Condition monitoring and maintenance for fibre rope moorings in offshore wind

WP7 FIRM (Fiber Rope Mooring)

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1 Introduction

1.1 Background

The FIRM project aims to develop innovative mooring systems for floating wind farms based on fibre ropes, including new and more efficient methods for installation, condition monitoring, maintenance, and decommissioning. The project shall deliver designs for three different mooring systems. This document describes the contents of work package H7 in the FIRM project, which is described in the project description as given below:

> *H7 Condition monitoring and maintenance (industrial research – NORCE and rope suppliers)*
>
> *Objective: Develop condition monitoring and maintenance system for the mooring systems developed under the work packages H4, H5 and H6.*
>
> *Description: Based on experiments in H2, this work package supports and is well integrated with H4, H5, and H6. Since many aspects of monitoring and maintenance should be the same for the different flavours of mooring systems developed, the work is reported in this separate work package.*
>
> *Deliverables: Report describing the condition monitoring and maintenance systems developed for the mooring systems of H4, H5 and H6. Brief status reports after year 1 and 2, final report due at end of project.*

The importance of accurate knowledge of maintenance cost is highlighted by Rinaldi et al.[1]. They showed how the use of detailed models gave improved insight as compared to the often-used approximate methods used to estimate these costs. A clear plan for condition monitoring and maintenance is a prerequisite for reliable cost estimates for operation and maintenance.

The present project is limited to self-floating, self-stable structures, i.e., capsizing is not considered. The worst-case scenario for mooring failure is therefore drift-off, which could give collision and/or power cable problems. If one of three lines is lost, the other two lines may also get intertwined. It is not a requirement to determine where on a line there is a problem, only if a line is broken, or if it is about to break.

The present report focuses on the fibre rope part of the solution. Any condition monitoring and maintenance of anchoring, chains, clump weights, buoys, power cables, tension limiting system, etc. are therefore treated in less detail. The design of anchor piles is covered in detail in the project's work package H8, and a review of the basics of installation and monitoring of suction anchor piles is given for example by Colliat et al.[2].

The report starts by describing the mooring systems considered, followed by a listing of failure modes, how these problems can be detected, and how the ropes can be maintained, before the report concludes by giving concrete designs for condition monitoring and maintenance for the solutions that are part of the FIRM project.

1.2 Method

The work started with a literature search on the topic. All project partners were then invited to short interviews, ideas were discussed with NORCE colleagues, and a local equipment supplier in Arendal, Volue (Industrial IoT), previously Scanmatic, gave a brief presentation of their relevant solutions.

During October and November 2020 interviews were held with Øystein Refsland Andreassen from Aibel, Torkjell Lisland from Seasystems, Niklas Norman from Semar, Håkon Andersen from Dr. techn. Olav Olsen, Jose Canedo from Lankhorst, Timothy Hunter and Greg Mozsgai from Bridon, Øystein Ryste from Kongsberg Maritime, and Tor Anders Nygaard from IFE. From NORCE Alessio Gomiero, Gunhild Bødtker, Jon Oddvar Hellevang, Peter James Thomas, and Rune Schlanbusch have all given valuable contributions. Thanks to all for sharing their insight!

For concrete designs, prices and other information for possible systems must be retrieved. A workshop for all interested partners was held October 14th 2021. This led to specific designs for the FIRM projects, but also to the identification of topics where more information is needed.

1.3 Abbreviations

The list below defines some abbreviations frequently used in the report

ABS = American Bureau of Shipping

ARIMA = AutoRregressive Integrated Moving Average

CCS = Carbon Capture and Storage

CFD = Computational Fluid Dynamics

DAS = Distributed Acoustic Sensing

FEM = Finite Element Modelling

FLS = Fatigue Limit State

FTIR = Fourier-Transform Infrared Spectroscopy

GCMS = Gas Chromatography Mass Spectrometry

GNSS = Global Navigation Satellite System

HMPE = High-Modulus Polyethylene

HW = HardWare

ILMT = In Line Mooring Tensioner

MBL = Minimum Breaking Load

MIM = Mooring Inspection and Monitoring

MRE = Marine Renewable Energy

MRU = Motion Reference Unit

PMMA = PolyMethyl MethAcrylate

RBI = Risk Based Inspection

ROV = Remotely Operated Vehicle

SCADA = Supervisory Control and Data Acquisition

UHMWPE = Ultra High Molecular Weight PolyEthylene

ULS = Ultimate Limit State

UV = UltraViolet

VIV = Velocity Induced Vibration

WEC = Wave Energy Converter

WT = Wind Turbine

2 System description

2.1 Mooring solutions

The project specifies three different mooring solutions:

- Base case mooring
- Taut leg mooring
- Innovative mooring

Relevant details for these solutions are given in the following subsections. In all cases, chains used above water and in contact with the sea floor. The wind turbines (WTs) shall be expected to stay in operation for 20 years, and a wind park of 300 WTs is envisioned.

