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Deliverable Report

D4.1 Monitoring technology and specification of the support structure monitoring problem for offshore wind farms

745625

ROMEO

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List of abbreviations

ADCP: Acoustic Doppler Current Profilers
AE: Acoustic Emission
CM: Condition Monitoring
CMS: Condition Monitoring System
CP: Cathodic Protection
ER: Electrical Resistance
EOC: Environmental and Operational Conditions
FBG: Fiber Bragg Grating
FEA: Finite Element Analysis
FEM: Finite Element Model/Modelling
FMECA: Failure Modes, Effects and Criticality Analysis
GPR: Ground Penetrating Radar
ICCP: Impressed Current Cathodic Protection
HS: Health and Safety
LCC: Life Cycle Cost
LVDT: Linear Variable Differential Transducer
MIC: Microbiologically Influenced Corrosion
MTTF: Mean Time to Failure
MP: Monopile
NDE: Non-Destructive Evaluation
NFA: Natural Frequency Analysis
NN: Neural Network
O&M: Operation and Maintenance
OWF: Offshore Wind Farm
OWT: Offshore Wind Turbine
OMA: Operational Modal Analysis
ROV: Remotely Operated Vehicle
SHM: Structural Health Monitoring
SHMS: Structural Health Monitoring Systems
SMC: Sliding Magnetic Collar
SPC: Statistical Process Control
SRB: Sulphate Reducing Bacteria
TDR: Time Domain Reflectometry
TP: Transition Piece
TRL: Technology Readiness Level
UT: Ultrasonic
VBDD: Vibration Based Damage Detection
WDAS: Wireless Data Acquisition System
WSN: Wireless Sensor Network

1. Executive Summary

This report is the first deliverable of work package 4 (WP4) which aims to present a review of monitoring technologies and to specify the support structure monitoring problem for offshore wind farms. After a review of direct measurement systems, the indirect measurement systems are presented following the four stages of the statistical pattern recognition paradigm (operational evaluation; data acquisition, normalization and cleansing; feature extraction and information condensation; statistical model development). A summary of current practice based on partners' operational experience is included. Selection of the most appropriate monitoring technologies is linked to the physics of the failure modes identified as part of the FMECA (Failure mode, effects and criticality analysis) exercise of WP1, and relevant criteria and key performance indicators are established.

2. Introduction

As offshore wind energy is maturing as a technology, reducing uncertainties during the operation and increasing availability of farms, decreasing unscheduled maintenance and eliminating unexpected catastrophic failures, are pertinent prerequisites towards reducing service life costs and increasing profitability. Structural Health Monitoring Systems (SHMS) can contribute to this aim through offering more systematic operational management approaches. Structural Health Monitoring (SHM) represents the procedure of implementing a damage detection strategy for engineering infrastructures related to aerospace, civil and mechanical engineering, with damage referring to the variations in material and/or geometric properties of these systems.

Common structural damage roots are: moisture absorption, fatigue, wind gusts, thermal stress, corrosion, fire and lightning strikes. In traditional SHMS, there are two critical aspects that influence SHMS development: the sensing technology (and the associated signal analysis), and the interpretation algorithm. Damage identification can be performed through five approaches [1]:

- Structural Health Monitoring (SHM);
- Condition Monitoring (CM);
- Non-Destructive Evaluation (NDE);
- Statistical Process Control (SPC);
- Damage Prognosis.

In an article from 2016, Martinez-Luengo *et al.* [2] state that first generation wind farms (3 to 12%) were equipped with sensors after deployment, and the most used technologies were strain, fatigue and modal properties. However, in 2016, it appeared necessary to develop new methodologies to collect, process and analyse data collected by CM and SHMS. Indeed, monitoring appears as the only solution to have a more realistic understanding of the physics behind the behaviour of structures under real conditions. Compiling the information provided by Martinez-Luengo *et al.*[2], El-Kafafy *et al.* [3] and Ciang *et al.* [4], the expected benefits and outcomes of monitoring are as follows:

- Avoidance of premature breakdown by preventing catastrophic failure and secondary damages
- Reduction of maintenance cost
- Supervision at remote sites and remote diagnosis
- Improvement of capacity factor: with early warning of impending failures, in combination with well-known Mean Time to Failure (MTTF), repair action can be taken during low wind season and hence will not affect the capacity factor
- Support for further development of turbines as the data gathered can be used to improve the design of the next turbines
- Contribution to regulation and standardization.

Hence, in summary, monitoring would help optimize Operation and Maintenance (O&M), assess the lifetime of offshore wind turbine structures during their operation and provide guidelines to improve the design of future turbines, and possibly contribute to regulation and standardization.

As for costs related to monitoring, Nilsson and Bertling [5] conducted a Life Cycle Cost (LCC) analysis of a Condition Monitoring System (CMS) installed on a single wind turbine onshore and on an offshore wind farm, comparing the effect of implementing different maintenance strategies. In that study, the same monitoring system was installed on the turbines (one offshore and thirty onshore). This system, developed by Vestas (VCMS), monitors failure modes related to gear wear, main bearing and main shaft, generator and tower. The same study also showed that availability would not have to be increased by more than 0.43% to reduce the cost of production loss to cover the cost of a CMS. Since a CMS enables planning maintenance more efficiently, CMS costs can be covered quite easily, especially on offshore wind farms (OWFs).

The present report is associated to *WP4 – Structural condition monitoring*, and more specifically to *Subtask 4.1.2. Structural condition monitoring requirements and selection criteria*. It is aimed to be used for the preparation of deliverable D4.1. Subtask 4.1.2 is described as follows:

The primary objective of the structural condition monitoring is to supply measurements that facilitate the predictive maintenance strategy and extension of the support structure lifetime. Based on the physics of the failure modes subjected to monitoring (result of WP1) and EDF's research on damage modelling, Ramboll and EDF identify the physical values that show changes over time due to occurrence of the specific failure. Ramboll establishes the requirements and selection criteria for hardware solutions in terms of suitability for the monitoring objectives from a design point of view. EDF and Iberdrola each provide a sensor technology review based on operational experience, considering the applicability to the given environment [6].

Approach:

In order to achieve this task, the adopted approach consisted of:

- Reviewing FMECA sheets and extracting all relevant failure modes;
- Reviewing the failure mechanisms from root cause to failure mode;
- Identifying more promising mechanisms to be monitored and associated monitoring solutions. Those mechanisms:
    - Show time behaviour to allow for enough time for maintenance mobilization/failure prevention or mitigation.
    - Have a monitoring solution with an adequate maturity level, thought to enable either reduced inspection frequency, reduced inspection extent, mitigation of unplanned maintenance, update of structural capacity, avoidance of secondary damages.
- Performing a review of monitoring solutions related to these more promising mechanisms, taking into account operational experience and a bibliographic study.
- Providing a list of general requirements for a reliable and efficient monitoring system.

This report links activities planned for WP4 with work already performed as part of WP1 and sets the specification for the subsequent tasks of this present work package (Tasks 4.3-4.5). The following topics will be covered:

- Specification of the support structure monitoring problem for OWFs is established.
- Review of available direct and indirect monitoring systems is presented with the latter following the four stages of the statistical pattern recognition paradigm (operational

evaluation; data acquisition, normalization and cleansing; feature extraction and information condensation; statistical model development).

- Selection of the most appropriate monitoring technologies is linked to the physics of the failure modes identified as part of the FMECA exercise of WP1, and relevant criteria and key performance indicators are also established.
- Sensor technology review from operational experience.

3. Specification of the Structural Monitoring Problem

3.1. Definition of Monitoring

The differentiation between monitoring and inspection is not clearly defined when referring to the offshore (wind) sector and both terms are often used interchangeably. “monitor” (Lat.) is correctly translated as “to warn” or “to remind”, inspection (“specto” Lat.) means “to observe” or “to watch”. Several measurement applications are not obviously allocated to one of these terms, such as data which is continuously measured/monitored, but human offshore work is needed to collect the data at the offshore wind turbine, e.g. on a hard drive.

To avoid misunderstandings a terminology of **monitoring** as an **automated inspection,** being a subset of **inspection** (c.f. Figure 1), is defined. In this understanding, a monitoring system collects and stores data automatically and continuously in a predefined time-step (usually short-term) or if a predefined threshold value is reached. It continuously measures conditions without the need for offshore human operation. Usually, the monitored data is transferred directly to onshore servers for storage and further usage, therefore reference to “online measurements” is made.

In that terminology **inspection** is when **human action** (offshore or onshore) is required and executed. Inspection can be performed on-site with inspection equipment, but also onshore by, e.g., evaluating (monitoring) data on a screen. The latter is refered to as “inspection of monitoring data”. If monitoring data are only collected and stored but no further human action is conducted the terminology “monitoring” is used.

In both cases the frequency of data collection is not the indicator for differentiation. However, monitoring data is usually measured continuously or in short-term steps (minutes, seconds), whereas inspections can be performed after longer time periods (weeks, months, years) or unscheduled on demand.

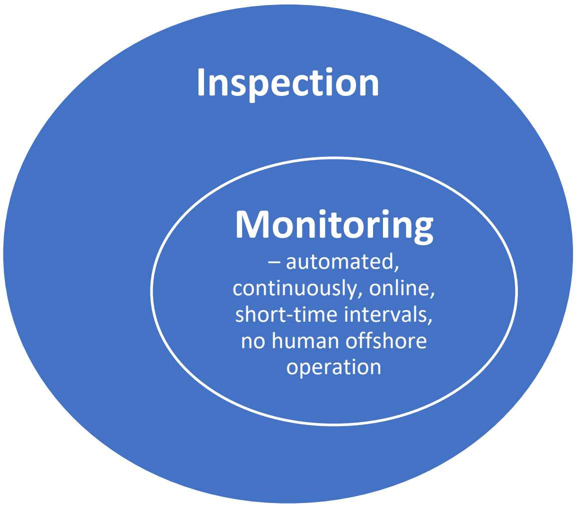

Figure 1: Classification of monitoring as a subset of inspection

The following symbols are introduced for monitoring and inspection:

Figure 2: Icon for Monitoring (left) and Inspection (right)

3.2. Approach

It is a challenge to find the optimal combination of required sensors and physical equations to assess the structural integrity balancing costs and risks. A first suggestion is to structure the existing monitoring systems in terms of complexity and users.

Monitoring systems can be applied on different complexity levels. For lowest complexity only one sensor and a simple physical equation, e.g. a lookup table that translates resistance to temperature, are required. For high complexity monitoring systems, a number of sensors need to be combined using system knowledge in the format of physical equations, e.g. when monitoring the remaining useful lifetime of a particular hot spot. The goal of a monitoring system is to deliver an indicator signal that can inform the user about changes in the process, function or system in general. It is suggested to look at the failure paths from root cause to failure modes and assess which physical quantities can be measured and could be fed into a monitoring system. Figure 4 provides an example of different failure paths leading to crack initiation and propagation that will eventually result in downtime if not treated. A monitoring system could work on different levels, e.g., delivering only information on the corrosive environment such as via pH-value monitoring or e.g., monitoring only the tilting of the system.

Figure 3 shows a hierarchy of users and experts that are typically involved in interpreting the monitoring results.

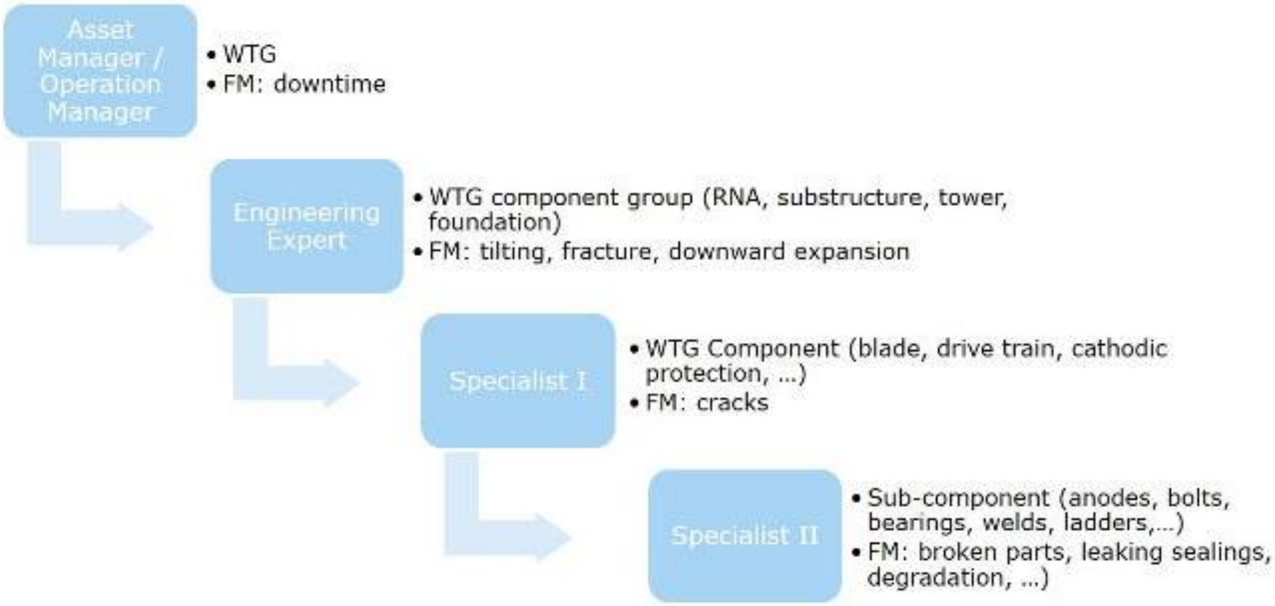

Figure 3: System boundaries/Levels of impact of a failure mode

On the top of the pyramid the **Asset Manager/Operation Manager (Level A)** takes the responsibility of turbine downtimes, which are mostly related to cost and safety consequences.

In the level below, **Engineering Experts (Level B)** sustain failure modes in wind turbine component groups (RNA, tower, substructure, foundation), such as tilting, downward expansion and fractures.

Specialists I (Level C) are responsible for WTG (wind turbine generators) components such as blades, drive train, cathodic protection (CP), grout or scour protection. Crack initiation and propagation are the main failures, occurring, e.g., from broken grout connections, loosening bolts, loss of scour protection, or corrosion.

One level below, **Specialists II (Level D)** look at failures in subcomponents (e.g. bolts, anodes, coating, welds, ladders, …). Failures in the subcomponents could be, e.g., the complete consumption of anodes, defects in grout sealing, anode interference, but also changes of pH value or oxygen content. The levels of Specialists I and II are sometimes interlinked and blended.

The pyramid of failure mechanism could be built further down to include micro changes in atomic structure which might be analysed by a Chemist or Physicist. However, for the monitoring application in offshore wind the analysis of subcomponents at Level D should be detailed enough, but could always be extended to include more detail.

