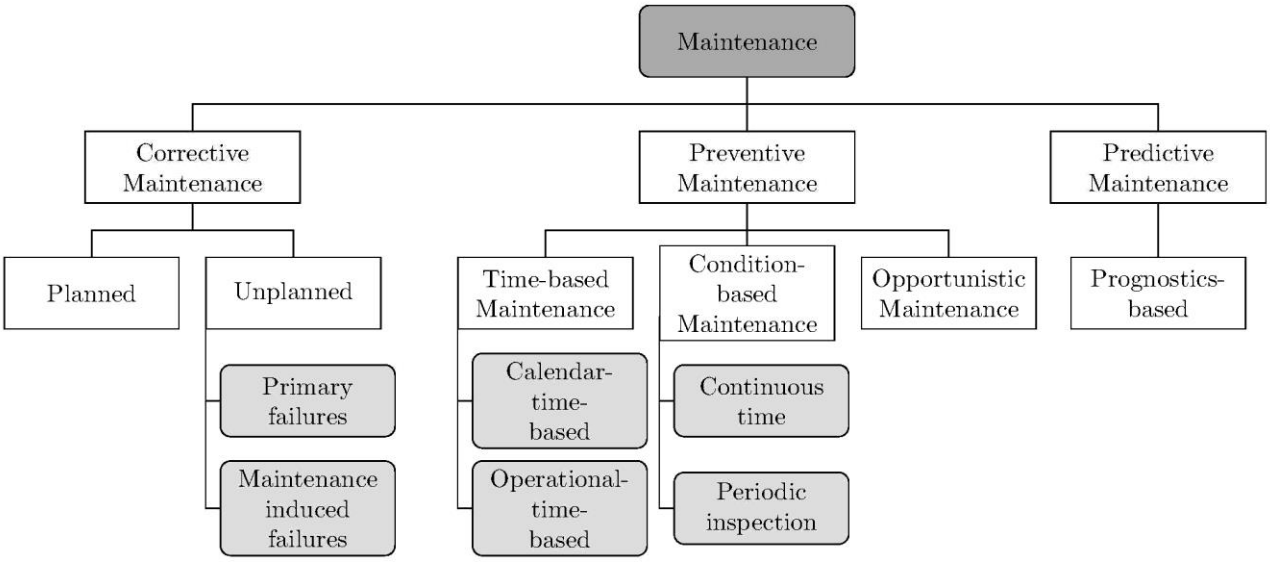

Figure 3 – Maintenance strategy options [38]

5.1.2. Risk based maintenance strategy selection

The proposed framework consists of 11 steps that are described below and stand as the basis for a risk assessment/failure mode and effect analysis workshop.

- Step 1: The asset/sub-system under consideration is divided into systems and components, usually employing a standardized designation system, such as the RDS-PP system.
- Step 2: The main functional description should be added to each item/component as text. This description should reflect the main design intent and will help to, in a later stage, assess the effects and consequences of a functional failure.
- Step 3: The failure modes relevant to the component and its function should be specified. The failure mode contains information about the event that causes a functional failure – in basic terms, it will answer: “What happens?” Practically, it is the description of the failure from an ‘eagle’s-eye’ view.
- Step 4: The failure cause describes what made the failure mode occur. This is documented in order to be able to document the likeliest root causes of the failure mode under consideration.
- Step 5: A rating describing the likelihood of the occurrence of a failure scenario to occur is documented, and is linked with the failure cause.
- Step 6: The failure end effect describes what happens when a failure mode occurs. It is this scenario which is assessed in terms of consequence in subsequent steps. The failure effect description will consider the realistic worst-case scenario.
- Step 7: The β-factor is analyzed and documented. This represents the conditional probability of the failure end effect to materialize, given that the failure mode has occurred. In practical terms, this factor should capture any controls that are in place in order to prevent the failure mode from occurring should the cause be present, or the consequences that occur should the failure mode materialize.
- Step 8: The consequence of the described failure end effect is assessed. In this instance, five consequence factors have been distinguished, namely Production Availability, Personnel Safety, Environment, Spare Part Cost and Intervention.

- Step 9: The criticality value is a quantified result of the priority of each failure mode:

$$CN = Likelihood * \beta factor * (\sum Severity) \quad (1)$$

- Step 10: The failure mechanisms of any prioritized failure mode are analyzed. The physical, chemical or other processes leading to the failure are recorded. This should potentially relate to the quantity that can be measured throughout operation of the asset and can be associated with assessment of damage mechanisms.
- Step 11: Following the proposed decision tree, optimum maintenance strategies will be selected, and associated monitoring/inspection activities will be determined for the identified critical failure modes.

The above-mentioned framework has a broad applicability and is suitable for the assessment of various subsystems with the same objectives. The underlying risk policy that is proposed, assumes a higher weight for the effect of consequence in the criticality assessment, which is a common trend among asset operators' organizational risk culture. For the likelihood of occurrence, three levels are distinguished as Not expected, Possible or High, with corresponding factors for the criticality assessment (1, 2, 3). Similarly, for the β-factor, three levels are distinguished as Low, Medium or High, with corresponding factors of (1, 2, 3). Finally, for each of the consequence factors, three levels are assumed, Marginal, Medium and Critical with corresponding factors of (1, 2, 3).

Based on these factors and the criticality assessment formula presented in Step 9, the two extreme values for the criticality assessment are 5 and 135. In order to determine different risk levels, this domain is split into three ranges:

- Low: 5-43
- Medium: 44-90
- High: 91-135

5.1.3. Decision tree for maintenance strategy selection

After the criticality of different failure modes has been determined, the next step toward assigning appropriate maintenance strategies for each failure mode is to identify the failure mechanism and determine the most appropriate maintenance strategy following a structured approach. The selection of a strategy is driven by corresponding monitoring/inspection requirements and their feasibility (technical and economical). The structured approach developed in ROMEO is the following decision tree and is illustrated in Figure 4. The tree consists of a series of questions leading to the different strategies that are applicable: (i) corrective maintenance (run-to-failure), (ii) predictive or preventive condition-based maintenance, (iii) preventive planned maintenance and (iv) recommendations for improvement.

The structured questions are as follows:

1. Is the criticality of the failure mode above the threshold set for low criticality risks? Failure modes exceeding the threshold criticality number will be considered as maintenance critical.
2. Can the condition of the item be measured? Here we refer to whether a certain feature can be associated with a given failure mechanism through inspection or continuous monitoring.

3. Is condition-based maintenance technically and economically feasible? Can we associate damage accumulation/performance deterioration models with the monitoring of identified features?
4. Is predetermined maintenance technically and economically feasible? Based on standard requirements or reliability data for each component can we consider maintenance interventions in predetermined intervals?
5. Is run-to-failure acceptable and in line with risk policy? Is it acceptable, based on organizational policies, to accept certain risks during operations or should a different risk control strategy be adopted?

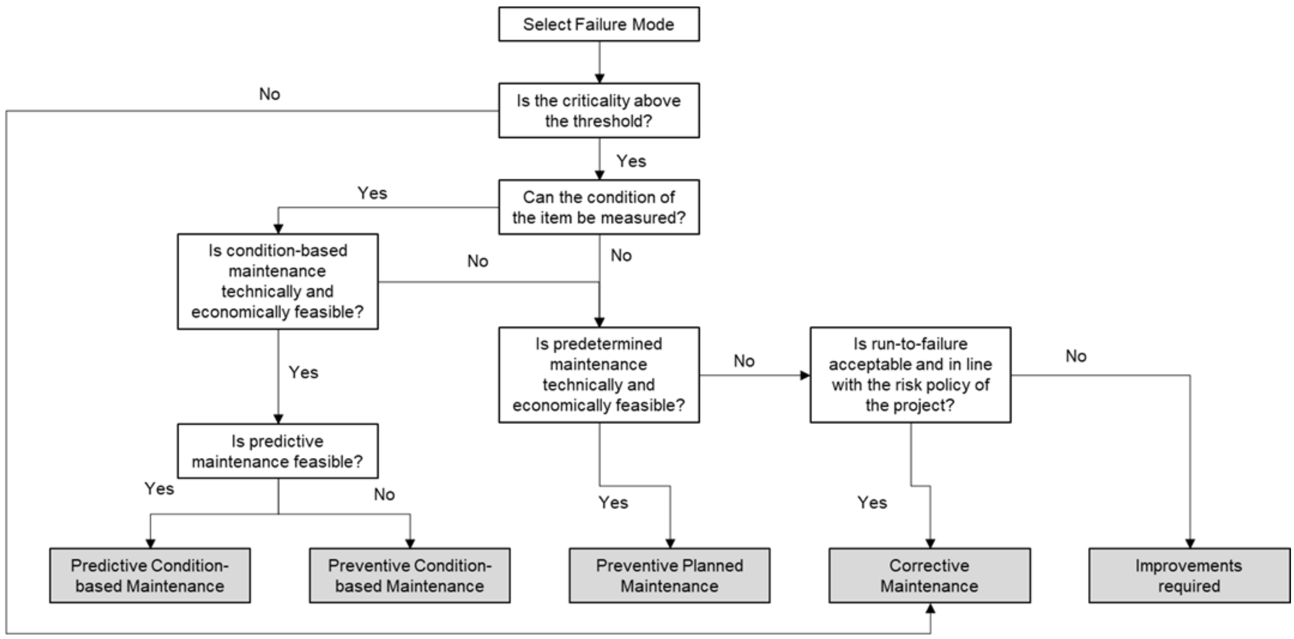

Figure 4 – Maintenance strategy decision tree [38]

It should be noted that the process presented above is indicative and it is always recommended that organisational risk policies are adopted, where possible, in order to identify, evaluate and prioritise risks.