2.1.1 Base case mooring

The concept is illustrated in Figure 1, and key properties of the solution are given below. The rope properties will be subject to further optimization. Presently, the solution at 800 m depth is designed without buoy or clump weight.

- OO-Star Wind Floater
- DTU 10 MW rotor
- Polyester fibre ropes for 150 m depth, polyester or nylon ropes for 800 m depth
- Rope diameter: 250 - 270 mm
- At 150 m depth:
  - Mooring line length: 811 m, of which 740 m rope
  - Mean tension: 30 % of MBL, max tension: 57 % of MBL
- At 800 m depth polyester:
  - Mooring line length: 1 500 m of which 1 400 m rope
  - Mean tension: 26 % of MBL, max tension: 46 % of MBL
- At 800 m depth nylon:
  - Mooring line length: 1 280 m of which 1 180 m rope
  - Mean tension: 31 % of MBL, max tension: 41 % of MBL

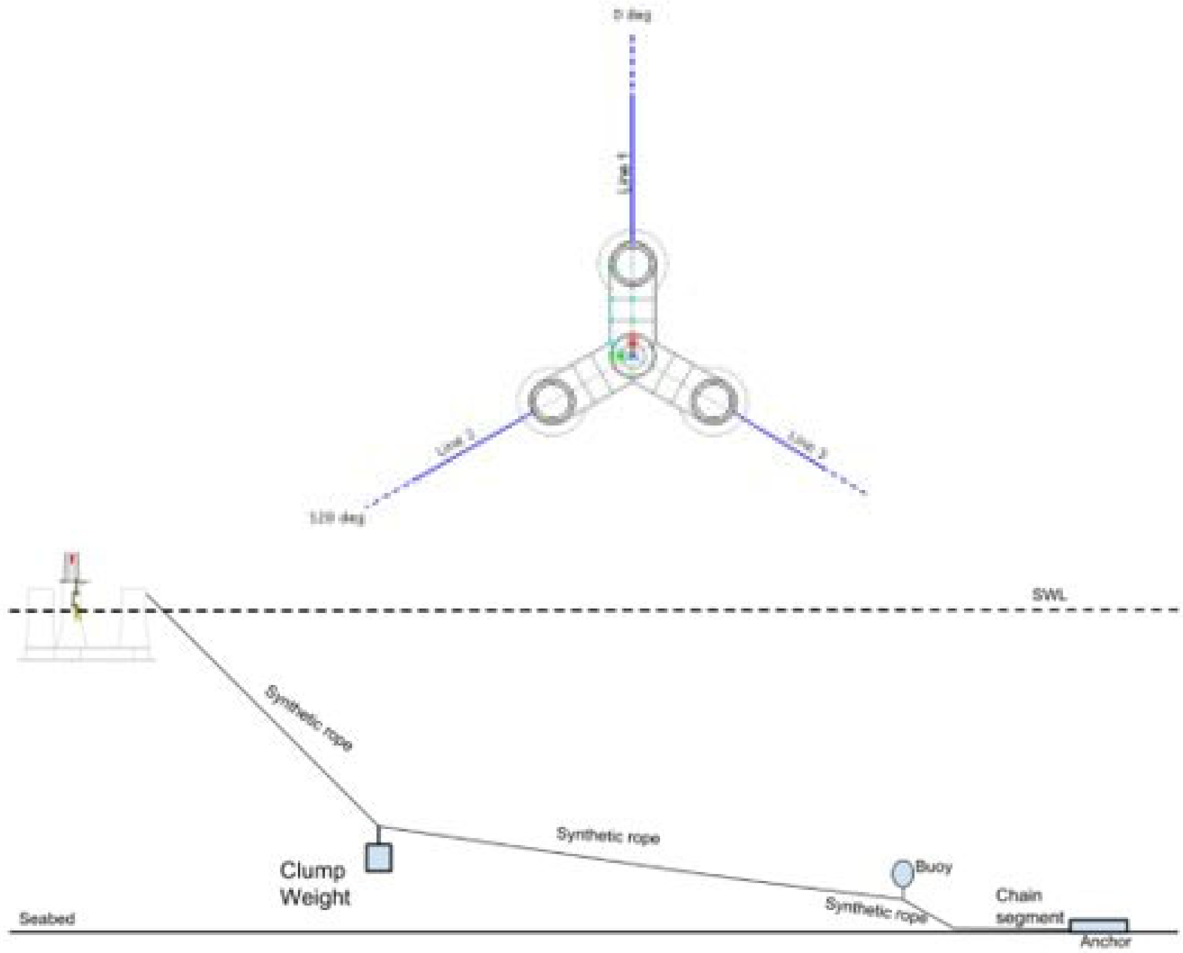

Figure 1. Base case mooring illustration

2.1.2 Taut leg mooring

The concept is illustrated in Figure 2, and key properties of the solution are given below. The design here is not yet as well developed as for the base case mooring.

- OO-Star Wind Floater
- DTU 10 MW rotor
- Nylon ropes
- At 800 m depth:
  - Rope length: less than 2 000 m
  - Mean tension: 34-39 % of MBL

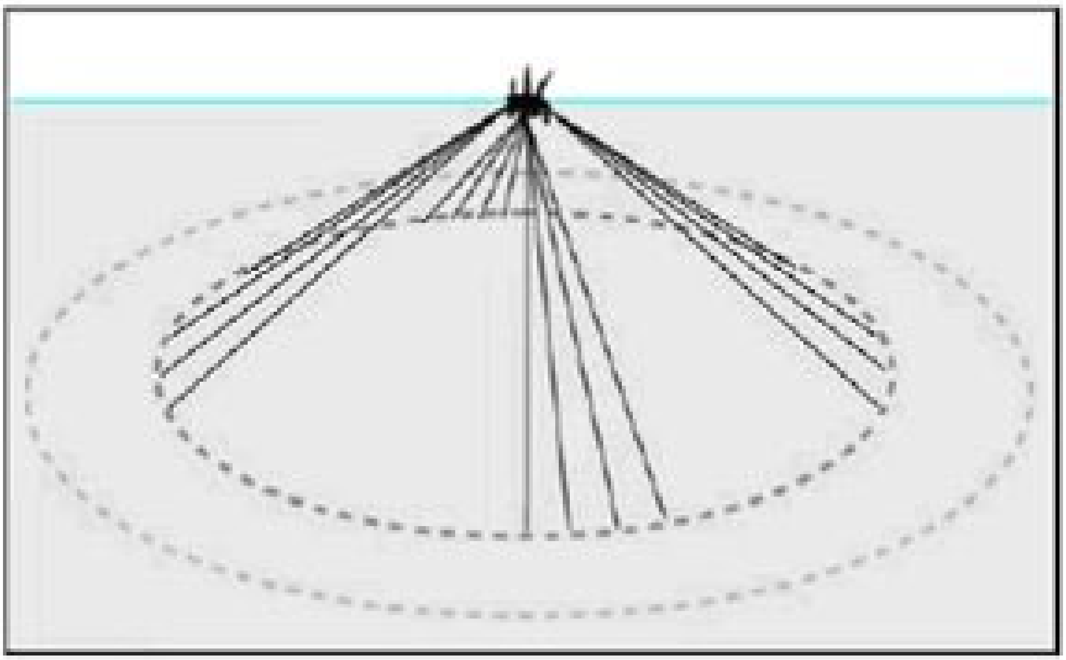

Figure 2. Taut leg mooring illustration

2.1.3 Innovative mooring

One option for the innovative mooring is the Honeymooring solution, as illustrated in Figure 3. Another option is looking at polymer flex element inserts or at smart buoys as illustrated in Figure 4. Workshops were held in November 2020 and in April 2021 to identify relevant ideas.