A failure occurs due to a root cause (e.g. icing, missing corrosion protection, boat collision, …) and usually runs from lower levels upwards (to downtime or safety risks). Monitoring systems could help to identify failures in an early stage (low level) and start corrective measures before serious failures and inherent safety consequences can develop. If monitoring systems are implemented in a higher level, the failure mode might be detected, but the failure cause might not be obviously clear. The reason is that one failure mode in an upper level can result from different root causes and can run through several failure mechanisms. It could become a challenge to act at the right position and take corrective measures. Therefore, monitoring in lower levels might be preferable since they could allow for an early identification and thus avoidance of crucial failures and consequences in upper levels, such as downtimes or safety risks. The deeper the level where monitoring is planned, the more subcomponents need to be monitored, including more monitoring systems and equipment. Data from monitoring could be further used to feed a so-called 'Digital Twin'[1] to drastically reduce inspection and maintenance action.

Cost and risk analyses are recommended for evaluation of the depth level of the monitoring system implementation (including time and costs for data storage and evaluation) against the consequences of possible downtimes resulting from unidentified root causes.

[1] A digital twin is a virtual model of a process, product or service.

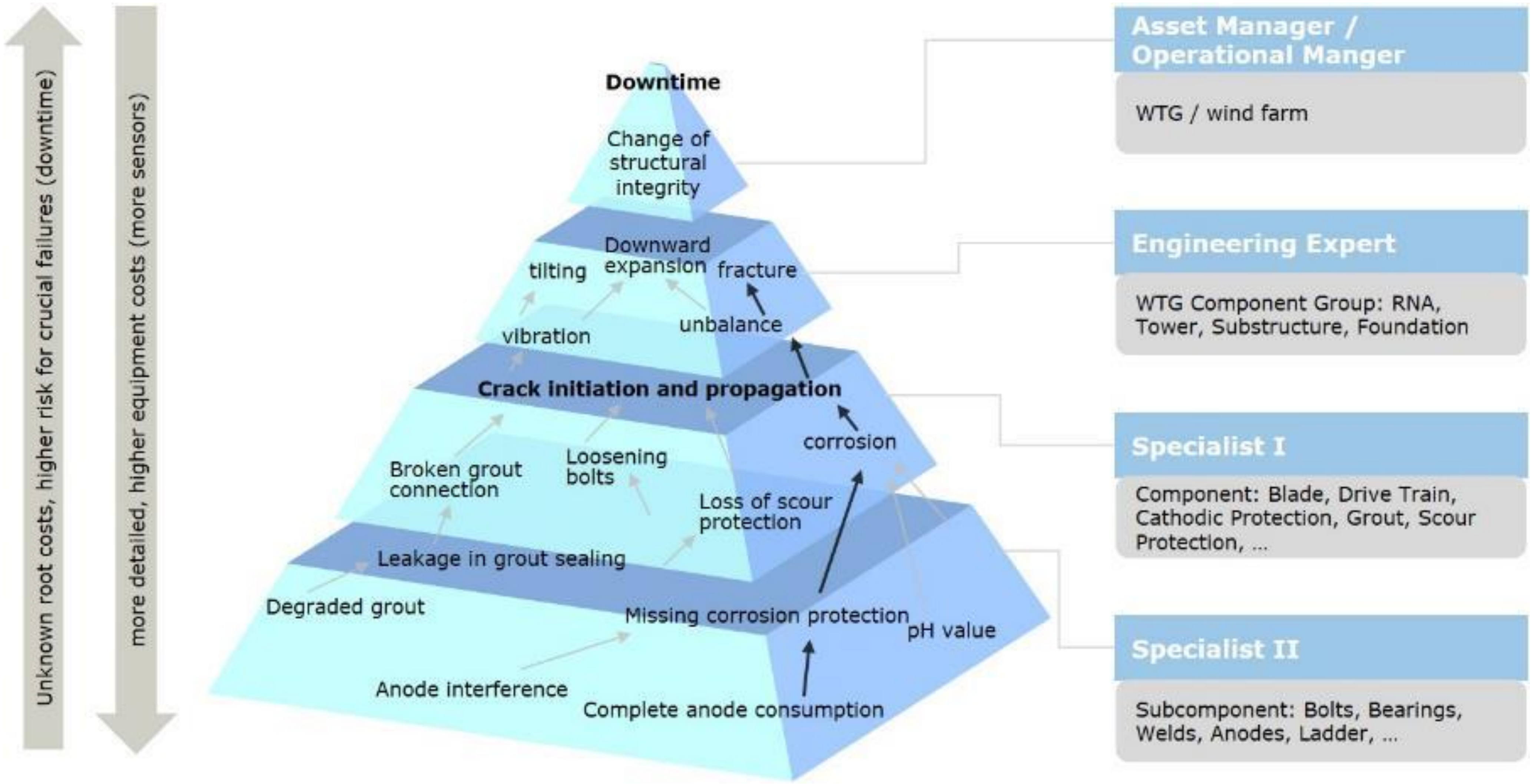

Figure 4: Visualisation of monitoring solutions applied at different levels

4. Review of Offshore Wind Turbine Support Structures Monitoring Systems

4.1. Review of Direct Measurement Technologies

DNVGL-ST-0126 standard [7], provides a list of issues and items that should be covered by *inspection* in steel structures, on both onshore and offshore assets. Such a list gives a good overview of what should be monitored and monitoring guidelines can be based on that. The non-exhaustive list is as follows:

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

Considering FMECAs performed at the beginning of the ROMEO project and the outcomes of the discussion aforementioned, direct measurements of crack propagation and strain, corrosion and bolt tensioning are under consideration in this section. The areas of the support structure in which crack propagation and strain should be monitored are mainly steel parts and grout connection, as addressed later in this document.

Regarding measurement systems in general, according to [8,9] (and also mentioned in other articles), the most common sensors installed on offshore support structures are:

- strain gauges
- displacement sensors
- accelerometers
- optical fibre sensors
- inclinometers
- load cells
- temperature sensors
- wind speed and direction sensors
- wave height sensors.

4.1.1. Crack propagation and strain monitoring

The main materials in which crack propagation can occur in support structures are the following:

- Steel
  - Within the steel, in a continuous medium

- In welds
- Grout
    - The grout in the transition piece (TP) carries the shear and bending loads between the tower and the pile [10]. The grout is a brittle material [11]. Furthermore, as explained by Jia in [12], no adhesion between the grout and steel surfaces can be achieved during grout casting. Hence, the fixation of the pile and TP by means of grout is obtained by the static friction due to the surface roughness of the contact areas. Grout connection is considered as a critical area since major problems occurred in 2010 when the grout between the pile foundations and the tower's TP was failing, causing the tower to slip downward by more than 25mm until caught by supporting brackets used during construction [13,14]. These brackets are not designed for this permanent load path. These problems have led to modification of the design of the grouted connection to a cone shape and with shear keys. With regards to the grouted connection at jackets, the issue mainly lies on the confinement of this connection and the total lack of access. Also, how cyclic loading can ultimately affect the upper section of the connection and lead to early grout degradation. At present there are no suitable inspection techniques. Should inspection be required the only way forward at present is coring, which is totally destructive of the material.
    - DNVGL-ST-0126 [7] provides guidance as regards grout connection inspection: the grout seal, ensuring confinement, should be inspected for cracks and loss of grout at the top and bottom of the connections, especially for connections where bending moments are transferred through the grout. For conical-shaped connections, the standard states that it is important to check whether the amount of settlement is as expected. Such inspection guidance should also be used as a guidance for monitoring, especially to locate critical areas.

4.1.1.1. Strain monitoring

The most used strain monitoring systems (on-site) are strain gauges and LVDTs (Linear Variable Differential Transducers). The latter measure displacements with high reliability and accuracy, they are however expensive sensors [2]. Wymore *et al*. [13] and Faulkner *et al*. [15] mention Strainstall monitoring systems installed on wind turbines and consisting of strain gauges, displacement sensors, and accelerometers installed:

- between the MP and TP to measure displacement and strain,
- on the main tower to measure bending, torque and axial load.

Hence, strains and stresses at critical areas are monitored, and damage and fatigue life can be calculated and estimated, respectively. Besides, Coronado and Fischer [8] also mentioned strain sensors and horizontal displacement transducers installed at grouted joints (that are part of the critical areas). LVDT sensors and strain gauges are described in the following paragraphs.

4.1.1.1.1. LVDT sensors

LVDT sensors are known for being reliable and accurate displacement sensors, and used in many applications. On-site, they are used to monitor civil engineering structures. Currie *et al.* [16] state that LVDTs are robust and immune to the large magnetic fields surrounding the high voltage cables coiled in the foundation, which is a significant advantage for wind turbines.

4.1.1.1.2. Electrical and optical strain gauges

Both electrical and optical strain gauges are used in the industry for strain monitoring. Electrical strain gauges are generally cheap and easy to install. Such sensors have been widely used in the industry for a long time.
Optical strain gauges rely on the use of optic fibers[2]. Two different kinds of strain measurements based on optic fibres can be used:

- Distributed strain *and* temperature measurement (mainly Brillouin method)
- Fibre Bragg Grating (FBG), commonly used to measure axial strain and temperature [17].

For details of physical principles on which the sensors are based, the reader can refer to [17] by Ramakrishnan *et al.* Other sensors using optic fibres are described in this article but are not used for offshore structure monitoring (to the authors' knowledge). Besides, it is important to note that FBG sensors are used in combination with temperature compensation, which is necessary due to the different positions of the sensors [8].

Furthermore, Ciang *et al.* [4] mention that, besides measuring strain, FBG can be used to detect transverse crack propagation and impact damage by comparing strain changes and arrival time between different sensors. This would, obviously, require the installation of FBG sensors over the structure.
As for industrialized solutions, *HBM* can be mentioned as one of the best known companies developing monitoring systems based on optic fibre.

Ziegler *et al.* [18] proposed a methodology for lifetime assessment of MP structures based on both strain measurements and modelling. Briefly summarizing, this method requires the calculation of loads at the tower bottom based on strain measurements, transforming such loads into damage equivalent loads and extrapolating them to other hot spots (methodology is described in [18]). Calculation can thus be performed on the entire structure with updated loadings (from measurements and at hot spots where extrapolation has been performed) and the remaining lifetime can be assessed. It is important to note that some parameters of the model must be updated over time as they will evolve. One advantage of this method is that each turbine of a wind farm would be monitored, avoiding uncertainties of interpolation between turbines.

As far as the grout connection is concerned, it could be interesting to measure the relative displacements between the TP and the MP. In that case, four points (spaced at 90°) around the structure would be sufficient. Strain gauges or displacement sensors could be used [9].

4.1.1.2. Crack propagation monitoring

The two techniques identified as adapted to crack propagation monitoring are Acoustic Emission (AE) and the Strainstall CrackFirst™ system. AE relies on the fact that, when the structure of a metal is subjected to a mechanical loading and is altered, a rapid release of energy in the form of

[2] Advantages of optic fiber: reliability, robustness, long life, immunity to all electromagnetic effects. Disadvantages: fragility, distance between emitter and receiver that has to be short, in some cases.

elastic waves occurs. Hence, AE is based on the recording and analysis of such elastic waves. Sensors used for AE monitoring (in general piezoelectric sensors, but FBG systems can also be used [17]) convert the mechanical waves generated through the structure into electrical signals that are then post-processed and analysed. AE has primarily been used on metallic materials but is now used on many kinds of materials, such as composite materials. Considering an article by García Márquez *et al.* [19], the generation and propagation of cracks are the primary sources of AE in wind turbines and this technique is believed to enable fault detection earlier than other techniques such as vibration analysis; however, even though crack generation and propagation are the main sources of AE, it might be difficult to distinguish such phenomena from others that would not be related to the damage mechanisms of the structure.

Angulo *et al*. [11] investigated the ability of AE to detect defects such as debonding of the grout and steel, and the capability of the sensors in detecting cracks and crack propagation within the turbine structure. This study was performed using a 1:1 scale mock-up of a grout connection, as visible in Figure 5. One of the problems in using AE in a brittle material such as the grout is that it is a heterogeneous material due to cracking occurring during drying, which leads to a non-uniform wave speed in the material. This study also showed how a model could help simulate wave propagation in a grout connection and how to place the sensors. The detection of possible cracking occurring in the mock-up have not, however, been proved in that study. This was mainly because of a defect in the mock-up (debonding of the grout from the MP) so the AE technique should not be rejected based on this study.

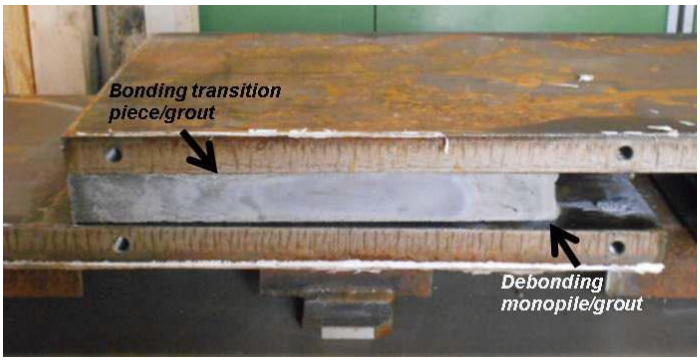

Figure 5: Grout connection mock-up [11]

However, even though acoustic emissions may appear as an attractive solution to detect cracks, it is important to keep in mind that setting all the acquisition and processing parameters enabling the actual detection of cracks, and not noise, can be arduous; furthermore, this might require performing lab tests prior to implementing the system on-site, and the transposition of the system from the lab to a real asset is not straightforward. Besides, wave speed evolves in the material as damage appears, and this has to be taken into account and the wave speed must be re-evaluated continuously.

Strainstall developed the CrackFirst™ system for crack propagation monitoring in welds; this system enables the monitoring of crack propagation at welded joints and has been installed on different wind farms, even though it has primarily been developed for a vessel's hull [15,20]. The system is described by its manufacturer as follows: "*Consisting of a thin shim of material with a manufactured pre-crack at its centre, it is attached to the target structure close to a critical joint.*

Under the action of cyclic stress, the pre-crack extends in proportion to the cumulative fatigue damage for a welded joint subject to the same loading. The condition of the sensor then indicates the amount of design life consumed in the adjacent weld. This allows for maintenance to be determined by component usage rather than time so preventing unnecessary or tardy replacement work." [20]. In fact, this system cannot strictly be considered as a monitoring system for crack propagation at a welded joint, since only the crack of the sensor itself is monitored. Such a sensor can, however, provide information on the state of the structure nearby, and especially welded joints, as stated in the description.

A list of industrialized systems is provided in Annex 1: Examples of industrialized solutions.

4.1.2. Corrosion monitoring

Corrosion affects both crack initiation and crack growth and must be taken into account when evaluating structural strength and corrosion fatigue risks. Indeed, corrosion affects surface roughness, increasing it, and corrosion pits can have the same effect as notches, depending on their geometry, hence facilitating crack initiation [21,22]. Moreover, aggressive media such as the offshore environment can increase the crack growth rate [21]. Besides, offshore conditions vary from place to place and over time, making corrosion rates change, depending on these same parameters. Hence, in order to detect changes and/or check mitigation efforts, continuous monitoring is highly relevant [23]. Corrosion occurs both on the internal and external sides of MP foundations.