5.2. Risk strategy and monitoring objectives

This risk-based maintenance approach can be relevant to both existing and future wind farms, the key objectives however are somehow different. As a general rule though, it could be stated that an early establishment of such an approach adds more value generation as it releases multiple degrees of freedom in the decision making.

5.2.1. Existing wind farms

In existing wind farms, key barriers in the implementation of CMS relate to the lack of accessibility to optimal deployment locations as well as the existing bandwidth for data communication. This mainly relates to the application of direct sensing, while retrofitting of indirect sensing has less limitations. The motivation for retrofitting existing assets of wind farms with CMS is summarised in the following points:

- Commonly, installation of CMS on existing assets is motivated following an initial insight from a deviation of performance or integrity from the design intent. For example, if excessive fouling on a foundation is observed, relevant sensors can be deployed in order to monitor and potentially mitigate the adverse effects of this risk, in a single unit and as a consequence across the farm.
- As turbines approach the end of the nominal service life of 20-25 years, the consideration of the most appropriate end of life strategy becomes relevant. Across repowering (full or partial), service life extension or decommissioning, which will be the ultimate fate of the asset, decision making requires data which will allow for a confident assessment of the integrity state of critical components and the system in general, as well as to predict the residual capacity and potential subsequent profitability of the asset which can qualify service life extension as the optimal strategy. Experience from oil and gas and the assessment of assets through certification requirements highlights the importance of response data from the asset for a period before such a decision can be taken. This will allow for the calculation of the residual lifetime with sufficient confidence to support forward planning.
- Finally, once the installation is mature and an understanding of its performance is achieved by the operator, potential for reduction in O&M costs can be explored with a view to achieve savings throughout the remaining service life. It is important to mention that design standards and manufacturers' guidelines should be consistently consulted, however advanced methods which update the understanding of structural performance in light of incoming data from the operational asset can potentially reduce costly inspections and other maintenance activities. Concepts of risk-based inspection (RBI) and data/digital enabled asset management are also applicable here.

5.2.2. Future wind farms

In addition to the benefits listed above for existing wind farms, further objectives of a structured monitoring system can qualify.

- A monitoring campaign can serve the important purpose of design validation. The interaction of the structure with the local environment is among the most critical sources of uncertainty. To this end, a limited number of measurements can evaluate the level of agreement with the initial design and hence a more detailed calculation of the residual life can be performed. This practice is particularly relevant to new locations where limited information on the geotechnical conditions exist. It is important to mention here the difference between a short-term monitoring campaign and a service life-oriented monitoring scheme as the requirements in durability of the sensors network as well as the resolution of data would differ. Finally, in the latter case, monitoring can serve the purpose of specifically quantifying the impact of extreme events on the 'consumption' of the fatigue life of a structural system (particularly relevant to certain regions).
- Further, instrumentation can be used to reconcile the CAPEX/OPEX ratio, informing appropriate investment decisions. This assumes accepting or avoiding certain risks which can potentially be related to failure modes that can be monitored effectively allowing sufficient time to intervene and avoid failures that lead to requirements for unplanned maintenance. Such practice can also be linked to the funding strategy of the investment as well as potential additional savings related to warranties and insurance. The latter is linked to the fact that

additional information coming from the asset increases confidence not only to the operator but also to associated stakeholders, such as OEMs, insurers, regulators, etc.

- Finally, considering monitoring from the beginning of the design of a wind farm, allows for a streamlined operational management through a potentially (fully) integrated data-driven approach. This practice, which is currently considered as mainstream in other industries such as thermal power plants, can be applied in different levels, from associated directly signals to decisions, all the way to developing plant databases that will be automatically informed, through connection to ERP systems, associated with high fidelity analytics toolkits and decision support frameworks which incorporate organisational strategies and objectives. Application of this practice can benefit the design of future wind farms and further optimise operations through a facts-based approach.

It should be noted that operators of wind farms that are currently under development are more willing to adopt a more systematic monitoring approach. This suggests that previous experience with limited access to data from the operating asset limits the potential for optimal operating strategies.

5.3. Input for low-cost maintenance

Operation and maintenance of offshore wind turbines is more challenging than operating an onshore wind farm, especially when the substructure is under consideration. Indeed, if the monitoring system fails, maintenance can be difficult as it may require going offshore under harsh environment conditions and have divers perform the maintenance introducing significant safety concerns. Compared to the oil & gas experience, Wymore et al. [35] pointed out that the loadings and solicitations that wind turbines must withstand are different from those of common offshore platforms.

5.3.1. Design reports and virtual prototypes

A successful, low-cost monitoring strategy first of all requires access to design assumptions. Within the ROMEO project the benefits that can be achieved through data sharing was highlighted. To create an effective response model of the structure, such as a digital twin, one must first model the structure. Thus, having the geometrical, topological, and material information on the structure takes the designer one step closer to representing it digitally.

To successfully develop and subsequently use a low-cost monitoring models, various types and sources of data are required. A numerical model (aka virtual prototype) of both the foundation and the turbine is required. Usually, models are prepared by specialised consultants who do not necessarily share the detailed information required to establish the models. A wind turbine supplier is responsible for preparing a numerical model of the wind turbine, including detailed geometry of the blades, nacelle, and control systems. Typically, such information is confidential and not explicitly shared externally. Consequently, high-quality numerical models of a turbine are difficult to obtain from any party other than a turbine developer; this topic is explored in more detail in [39].

5.3.2. Maintenance reports

A maintenance report is one of the main tools used to document O&M activities. The report involves the process of checking, servicing, and repairing operating equipment to make sure that businesses operate smoothly without unwanted or unexpected interruptions. One of the main benefits of these reports is the value created from the knowledge on the offshore structures. This information can be utilised in the digital-twin technologies to update the model.

5.3.3. Data handling

For monitoring systems already offered in the market, TRL (Technology Readiness Level) must also be considered as several concepts have not been applied in the reference application. Besides, most systems must be tested and validated in a lab before being installed on-site. It is also important to think about a back-up plan if the system fails as introduction of monitoring systems may increase complexity and affect additional failure modes. An analysis of integration costs should also be performed for on-site testing to quantify expected benefits [40]. Hence, if the system is proven satisfactory in real conditions, and cost-efficient, then it can be deployed on several wind turbines. Finally, as far as mechanical damages are concerned, hotspots to be monitored should be defined using finite element analysis and other numerical models. Such calculation would also provide valuable information on the operating range of the sensors that should be chosen. The parameters to be considered when handling data from CMSs are as follows:

- Data collection and storage
    - Sensors: sensitivity required, calibration, parameters that could bias the measurement and how to control such parameters, drift of the measurement along time and how to correct it, redundancy (in case of damage), range of the physical parameters to be measured, optimized location of the sensors
    - Data collection: frequency of data acquisition and means of communication for data collection
    - Data storage means
- Data processing
    - Complexity of post-processing (whether a further development is required or not, time required for such developments, etc.)
    - Parameters required for post-processing and their influence on the sensitivity (e.g. temperature, relative humidity, service life of the glue and its effects on measurement of glued sensors)
    - Identification of such parameters and possibility to have access to such data
- Security of the entire system.

5.4. Modelling and analysis

The major steps of a SHM process are: (i) the modelling of the structural components, (ii) the calibration of these models based on the collected data, and (iii) their implementation for the analysis of low-cost monitoring solutions.

This subsection aims to address these aspects, starting from the effective gathering of the field data and their processing (in section 5.4.1 and 5.4.2). This is followed by the calibration of virtual prototypes of the assets (aka digital twin, in section 5.4.3) using these data, and by concludes with the deployment of data-driven, model-based and/or hybrid approaches to enable prognostic and diagnostic models (in section 5.4.4 and 5.4.5, respectively).