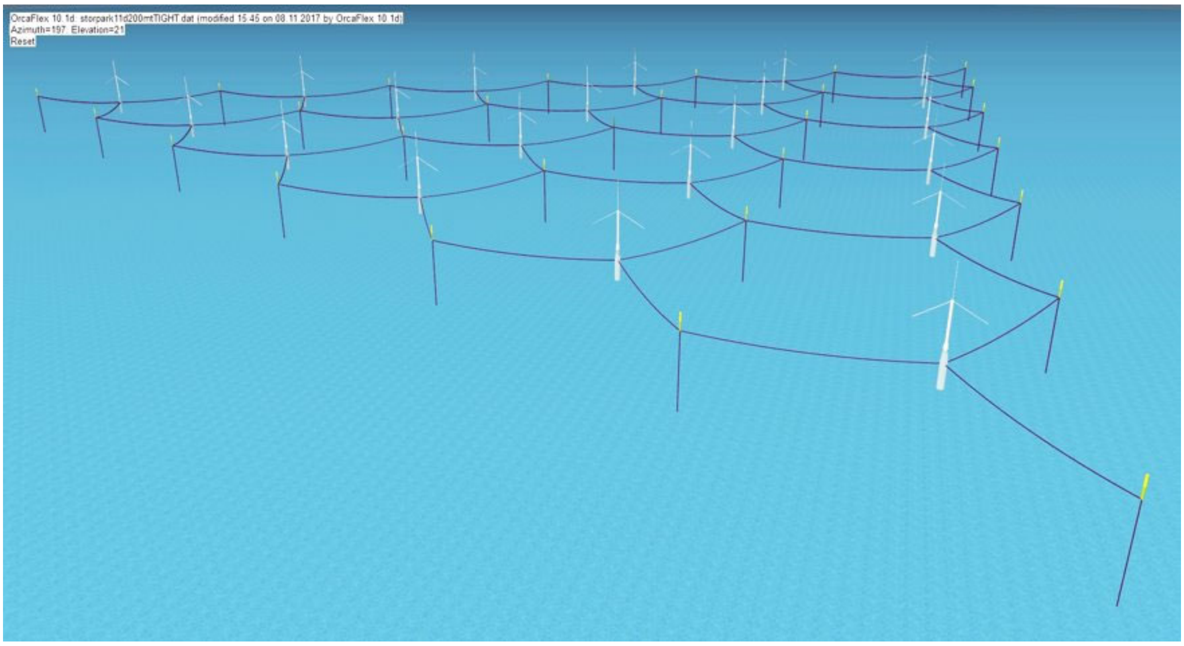

Figure 3. Honeymooring illustration

Figure 4. Smart buoy from Dublin Offshore

2.2 Sea depth and ambient conditions

All three kinds of moorings shall be investigated at two depths, 150 m and 800 m, each at two climates, one typical for the North Sea, exemplified by Buchan Deep outside Scotland, and one with higher temperatures, where the installation will be subject to typhoons, exemplified by Donghae outside Korea. In total this yields 3 x 2 x 2 = 12 example systems.

Water temperature in °C and salinity in PSU are given for Buchan Deep in Figure 5 and Figure 6, respectively. Similar information is not as readily available for Donghae.

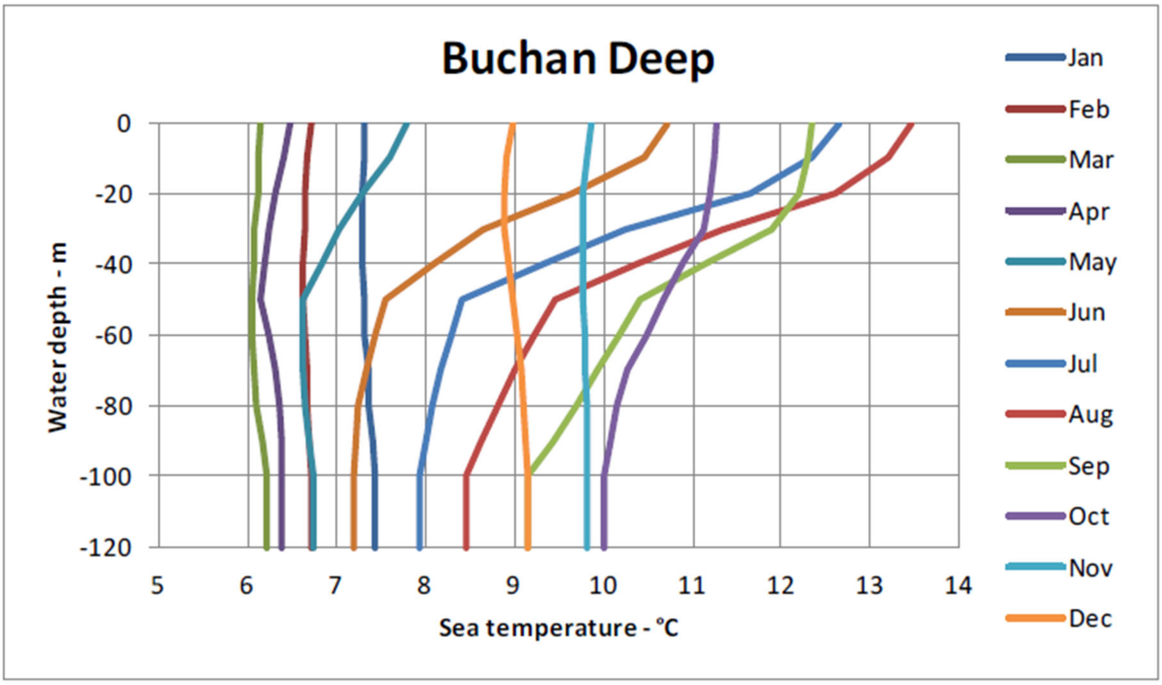

Figure 5. Monthly average sea temperatures at Buchan Deep, from[3]