On the external sides, steel is in contact with open sea water, and the most critical zones for corrosion are the atmospheric zone, splash/tidal zone, submerged zone and mud zone. The highest corrosion rate is in the splash zone or in the zone just below the water level for more stagnant water [22,23]. As for internal sides, in early projects there was no corrosion protection for internal surfaces as the structures were assumed to be water- and airtight [21,23]. However, as problems of internal corrosion emerged, (compartments not being totally sealed or airtight), recent projects have included coatings and/or CP as part of the internal corrosion protection. Indeed, in a completely airtight structure, the dissolved oxygen in seawater is quickly consumed by uniform corrosion of the entire steel surface. Once all oxygen is consumed, the media turns anaerobic and corrosion rates decrease; however, microbial activity in the sediments generate H_2S, and hence corrosion. As renewal of nutrients is difficult in such a closed environment, the microbial activity is expected to decrease over time and so would the corrosion rate [21]. Microbiologically Influenced Corrosion (MIC) is dealt with in section 4.1.2.1.

As stated by Black *et al*. [23], no precise guidelines for the internal corrosion protection are available to date. Hence, each designer or owner is free to implement their own corrosion protection strategy for the internal surfaces. A corrosion allowance is taken into account when designing steel structures, which is applicable in case of uniform corrosion. However, in case of local corrosion mechanisms, such as MIC, the structural integrity of the structure must be re-evaluated (fatigue loading) [22] in order to assess the remaining lifetime of the asset. This makes corrosion monitoring essential. MIC and increased corrosion due to low pH are described in the next paragraphs.

4.1.2.1. Microbiologically Influenced Corrosion (MIC)

The MIC phenomenon is explained by Beech in [24] as follows: diverse microbial species (within biofilms) present on the MP walls and in the mud zone [21] are responsible for the consumption of oxygen and production of acids, sulphides and enzymes that promote the establishment of localized chemical gradients at the metal surface. Such gradients facilitate the development of electrochemical cells, which influence anodic and/or cathodic reactions, leading to the loss of metal from the discrete locations on the surface [24]. Hilbert *et al*. [21] differentiate between different kinds of bacteria forming such biofilms:

- sulphate reducing bacteria (SRB): depolarisation of the steel, hence reducing effectiveness of CP [9,25]
- sulphur oxidising bacteria (SOB),
- organic acid producing bacteria (APB),
- iron related bacteria (IRB)

Hence, depending on the chemical effects for which the different bacteria can be responsible, parameters to be monitored can be identified. Considering Riggs Larsen's article [25], SRB are a significant risk and hydrogen sulphide sensors can be installed within the MP to monitor SRBs activity [9].

4.1.2.2. Increased corrosion due to low pH

As explained by Barbouchi *et al.* in [9], aluminium ions from the sacrificial anodes (used as CP) react with chloride ions to convert water molecules into hydrochloric acid, thus acidifying the water and increasing corrosion rates. Yet, a more acidic environment depolarises cathodic steel, causing Fe atoms to become ionised and water soluble, and allowing the formation of corrosion products. This will also prevent the formation of a protective layer of carbonates that would normally be expected and would protect the steel structure. Thus, both water acidity and cathodic steel potentials can be monitored using, respectively, pH sensors and drop cell sensors. Besides, acids present in the water can react with steel, resulting in a production of H_2 and possible embrittlement of the steel structure (hydrogen concentration is indicative of corrosion rates). It can, hence, be useful to monitor H_2 concentration in the water, too.

4.1.2.3. Relevant techniques for corrosion monitoring

Corrosion monitoring (including both internal and external sides) can be performed through accumulated techniques, such as coupons, or real time techniques, using sensors. Mathiesen *et al.* [26] provided a list of relevant techniques for corrosion monitoring, for both internal and external sides of MPs. Such a list, completed by other techniques mentioned in the literature, is as follows:

- Internal side of the MP
  - Corrosion coupons for visual evaluation and weight loss determination (1 in Figure 6)
  - Full-length corrosion coupon that includes macro galvanic elements and mud zone (2 in Figure 6)
  - Electrical resistance (ER) probe for real-time measurement of the corrosion rate (3 in Figure 6)
  - Magnet-mounted reference electrodes measuring the protection potential in projects with CP (4 in Figure 6)

- Lowerable rack of sensors including potential, pH, dissolved oxygen, temperature and resistivity (5 in Figure 6)
- Hydrogen sulphide sensors
- Hydrogen sensors
- pH sensors
- Dissolved oxygen sensors

- External side
  - Drop-cell (reference cell) measuring protection potential of CP (A in Figure 6) (requires human intervention on-site; it is inspection rather than monitoring).

B and C on the figure are, respectively, a stabber (contact reference cell) mounted on a remotely operated vehicle (ROV) to measure the protection potential of CP, and a UT crawler for measuring wall thickness. These inspection techniques mentioned in [26,27], cannot be considered as monitoring systems, but rather are inspection ones, and thus are not described in this document. Besides, corrosion coupons need to be retrieved to measure the weight loss and do not provide real-time data.

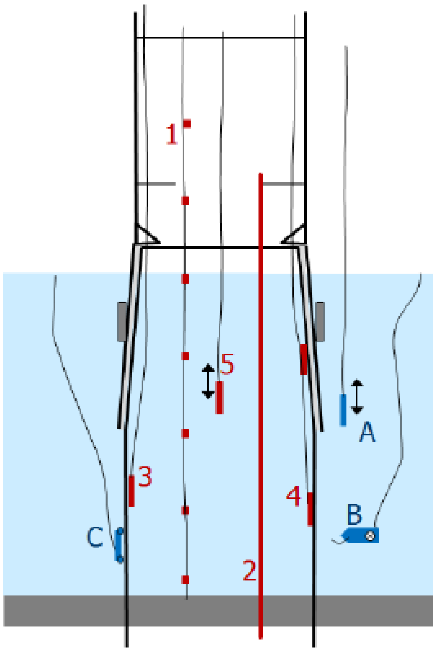

Figure 6: Techniques for corrosion evaluation inside and outside monopiles. 1- Corrosion coupons. 2- Full-length corrosion coupons. 3- Electrical resistance probes. 4- Reference electrodes. 5- Potential, pH, dissolved oxygen, temperature and resistivity sensors. [26]

It is interesting to note that some probes can be magnet mounted as the structure under consideration is made out of steel.

Finally, ROVs [28] or diver-based inspections can be performed but these remain inspection techniques, not suitable for monitoring, although they are presented as such in some articles.

4.1.3. Scour monitoring

Scour is a major problem for all offshore structures. Michalis *et al*. [27] listed the main issues related to scour around wind turbine foundations:

- Reduction of the structure's stability,
- Increased hydraulic loading on the vertical face of the structure,
- Increased maximum moments at the foundation structure,
- Decrease and variation in the natural frequency of the turbine,
- Need for more complicated foundation design requirements,
- Increased bending stresses on cables, which may exceed the design limit.

El-Kafafy *et al*. [29] explain that the scouring process leads to an increase of the support structure length, hence reducing the fundamental structural resonance of the support structure (consistent with Zaaijer [30] and Weijtjens *et al*. [31]). Devriendt *et al.* [32] explain that scour and reduction in foundation integrity over time are especially problematic because, since they reduce the fundamental structural resonance of the support structure, this frequency hence becomes close to the lower frequencies at which much of the broadband wave and gust energy is contained or close to the rotational speed (1P) frequency. Wave energy can thus create resonant behaviour and increase fatigue damage. Moreover, the reduced natural frequency could align more closely with the first harmonic of the rotation frequency of the rotor, which could be dangerous for the wind turbine.

At the present time, most O&M companies use bathymetric measurements to detect scour. Such measurements, however, only detect changes in the seabed level but cannot quantify the effect of scour on the dynamic behaviour and fatigue life of the structure [31]. Furthermore, it is not possible to forecast the extent of scour around offshore foundations due to currents at the sea bed, but it is well-known that storms and harsh environmental conditions have an important impact on scour development [8] and that scour depth can vary over short- and long-term scales [33]. Hence, it appears mandatory to be able to detect and monitor scour around wind turbine foundations.

Besides, apart from the obvious reasons related to the O&M of offshore wind turbines (OWTs), scour monitoring can provide valuable information and help in obtaining a better understanding of the scour phenomenon, thus enabling *(i)* robust and reliable modelling of the scour phenomenon, and *(ii)* a better design of future wind turbine foundations and/or wind farms. Whitehouse *et al*. [33] studied the development of scour due to waves and currents around the installed foundations of five different sites in Great Britain.

Scour monitoring systems for OWTs can be developed using past experience in other offshore industries, such as Oil & Gas, for example, or in bridge engineering. The latter seems to be the most interesting for offshore wind turbine's foundations, considering the literature review performed [34,35].

Cai [34] and Prendergast and Gavin [35] studied bridge scour monitoring and published literature reviews on existing monitoring systems. The main techniques used for measuring bridge scour are the following [34–36]:

- Pulse or radar devices
    - Time Domain Reflectometry (TDR),
    - Ground Penetrating Radar (GPR),
    - Sonar mounted on the structure,
    - Acoustic Doppler Current Profilers (ADCP),
- Optic fibre sensors of different technologies (mainly FBG sensors and the Brillouin method),
- Driven or buried rod devices
    - Sliding Magnetic Collar (SMC),
    - Steel rod,
- Electrical conductivity/resistivity devices,
- Electrical capacity devices.

Some of these techniques that seem to be the most efficient and the most reported in the literature are described in the next sections.

4.1.3.1. Pulse or radar devices

Time-domain reflectometry (TDR) and ultrasonic (UT) inspections are described in this section. Ground-penetrating radar (GPR) can also be used to detect scour. This technique uses radar pulses to determine the water-sediment interface and hence the depth of scour [35]. However, it requires manual operation and cannot be considered as a monitoring solution.

4.1.3.1.1. Time-domain reflectometry

TDR enables location of the sediment layer by using electromagnetic waves. The technique is based on the fact that the dielectric permittivity constants change between materials [35] (the electromagnetic wave speed depends on the dielectric properties of the surrounding medium [36]) and require the use of metal rods installed into the soil which act as waveguides: electromagnetic pulses propagate along the metal rods and, by analysing such pulses, the interaction between the water and soil can be detected [36]. Indeed, when the propagating wave reaches an area where the dielectric permittivity changes (e.g. the water-sediment interface), a portion of the energy is reflected back to the receiver.

In [37], the authors state that TDR has been found to be more robust and more accurate than sonar devices but the salinity of water and temperature can render the technique inaccurate for scour monitoring [35]. However, as mentioned in [35], monitoring the channel temperature in addition to the TDR waveform can partially mitigate this effect (salinity of water effect remains).

4.1.3.1.2. Ultrasonic inspection (sonar)

Sonar inspection is a reliable technique and avoids sending ROVs or divers on-site. Sidescan sonar, single beam sonar, multi-beam sonar are usually used for bathymetric mapping. *iXSurvey* is in France one of the most competent companies in this particular field. *R2Sonic*, and *EchoScope* from *CodaOctopus* are sonar imaging equipment among the best known. *Kongsberg* also provide valuable sonar imaging equipment and services [36]. These remain, however, inspection equipment, and cannot be used as monitoring systems. The Norwegian company *Nortek* is providing an acoustic scour monitoring system [38] using four narrow acoustic beams to detect the along-beam distance from the sensor to the seabed at four points away from the structure, as visible in Figure 7.

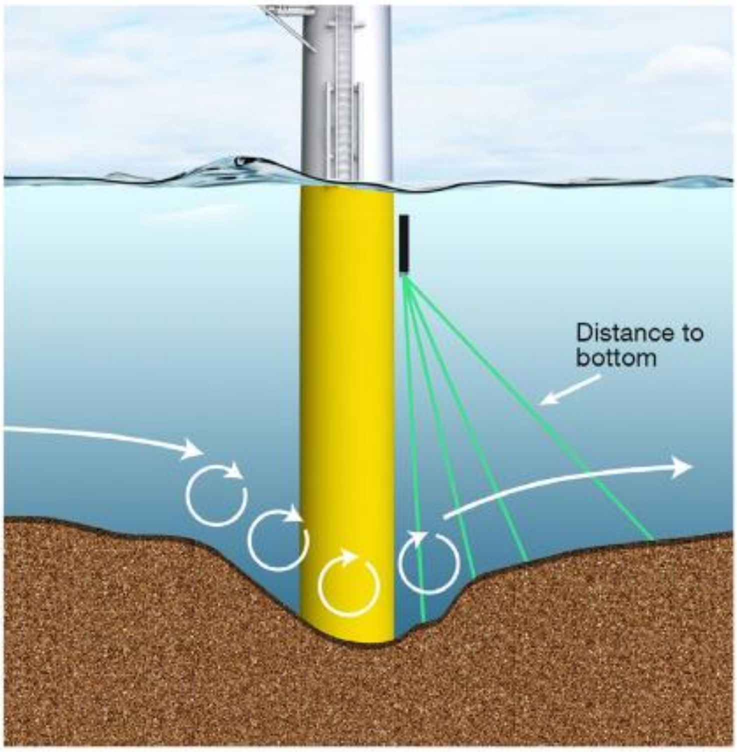

Figure 7: Scour monitoring system provided by *Nortek* [38]

The data is collected at a specified sampling rate (that can be chosen), providing the acoustic scattering profile along the beam, thus providing information on both the changing location of the seabed and the nature of the suspended sediments. The system includes the *Nortek Autonomous Online System (AOS)* that enables data collection, processing and transmission to a *Nortek* server. The real-time scour levels can be displayed on a website (password-protected) for easy data access or output to an external processing unit linked to a PLC/SCADA system. Data can also be stored and processed after recovering the system on-site (this cannot be considered as monitoring) [38]. This system appears to be one of the best technical solutions for scour monitoring.

4.1.3.2. Driven or buried rod devices

Strainstall provides a scour monitoring system based on "*a magnetic collar resting on the seabed which moves down the sensors whenever erosion takes place. Each time the magnetic collar passes one or more sensors, an alarm sequence is activated. This is sent as a text message warning that scour has occurred, enabling inspections to take place and any remedial work to be undertaken*." as described by the manufacturer [14]. However, no further description of this system is available. Such a system could be efficient when there is a sediment removal, as long as the collar goes down with the sediment. However, if the collar is buried because of an upwelling of the sediment, then scour cannot be monitored any more and no information of the scour state around the foundation can be retrieved. This major problem applies to all kind of systems based on moving parts resting on the seabed (gravity-based) and should be taken into account when considering scour monitoring systems. Prendergast and Gavin [35] mentioned other driven or buried rod devices that do not seem relevant to this study but could, however, be of interest for other offshore wind applications.

4.1.3.3. Optic fibre

In this section, FBG is under consideration. Scour monitoring techniques using FBG sensors are based on the measurement of strain along embedded cantilever rods [35]. Indeed, when an embedded rod becomes partially exposed due to scour, it will be subjected to hydrodynamic forces from the flow of water that induces bending in the exposed rod. Hence, strain varies along the rod depending on the location (free or embedded area), and measuring strain all along the rod using FBG sensors as strain gauges enables monitoring of the scour (the authors mention that the shift of the Bragg wavelength has a linear relationship with the applied strain in the axial direction [35]. Prendergast and Gavin [35] also mention that the resolution depends on the spacing of the sensor array along the rod and can be highly sensitive to vibrations of the support structure used, with vibrations occurring due to flowing water. A study by Cai [34] on bridge scour monitoring using FBG sensors confirmed that the position of the maximum moment (strain) in the studied pile is close to the interface of the sand and water. The study has also confirmed the feasibility of the scour monitoring method based on the bending moment (strain) profile. Finally, it is important to note that the main advantage of scour monitoring techniques using FBG sensors is that they enable monitoring in both sediment removal and refill cases.