5.4.1. Structural response analysis

The benefits of a monitoring system for the support structure of an offshore wind turbine lie in real-time information on the structural integrity, which should be assessed in regular intervals and after extreme/unforeseen events. The data also provides the basis for an optimised asset management with reduced maintenance and inspection costs and improvements in the asset operation. Finally, the continuous monitoring can support life-time extension strategies.

In general, monitoring objectives should be rooted in organisational strategic plans, see chapter 5.1. This can be ensured via dedicated workshops with key stakeholders of the organisation. A joint understanding of critical risks, stemming from Failure Mode Effect and Criticality Analysis (FMECA) and systematic identification of maintenance strategies according to a decision tree, is very important in an early project stage. The FMECA workshop for the Wind Farm is documented in WP 4.1.

To derive a detailed monitoring concept, the following steps are typically executed:

1. Establishing critical failure mechanisms for the structure
2. Checking the feasibility of direct sensing for critical failure mechanisms
3. Checking the feasibility of indirect sensing for critical failure mechanisms
4. Establishing monitoring purpose and objective based on failure mechanisms
5. Definition of benchmark metrics for monitoring hardware
6. Execution of benchmarking to identify hardware components
7. Establishing sensor layout(s) in wind turbine(s)
8. Establishing monitoring locations within the offshore wind farm
9. Establishing a monitoring programme throughout the lifetime of the asset

A case study of the feasibility of the indirect sensing for critical failure mechanisms (point 2 above) for the WTG is documented in [41]. This analysis conducted a sensitivity study on the changes in the dynamic response of an offshore wind jacket structure, for several classes of anomalies and by ranging their severity; the variation of the modal properties of the WTG is investigated for: (1) changes in the operational conditions (i.e., the nacelle yawing), (2) structural damage, including cracks on structural joints, and (3) the exceedance of design allowances, such as corrosion, scour, marine growth profiles and tower bolt tensions.

5.4.2. Sensor Layout validated against monitoring objectives

The objective of monitoring data is to provide accurate information on the monitoring objectives selected in point 4 of the FMECA workshop. The aim of low-cost monitoring is to provide that information with an optimal number and places for mounting sensors such that the monitoring system can achieve:

- The capability to extract linearly independent mode shapes of OSS and WTG up to a defined number of harmonics;
- The observability of mode shapes by distinct differentiation up to a defined number of harmonics;
- A minimum amount of hardware (sensors and data acquisition system) while saving costs but keeping high-quality data analysis level;

- Relies only on mounting locations that are regarded acceptable in terms of installation risks, maintainability, and its exposure to potentially harming environment.

To accompany the accelerometers that facilitate OMA, see chapter 3.3.2, strain gauges are installed for:

- Calibration of the FE modelling to improve the fatigue assessment in hotspot locations that are not instrumented.
- Validation of the indirect fatigue assessment
- Reassessment of the remaining life of the structure.

To determine the optimal sensor placement for OMA of the OSS and WTG an algorithm utilising the modal assurance criterion (SEAMAC – Sensor Elimination Algorithm using Modal Assurance Criterion) is conducted in WP 4.2. The approach incorporated the following steps:

1. Analyse the current sensor set-up through the modal assurance criterion (MAC)
2. Define the location of possible sensor installations on the structure
3. Optimise the layout by addition of new sensors
4. Repeat until MAC meets the threshold.

A case study on the application of this approach to the sensor placement in the OSS of the Wikinger wind farm is documented in [42]. This study demonstrated that this approach can be implemented for an offshore support platform without compromising the quality of global mode extraction.

Sensor setups are developed according to the criteria in Table 1. Setup 1 aims at an optimal sensor layout with a balance between number of sensors and small values in the off diagonal of the MAC matrix. For setup 2 the number of sensors is reduced to find the minimal setup with off-diagonal values of around 25%.

Table 1 - Table highlighting the different schemes used to determine the sensor layout

	Setup 1	Setup 2
Investigated mode shapes	1-5	
Number of sensors	Optimal - balance between sensors and MAC	Minimal - as few sensors as possible
MAC: minimum diagonal value	As high as possible	More than 90%
MAC: maximum off-diagonal value	As low as possible	Less than 25%

5.4.3. Digital twin for fatigue reassessment and enabler of diagnosis and prognosis models

Although most of structural damage events are not likely to reach a safety-critical level, their late detection can lead to critical consequences which will result to high cost of mitigation actions [43]. Furthermore, the technical assessment and knowledge of the fatigue accumulation in the structures are necessary to prove that the operating assets can maintain the required safety levels during their lifetime, and in case of an extension of their operation life [44].

To address these issues, the digital twin technology can be applied to continuously monitor the condition of the offshore wind turbines. The concept used within the ROMEO framework for SHM, and implement by Ramboll in the deliverable from D4.2 to D4.5 [2]–[4], is the so-called “true digital twin" [45], [46]. This concept is based on the idea of creating a coupling between the virtual prototype and its physical twin by the mean of SHMS measurements. This process, initially developed for oil and gas assets, is extended to the offshore wind industry in [47], by focusing on the development of a digital twin to estimate the fatigue damage accumulation for joints and other fatigue-driven structural components of jacket substructures.

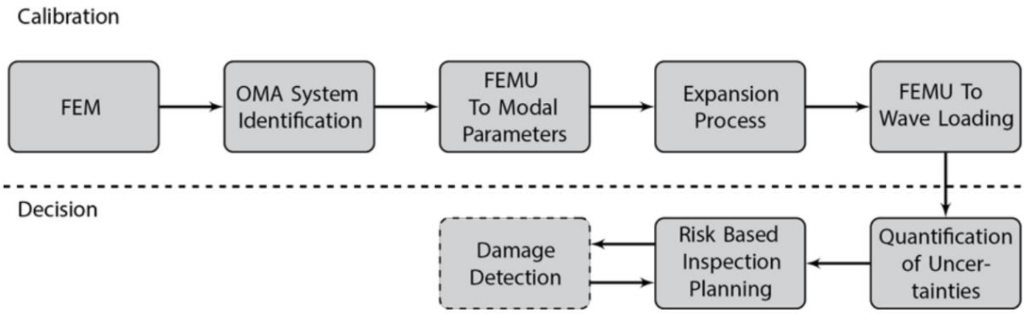

Figure 5 - Digital twin framework for improved decision models in an offshore oil and gas application, from [45], [46]

The measurements of the vibration based SHM sensors installed on the structures of the OSS and the WTG are used to calibrate their virtual prototypes, in this case Finite Element Models (FEMs) which are initiated using design documentation. Specifically, the calibration procedure consists of the following steps.

1. Engineering-, and expert-, based update of the virtual prototype, to integrate the offline information on the structural health status of the offshore asset.
2. Acquisition and processing of the online data: (i) extraction of the global modal properties from the SHMS via OMA system identification techniques – cf. section 3.3.2 –, (ii) manual or data-driven clustering of modal properties based on the environmental and operating conditions –e.g., the SCADA system for the WTG.
3. Data-driven model updating of the wind turbine support structure.

The jacket substructure and the wave loads can be modelled using a specialist response modelling tool, such as ROSAP (Ramboll Offshore Structural Analysis Package). The turbine and its response to wind loads is modelled in wind turbine design software of turbine manufacturers or modelled in a software capable to replicate the interaction of the turbines with the substructures, such as Ramboll's in-house LACFlex aero-elastic code [50].

The cumulative fatigue of the individual structural components is calculated with the ROSAP model of the substructure in a semi-coupled manner with the aero-servo-elastic code of the WTG. The LACflex software calculates the wind turbine response in time domain, by modelling of the tower and the rotor-nacelle assembly, together with the control strategies in response to the stochastic turbulent wind loads [50]. Not having access to all details from the manufacturer, the simulations can be run by using a generic representation of the turbine. A force-controlled recovery run is performed in ROSAP based on the load calculated at the interface – between the substructure and the turbine tower –, to derive the damage equivalent loads and fatigue of the elements of this virtual prototype.

The process of the used data-driven FEM updating (FEMU), finds a match between the model eigenfrequencies and measured modal properties, is presented for the WTG in [39], and documented thoroughly in D4.2 [2]. The updated numerical models can be then used to deterministically reassess the fatigue life of the assets – cf. Figure 6 in case 1). This procedure was shown to have the potential to increase the lifetime of the offshore wind asset installed on jacket substructures [48].