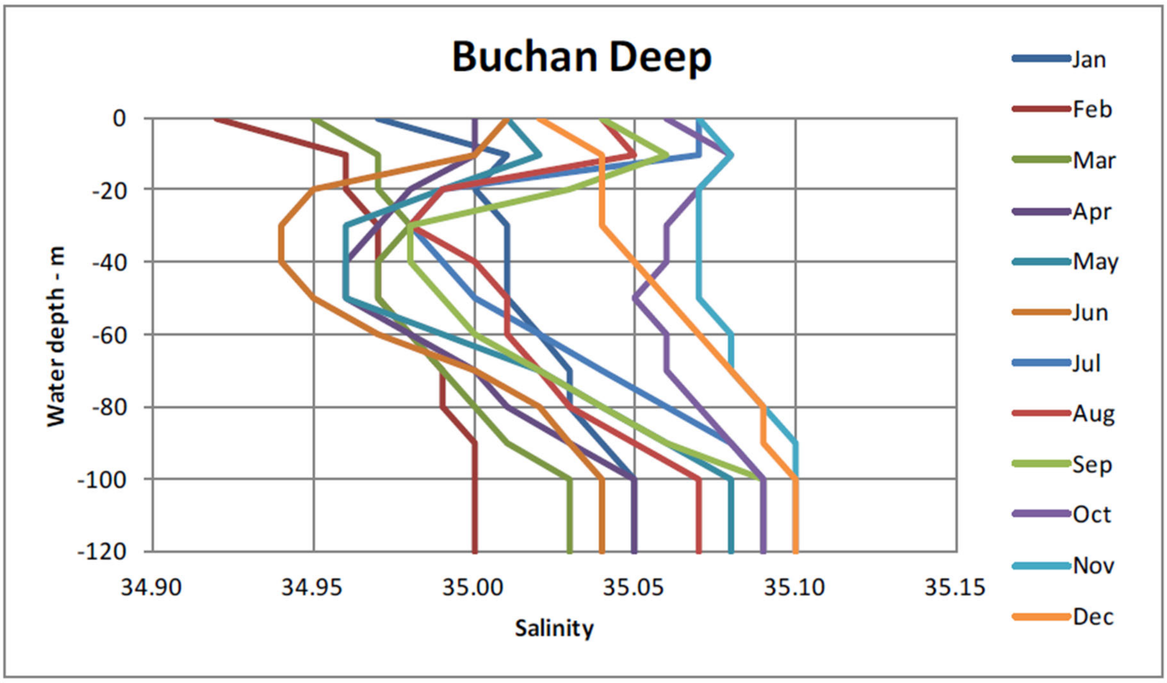

Figure 6. Monthly mean salinity profiles at Buchan Deep, from[3]

3 Failure modes considered

Weller et al. list the following degradation mechanisms in their review[4]:

- fatigue
- particulate ingress
- hysteretic heating
- ultraviolet (UV) light
- creep
- wet/dry cycling
- snatch loading (high loads)

These are all discussed in the following subsections. In addition, rope compression, external damage, marine growth and the related topic of biodegradation are considered.

3.1 Fatigue

Fatigue is a highly relevant failure mechanism, since the generator will be subject to changing winds, currents, waves, and, if placed near the coast, even tidal water. In particular, taut mooring lines may be susceptible to velocity induced vibration (VIV) in high flow environments.

Moorings are in general designed to have natural frequencies which do not coincide with typical environmental excitation frequencies in order to provide safe operating conditions[4]. In general, the natural periods for platform movements are designed to be above the wave spectrum.

Long-term studies conducted for the oil and gas industry have concluded that fatigue is not an issue for well-designed polyester rope moorings[4], a fact also confirmed by the FIRM project's rope suppliers. The relevant standards now reflect polyester ropes' fatigue properties, leading to safe designs and procedures.