4.1.3.4. Capacitive method

Michalis *et al*. [27] proposed a new scour monitoring system based on a capacitive method. The system consists of arrays of capacitive probes installed around the foundation and linked to a wireless network for remote data acquisition. The system enables to wirelessly detect scour, sediment deposition and seabed deterioration.

The probes are capacitive sensors and the measurement is based on the difference of the dielectric constant of saturated sediment and water. The four probes are located around the MP; each probe consists of six capacitive sensors mounted on a non-conductive shaft and located at different predetermined depths along the shaft. For each probe, the uppermost sensor is in the water and serves as a reference, while the five other sensors are embedded into the sediment next to the foundation structure.

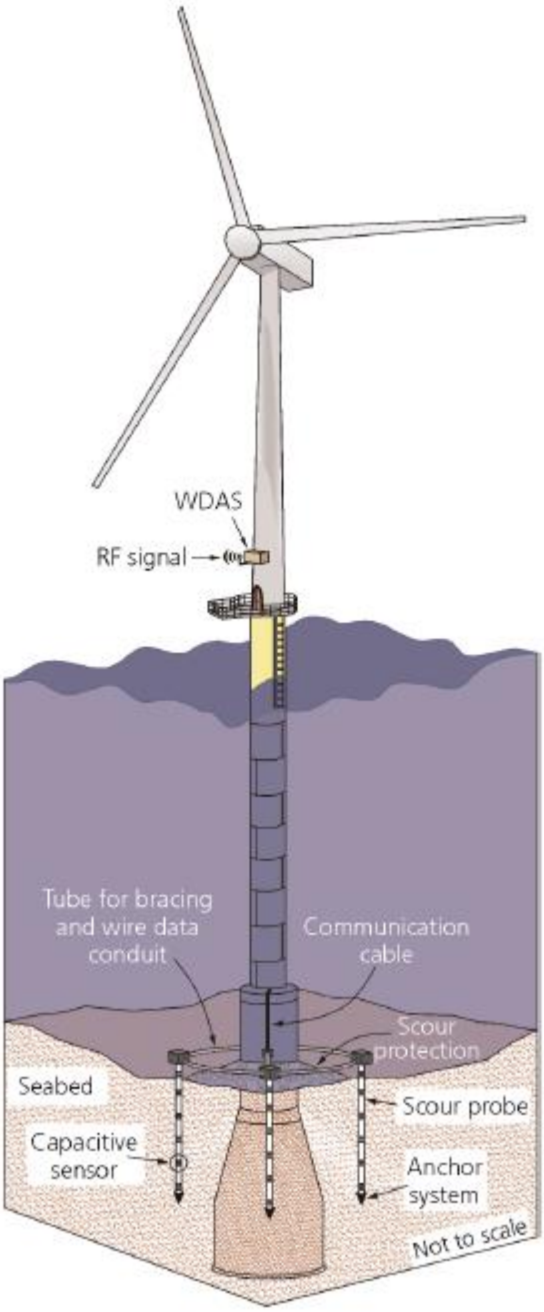

Figure 8: Scour monitoring system proposed in [27]

Data from each probe is transmitted to the Wireless Data Acquisition System (WDAS), attached to the tower, through a communication cable. Data is transferred at predetermined schedules or through a trigger mode when scour is detected. The WDAS contains a memory for data storage, an emitter/receiver antenna for remote data retrieval, a programmable timer unit for scheduled communication with a remote monitoring data collection system and a trigger unit for emergency data retrieval when scour is detected. The different turbines of the wind farm form a wireless sensor network, in which selected turbines act as master nodes and each turbine relays its information to the nearest master nodes. The master nodes send all the data to a remote location through a radio link [27].

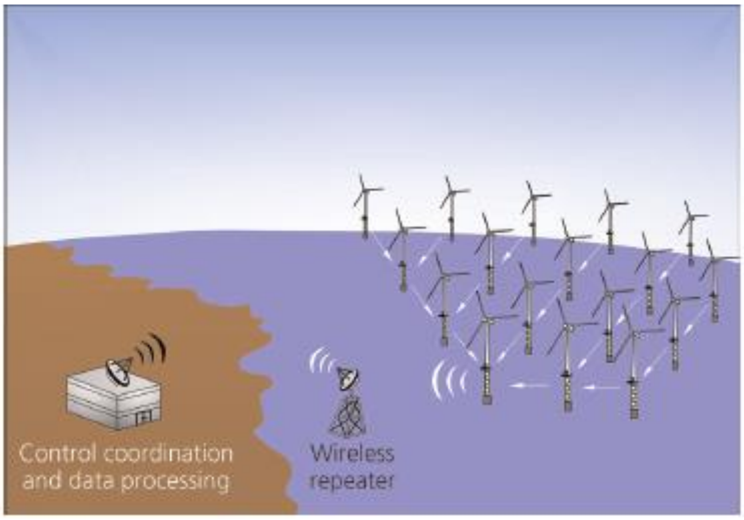

Figure 9: Concept for remote surveillance and monitoring systems of offshore wind farms proposed in [27]

The authors [27] also showed the influence of temperature on the measurements. Hence, in order to avoid temperature effects on the measurement, the ratio output of the sensor under consideration / output of the reference sensor could be used to monitor the scour. A list of industrialized systems is provided in Annex 1: Examples of industrialized solutions.

4.1.4. Bolt monitoring

Self-loosening of bolts has been identified as one of the main phenomena to monitor. Different techniques exist and are industrialized, but one of the main issues when dealing with bolt monitoring is to determine which bolts should be monitored, as, for cost reasons, it is not possible to monitor all bolts. The main techniques are the following [39,40]:

- Strain gauge mounted on the body of the bolt
- UT-based method (Ultrasonic testing): the velocity of the ultrasonic waves depends on the axial load
- Vibration-based damage assessment of bolted structures. Post-processing of vibration signal is complex and it can be difficult to detect bolt looseness using this technique.
- Acoustoelastic effect based method
- Piezoelectric active sensing method: *"the variation of the interface contact characteristics can be monitored by the ultrasonic signal generated by the piezoelectric transducer; thus, the bolt connection status can be monitored"* [39]
- Piezoelectric impedance method.

A list of industrialized systems is provided in Annex 1: Examples of industrialized solutions.

4.2. Review of monitoring solutions - indirect measurements of scour and damage of the structure

In this section, indirect measurements of damage, in the general sense, through inclination measurements and vibration/modal analysis, are described. It is important to keep in mind that, even though such methods can provide valuable information on the state of the structure, it can be difficult to identify which is the phenomenon responsible for the deviation from the normal behaviour. Furthermore, some systems, such as the Strainstall monitoring system, include load cells[3] [15]. Knowing the loads in identified hotspots can enable *(i)* determining whether the material is damaged (knowing the stress-strain curve and load history of the structure) and, above all *(ii)* calculation of the remaining fatigue life using finite element analysis (FEA). Besides, registering loads can provide valuable information for future wind turbine and wind farms' design.

4.2.1. Inclination of the structure

As mentioned by Wymore *et al*. [13] and Faulkner *et al*. [15], in addition to the "regular" Strainstall structural health monitoring system including strain gauges and displacement sensors already mentioned, inclinometers and accelerometers (reported in the next section) have been installed on some turbines. Inclinometers can provide an indication of the possible loss of equilibrium of the structure. As mentioned by Weinert *et al.* [41], pile rotation may be measured by an inclinometer at mud line. Prendergast and Gavin [35] mentioned scour monitoring of bridges using 2-axis inclinometers. Such sensors can, indeed, provide information on whether scour is processing or not, but cannot provide any information on scour depth. Therefore, vibration or modal analysis should be performed.

Inclinometers could also be installed on the TP and on the MP; indeed, knowing the inclination along the tower at different levels, for example at mud line, on the TP and on the tower would enable 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. A combination of both phenomena could also occur, which would make the interpretation more difficult. There are different kinds of inclinometers, among them optical inclinometers [42] and laser inclinometers. Ideally, 2-axis inclinometers should be used in order to have a better understanding of the behaviour of the structure.

4.2.2. Vibration and modal analysis

Vibration Based Damage Detection (VBDD) and modal based analysis are based on the fact that, when damage appears in a structure, its material and dynamic properties change, so its response (e.g. frequencies, mode shapes and modal damping) to forces also changes [4,13]. Thus, considering information provided in [8] such a *global monitoring* approach, based on Operational Modal Analysis (OMA), can be used to detect structural damages. Indeed, both small and large damages can have an influence on the modes of the structure:

- small damages can be correlated to high frequency local modes,
- large damages and structural changes have an influence on the global modes.

As far as major structural changes are concerned, vibration analysis can be used to detect scour [9], accidents and environment actions (such as wind and wave actions) [11]. Hence, analysis of the Eigen-frequency, mode-shapes and modal curvature, and damping ratios[4] [29], for example,

[3] Load cells are considered to be indirect measurements of damage in this report since the damage state of the material, at the specific monitored hotspots, can only be assessed knowing stress-strain curves *and* the load history of the structure, which can be quite complicated.
[4] The main damping phenomena on an offshore wind turbine are: aerodynamic damping, damping due to the structural steel, hydrodynamic damping and damping caused by the influence of the soil [30].

can provide valuable information on the structural integrity of the structure. Furthermore, Weijtjens *et al*. [31] mention that strong changes in the resonance frequency can reduce fatigue lifetime due to an increased rotor harmonic–tower interaction.

Martinez-Luengo *et al.* [2] state that, to date, natural frequency analysis (NFA) is the most commonly applied to detect deviations from the design in wind turbine foundations, mainly because of the highest cost, low maturity or low accuracy of other techniques (besides strain measurements using optic fibre). However, as mentioned by El-Kafafy *et al*. [29], since the natural frequencies and damping ratios of the modes may change due to changes in the operating condition, it can be difficult to compare datasets recorded at different times. Besides, two modes can cross each other in terms of natural frequency or damping ratio, hence providing wrong information regarding the actual state of the structure. Issues related to date processing can also occur when two modes cross each other. Finally, Angulo *et al.* [11] mentioned that data collected from accelerometers could be used to identify noise in the AE signal, but this should be verified as, in general, the range of frequencies measured by both techniques are quite different.

Most common accelerometers are piezoelectric sensors; FBG can also be used to measure vibrations [17,42], and the company *HBM* has been installing such sensors on wind turbines for a few years. As aforementioned, some Strainstall SHMS include accelerometers, in addition to the “regular” sensors already mentioned.

4.2.2.1. Grout connection monitoring

The grout connection is one of the main critical areas on MP foundations. Gupta *et al.* [10] studied the mechanical behaviour of the grout connection through finite element modelling (FEM) (using a wind turbine model developed in Abaqus) in order to identify possible monitoring schemes. The grout connection is a critical area since the grout carries shear and bending loads between the tower and the pile. Hence, loss of adhesion between the grout and steel surfaces could result in relative shear displacements between the grout and the MP, which in turn could result in a loss of grout stiffness and/or loss of steel thickness by abrasion of the steel by the grout [10]. As mentioned earlier in this report, problems have been encountered in the past in the grout connection, resulting in major repair. The objective of Gupta *et al.*’s study was to determine whether accelerometers (installed on the nacelle of many wind turbines) could be used to diagnose any of the failure modes identified by FEA. Hence, natural frequency of the system was calculated after representing each damage mode. The study showed that damage could be detected in the grout by monitoring the natural frequency of the structure when the change in frequency was higher than 2% for all damage modes considered in the study. The natural frequencies calculated for the studied failure modes and the percentage of the natural frequency of the undamaged structure are listed in Table 1.

Table 1: Natural frequency of the studied wind turbine for various damage cases, from [10]

Damage cases	Failure mode	Frequency (Hz)	% of undamaged frequency
0	Undamaged structure	0.3125	
1	De-bonding between external face of mono-pile and grout	0.2941	94%
2	De-bonding between internal face of transition piece and grout	0.2941	94%
3	10% bulk loss of grout from the base	0.2941	94%
4	50% bulk loss of grout from the base	0.2777	88.8%
5	Cone type cracking	0.2857	91.4%
6	Wear of grout by pile 1mm	0.2730	87%
7	Wear of grout by pile 2mm	0.2597	83%
8	Wear of grout by TP and pile (2mm on each side)	0.232	74%
9	Compressive failure of grout	0.294	94%

Another way of using data collected, using accelerometers, is by computing the acceleration in order to calculate displacements. Then, in order to obtain the stresses from the calculated displacements (using models), simplifications and assumptions have to be made, which might lead to stresses different from those that the turbines actually undergo (see [43]). Hence, such data processing should be avoided. Finally, considering the information available in the literature, it can be concluded that it could be interesting to install accelerometers on the mast to determine whether there is a slack between the mast and the TP.

4.2.2.2. Scour monitoring

Devriendt *et al*. [32] explain that scour and reduction in foundation integrity are major issues when dealing with OWTs since such phenomena reduce the fundamental structural resonance of the support structure, aligning that resonance more closely to the lower frequencies at which much of the broadband wave and gust energy is contained or because they align this resonance more closely with the natural frequency of the structure. Hence, when the natural frequency is lowered, the higher is the risk that wave energy creates a resonant behaviour of the structure, hence increasing fatigue damage.

El-Kafafy *et al.* [29] explain that the scouring process leads to an increase of the support structure length, hence reducing the fundamental structural resonance of the support structure, which is consistent with [10,30,31,41]. Weijtjens *et al.* [31] suggest using resonance frequency to detect scour, as this physical parameter is scour-sensitive, as shown by Zaaijer in [30]. The authors studied Belwind offshore wind farm (55 Vestas V90-3MW turbines, all on MP foundations at water depths up to 30 m) located 46 km outside from the Belgian coast. In this section, the focus is on processing accelerometers' data for scour monitoring, obtained from one turbine. As visible in Figure 10 (c), published by Zaaijer in [30] and addressed in [31], both first and second natural frequencies are affected by scour (whether it is an MP or a tripod foundation). Weijtjens *et al.* [31] proposed a post-processing for SHM.