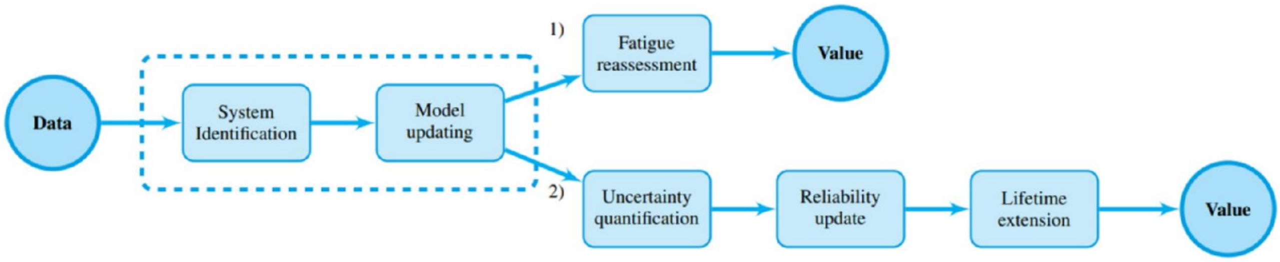

Figure 6 – Framework for the application of a digital twin for lifetime extension, from [39]. The dashed rectangle highlights calibration procedure.

To further reduce the modelling uncertainties for the estimation of the fatigue damage cumulated in the structural elements of the WTG jacket substructure, a FEMU to the wave loading is implemented in D4.5 [5]. The scope is to calibrate the wave load model such that the predicted stress distribution corresponds to the measured distribution from the MDE – for more information on the latter the reader is referred to [49]. The MDE algorithm utilises sensor data as well as the updated FEM [39]. This update leads to a more accurate modelling of the fatigue load on the structure in response to the wave excitations.

Prognostic and diagnostic models can then be developed based on these digital twins (i.e., updated FEMs), that have the power to accurately replicate the dynamics of the WTG, as well as model its response to the presence of anomalies in the WTG substructure.

5.4.4. Low-cost monitoring of fatigue: models for prognosis

There are different use cases how low-cost fatigue monitoring can provide benefit to the wind farm operator. Table 2 summarises the three approaches pursued in ROMEO, their potential value, data requirements and challenges.

Table 2 - Comparison of low-cost fatigue monitoring approaches evaluated in ROMEO (adapted from D4.4 [4])

Approach	Potential value	Data requirements	Challenges
Machine learning (ML) ***Radom Forest Regression***	Continuous damage equivalent load estimation after initial measurement campaign *Possibly*: Application of trained model to other WTGs without strain measurements	- SCADA statistics - Strain at interface (only for a limited training period)	- Relying on collection of representative training data - No insight in fatigue damage distribution that were not part of training dataset
Modal decomposition and expansion (MDE)	Continuous fatigue damage estimation for all hotspots in the jacket, utilising design knowledge	- Acceleration at tower and interface - SCADA / buoy data statistics - *Optional*: wave radar to improve estimate	- Need for FEM to represents real structure very well - Limitations in capturing fatigue at locations which are governed by local modes
Stochastic Kalman filter (KF)	Continuous fatigue damage estimation for all structure's hotspots	- Acceleration and strain at tower and interface - 20 Hz SCADA data (ideally)	- Distinguishing fatigue damages at several frequency bands - Building a representative FE model of the structure and estimating its dynamic properties - Properly modelling the process noise

The ML approach has been trained to estimate the Damage Equivalent Moments (DEMs) based on SCADA data and the DEMs calculated from strain measurements. Although, it seems not always to be possible to obtain a high accuracy or reliable results in e.g., extreme conditions with machine learning approaches, the prediction of the fatigue loads from SCADA data only still represents a powerful tool. For instance, it opens up the possibility to monitor the fatigue status of the turbines in the wind farm with respect of each other, relying only on the low-frequency SCADA data and the temporary measurement of strains used to train the model, see chapter 5.4.6.

The MDE algorithm is configured to estimate DEMs based on acceleration measurements and selected operational signals from SCADA and a wave buoy. For benchmarking, resulting DEMs from both approaches are compared with reference DEMs derived from strain measurements. The verification of the modal expansion method with direct measured strain, a slight overestimation of DEMs was observed. It should be noted, that even the reference DEMs derived from strain are not necessary the truth, as these measurements could be faulty. The biggest value of the modal expansion lies within the estimation of fatigue at all hotspots of the structure, which could not be verified with the available data.

The KF can be implemented for fatigue monitoring with relative success with the combined use of acceleration and strain data. Even when SCADA data is not available, low frequency thrust forces can be found from the strain data. However, past experiences have found the KF to yield worse results than the modal expansion and joint input-state estimation approaches. Particularly in the frequency domain, the low frequency responses are not fully recovered by the KF. In addition, relevant obstacles in the application of the KF are:

- the tuning of the algorithm when the system's inputs are unknown;
- the modelling of the process' noise (including the most commonly assumed premise that the noise is zero mean and white);
- the often-high computational cost, described in several references.

5.4.5. Low-cost monitoring for damage detection: models for diagnosis

Potential structural damage and environmental anomalies - like failure of braces, excessive scour, or corrosion-, call for the continuous monitoring of the asset health status, in order to ensure the structural integrity. Again, low-cost monitoring approaches were investigated that use data which is already required for operational purposes (SCADA) or fatigue monitoring (e.g., accelerations). As such extreme events rarely occur, feasibility studies rely on simulation studies.

To develop a damage detection scheme, for offshore wind jacket structures, and to check its feasibility, data-driven and model-based detection approaches are combined.

- Data-driven methods rely on a representative set of data for building up a digital twin of the structure's normal behaviour,
- Model-based simulations allow to simulate the effect of rare events for which data are usually unavailable.

In a first step of model development, sensitivity studies are to investigate the impact of anomalies and damages on structural dynamics. In [41], [51], [52] it was shown that the jacket brace member losses, the scour phenomena, and the variation of the corrosion profile mainly affect the 2nd tower bending modes of the WTG, while having only a little impact on the displacements, rotations and accelerations at the interface between transition piece and tower. The fatigue accumulation in the structural elements of the foundation might be affected by the anomalies; however, the impact varies for each element and event.

Accordingly, the indirect monitoring of anomalies through fatigue monitoring might not be successful, while the anomalies still pose a risk to the integrity of the WTG. Two approaches for low-cost detection of damage scenario are investigated in D4.4 [4]:

- By tracking the modal properties, based on the natural frequencies, the mode shapes, and the damping retrieved through the application of OMA on the measured accelerations of the tower and the transition piece. The monitoring of the modal properties showed good capabilities to not only detect anomalies, but also identify the type or location of the anomalies if combined with a database of anomaly scenarios and supported with clustering algorithms [53].

- By classifying the status of the WTG foundations and/or modelling its normal behaviour. These approaches are based on the detection of abnormal behaviour by deploying machine learning supervised and unsupervised algorithms on the 10-minute SCADA statistics. They are showed to be generally feasible in [52]; however, the uncertainties of the simulation model with respect to the real structure, can significantly reduce the reliability of the detection. Therefore, normal behaviour models are also investigated in [51], and they are shown to be more robust to uncertainties than classification approaches.

A comparison of the potential value, data requirements, and the challenges with implementing low-cost damage detection approaches are presented in Table 3. The approaches are ready to be operated as a monitoring concepts; hence, they can be applied to structures that have the necessary systems.

Table 3 - Comparison of low-cost damage detection approaches tested in the ROMEO project, adapted from D4.4 [4]

Approach	Potential value	Data requirements	Challenges
Fatigue monitoring approaches	- Detecting anomalies through deviating fatigue	Ranging from SCADA statistics to acceleration at tower and interface	- Anomalies might not clearly affect the fatigue consumption but are still critical for integrity
Modal properties tracking and clustering (ML)	- Detecting anomalies through deviating modal properties - Identification of anomaly source / localisation if supported with anomaly scenario database	Acceleration of tower and foundation (above the MWL)	- Variation in modal properties due to changing operational conditions - Need for FE model to represent real structure and anomaly scenarios very well
Low-resolution (statistics) data monitoring		SCADA statistics	- Need for an extensive amount of time domain simulations
***- Classification* (ML)**	- Detection of pre-trained anomaly scenarios		- Misclassification possible due to uncertainties applying a model that was trained on simulations to measurements
***- Normal behaviour* (ML)**	- Detection of anomalies, even previously unseen scenarios		- No identification of source of anomalies - Risk of misclassification if system deviates from the one used for training

5.4.6. Population based structural health monitoring

This section discusses a process of determining the level of knowledge sharing within a wind farm and the degree of transferability within the population form. This process is described in WP 4.5 and is about collating the relevant information, and the necessary processes required to determine the heterogeneity of the population form. The framework investigates the four elements that define the population; geometry, operation, topology, and material.