Nylon however has far less experience data available, leading to more uncertainty. Strength and stiffness must here be seen together - nylon stretches more than polyester and will therefore have lower load amplitudes. There is ongoing work on improving the fatigue performance of nylon ropes, as exemplified by the work of Chevillotte et al.[5], who studied the effect of a new coating on yarn-on-yarn abrasion.

Buoys and clump weights may experience fatigue themselves, at the connection points, and they influence the fatigue experienced by the mooring lines.

Fatigue is a relevant problem for the chain parts of the mooring used for attachment and tightening. Consequently, fatigue is considered when these chains are designed. One may use the chain weight actively in the mooring design, resulting in heavy chains that do not have fatigue problems, or different designs may call for lighter, less costly chains, which will then experience fatigue problems.

To summarize, fatigue is a relevant problem for fibre rope mooring in the FIRM project, a problem which is typically handled through

- Design of platform geometry and weight to avoid resonance
- Design of mooring components like chain, buoys, or inserts
- Modelling of mooring loads under various conditions, leading to a safe choice of rope material, size, and construction
- Rope development
- Monitoring, see Section 4.

3.2 Particulate ingress

The fibre ropes are not in contact with the seabed during operation. Either there is a chain segment connecting the rope to the anchor with a buoy lifting the rope for the base case system, or the mooring does not touch the seabed at all for the taut leg system. However, during installation, the ropes will be placed on the seabed and then hauled up to connect to the WT. The severity of this problem depends on the specific site, with silt and coral reefs on opposite ends of the scale.

There are ropes designed for use on the sea floor. These have filtration tape, placed between the loadbearing rope and the jacket, that hinders particulate ingress. The filter is typically non-woven material made of polypropylene or polyester, effective down to 5-micron particle size. For some offshore applications, these filters are made for a duration of 1-2 years, a time period sufficient for the pre-hook-up phase. However, further investigations must be performed if the mooring can be expected to be in contact with the seabed also during operation, e.g. due to WT maintenance.

3.3 Hysteretic heating

Hysteretic heating can be caused by slip between strands followed by insufficient heat transport within the rope. Weller et al.[4], stated that “Research conducted by the offshore petroleum industry has suggested that this may be an issue for large diameter ropes subjected to large strain ranges.” This idea is supported by the low thermal conductivity and low maximum operating temperature of high-modulus polyethylene (HMPE) ropes.

However, the offshore wind mooring ropes will be surrounded by water and also filled with water, which will give very good cooling, far better than what could be supplied in a lab or by e.g. spray cooling of ropes used on land or above water. Also, polyester and nylon ropes can handle higher temperatures than HMPE ropes can. Hysteretic heating needs therefore only be considered for any parts of the ropes that are above water.

3.4 UV light

UV light penetration into the ocean depends on geographic location, wavelength and on the local ozone layer, as illustrated in Figure 7. However, significant penetration is only a few tens of meters[6]. Therefore, UV damage of mooring ropes is most relevant near the top, and precautions against UV light need not be taken near the bottom.

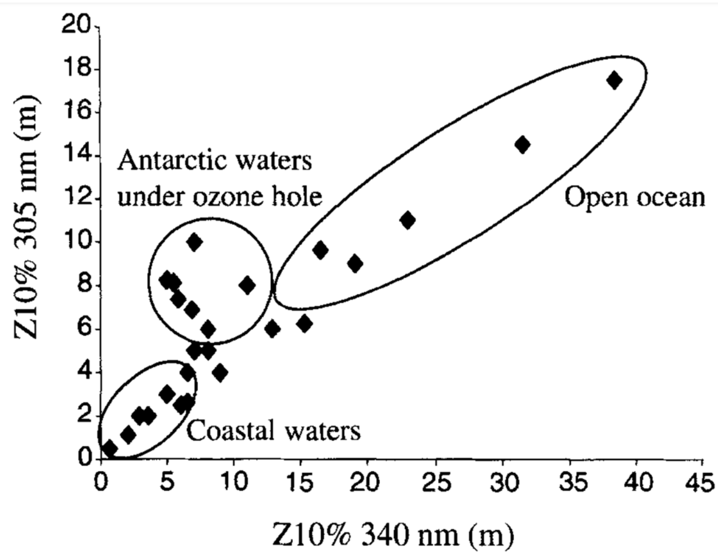

Figure 7. Depth at which 10 % of the incident UV light of wavelength 305 and 340 persists, from[6]

The ropes are typically jacketed, as was the case at the top part of the lines for the Goliat platform mooring. Since UV only penetrates a few mm into a rope, the jacket will stop the UV radiation from reaching the load bearing rope. Such jackets can be made by the rope manufacturers or by others, and they are typically made to braided polyester or HMPE.