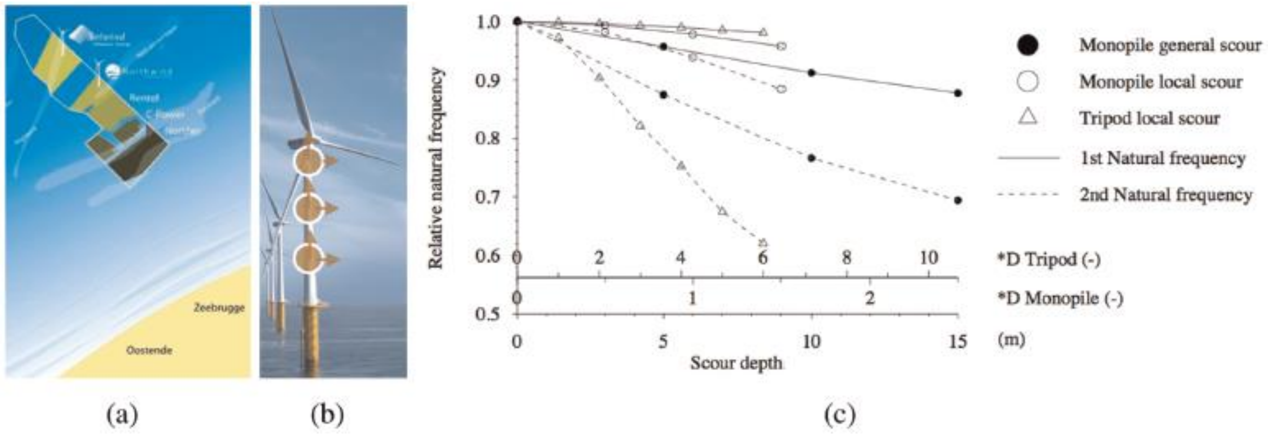

Figure 10: (a) Location of Belwind (Belgium) wind farm. (b) 6 accelerometers (X–Y configuration measuring vibrations in a plane parallel to the sea level) mounted on one of the turbines of Belwind wind farm. (c) Drop in the tower resonance frequency caused by scour for both monopile and tripod support structures. From [30,31]

The study by Gupta *et al.* [10], described in the previous section (4.2.2.1), also covered the possibility to detect scour by analysing the natural frequency of the structure, using a model different from the one used for the study of different damage modes (described in 4.2.2.1). Hence, the natural frequency was calculated for four different scour depths, up to 10 m. It showed that increasing scour depth causes the length of exposed MP to increase, which reduces the natural frequency of the system. Although the result of this study may appear interesting, it is important to note that scour was studied by removing sand all around the MP, which may not be considered as representative since scour is not always symmetrical. Hence, different geometries should be studied in order to assess whether it is possible to detect scour using such a method, or not.

The authors then combined the two investigations on damages and scour in order to determine whether it would be possible to decouple the two phenomena and possibly propose a global monitoring scheme. It appeared that the effect of both scour and grout damage is to reduce the natural frequency of the turbine structure, and that the reduction for each phenomenon is in a similar range, making it impossible to decouple the two phenomena by analysing the natural frequency. Besides, as aforementioned, different geometries of scour should be studied in such a study; decoupling two phenomena might, indeed, be even more difficult in the case of combined grout damage and scour.

Furthermore, while performing vibration and modal analysis, it is important to take into account parameters such as, for example, biofouling and damage of the structure, or weather conditions (as mentioned by El-Kafafy *et al*. [29]). Indeed, Weinert *et al*. [41] mention that the natural frequency can be affected by any stiffness or mass change of the system, e.g. more mass due to marine growth, less mass and stiffness due to corrosion, more or less oscillating added water mass due to changing water levels, or a stiffness reduction as a result of soil degradation. Stiffness changes can occur because of damages occurring anywhere in the structure, including in the grout connection. It can, however, be difficult to quantify such phenomena and take them into account. This also leads to the conclusion that it can be difficult, when observing a deviation of the natural frequency (or any other vibration-related variable) from its original value, to decouple the different phenomena and identify the exact cause of such variation. Devriendt *et al.* [32] also mention that identification of the modal parameters of a wind turbine is particularly difficult and that much effort is made in the research community to develop methods to address that. Hence, although modal and vibration analysis may appear as attractive monitoring techniques, the results must be carefully considered. Indeed, as stated by Devriendt *et al*. [32], wind turbines can fail to comply with the OMA assumptions because of the presence of rotating components and their corresponding harmonic force contributions or due to the wind wave interaction with the structure, for example, creating a lot of noise. However, as aforementioned, there are some ongoing research studies to address that and the technique should still be considered.

Weinert *et al*. [41] performed NFA for two MP designs and the results confirmed the correlation between natural frequency and scour. The commercial numerical tools used for that study enabled a parametric study on natural frequency calculation taking into account environmental parameters such as scour depth, marine growth, corrosion and water level.

Finally, in order to avoid taking into account phenomena that are not scour-related, it could be useful to monitor a fully-immersed rod (to avoid tide effects) located very close to the pile foundation. The scour around the rod and the MP could, hence, be considered as comparable (this has, nevertheless, to be verified through calculation). Prendergast and Gavin [35] mention such a system (developed by [44]), for which changes in the natural frequency of the rod are related to the scour depth (based on the fact that the natural frequency of a cantilevered rod is inversely proportional to its length).

4.2.2.3. Loosening of bolts monitoring

Bolt loosening, when reaching a certain extent, can be responsible for a slack between the two parts, which could, possibly, induce a change in vibration properties of the structure. Hence, a good solution to detect a possible bolt-loosening would be to perform a vibration or modal analysis of the area of concern in order to detect a deviation from the original state, using accelerometers. This would, furthermore, be much less expensive than installing bolt-loosening monitoring systems on bolts. It is, indeed, difficult to know which bolts should be monitored and all bolts should, hence, be monitored, which is almost impossible because of the cost and, for some of the bolts, because of the configuration.

A list of industrialized systems is provided in Annex 1: Examples of industrialized solutions.

4.3. Review of indirect evaluation / Measurements Methods

Review of SHMS for OWTs will be based, in this section, on the Statistical Pattern Recognition Paradigm initially introduced in [45] and further applied to the specific application of OWTs in [46]. The basic steps of the approach are summarised below:

1. Operational Evaluation: This step sets the boundaries of the problem through addressing the four key questions relevant to damage identification; motivation and economic justification for implementing the SHMS; the different systems' damage definitions; the

Environmental and Operational Conditions (EOC) in which the SHMS are used; and the data acquisition limitations in the operational environment.

2. Data Acquisition, Normalization and Cleansing: Data Acquisition refers to the selection of the monitoring methods, type, quantity and location of sensors, and the Data Acquisition/ Storage/Transmittal Hardware. Data Normalization is the procedure of separating variations in sensor readings produced by damage, from those produced by the variation in EOC, accounting for the different conditions and properties of obtained measurements. Data Cleansing is the procedure of selecting data which is passing or being rejected from the Feature Selection procedure. Filtering and resampling are two examples of Data Cleansing processes which constitute Signal Processing Techniques.
3. Feature Extraction and Information Condensation: This is the aspect of the SHMS that attracts most attention, as these features allow the distinction between damaged and non-damaged structures. Data Condensation is essential when analogue feature sets acquired along the structure's lifetime are envisioned. Due to the extraction of data from a structure during long periods of time, robust data reduction techniques have to be developed to preserve feature sensitivity to the changes of interest, keeping in mind that such data reduction processes always cause a loss of information.
4. Statistical Model Development: This step is related to the implementation of the algorithms that adopt the extracted features and calculate the extent of the damage to the structure. These algorithms can be divided into supervised and unsupervised algorithms, as shown in Figure 11. These algorithms assess statistical distributions of the measured or derived features, to enhance the damage identification process.

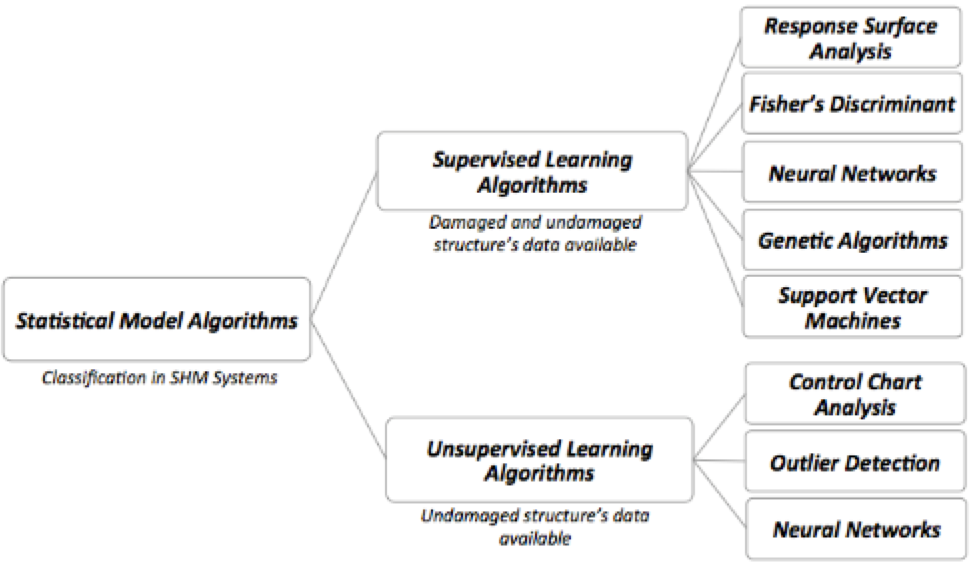

Figure 11: Classification of algorithms for statistical model development [46]

4.3.1. Review of SHM Technologies

New generation OWFs include larger rotors, deployed in deeper waters and further offshore, making the requirement for more efficient monitoring technologies ever more relevant. SHMS should allow the prediction of progressive structural changes in order to reduce O&M costs and to assess the remaining lifetime of these structures. An example of a good application of SHMS to an onshore WT is presented in [47], where a life cycle management framework for online monitoring and performance assessment is applied to WT. Information gathered from SHM can be employed in the development of a tailored, condition-based maintenance programme aimed at reducing downtime due to components inspection, preventing unnecessary replacements and failures, and increasing availability. Furthermore, due to the capacity of monitoring the structure's integrity, design improvements can be implemented, such as selection of lighter blades that will enhance performance with less conservative margins of safety and which will adapt more quickly to the wind's variability, capturing more energy.

Assessment of different SHM technologies can be found in [48–50], however, these reviews mainly refer to civil infrastructure. A review of the effect of EOC on SHM techniques and the normalization of the data that needs to be carried out for compensating these variations is provided at [51] while a discussion between SHM and CM costs can be found in [52].

Within this section, the different SHM techniques and especially those suitable for OWT blades, tower and foundation, are presented in greater detail:

- Acoustic emission monitoring
- Thermal imaging method
- UT methods
- Fatigue and modal properties monitoring
- Strain monitoring

4.3.1.1. Acoustic Emission monitoring

Monitoring the changes in the stored elastic energy in critical locations of a structure or component can be utilised to monitor WTs and more particularly in failure modes/mechanisms that are associated with cracking, excessive deformation, debonding, delamination, impacts, crushing, among others. AE monitoring is an effective technique that detects failure mechanisms at a microscale level. The technique becomes less suitable when it comes to the actual characterization and assessment of damage if appropriate algorithms are not developed. This sort of trained algorithm can allow for the understanding of more complex damage mechanisms in WT blades. The method can also be used for fatigue tests, such as the sound produced due to stress released waves or energy dissipation using piezoelectric sensors [53,54].

AE signals are defined by their amplitude and energy and points of interest are particular points at a structure under loading. These are the points that have a higher likelihood to fail during the structure's life cycle and these features are very useful in identifying the failure location. [55] is using a broadband radio to send the AE data from the rotating frame to the ground, explaining how the method can be applied to a WT blade during operation.

4.3.1.2. Thermal imaging method

The method is based on the subsurface temperature gradient of the material of a structure, aiming to detect defects or anomalies beneath the surface. This is achieved from the installation of infrared cameras which can detect these anomalies due to the variation of thermal diffusivity [56]. The technique can be applicable for the inspection of WT blades rather than the support structure components. Thermal excitation can be active when using an external stimulus source such as optical heat lamps, or passive when the aim of the method is to investigate variation of structures at temperatures different from ambient.

The thermoelastic stress method is a type of active thermal imaging method and is based on the change of temperature of an elastic solid as a result of a change in its stress range. In the location where some sort of damage is present, a series of effects are present such as different heat conduction, higher acoustical damping, and stress concentration [57]. Applications of the method on WT blade fatigue tests have been reported in [58] as stress concentrations during the test can be observed before the damage to the surface is noticeable. The vibro-thermographic acoustic emissions method integrates high power ultrasounds or oscillating stresses with a mechanical shaker in order to locate and evaluate crack dimensions [57,59]. This approach is particularly applicable to composite materials to assess voids and stress concentrations. The methods could be effective as part of SHMS for OWTs; however, more research is required to reduce uncertainties based on environmental conditions (i.e. temperature).

4.3.1.3. Ultrasonic methods

UT methods are methods commonly used to assess the inner part of solid objects having found application to steel and composite structures [60]. UT waves emitted by a transmitter pass through the material under consideration and are reflected and/or mode converted by the existence of potential defects. A receiver collects the altered signal once it has gone through the material. Transmitter and receiver are placed on opposite surfaces of the material, although more complex configurations can be applied [61]. The technique can reveal planar cracks that take place perpendicular to the sound wave propagation direction [62] and can detect cracks measuring a few millimetres.

It should be noted that Thermal imaging and UT methods are mainly inspection (rather than monitoring) techniques, even though passive IR can, in some cases, can be used for damage monitoring during mechanical tests in labs. These techniques have been proved efficient for composites materials (mainly polymer matrix composites), ie in blades, but their applicability for materials relevant to monopile/jacket foundations is yet to be proven.

4.3.1.4. Fatigue and Modal Properties Monitoring

Monitoring of Modal Properties is based on the principle that variation of physical properties of a structure (i.e. its stiffness) will lead to variation of its modal parameters such as resonance frequency, damping coefficient and modal curvatures, among others. Comparing the actual state of these properties with the non-damaged values, can allow identification of the damage and potentially its location. In this case, modal properties changes are damage indicators hence this SHM technique is considered as a pattern recognition problem.

The dynamic response of a structure can be defined by its mode shapes, which can be derived through the use of accelerometers, curvature mode shapes and wavelet maps. These analyses are particularly relevant when they are carried out in service conditions [63]. Performing this analysis accurately on a full scale OWT during operation is challenging due to the high number of uncertainties of the offshore environment and extensive effort is employed to overcome this issue [64,65]. The combined wind and wave loading acting on the structure that cannot be measured accurately in a continuous way requires OMA to be adopted in order to calculate the modal parameters assuming an unknown random loading pattern [66]. Methods for OMA are based on the concept that in the analysed time interval the system is linear and does not vary with time. A key limitation of research activities taking place at the moment is because data variability, due to changes in EOC on a laboratory scale, requires basic signal processing techniques sufficient to detect damage; however, such techniques are not enough for the full scale operational environment [67,68]. Identification of scour formation based on the variation of natural frequency of an OWT is presented in [31] where natural frequencies of the support structure decreased with an increase of scour. Variation of modal properties can lead to approaching the rotor's frequency of rotation. Therefore monitoring of these values is recommended and currently applied towards developing maintenance intervention activities with respect to scour [31,64].

Resistance-based damage detection offers the capability for local damage detection through piezoelectric materials which can detect the damage by monitoring their electrical impedance. In case the excitation frequency is of a certain magnitude, only the local response of the structure will be transmitted to the sensor. This technique can be effective for multiple applications and materials including composite structures [69–71].

Fatigue and Modal Properties Monitoring are among the most common SHM techniques for OWT structures with very broad applicability. This is primarily due to their simplicity and integration into CM techniques, which refers to the instrumentation and monitoring of rotating machinery, based on the vibration-based inspection method [72].