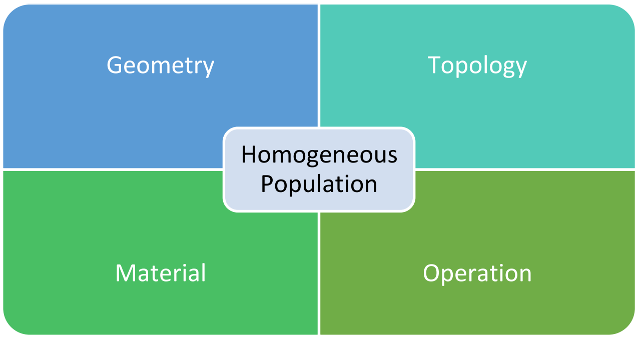

Figure 7 - Categories of heterogeneous populations within the PBSHM framework, in the centre, where all 4 categories are alike to a sufficient degree, a homogeneous population exists. Noting that all 4 attributes can influence each other separately to create independent heterogeneous populations.

The differences in wind turbine forms are a result of manufacturing tolerances and different installation sites, resulting in diverse design requirements. To contextualise the potential differences, there is one main area with creative freedom, that is with the geometry of the design, which varies based on the boundary conditions of the location. The final differences are the topology of the wind turbine, how it is operating in context to another WTs and where it is in comparison to the other wind turbines, and the material which is currently mostly uniform across designs. Figure 8 highlights how the four classes are intertwined, where one class may overlap with another forming a different class of heterogeneous populations.

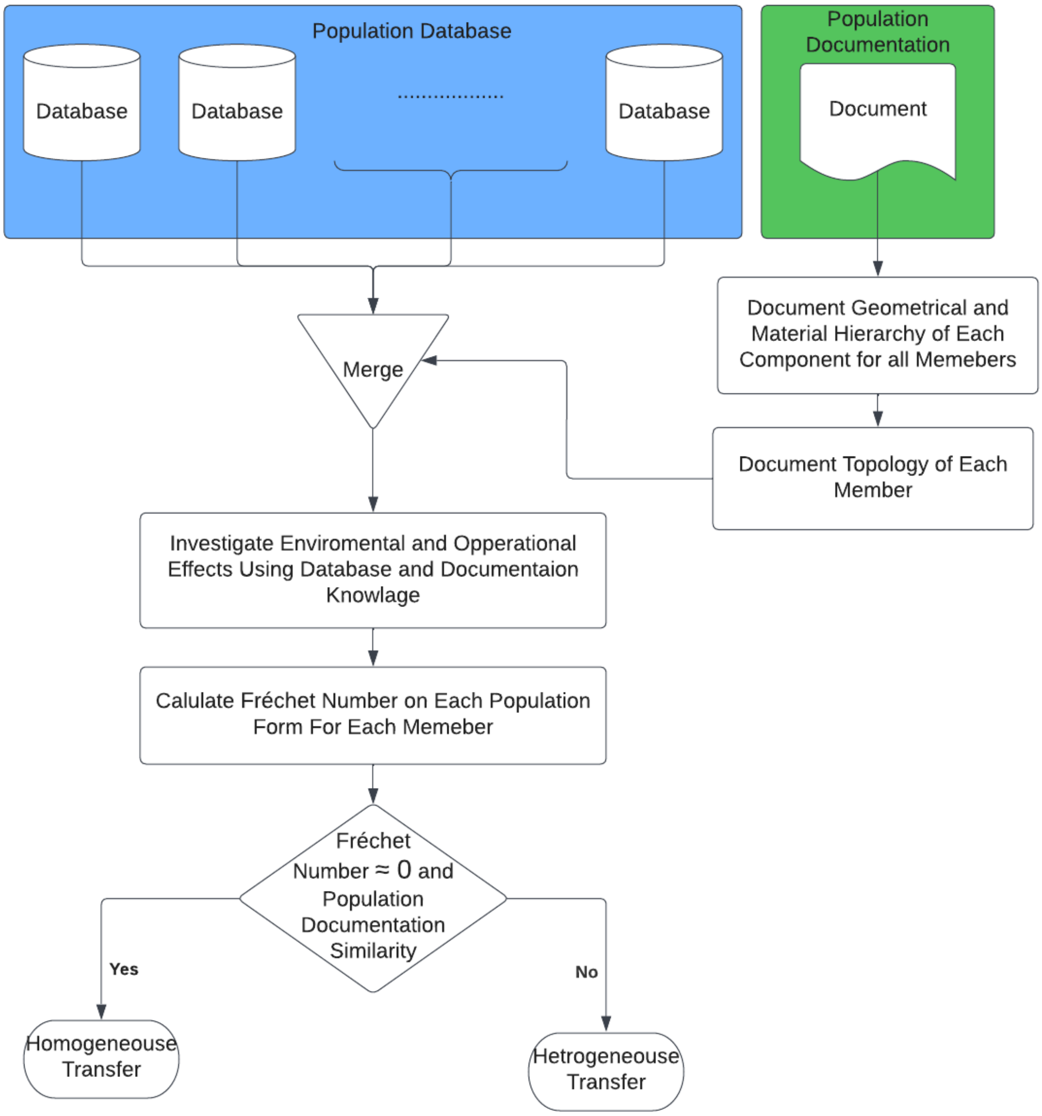

Figure 8 - Process of determining the degree of transferability of an operational wind farm. The blue section contains all the buckets of data, this could be SCADA data and/or CMS for individual wind turbines. The green segment is all the design documentation available on the individuals within the population.

Starting with the documentation of the individual wind turbines within the population form, it is impractical to cross examine the geometry of each of the wind turbines within the population using finite element analysis, hence we reduce the elements of the main components into a hierarchy of shapes. For example, we reduce a jacket connection pile component into a geometry of a beam of cylindrical shape and compare this to a monopile foundation which would have the same geometry and shape. This would indicate that there is a degree of transferable knowledge, which does not require an exhaustive finite element comparison.

To accompany the knowledge from the geometry, the material of the components is reduced into a hierarchy from the properties of the material such as Youngs modulus to material class. The detail and levels to the hierarchy are dependent on the documentation available. The first level would be material class, then material and then properties. The material properties determine whether it is possible to make inferences of damage assessment and classification with labels between two structures. Two materials of the same material class will experience similar failure modes and may exhibit the same material responses giving more confidence in the classification of damage. The greater the similarity between the materials, the more likely the assessment of the damage will be the same between the two structures.

Merging the knowledge gained from documentation with the dataset available is how to empirically determine the degree of transferability. Generating plots of the population form with respect to the operational context highlights the operator’s philosophy. If the operational modes are similar, then a general model may work. Conversely, this may require that the elements of curtailment may need to be dealt with separately to increase the accuracy of knowledge sharing. By discretising the population form of an operational wind turbine into modes this may reduce negative transfer.

The second element that synergises with the documentation is the comparison of environmental effects on the individual wind turbines within the population. Knowing the location of the individual wind turbines within the windfarm and generating plots of the features from the SCADA data and the form, will highlight how the dynamics vary throughout the wind farm. One important investigation of the environment is the turbulence intensity from different wind directions and how this relates to the similarity of the population form. Based on this, the degree of similarity may be visible. But to reinforce the judgment, the Fréchet number can be used to empirically determine the degree of similarity of the population form and accompanying this with the statistical measures of the underlying base distribution; hence, the mean, min, max and standard deviation can be used to highlight the similarity.

In the case where the finding from the documentation highlights that there is a strong degree of similarity within the population form, the Fréchet number is small, and the statistics are similar. This would indicate that the population is heterogeneous. This means that there is a high change of an accurate knowledge sharing within the population and conventional SHM techniques may be applicable. If not, domain adaptation methods will provide strong results. Conversely, if the Fréchet number is large, this indicates that the population is heterogeneous and conventional SHM techniques will fail. Domain adaptation techniques must be implemented, and the degree of accuracy will depend on the size of the dataset, the model implemented and the degree of heterogeneity.

5.5. Dashboards and visualisation

The reader is referred to D6.5 “Use-case demonstration into O&M Platform” [54], while this chapter summarizes the key functionalities of dashboards and visualisations supporting risk based monitoring strategies for offshore wind substructures.

Organisations need information that is timely and clearly presented to support effective decision making to drive increased/optimal performance. Dashboards and visualisations that satisfy this need by providing easy to understand, real time information on the key performance management parameters. Dashboards help organisations improve O&M by enhancing the way in which offshore structures are measured and reported, while at the same time providing access to more stakeholders who do not need to follow the details provided in raw data.