3.5 Creep

Polyester and nylon ropes both increase in length over time even at constant tension. This is due both to a straightening of various elements of the rope construction, see Figure 8 for examples of rope structure, and to creep of the polymer material itself.

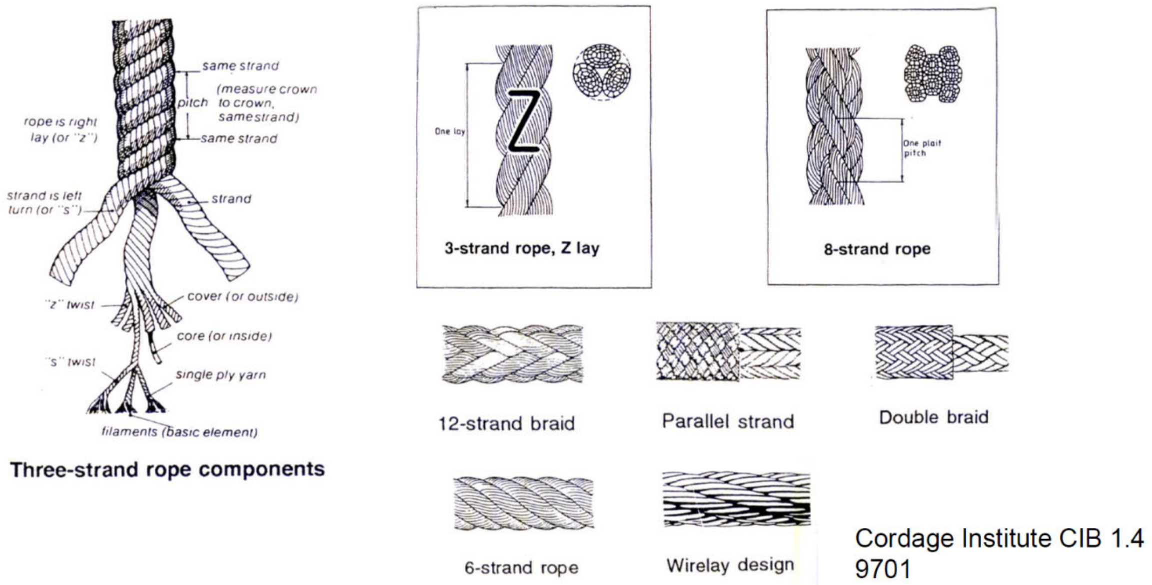

Figure 8. Examples of rope structure

The ropes will be chosen so that the expected tension will not lead to creep to rupture, but the ropes getting longer may lead to need for re-tensioning during the ≈20 years of operation. Creep will also give longer and stiffer lines, which must be taken into account during design.

Nylon rope creep was tested by DNV GL as part of the FIRM project for all three rope supplier partners. This gave valuable input to which tightening mechanisms are required for the project's mooring solutions. The results are reported in a dedicated report.

3.6 Wet/dry cycling

If all parts of the fibre ropes are assumed to be under water at all times, this failure mode needs not be considered. However, one may choose to connect the ropes directly to a connection point above the water line. In this case, wet/dry cycling must be taken into account.

Salt crystals may form within the rope during wet/dry cycling, as observed for aramid braids by Sampathkumar and Schwartz in 1989[7]. They used SEM to observe the salt crystals, as shown in Figure 9. They also saw deformation of the fibres around the salt crystals, but no strength reduction was observed. Still, the salt crystals can contribute to increased abrasion between contacting fibres as mentioned more recently in 2013 and 2015 by Johannig[8] and Weller et al.[4].