4.3.1.5. Strain Monitoring

Strain monitoring detects microscopic length variation on a structure at pre-established locations of interest, which does not directly infer damage detection but can be translated to damage once set values of strains (that can be translated into stresses) exceed certain limits and the prior stress field of the structures is known. Strain sensors should be positioned in locations of large enough deformation so as to identify local damage and this may be a limiting factor for their further applicability [73]. Application of strain monitoring has been documented for the case of continuous monitoring of an operational 4.5 MW WT [74]. In WTs, damage to blades, tower and foundation can be identified based on strain monitoring mounted in critical areas.

The Strain Memory Alloys Method relies on an irreversible crystallographic transformation for its smart properties, where this transformation consists of the change from one crystalic state to another (paramagnetic to ferromagnetic). These are passive systems as continuous power supply and data storage is not required (apart from the interrogation phase) [75].

Table 2: Technology assessment: capabilities and limitations

Technology	Capabilities	Limitations
Acoustic Emission Monitoring Type of sensors: - Piezoelectric Transducers	• Very effective in detecting failure mechanisms up to microscale. • Allows a simple, rapid and cost-effective inspection or monitoring of a structure. • Good response at low frequencies. • Multifunctional character of piezoelectric sensors.	• Limited application offshore. • Variable damage characterization and assessment effectiveness depending on the algorithm. • Optimization of data processing needed as it still takes up much time and computational effort. • High sensitivity to background noise. • AE systems can only qualitatively gauge how much damage is contained in a structure. • Determining acoustic signature of the structure is very difficult.

Thermal Imaging Method Type of sensors: - Impedance tomography - Thermography (infrared cameras)	• Fast. • Cost effective. • Trials using drones are currently being conducted, which will detect cracks up to 0.3mm based on technology limitations, avoid the necessity of having personnel inside the turbine and be even more cost-effective. Moreover, time required would be less than for traditional sensors.	• Limited implementation in offshore structures. • Camera resolution for detecting cracks. • Laborious image processing. • Cracks detection needs more automation from footage.
Ultrasonic Methods Type of sensors: - Piezoelectric Transducers	• Sensitive to both surface and subsurface discontinuities. • The depth of penetration for flaw detection or measurement is superior to other NDT methods. • Only single-sided access is needed when the pulse-echo technique is used. • It is highly accurate in determining reflector position and estimating size and shape. • Minimal preparation is required. • Electronic equipment provides instantaneous results. • Detailed images can be produced with automated systems. • It has other uses, such as thickness measurement, in addition to flaw detection.	• Surface must be accessible to transmit ultrasound. • Skill and training required is more extensive than other methods. • Coupling medium to promote the transfer of sound energy into the test specimen is required. • Difficulty of inspection of rough, irregular, very small, exceptionally thin or not homogeneous materials. • Difficulty of inspection of cast iron and other coarse grained materials. • Linear defects oriented parallel to the sound beam may go undetected. • Reference standards are required for both equipment calibration and the characterization of flaws.
Fatigue and Modal Properties Monitoring Type of sensors: - Accelerometers. - MEMS. - Plastic optical-fiber based accelerometers. - Velocimeters.	• High reliability, mature technology. • Easy installation. • There are many different techniques available for this purpose. • Recent developments in Operational Modal Analysis solve some limitations. • Stable performance.	• Difficult analysis in operating conditions. • High number of uncertainties when applied in the offshore environment. • Environmental and Operational Conditions changes have to be accounted for in the results. • Difficulties in wind and wave loads measuring.
Strain Monitoring Type of sensors: - Strain gauge (capacitance, inductance, semiconductor and resistance). - Fiber optic cables. - Fiber Bragg Grating (FBG).	• Easy installation process once appropriate training has been undertaken. • Mature technology. • Optical fiber might be the future of strain monitoring as it is less prone to fatigue, eliminates wiring issues and allows more points to be monitored with the same cable.	• Not very robust system. • The installation is very sensitive to misalignments. • Reduced service life. • Distance between the sensor and the Data Acquisition System influences accuracy and limits sensor location. • Mechanical properties limitations. • Can be affected by EMI noise.

Table 3: Technology providers

Technology	Providers
Acoustic Emission Monitoring	• Physical Acoustics (USA) • Mistras (USA) • Vallen Systeme (Germany) • McWade Monitoring Systems (UK) • National Instruments (UK)
Thermal Imaging Method	• Mistras (USA) • UTC Aerospace Systems. Sensors Unlimited (USA) • MOBOTICS (UK) • FLIR (USA) • COWI (Denmark)
Ultrasonic Methods	• Mistras (USA) • Mistras Eurosonic (UK) • PEPPER+FUCHS (UK) • National Instruments (UK)
Fatigue and Modal Properties Monitoring	• Mistras (USA) • PEPPER+FUCHS (UK) • National Instruments (UK)
Strain Monitoring	• PEPPER+FUCHS (UK) • National Instruments (UK) • HBM (UK) • RES Offshore • Vishay

4.3.2. Operational Evaluation

During the Operational Evaluation stage, the problem's boundaries are set by defining clearly what constitutes damage for the specific application or class of structures. Furthermore, from the initial design stages of the SHMS, the identification of causes, effects and features is completed [76]. Approaches such as FMECA are particularly compatible to this aim, which is shown in some of the following reviews of OWT failure modes [4,19,77].

Effective detection of structural damage can be carried out by some of the different technologies mentioned earlier. The election of the most suitable technologies constitutes a multi-criterion problem and should take into consideration the accuracy of damage detection these possess and their cost. A review of damage detection methods through the change in modal properties is presented in [49], while more specifically relevant methods are classified as: Natural Frequency Based Methods, Mode Shape Based Methods, Mode Shape Curvature Based Methods, Strain Mode Shape Based Methods, Dynamically Measured Flexibility Based Methods, and Neural Network Based Methods.

The principal failure mechanisms that an OWT's tower and foundation might undergo are corrosion due to harsh environments and fatigue due to combined wind and wave loading [78,79]. These are produced by the augmentation of stresses due to resonance, which takes place when natural frequencies are found to be similar to the rotor's frequency. For pile foundations, scouring and reduction in the foundation's integrity is another issue to be considered, as it reduces the fundamental structural resonances of the support structure. By the detection of this reduction, scour development is considered as a damage indicator as it can be correlated to a change in the natural frequency of the tower and an increase in the fatigue damage [31,80].

The structural integrity of an OWT is typically represented as a stochastic function influenced by the loads acting on it. Damage is acknowledged to have occurred when at least one of its properties varies. Nevertheless, changes in EOC may produce changes in these properties without the occurrence of real damage [67]. This constitutes a very important feature to be accounted for during the design of SHMS, as the extent to which these EOC influence the integrity of the unit is often difficult to determine [45]. The consequences that the variations in the EOC have on the dynamic behaviour of structures are discussed in [81]. To conclude, any methodology employed must be able to differentiate whether the source affecting the signal at every moment is a variation in EOC or damage, in order to ensure that the SHMS is detecting only real damage within the structure. The application of SHMS in offshore environments introduces additional challenges as they need to overcome these additional constraints in addition to the actual loading, providing accurate results.

4.3.3. Data acquisition, normalization and cleansing

4.3.3.1. Sensors

Tower and foundation are critical components that must sustain associated loads, partial failures of which would cause catastrophic consequences, as no replacement can happen without undertaking significant costs. Sensors should be considered in these components both for the operational management as well as design verification, ensuring accuracy of the design calculations. For each of these two purposes, SHMS should have different characteristics. Relevant SHMS consist mainly of fatigue and modal properties monitoring (strain and vibration monitoring), corrosion and scour monitoring.

These monitoring techniques comprise vibration monitoring-based methods (accelerometers, piezo or micro electromechanical systems (MEMS)), strain (strain gauge or fiber optic cables), UT waves which are widely applied in composite structures (piezoelectric transducer), acoustic emissions (usually barrel sensors), impedance techniques, laser vibrometry, impedance tomography, thermography (infrared cameras), laser ultrasound, nanosensors, and buckling health monitoring. The required sensors for fulfilment of these techniques are introduced in this section.

Structural dynamic responses are usually monitored by embedded strain gauges, piezoceramics or accelerometers. Accelerometers are mechanisms which measure the acceleration at a particular moment and compare it with gravity. They are commonly provided as MEMS which are very small devices with computing capability. Accelerometers are usually employed for modal parameters and vibration monitoring of the blades, tower and foundation of the WT. There are various types of accelerometers available, such as piezoelectric, optical, laser, capacitive, and servo. A few factors influence the election of accelerometers for a particular application; these are the amplitude and frequency range of the response, sensitivity, resolution, etc. [82].

A different type of sensor, which could also be employed for the analysis of modal properties, is the piezoelectric patch. These are installed at critical locations of the support structure with the aim of comparing their natural frequency. Velocimeters, on the other hand, are based on a principle similar to interferometry. In SHM these devices are employed to determine displacement by integrating acceleration or velocity measurements of the structural members to which they are attached [83].

Two approaches using different type of sensors are generally used for strain measurement: traditional electrical strain gauges and relatively modern fiber optic [84]. Electrical strain gauges have become so widely applied that they dominate the entire field except for special applications. They are, along with electrical resistances, the most popular types of sensors, closely followed by Fiber Bragg Grating (FBG) sensors, which recently have experienced considerable improvements [85]. Different electrical sensor types exist including capacitance, inductance, semiconductor and resistance. Each is sensitive to a differing electrical property. Resistance strain gauges record the resistance variation of an electrically conductive wire relative to displacement. This resistance variation occurs due to a change in the cross-sectional area and length of the wire, as the specimen is elongated. Strain gauges are also employed for failure identification in conductive bolted joints. A novel methodology for assessing the SH of alumina nanocomposites, due to the variation in electrical conductivities after indentation, is proposed in [86].

Piezoelectric materials, when subjected to stress, produce an electric field and vice. Thus, variations in the structural behaviour produced by reductions in mass, stiffness or damping, would certainly produce a change in the mechanical impedance, which makes this variation a clear damage indicator [87]. Some common drawbacks that strain gauges could undergo are explained in [84]; these are: nonlinearity, hysteresis and zero shift due to cold work.

Cracks and displacements can also be monitored by fiber optic sensors which usually are: spectrometric, interferometric or intensity-modulated. An optical fiber is a glass or plastic fiber designed to guide light along its length. Moreover, FBGs were also proved to be useful as a corrosion transducer and temperature sensor simply by adding a metal coating to one segment of the fiber [88]; as a pH-sensitive corrosion detector [89]; and good at delamination identification [90].

4.3.3.2. Data collection and storage

Dynamic data acquisition is a complicated, laborious and expensive procedure. The recently achieved maturity of wireless monitoring constitues a big progression in SHM and Infrastructure Asset Management as it integrates wireless communications and mobile computing with sensors. The result is a more economic sensor platform that has three aims: acquisition of structural response data, local interrogation of collected measurement data, and wireless transmission of that data or analysis results to a Wireless Sensor Network (WSN), which comprises other wireless sensing units [91]. As explained in [92], a WSN is constituted by four stages: communication, data acquisition, processing, and fusion stages. Moreover, WSNs encompass many fields: wireless communication, network technology, integrated circuits, sensor technology, MEMS, among many others. The data acquisition systems have multiple design parameters: a number of channels, a maximum sampling rate, and resolution, among others; a computational core, where data is stored and which possesses processing capabilities; and the wireless communication channel.

An assumption usually made, is that traditional cable-based monitoring systems are cheaper and easier to install. However, this is not true as it is not only more expensive, but also brings up complications during installation due to the cabling. Furthermore, wireless sensors are considerably cheaper and easier to install than traditional cable-based systems. Wireless sensors are not exactly cable-based sensor replacements; without wires, wireless sensors usually depend on internally stored power for operation, which needs to be accounted for during the design phase of the SHMS. A few issues with WSN for SHMS are [93]: compatibility issues between sensors, their sampling frequencies, the problem of transmission bandwidth and real-time ability variance, the selection of a wireless transmission frequency, topology choice, data fusion method, and the contrast between the energy consumption requirements of different applications to that of each different device.

The numerous acquired data from WTs contains key features crucial for future developments in the field. For that reason, operators have started appreciating the importance of investing in SHMS. Although monitoring has many proven advantages, it is expensive, which is why only a few operational turbines have extensive sensor instrumentation.

4.3.3.3. Data Normalization and Cleansing

The capacity to normalize the acquired data according to the variation in EOC is a fundamental element of the SHM process, which is vital for avoiding false positive indications of damage. Two strategies can be employed for normalizing these data: when the EOC are and are not available. The most important aspect related to the correctness of the normalization process involves the damage sensitive features to be extracted from the data. It is importhat not to lose these damage sensitive features during the normalization. There are several data normalization approaches: off-sets removal by subtracting the mean value of a measured time history, the division by the standard deviation of the signal for normalizing varying amplitudes in the signal, curve fitting of analytical forms of the frequency response function to measured frequency response functions in experimental modal analysis, etc.

Data normalization is a crucial aspect of the damage identification process as it affects significantly Neural Network (NN) performance. The different uncertain parameters in the data acquisition stage must be identified and, if possible, minimised or removed [94]. Therefore, appropriate measurements need to be carried out in order that such sources of variability can be statistically quantified. Data normalization for SHMS in OWTs is a topic currently under development as, in order to achieve successful SHM goals, procedures capable of determining whether the measurement's variations are motivated by damage in the structure or by changes in the EOC, are required [95].

Data cleansing is the procedure of selectively choosing data to pass on to or to reject from the feature selection process or, in other words, the procedure of selectively discarding data that might not represent the system's behaviour. Data cleansing is a complicated exercise, as it usually relates to experts' knowledge acquired during previous campaigns. An example of data cleansing could be when measurements are odds due to the fact that a sensor results in being loose wherever it is placed and therefore its measurements are no longer accurate, as they can jeopardise the accuracy of the data set. Signal processing techniques, such as filtering and resampling, can also be thought of as data cleansing procedures [51,96,97].

4.3.4. Feature Extraction and Information Condensation

Damage sensitive characteristics are application-specific and are identified during the feature extraction process from data obtained from the structure. A typical approach is a direct comparison between actual data from an SHMS and data obtained (from observations, testing or simulations) at an instance of a damage inducing event. Sources of uncertainty when considering data from testing or simulations should be taken into account as loading conditions should be realistic to the application and should include effects of fatigue, corrosion or temperature to evaluate the cumulative effects of certain types of damage [98–100].

An inherent part of the feature extraction procedure is that of data condensation as different sources of data collection normally produce large and unmanageable amounts of data, hence reasonable processing (averaging, dimensionality reduction) should take place in order to allow analysis through statistical models. This process can allow benchmarking of various datasets which correspond to different time intervals of the structure's service life. When applying such techniques, ensuring sensitivity of data against EOC is pertinent. Robust data reduction techniqes reported are the Principal Components Analysis, Discriminant Analysis, and Regression Analysis.

In cases when a high level of accuracy needs to be achieved, the process can also employ a combination of dedicated sensors in a technique referred to as Structural Neural Systems where several sensors are distributed across the structure [101]. This approach, however, can have high requirements in computational power.