Dashboards integrate two key imperatives required by any evolving organisation: asset management and business intelligence. When presented together they form a synergy that pushes an organisation to greater levels of maturity. Together, these two disciplines provide a powerful new way to communicate strategy within an organisation and monitor and analyse organisational activity. This approach provides insights, explanations and shared understanding of critical organisational information which facilitates optimised performance. When properly designed and deployed, dashboards provide several benefits to executives, managers, and staff.

An O&M dashboard allows users to peel back layers of information to get to the root cause of a problem. Each layer provides additional details, views, and perspectives that enable users to understand a problem and identify the steps they must take to address it. These three layers are:

- Graphical abstracted data to monitor key performance metrics.
- Summarized dimensional data to analyse the root cause of problems.
- Detailed operational data that identifies what actions to take to resolve a problem.

5.5.1. RamView360

For Ramboll, the overall objective of WP 6.5 was to develop a proof of concept for a lightweight visualisation tool for effective communication between different WF stakeholders through advanced visualisation technologies like Virtual Reality (VR)/ Augmented Reality (AR) as a final goal for effective communication and cost optimisation. The O&M information management platform developed in ROMEO project is built as a web-based application which makes different types of data and information available to the user. The general goal of the platform is to provide relevant information for stakeholders in the O&M process, to support their work and facilitate decision making in this context.

Proof of concept of the DT model is developed in RamView360. The Wikinger WF is considered as a reference wind farm and “WTG–64” is used as a reference WTG in this demo. In Figure 9, the desk panel of RamView360 is shown.

This demo contents five different use-case examples:

- HSE Training on boat landing ladder
- Structure inspection of K-joint of Jacket structure
- Maintenance example of davit crane component
- Inspection example of J-tube cable connection
- Inspection example of scour protection

An example of the inspection of a Jacket structure is shown in Figure 10. In this figure, it is shown that the user can easily visualize the inspection information by clicking on the annotation point integrated into the RamView360 model. An annotation point is a point which is marked in the 3D model to link additional information, such as O&M issues, documents, graphs etc. This annotation point is marked in blue colour in Figure 11.

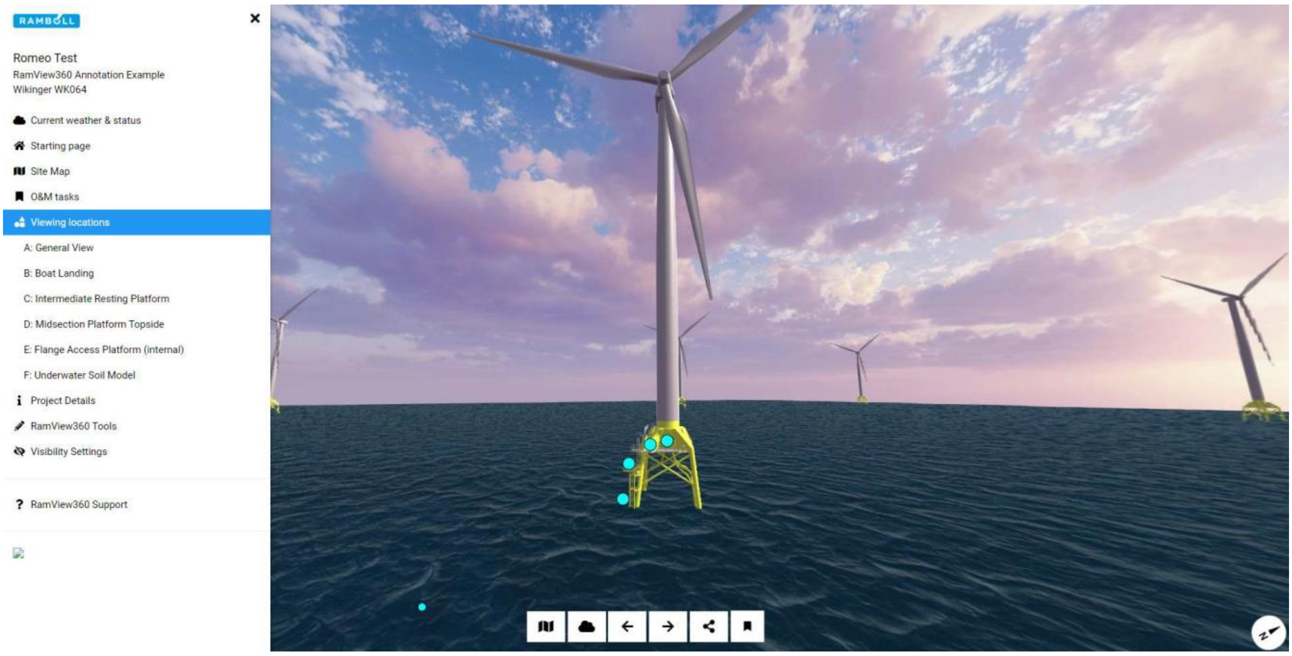

Figure 9 - RamView360 desk panel [54]

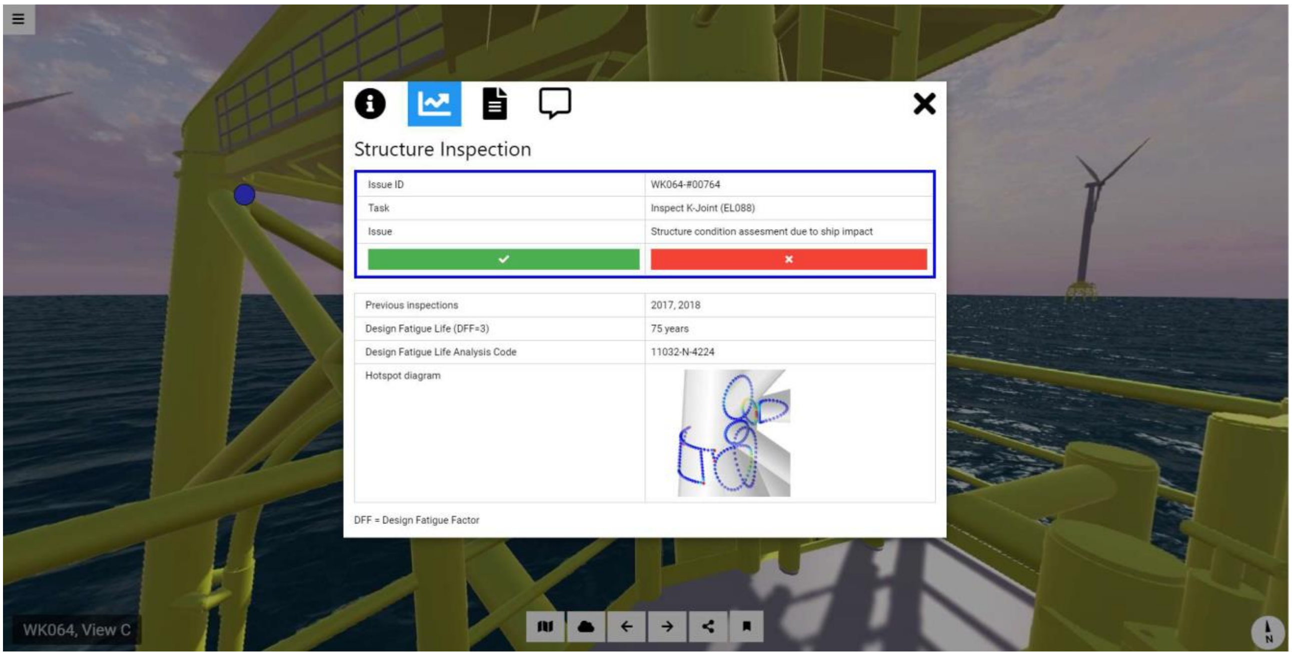

Figure 10 - Structure inspection example in RamView360 [54]

5.5.2. UE HARVEST

The IBM CloudTM and Uptime HARVEST interface developed in WP 6.2 is used to provide important input data to the HARVEST Operation and Maintenance Management Platform. The developed interface specifications and data sharing protocol is also meant to serve as a common mechanism for data exchange between the IBM Cloud and other third-party products like Domina G. The following use cases generate data requirements:

- Calculation of KPIs
- Monitoring and visualisation
- Event based Reasoning

The transmission of qualitative data requirements generated from use cases include:

- Time series data (10 min mean and real time)
- Turbine operational states (according to IEC or other specification)
- Turbine alarms and events
- Damage model outputs in standardized structure

		SCADA Alarm	Feeding fault : To low power inverter 10	62	65	04/03/2014 19:02:00	04/03/2014 19:56:00
		Planned Servi...	Scheduled maintenance	1	4	09/03/2014 00:00:00	13/03/2014 00:00:00
		Planned Servi...	Scheduled maintenance	1	4	09/03/2014 00:00:00	14/03/2014 00:00:00
		Planned Servi...	Scheduled maintenance	1	4	09/03/2014 00:00:00	14/03/2014 00:00:00
		Uptime HARV...	High oil temperature	800	2	16/02/2014 00:00:00	27/02/2014 00:00:00
		CMS Alarm	High oil particle count	700	1	02/03/2014 00:00:00	02/03/2014 03:00:00

Figure 11 - State & Event data

The dashboard in Figure 9 is intended to illustrate various functionalities in monitoring offshore structures. This data is utilised to provide the user with an overview of the current asset condition. Alarms can also be linked to issues and workorders, which will start the maintenance process.

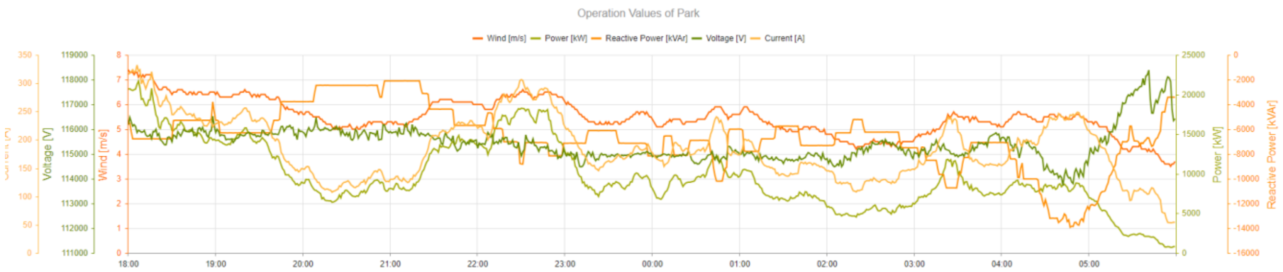

Figure 12 - Time series visualization

Time series data is used to visualise the current condition of assets and can also be used for further functionalities such as power curve analysis. Figure 12 shows the visualisation of substation performance according to certain KPIs.

5.6. Decision making

5.6.1. CAPEX - OPEX modelling

Decisions related to an investment in a more or a less extensive monitoring system rely on a cost benefit analysis evaluating the return of investment. Such an assessment should follow a life cycle approach considering initial costs as well as future savings. Monitoring will require an initial capital investment for the hardware acquisition and the development of a data collection, transmission, storage and processing framework.

Different strategies should also take into account the consideration of cash flows in the project, as offshore wind farms are capital front-loaded investments, and hence there is a pressure to reduce CAPEX. It is important however that decisions are well informed and follow a systematic financial impact assessment framework, relying on realistic KPIs. To this end, relevant KPIs for decision making include:

- NPV, considering costs of both scenarios (with and without extensive monitoring) at a given instance in time;
- ROI, allowing a comparison of alternative risk mitigation options;
- Availability performance and associated impact in profitability;
- Reduction in human visits on a wind farm.

It is relevant to reiterate that within the development process of monitoring strategies, certification requirements as well as OEM guidelines should be carefully considered and any deviation from the minimum requirements should be effectively discussed and agreed between involved stakeholders in order to ensure that liability remains at the relevant parties.

In addition to this, alternative scenarios should be considered, as monitoring could potentially enable decisions for service life extension, which can further increase the ROI of an initial investment.

5.6.2. Adoption of Design Safety Concept

A competent monitoring system will potentially prevent or reduce the requirement for on-site inspections, while by enabling condition-based maintenance it can reduce underutilisation of components' operational capacity as well as downtime due to unplanned failures. This can indeed decrease risks related to the asset as well as people involved in operation and maintenance. Reduction of visits is a key requirement that operators are aiming to achieve as new deployments are planned further offshore, yielding for higher costs and exposure to safety related risks. To this end, monitoring can contribute to a safe-by-design approach.

Apart from the impact on safety, the earlier prediction of failures that CMS can potentially achieve, subsequently allows for more effective planning during periods of more favourable weather conditions. This reduces the intervention times which, in effect, further reduces the human related risks.

5.6.3. Incident handling

Following the development of a monitoring strategy, it is important to develop a logging protocol for incidents which force the system to deviate from its design intent. Such events could include extreme environmental conditions and cascade events which can have a detrimental impact on the residual service life of the component/system. Consequences of such risks should also be quantified and included in the cost/benefit comparison between different strategies.

6. Conclusions

The level of a CMS approach adopted for a project is dictated by the level of precision required, the appetite for risk mitigation and subsequently the resulting costs, which is driven by two aspects. The first is the monitoring campaign and the extent that an operator wishes to install sensors on the offshore structure and plan maintenance. The second is the class of inspection service on the monitoring data and the expertise applied. WP4.4 demonstrated a value driven approach that seeks to provide an effective balance, shaking up the hierarchy by conducting an effective approach based on an FMECA-based approach, as executed in WP1.2 and indirect sensing technologies, reducing the cost but providing sufficient input for O&M related decisions.

An overview of the ISO standards for digital solutions related to CMS was presented, indicating that the existing codes and standards cover topics related to mainly inspection and to a less extend CMS of offshore structures. The application of CMS is considered mature from a scientific perspective however, there is limited information, guidance, or frameworks existing in codes and standards. Information in relation to the process of inspection of offshore structures is well documented with codes, standards, and recommended practices. To conclude, further standards and recommended practices that consider and enables the roll out of CMS in offshore structures would benefit best practice in the offshore wind industry.

A guideline to design a low-cost monitoring campaign is presented as a summary of findings from the project, covering risk-based approaches, risk strategy and monitoring objectives, the requirements for low-cost maintenance, modelling and analysis, and visualisation of O&M digital enabled asset management approaches. Organisations need information that is timely, clearly presented, and which support effective decision making to drive better performance. Dashboards satisfy this need by integrating performance management and business intelligence to provide a powerful new way to communicate strategy within an organisation and monitor and analyse organizational activity.

Decisions related to the development of monitoring strategies should consider cost effectiveness of a solution. Such assessments should account for all service life costs and potential benefits in a comparison with a traditional inspection-based approach. There is no doubt that offshore wind farms will follow the paradigm of fully developed technologies such as thermal power plants, and it is expected that further research and demonstration will enable further adoption from operators in future wind farms, which, considering the more complex nature (i.e., in floating wind farms), will bring additional benefits towards an effective and profitable operation.

List of references

[1] A. Kolios, U. Smolka, C. Ben Ramdane, L. Tremps, and R. Jones, “Monitoring technology and specification of the support structure monitoring problem for offshore wind farms,” *ROMEO deliverable D4.1*.

[2] S. Siedler *et al.*, “Report on design validation of WTG jacket and substation jacket based on FE updating,” *ROMEO deliverable D4.2*, 2019.

[3] J. Tautz-Weinert *et al.*, “Report on lifetime extension potential and remaining uncertainty,” *ROMEO deliverable D4.3*.

[4] C. Wendelborn *et al.*, “Report on the implementation of low-cost monitoring algorithms,” *ROMEO deliverable D4.4*, 2020.

[5] S. S. Siedler, I. M. Black, C. Wendelborn, M. W. Häckell, J. Tautz-Weinert, and D. Cevasco, “Update of report D4.3 considering long term findings,” *ROMEO deliverable D4.5*, 2022.

[6] C.R. Farrar and K. Worden, *Structural Health Monitoring: A Machine Learning Perspective*, Wiley. 2012.

[7] J. Weinert, U. Smolka, B. Schümann, and P. W. Cheng, “Detecting Critical Scour Developments at Monopile Foundations Under Operating Conditions,” *Proceedings of the European Wind Energy Association Annual Event, EWEA 2015*, pp. 135–139, 2015.

[8] L. J. Prendergast and K. Gavin, “A review of bridge scour monitoring techniques,” *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 6, no. 2, pp. 138–149, Apr. 2014.

[9] A. Kolios, “ROMEO project, D4.1 Monitoring technology and specification of the support structure monitoring problem for offshore wind farms,” 2018.

[10] DNV GL AS, “DNVGL-ST-0126 Support structures for wind turbines,” 2016.

[11] A. Skafte, U. T. Tygesen, and R. Brincker, “Expansion of Mode Shapes and Responses on the Offshore Platform Valdemar,” 2014, pp. 35–41.

[12] J. S. and U. T. T. E. Dascotte, “Continuous Stress Monitoring of Large Structures,” in *International Operational Modal Analysis Conference (IOMAC)*, 2013.