4.3.5. Statistical Model Development

Statistical Model Development aims to process the extracted features, identifying and quantifying damage in a structure. The available algorithms are classified in supervised and unsupervised learning [51,102,103], depending whether the algorithms contain or not information from the damaged structure. This section will briefly present methods for both approaches.

4.3.5.1. Supervised Learning

Supervised learning algorithms normally involve higher amounts of data than unsupervised ones from various potential damage situations of the asset. Such data can come from numerical modelling (i.e. FEA models) or testing (i.e. through experiments). Special care should be placed in the uncertainty that incomplete data or unrepresentative testing may introduce in the analysis.

Table 4: Supervised learning algorithm

Method	**Description**	**Relevant References**
Response Surface Analysis	The RSA obtains the approximation relationship between the resonance frequencies and other damage parameters (i.e. damage location, and size). Applications on the identification of composite structures have been	[104]

(RSA)	effectively reported. Drawback of the method is on the requirement for extensive data from various damage conditions.	
Fishcer's Discriminant	This method introduces a linear transformation of the original multivariate distributions into univariate distributions whose means are as far apart as possible, while the variances of those transformed distributions are as small as possible. It has been satisfactorily applied to concrete columns subject to static and dynamic testing but has not been applied to OWTs yet.	[105]
Neural Networks (NN)	NNs are the group of statistical learning models inspired by biological NN and are commonly used in SHMS for identifying, locating, and quantifying damage in structures. They are used to approximate functions that can relate to a large number of inputs having various outputs. They have been used for the assessment of structural damage and damage detection and location of complex structural systems with applications using FEA data to train the non intact states.	[106]
Genetic Algorithms (GA)	GAs can be used for the identification of location and characteristics of damage mechanisms such as cracks through employing structural parameters such as modal properties. There are some practical issues to be overcome as the complexity of the system increases as computation may become difficult.	[107]
Support Vector Machine (SVM)	SVM constitutes a powerful framework for general classification and regression problems, as many different types of discriminant functions, such as linear, nonlinear, NN, and radial-basis discriminant functions, can be integrated in this tool with no real modifications.	[95,108]
Additive Tree models	The random forest (RF) is perhaps the best-known ensemble method; it combines decision trees to achieve an improved predictive performance, and offers various useful features: it provides an intrinsic evaluation of the results based on the data discarded by bootstrapping and variable importance estimates are also provided.	[109]

4.3.5.2. Unsupervised Learning

Unsupervised Learning is adopted when no damage state data is available. Its limitation is in the fact that it can be used to detect the damaged state but offering limited information about its characteristics [110,111]. Novelty or anomaly detection is to achieve training data from the normal EOC of the structure or system to establish the diagnostic. A model of the normal state is created with the aim of comparing it with the current state of the asset. If a significant deviation is detected this is characterised as novelty, hence denoting damage.

Table 5: Unsupervised learning algorithm

Method	Description	Relevant References
Control Chart Analysis (CCA)	This approach continuously monitors the features extracted from the measurements for anomalies. When the observations fluctuate outside the control limits, the monitoring system alarms the abnormality of the system's condition. CCA is frequently used for process control of complex engineering systems.	[105]
Outlier Detection	This is the primary class of algorithms applied in unsupervised learning applications by assessing statistical distributions of the measured or	[112]

	derived features to enhance the damage identification process. They are typically used to answer questions regarding the existence and location of damage. The basic principle of novelty detection is that a model of the system is built using training data only acquired from normal EOC of the structure. While the monitoring of the structure takes place, newly acquired data is compared with the model. In the case that significant deviations are found, the algorithm indicates novelty, which means that the system has deviated from the normal condition and, therefore, is damaged. The statistical models are also used to minimise false indications of damage (both false-positive and false-negative), as these are undesirable.	
Neural Networks (NN)	NN can also be used in an Unsupervised Learning mode when no data from damaging events is available. Data obtained from FEA simulations is used to train the NN; the modal parameters from the FEA simulations being used as inputs. The NN output will consist of structural parameters. Once modal parameters from the actual structure become available, the NN is used to calculate the associated structural parameters. Finally, the FEA model is updated using these new structural parameters, calculating the associated modal parameters. Training will stop when the measured modal parameters are acceptably not so different from those calculated from the FEA model.	[68]

4.4. General requirements for a reliable and efficient monitoring system

Dealing with offshore wind turbines is more challenging than dealing with onshore wind turbines, especially when the substructure is under consideration. Indeed, if the monitoring system fails, maintenance can be difficult as it may require to go offshore under harsh environment conditions and diver-based maintenance. Compared to the oil & gas experience, Wymore *et al.* [13] pointed out that the loadings and solicitations that wind turbines have to withstand are different from those of common offshore platforms, while, at the same time, being less massive than other offshore structures, which has to be considered when designing a monitoring system.

Taking into account past experience and considering the information provided in [5,13,21,113–116] parameters to be taken into account when considering using SHM are as follows, subdivided into six categories:

- Cost efficiency:
  - Service life of the whole system under harsh environment conditions
  - Cost of the system
  - Robustness of the different elements of the system
  - Modularity
- Installation and maintenance:
  - Hardware (sensors and data acquisition system):
    - accessibility of the areas to be monitored
    - downtime of the turbine if necessary
    - working lifetime without service
  - Software
    - possibility of remote maintenance

- Power requirement and/or autonomy of the system
- 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 parameter 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 the calculation 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.

For monitoring systems already available on the market, TRL (Technology Readiness Level) must also be considered. It is also important to think about a back-up plan if the system fails. Besides, most systems have to be tested and validated in a lab before being installed on-site, ideally for a first experiment. An analysis of integration cost should also be performed for on-site testing in order to quantify expected benefits [36]. Hence, if the system is proved 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 calculation. Such calculation would also provide valuable information on the operating range of the sensors that should be chosen.

5. Sensor Technology Review based on Operational Experience

Monitoring is the only solution to determine the state of the structure in real time, but it also enables gathering data of a different nature and, through post-processing, gain a better understanding of the behaviour of the structure in a harsh environment. Such knowledge can, in the short-term, be used as a decision tool for O&M and, in the mid- or long-term, improve wind turbine design. In this report, focus was placed, following an FMECA workshop on foundations, on crack propagation and strain monitoring, corrosion monitoring, bolt monitoring and scour monitoring based on experience from operational wind farms. However, except for grout connection, most failure modes and mechanisms are common to both MP and jacket foundations.

The areas of interest (hence to be monitored) appear to be the grout connection, welds, the internal part of the MP (looking for corrosion), bolted connections and the seabed around the MP (scour detection). There are similar areas of interest in jacket foundations, those being the steelwork and potential fatigue cracking, local and global scour development, the integrity of the connection between the jacket legs and the pin piles, and the tensioning of the TP-tower bolted connection.

In the case of indirect measurement, the physical dimension determined by measurement is not *directly* related to the damage mechanisms under consideration, but provides information on the damage state of the structure. Most common indirect measurements rely on vibrational and modal analysis as well as inclination, and enable detection of damage but not the identification of the nature of such damage. Different kind of damage can, indeed, lead to the same response of the structure. However, a structural CMS and defined data analysis method should aim to identify the sources of damage and localize the damaged areas as far as practical as this would provide very valuable information to the asset owners when it comes to operation of the offshore wind farm and planning of the required inspection and repair activities.

In a general manner, a structural CMS should fulfil one or more of the following objectives:

- Inform on the actual conditions of the support structures providing data for the life cycle and condition prognosis.
- Evaluate the real ultimate load and the remaining fatigue life.
- Identify changes in the load bearing capacity and dynamic response of the structure.
- Identify sources of damage and localize damaged areas as far as practical.

The following paragraphs give an overview of the operators' experience with specific monitoring sensor types and technologies.

LVDT and electrical strain gauges are the most common sensors used for strain monitoring, and are accurate and reliable. An optical strain gauge (FBG sensors) might also be used. Using FBG sensors, the temperature can also be measured, which is an advantage since several physical variables' measurement is temperature-dependent. Alternatively, strain gauges can be complemented with temperature sensors to ensure temperature correction and ascertain any specific behaviour resulting from thermal gradients.

As already mentioned, the grout connection and welds should be monitored. With regards to the grouted connection of jackets, the issue mainly lies with the confinement of this connection and the total lack of access. At present there are no suitable inspection techniques neither wide experience in monitoring. Welding areas could also be monitored using acoustic emission, but it might be difficult to identify the signals related to actual damage. Localization of the damage could also be performed using FBG, while it is usually done through acoustic emission. Thus, combining both techniques could also provide a better understanding of the phenomena and help optimize the measurement systems. As far as mechanical damages are concerned (whether corrosion is the root cause of the damage or not), hotspots to be monitored should be defined using finite element calculation. Such calculation would also provide valuable information on the operating range of the sensors that should be chosen. However, it can be difficult to take into account all the parameters involved. Inclinometers and accelerometers can also be used all along the monopile/jacket and corresponding transition piece in order to detect any possible deviation from a reference state, through modal analysis (for accelerometers). It is also common practise to equip the WTG tower with additional accelerometers to enhance the monitoring capabilities. Also, worth mentioning that typically the WTG RNA is equipped with one or more acceleratomers at the nacelle level as part of the “safety system” of the WTG. Although the information that can be extracted from those is limited, these are normally arranged on all WTGs of the offshore wind farm and, therefore, enabling to have a high-level overview of the dynamic behaviour of each individual asset. These techniques are reliable but it is important to keep in mind that, even though such methods can provide valuable information on the state of the structure, it can be difficult to identify which is the phenomenon responsible for the deviation from the normal behaviour. Furthermore, for modal analysis, identifying the cause of abnormal response requires a model for which it can be difficult to identify all the parameters.

As for the areas in contact with seawater, corrosion can be a major issue, for the fatigue life of the structure (reduced if affected by corrosion), but also for health and safety reasons. Considering the chemical substances appearing when there is corrosion, hydrogen, hydrogen sulphide and pH are the variables that should be monitored in monopiles. Such data would provide information in the evolution of corrosion within the monopile, but it might be difficult to correlate this to a damage state. pH, hydrogen and hydrogen sulphide sensors are also often installed within monoplies in wind farms for corrosion monitoring. In jacket structures, internal corrosion is not initially an issue and, therefore, there is less experience in the area of corrosion monitoring. In oil and gas it is common practise to equip some selected anodes with reference electrodes to have a continuous track record of the protection levels. However, in offshore wind, where there are many structures of the same type, the current trend is to carry out cathodic protection surveys on a number of pre-selected locations. As more offshore wind farms are developed with Impressed Current Cathodic Protection (ICCP) systems, corrosion monitoring would become more relevant as this is in inherent part of ICCP systems.

Scour can be detected using vibration and modal analysis or through direct measurements. The main advantage of direct measurement, performed preferably with a sonar mounted on the MP or by using a reference rod located near the MP (TDR technique, modal analysis, strain measurement), is that it provides scour depth. In jacket structures, direct measurement of scour might prove more challenging and complex, due to the larger footprint, appearance of local and global scour and the complexity of these assets. More sensors, cabling, etc. are required to be able to obtain a "picture" of scour around a jacket structure in comparison to an MP one.

Modal analysis can provide scour depth but, therefore, modelling using real parameters appears as mandatory, and it can be difficult to identify such parameters. Furthermore, several phenomena (and damages) can have an influence on the vibration response of the structure and it can be difficult to decorrelate them and identify the main cause of the deviation from the reference state. However, in the specific case of scour monitoring, evaluation of the natural frequency of the asset has proved to be useful for ascertaining failures concerning excessive scour as was the case of one WTG location at Scroby Sands offshore wind farm. The aforementioned caveat is applicable to vibration-based methods in general, not only when used for scour monitoring. Hence, as already mentioned, it can be interesting to combine different techniques to be able to decorrelate the physical phenomena present.

Finally, several systems are available for bolt tension measurement, but it seems difficult to use such systems as monitoring systems. Besides, as it might be very expensive and not cost-efficient to monitor all bolts, a good solution to detect a possible bolt-loosening would be to perform a vibration or modal analysis of the area of concern in order to detect a deviation from the original state, using accelerometers. However, once again, other phenomenon might interfere and it could be interesting to install two systems, e.g. bolt-tension measurement and accelerometers, for comparison and to have a better understanding of the physics. Another barrier in relation to the bolt tension measurement is the interface with the WTG OEM as in the majority of the cases these bolted connections refer to the connection between the support structure and the WTG tower. There are commercial obstacles which may impede the installation of monitoring devices in this area – an agreement with the OEM is strictly required which may be difficult to achieve. As more MPs are being installed with bolted connections between MP-TP rather than typical grouted connections, this monitoring technique may prove interesting to monitor the long-term performance of these connections and easier to achieve as the decision would mainly rely on the asset owner/operator.

Hence, in a summary, monitoring would help optimize O&M by enabling a potential reduction in the number and scope of offshore inspections, assess the lifetime of offshore wind turbine structures during their operation and provide guidelines to improve the design of future turbines by reducing the uncertainty levels and possibly contribute to regulation and standardization. A general summary table is presented in Table 6. Based on operational experience the following sensors can be found in an offshore wind farm:

Monopile monitoring sensor layout:

Strain monitoring sensors:

- Strain gauges: to estimate both general loading, and hot spot stresses, a combination of strain gauges installed on the TP.
  - vertical strain gauges
  - "T" strain gauges
  - torsional strain gauge

  } all located at the same distance from the weld, above the MP

- stress concentration strain gauges located at different distances from the weld, above the MP

Thermocouples installed on the TP for temperature correction of strain gauges.

- LVDTs: to monitor the grouted connection
  - Vertical LVDTs: measurement of the relative displacement between the stopper plate and the MP
  - Horizontal (radial) LVDTs: measurement of the relative displacement between the MP and the TP
  - Torsional LVDTs: measurement of the relative torsional displacement between the stopper plate and the MP.

Corrosion measurement sensors:

- 1 pH sensor, installed on the inside edge of the lower working platform, below the surface of the water at the time of installation.
- 2 Hydrogen sensors (H) installed within the lower working platform (1 sensor above the walkway / 1 sensor beyond the airtight platform)
- 1 Hydrogen sulphide sensor (H_2S), installed in the lower working platform (above the walkway, at the same level as one of the hydrogen sensors).

Inclinometer installed:

- 1 biaxial (X-Y) inclinometer: measurement of the inclination of the TP above the airtight deck. The inclinometer has been installed in the same position as the accelerometer (see below).

Accelerometers installed:

- 2 uniaxial accelerometers (1 X direction / 1 Y direction): measurement of the radial vibrations of the TP above the airtight deck, mounted within the turbine. The inclinometer and the biaxial accelerometer are installed in the same position.

Jacket monitoring sensor layout:

Strain monitoring sensors:

- 1 strain gauge per jacket leg to extract loads and estimate bending moment at the top section of the TP of the jacket structure. These are “Y type” and self-temperature corrected.
- 3 temperature sensors installed at the TP central annulus to identify any major contribution to the loads and stresses from thermal gradient.

Corrosion measurement sensors:

- Not applicable.

Inclinometer installed:

- 1 biaxial (X-Y) inclinometer installed at the TP central annulus.