[13] M. N. Scheu, L. Tremps, U. Smolka, A. Kolios, and F. Brennan, “A systematic Failure Mode Effects and Criticality Analysis for offshore wind turbine systems towards integrated condition based maintenance strategies,” *Ocean Engineering*, vol. 176, 2019.

[14] M. Arenas, “Analyse technico-économique de l’utilisation des nouvelles instrumentations pour la maintenance prévisionnelle d’une éolienne.,” 2016.

[15] C. C. Ciang, J.-R. Lee, and H.-J. Bang, “Structural health monitoring for a wind turbine system: a review of damage detection methods,” *Measurement Science and Technology*, vol. 19, no. 12, p. 122001, 2008.

[16] F. K. Coronado D., “Condition monitoring of wind turbines: state of the art, user experience and recommendations.,” 2016.

[17] M. Martinez-Luengo, A. Kolios, and L. Wang, “Structural health monitoring of offshore wind turbines: A review through the Statistical Pattern Recognition Paradigm,” *Renewable and Sustainable Energy Reviews*, vol. 64, 2016.

[18] M. El-Kafafy, C. Devriendt, W. Weijtjens, G. De Sitter, and P. Guillaume, “Evaluating Different Automated Operational Modal Analysis Techniques for the Continuous Monitoring of Offshore Wind Turbines,” 2014, pp. 313–329.

[19] International Standard Organisation, “Petroleum and natural gas industries — Specific requirements for offshore structures Part 3: Topsides structure,” *British Standard Publication*. BSI Standards Publication, London, UK, 2013.

[20] ISO, “ISO 19901-1:2015 - Petroleum and natural gas industries - General requirements for offshore structures,” 2019.

[21] ISO, “ISO 19901-4:2016 - Petroleum and natural gas industries - Specific requirements for offshore structures - Part 4: Geotechnical and foundation design considerations,” 2016.

[22] ISO, “ISO 19901-9:2019 - Petroleum and natural gas industries – Specific requirements for offshore structures – Part 9: Structural integrity management,” 2019.

[23] ISO, “ISO 19902:2020 - Petroleum and natural gas industries — Fixed steel offshore structures,” 2020.

[24] ISO, “ISO 19903:2019 - Petroleum and natural gas industries — Concrete offshore structures,” 2019.

[25] ISO, “ISO 19904 - 1:2019 - Petroleum and natural gas industries — Floating offshore structures — Part 1: Ship shaped, semi-submersible, spar and shallow-draught cylindrical structures,” 2019.

[26] ISO, “ISO 19905-1:2016 - Petroleum and natural gas industries - Site-specific assessment of mobile offshore units - Part 1: Jack-ups,” 2016.

[27] Ramboll - Petroleum Safety Authority Norway, “Report no REN2021N00099-RAM-RP-00004 - The use of digital solutions and structural health monitoring for integrity management of offshore structures - Industry study and guidance report,” 2022.

[28] DNV, “DNV-RP-0497 - Data quality assessment framework,” 2021.

[29] DNV, “DNV-RP-0510 - Framework for assurance of data-driven algorithms and models,” 2021.

[30] DNV, “DNV-RP-A204 - Qualification and assurance of digital twins,” 2021.

[31] DNV, “DNV-RP-0317 - Assurance of sensor systems,” 2021.

[32] DNV, “DNV-RP-0513 - Assurance of simulation models,” 2021.

[33] ISO, "ISO8000-8:2015 - Data quality - Part 8: Information and data quality: Concepts and measuring," 2015.

[34] ISO, "ISO/IEC 27000:2018 - Information technology - Security techniques - Information security management systems - Overview and vocabulary," 2020.

[35] M. L. Wymore, J. E. Van Dam, H. Ceylan, and D. Qiao, "A survey of health monitoring systems for wind turbines," *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 976–990, Dec. 2015.

[36] M. Martinez-luengo, M. Shafiee, and A. Kolios, "Data management for structural integrity assessment of offshore wind turbine support structures : data cleansing and missing data imputation," *Ocean Engineering*, vol. 173, no. November 2018, pp. 867–883, 2019.

[37] M. Martinez-Luengo and M. Shafiee, "Guidelines and cost-benefit analysis of the Structural Health Monitoring implementation in offshore wind turbine support structures," *Energies*, vol. 12, no. 6, pp. 1–26, 2019.

[38] J. C. Lopez and A. Kolios, "Risk-based maintenance strategy selection for wind turbine composite blades," *Energy Reports*, vol. 8, pp. 5541–5561, Nov. 2022.

[39] D. Augustyn, U. Smolka, U. T. Tygesen, M. D. Ulriksen, and J. D. Sørensen, "Data-driven model updating of an offshore wind jacket substructure," *Applied Ocean Research*, vol. 104, no. May, p. 102366, 2020.

[40] D. Cevasco, S. Koukoura, and A. J. Kolios, "Reliability, availability, maintainability data review for the identification of trends in offshore wind energy applications," *Renewable and Sustainable Energy Reviews*, vol. 136, 2021.

[41] M. Richmond, U. Smolka, and A. Kolios, "Feasibility for Damage Identification in Offshore Wind Jacket Structures through Monitoring of Global Structural Dynamics," *Energies*, vol. 13, no. 21, p. 5791, 2020.

[42] M. Richmond, S. Siedler, M. Häckell, U. Smolka, and A. Kolios, "Impact of accelerometer placement on modal extraction of offshore wind structures," in *Ocean Marine and Arctic Engineering (OMAE)*, 2020.

[43] M. N. Scheu, L. Tremps, U. Smolka, A. Kolios, and F. Brennan, "A systematic Failure Mode Effects and Criticality Analysis for offshore wind turbine systems towards integrated condition based maintenance strategies," *Ocean Engineering*, vol. 176, no. October 2018, pp. 118–133, 2019.

[44] L. Ziegler, N. Cosack, A. Kolios, and M. Muskulus, "Structural monitoring for lifetime extension of offshore wind monopiles: Verification of strain-based load extrapolation algorithm," *Marine Structures*, vol. 66, no. March, pp. 154–163, 2019.

[45] U. T. Tygesen, M. S. Jepsen, J. Vestermark, N. Dollerup, and A. Pedersen, "The true digital

twin concept for fatigue re-assessment of marine structures," *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE*, vol. 1, no. June, 2018.

[46] U. T. Tygesen, K. Worden, T. Rogers, G. Manson, and E. J. Cross, "State-of-the-Art and Future Directions for Predictive Modelling of Offshore Structure Dynamics Using Machine Learning," in *Pakzad S. (eds) Dynamics of Civil Structures, Volume 2. Conference Proceedings of the Society for Experimental Mechanics Series*, Springer, Cham, 2019.

[47] D. Augustyn, "Towards offshore wind digital twins . Application to jacket substructures . Towards offshore wind digital twins Application to jacket substructures," Faculty of Engineering and Science, Aalborg University, 2021.

[48] Newsroom, "Ramboll's True Digital Twin technology has the potential to increase lifetime of offshore wind farms," *January 11, 2021*. [Online]. Available: https://ceenergynews.com/innovation/rambolls-true-digital-twin-technology-has-the-potential-to-increase-lifetime-of-offshore-wind-farms/. [Accessed: 25-May-2022].

[49] D. J. Augustyn, R. Pedersen, M. D. Ulriksen, and J. D. Sørensen, "Feasibility of modal expansion for virtual sensing in offshore wind jacket substructures," *submitted to Marine Structures*, 2020.

[50] Ramboll, "LACFlex aero-servo-elestic tool v1.9.2.0," 2019.

[51] D. Cevasco, J. Tautz-Weinert, A. J. Kolios, and U. Smolka, "Applicability of machine learning approaches for structural damage detection of offshore wind jacket structures based on low resolution data," in *IOP Conference Series, to be presented at The Science of Making Torque from Wind (TORQUE 2020)*, 2020.

[52] D. Cevasco, J. Tautz-Weinert, U. Smolka, and A. Kolios, "Feasibility of machine learning algorithms for classifying damaged offshore jacket structures using SCADA data," *Journal of Physics: Conference Series*, vol. 1669, p. 012021, Oct. 2020.

[53] D. Cevasco, J. Tautz-Weinert, M. Richmond, A. Sobey, and A. J. Kolios, "A Damage Detection and Location Scheme for Offshore Wind Turbine Jacket Structures Based on Global Modal Properties," *ASCE-ASME J Risk and Uncert in Engrg Sys Part B Mech Engrg*, vol. 8, no. 2, 2022.

[54] M. Gräfe and D. Gambhava, "Use-case demonstration into O&M Platform," *ROMEO deliverable D6.5*, 2020.