Accelerometers installed:

- 1 triaxial accelerometer (3D) per jacket leg.
- 3 biaxial accelerometers (2D) installed at the TP central annulus.

Table 6: General summary table of the sensors and techniques available for fatigue monitoring due to mechanical loading and possibly to corrosion, scour and self-loosening of bolts

Sensor / system type	Fatigue (mechanical loading and, possibly, corrosion): Crack propagation	Fatigue (mechanical loading and, possibly, corrosion): Strain (vertical, horizontal, torsional, "T")	Corrosion	Scour	Self-loosening of bolts
Acoustic Emision	■				
Strainstall Crackfirst™ system	■				
Strain gauges (electrical, optical)		■			■
Stress concentartion strain gauges		■			
LVDTs		■			
Electrical resistance (ER) probe for real-time measurement of the corrosion rate			■		
Magnet-mounted reference electrodes measuring the protection potential in projects with CP			■		
Hydrogen sulphide (H_2S)			■		
Hydrogen (H)			■		
pH			■		
Dissolved oxygen			■		
Pulse or radar devices				■	
Time Domain Reflectometry (TDR)				■	
Ground Penetrating Radar (GPR)				■	
Sonar mounted on the structure				■	
Acoustic Doppler Current Profilers (ADCP)				■	
Optic fibre sensors of different technologies				■	
Driven or buried rod devices				■	
Sliding Magnetic Collar (SMC)				■	
Steel rod				■	
Electrical conductivity/resistivity devices				■	
Electrical capacity devices				■	
UT-based method					■
Acoustoelastic effect based method					■
Piezoelectric active sensing method					■
Piezoelectric impedance method					■
Inclinometers	■			■	
Accelerometers	■			■	■

In grey: techniques less interesting than the others

6. Selection Criteria and Key Performance Indicators of SHM

The scope of WP1 and WP4 are linked together as the first considers identification of failure modes and the second the investigation of the physics behind common causes and the characterization of the capabilities of different monitoring techniques for the timely identification of damage that can lead to failure. Following execution of the FMECA workshop from WP1, the delivery team of WP4 has come together in order to perform the task above. More specifically, the following approach was followed:

1. Review FMECA Sheets and extract all relevant failure modes.
2. Review the failure mechanisms from root cause to failure mode.
3. Review if any of the in-between steps of the failure mechanism can potentially be monitored based on known physics.
4. Focus on those mechanisms that show time behaviour to allow for enough time for maintenance mobilization/failure prevention or mitigation.

The identified failure modes were grouped where possible and three generic root causes were chosen to be relevant across all cases:

- Root Cause 1: Fabrication and installation
- Root Cause 2: Design
- Root Cause 3: Operation and Maintenance

The following six performance indicators were also selected in order to evaluate different techniques:

1. Reduce inspection frequency
2. Reduce inspection extent
3. Mitigate unplanned maintenance
4. Update structural capacity
5. Avoid secondary damages
6. Maturity level

Further, two extra codes were employed: [X]: Monitoring might not be useful in a preventive manner/continuous permanent monitoring and [F]: no monitoring solution yet available but is believed to be possible in the near future.

Table 7 documents the findings of the workshop that has taken place, where a traffic light system has been adopted with green denoting an increased performance towards the relevant performance indicator, yellow for average and red for low.

Table 7: Assessment of monitoring techniques

Failure mode	Route Cause	Path	Assessment
1. Fatigue at steel structure e.g. circumferential weld	Root Cause 1: Fabrication and Installation	Path 1.1 earlier crack initiation and crack growth/propagation [F] through cyclic loading (acoustic)	1 2 3 4 5 6
		Path 1.2 contamination of surface or insufficient surface preparation for coating, coating damaged e.g. peeled painting	[X]
		Path 1.3 excessive fatigue life consumption/loading during handling at fabrication site, during shipping and during installation (CMS in place before operational phase)	2 3 4 5 6 7
	Root Cause 2: Design	Path 2.1 industry standards e.g. material factor, e.g. SN curves not sufficiently applicable to wind, earlier crack initiation and crack growth/propagation through cyclic loading	[X]
		Path 2.2 ICCP system in place, ventilation system for compartment faulty, H_2 is exceeding allowed concentration, material becomes brittle, crack initiation and growth acceleration.	1 2 3 4 5 6
		Path 2.4 underestimation of wind turbine loads, environmental conditions and operational conditions e.g. extreme events, grid faults	1 2 3 4 5 6 1 2 3 4 5 6 For Jacket
		Path 2.5 underestimation of marine growth [F]	1 2 3 4 5 6
	Root Cause 3: O&M	Path 3.1 ventilation system is plugged, H_2 is exceeding allowed concentration, material becomes brittle, crack initiation and growth	1 2 3 4 5 6

		accelerated. See Path 2.2	
		Path 3.2 crack is not detected, crack propagation continues. See Path 1.1	1 2 3 4 5 6
		Path 3.3 ICCP system reference cell is broken and gives wrong values, underprotection, corrosion (hot redundancy of reference cell provides correct electrical potential)	1 2 3 4 5 6
		Path 3.4 scour protection damage, scour depth increased, degradation excessive loading	1 2 3 4 5 6
2. Excessive Corrosion MP	Root Cause 1: Fabrication and Installation	Path 1.1 coating peels off	[X]
	Root Cause 2: Design	Path 2.1 insufficient CP (electric potential) of MIC e.g. high sulphate concentration, excessive MIC (no access to mud line conditions, measurement campaigns with coupons exist)	1 2 3 4 5 6
		Path 2.2 acidification in internal compartment (pH measurement)	1 2 3 4 5 6
		Path 2.3 gases such as O_2, CH_4, H_2S and H_2 concentrate	2 3 4 5 6 7
		Path 2.4 (X) wrong anode spacing, anode interference	[X]
	Root Cause 3: O&M	Path 3.1 damage during installation	[X]
		Path 3.2 jet washing of marine growth, damage of coating	[X]
3. Deformation, Buckling, Displacement of steel	Root Cause 2: Design	Path 2.1 underestimation of environmental and operational condition, excessive loading, buckling, crack formation	1 2 3 4 5 6

		Path 2.2 overestimation of soil capacity, soil degradation, pile displacement rotation	1 2 3 4 5 6
	Root Cause 3: O&M	Path 3.1 scour degradation, scour depth increased, excessive displacement of scour material	1 2 3 4 5 6
		Path 3.2 accidental ship impact, reduced capacity	[X]
4. Scour global/local	Root Cause 2: Design	Path 2.1 underestimation of environmental and operational condition, damage of scour protection, excessive scour. See 3.3.1 and 3.2.1	
		Path 2.2 underestimation of extreme events, damage of scour protection, excessive scour. See 3.3.1 and 3.2.1	
5. Grouted Connection MP/TP	Root Cause 1:Fabrication and Installation	Path 1.1 failed grout seal, leakage/overspilling, volume of grout is insufficient, reduced capacity in connection, global dynamics changed	1 2 3 4 5 6
		Path 1.2 loss of hard material, water ingress in porous material, sliding (LVDT) of grout against steel	1 2 3 4 5 6
		Path 1.3 improper thermal environment during installation/curing process, reduced capacity of grout, global dynamics changed	1 2 3 4 5 6
		Path 1.4 eccentricity during installation caused reduced capacity at one side of the MP/TP connection. global dynamics changed	1 2 3 4 5 6
	Root Cause 2: Design	Path 2.1 loss of hard material, water ingress [F] in porous material, sliding of grout against steel	1 2 3 4 5 6

		Path 2.2 excessive loads and displacement, debonding/lack of contact between steel and grout, sliding	1 2 3 4 5 6
	Root Cause 3: O&M	Path 3.1 excessive load on grouted connection e.g. ship impact, local impact affects the rest of the connection, reduced capacity (uncertain about the real physics behind it)	[X]
6. Broken bolted connection	Root Cause 1: Fabrication and Installation	Path 1.1 poor lubrication, ineffective contact between bolt and nut, connection undone Path 1.2 improper bolting sequence, uneven stress distribution, stress concentration, overutilization Path 1.3 missing washers, improper stress transferral, loosening of connection	[X] [X] [X]
	Root Cause 2: Design	Path 2.1 poorly specified pretension force, loosening of connection at one bolt, more bolts to loosen	1 2 3 4 5 6
	Root Cause 3: O&M	Path 3.1 excessive tensioning during testing of bolts, exceeding elastic limit, loss of pretension, see path 2.1 Path 3.2 insufficient sealing against water through grease caps, corrosion Path 3.3 internal climate control broken, high humidity, corrosive environment,	1 2 3 4 5 6 [X]
7. Icing on platforms	Root Cause 2: Design	Path 2.1 missing inclination of the steel plate, icing occurs, HS risk	[X]
8. Excessive Corrosion Jacket	Root Cause 1: Fabrication and Installation	Path 1.1 (X) coating peels off	[X]
	Root Cause 2: Design	Path 2.1 2.1 insufficient CP (electric potential), Path 2.2 wrong anode	1 2 3 4 5 6

		spacing, anode interference Path 2.3 failed seal at jacket leg, internal corrosion, lost capacity	[X] [X]
	Root Cause 3: O&M	Path 3.1 damage during installation Path 3.2 jet washing of marine growth, damage of coating	[X] [X]
9. Grouted Connection Jacketleg/Pile	Root Cause 1: Fabrication and Installation	Path 1.1 improper thermal environment during installation/curing process, reduced capacity of grout, changed dynamics; 1 and 2 green due to BSH requirement Path 1.2 eccentricity during installation caused reduced capacity at the jacket leg/pile connection, lower stiffness of that node, overutilization, changed dynamics. See 1.1 Path 1.3 missing grout volume, not sufficient coverage of shear keys, reduced capacity, changed dynamics. See 1.1	1 2 3 4 5 6
	Root Cause 2: Design	Path 2.1 underestimation of loads, grout fails, relative movement between leg and pile	1 2 3 4 5 6

7. Annex 1: Examples of industrialized solutions

In this section examples of sensors already used on wind turbines or in other industries are provided.

7.1. General

HBM:
Condition Monitoring of Wind Turbines' Critical Components:
https://www.hbm.com/en/6089/condition-monitoring-offshore-wind-turbines/

Sherborne Sensors: http://www.sherbornesensors.com/international/

Measurement specialties:
http://www.mouser.com/ds/2/261/measurementspecialtiesinc_sensors_for_wind_turbine-558860.pdf

FORCE Technology: https://forcetechnology.com/en/energy-industry/wind-power/monitoring-of-offshore-wind-turbine-foundations

7.2. Stress, strain and displacement monitoring

7.2.1. Strain gauges

HBM: strain measurement
https://www.hbm.com/en/0014/strain-gauges/

Omni Instruments: LVDTs
http://www.omniinstruments.co.uk/displacement-position-sensors/linear-position-and-lvdt-sensors.html

Woodward: LVDTs
http://www.woodward.com/PositionSensorsLVDTs.aspx

MTS Sensors: Magnetostrictive Linear Position Sensors
http://www.mtssensors.com/fileadmin/media/pdfs/Gated_PDFs/551424A_Replacing_LVDTs_TA_0513.pdf

Vishay Precision Group: strain gauges
http://www.vishaypg.com/docs/11519/standard-weldable.pdf

RDP Group: LVDTs
http://www.rdpe.com/

7.2.2. Stress monitoring

HBM: force measurement
https://www.hbm.com/en/3241/force-measurement/

7.2.3. Fatigue monitoring

Strainstall: CrackFirst™ fatigue monitoring
https://www.strainstall.com/media/case-studies/crackfirst-fatigue-monitoring/

7.3. Scour monitoring

R2Sonic
https://www.r2sonic.com/who-we-serve/

iXSurvey
http://www.ixsurvey.com.au/

CodaOctopus
http://www.codaoctopus.com/products/echoscope

7.4. Corrosion monitoring

Industrial Scientific: Hydrogen sulphide detector
http://www.indsci.com/products/hydrogen-sulfide/

Euro-Gas Management Services Ltd.: Hydrogen sulphide detector
https://euro-gasman.com/gas-sensors/hydrogen-sulphide-h2s/gas-sensors.html

Spec Sensors: Hydrogen sulphide detector
https://www.spec-sensors.com/product-category/gases/hydrogen-sulfide-h2s-sensors/

Alphasense: Hydrogen sulphide sensor
http://www.alphasense.com/index.php/products/hydrogen-sulfide-air/

Unisense: Hydrogen sensor
http://www.unisense.com/H2/

NTM Sensors: Hydrogen sensor
https://www.ntmsensors.com/hydrogen-sensors/
https://www.ntmsensors.com/products/hydrogen-sensors/ntm-senseh2-hydrogen-sensor/

Oceanoptics: Oyxgen and pH sensors
https://oceanoptics.com/product-category/sensors/

Global Water: pH sensor
http://www.globalw.com/products/wq201.html

7.5. Inclinometers and accelerometers

Sussex Sensors: accelerometers
http://www.sussexsensors.co.uk/

Omni Instruments: inclinometers
http://www.omniinstruments.co.uk/displacement-position-sensors/linear-position-and-lvdt-sensors.html

Jewell instruments: inclinometers
http://www.jewellinstruments.com/inclinometers/

Sherborne: inclinometers
http://www.sherbornesensors.com/international/products/category/inclinometers

7.6. Bolt monitoring

HBM: Strain Gauge-Based Force Washer
https://www.hbm.com/fr/2423/kmr-anneau-dynamometrique-pour-le-controle/

Ultrasound bolt tension testing
Acoustic sound monitoring if one bolt in flange is lost
http://strainsonics.com/systems/loadmonitoring-bolts/

https://www.vfbolts.com/product/maxbolt-load-indicating-fastener-system/

Erreka: i-Bolt®
http://www.errekafasteningsolutions.com/en/ibolt/

ROTABOLT®
https://www.jameswalker.biz/rotabolt

SUPERBOLT®
http://www.nord-lock.com/fr/superbolt/superbolt/

SKF: BOLTSAFE
http://www.skf.com/binary/57-124618/PUB_MT-P2_10255_FR.pdf

INTELLIFAST
http://www.intellifast.de/fr/

FUTEK
http://www.futek.com/sensorSolutions.aspx

REMBE Fibre Force
http://www.dremodisc.de/products/monibolt.html
http://www.dremodisc.de/products/spassR-dremodisc.html

RINCENT BTP
http://www.rincentbtp.fr/groupe.php

HBM
http://www.hbm.com/en/menu/products/transducers-sensors/force/paceline-cfw/

ADVITAM
http://www.advitam-group.com/Content/brochures/FR/UPUS%20FR.pdf

ULTRA RS
http://www.ultrars.com/_doc/Controle_serrage.pdf

ELCOMETER
http://www.elcometer.com/fr/cnd-ultrasons/mesureurs-de-tension-de-boulon/jauges-de-tension-deboulons-bg80dl.html

TRAXX
http://www.traxx-group.com/
http://www.traxx-group.com/produits.php?Contenu=16

BOLTMIKE III (GE / Krautkrämer)
http://www.ge-mcs.com/en/advanced-systek/advanced-systek-systems-and-solutions/2972-siwebpl556.Html

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