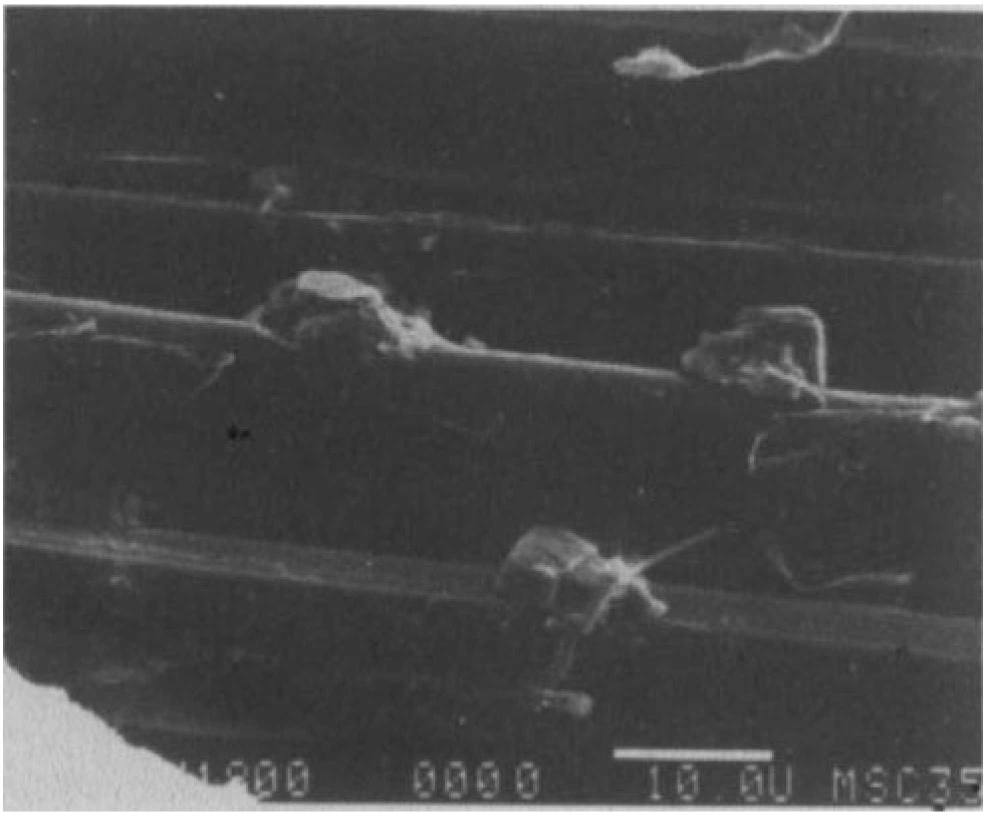

Figure 9. SEM photomicrographs of braid with NaCl crystals[7]

For Honeymooring it is assumed that the floaters are all under water, at varying depth, depending on the line tension or WT movement.

3.7 High loads

The ropes break if they experience too high tension, independent on the strain rate, making snatch load a disputed term. Too high tension or loads is avoided by proper design, i.e. ultimate limit state

(ULS) calculations taking e.g. extreme weather conditions into account. These considerations result in choice of rope material, construction and thickness, inserts, buoys, etc.

High tension may be more of a problem for the taut leg mooring system than for the base case mooring. On the other hand, the chains in the base case mooring may give rise to sudden, large tensions if the chains get tangled.

3.8 Rope compression

Tradition has it that fibre ropes shall never be axially compressed, a tradition that according to Flory et al.[9] dates back to an aramid rope mooring failure at the Lena Tower in the Gulf of Mexico in 1984. Flory et al. describe axial compression fatigue as buckling and kinking of single synthetic fibres when compressed, leading to fibre loss of strength and ultimately to fibre failure and thereby to reduced rope strength. An example is shown in Figure 10. Axial compression fatigue is a regressive failure mechanism, in that when the longest fibres have failed, the shorter fibres will not experience compression, and the number of failures due to compression will halt.

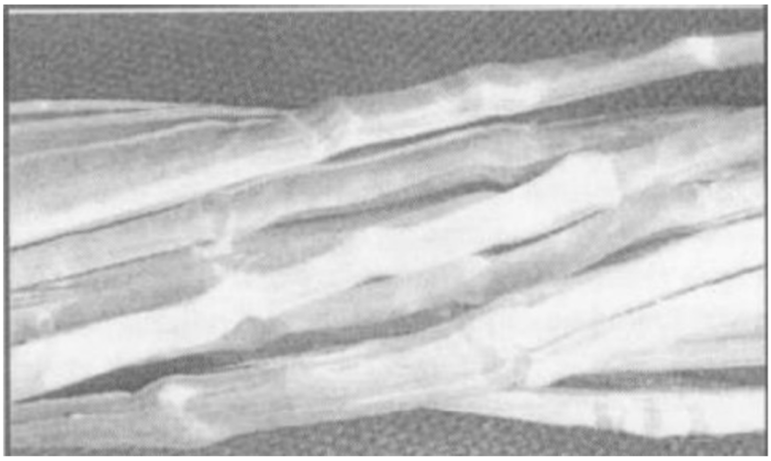

Figure 10. Axial compression fatigue within strand of aramid rope[9]

According to the American Bureau of Shipping (ABS) Guidance Notes on the Application of Fiber Rope for Offshore Mooring[10], axial compression fatigue is a concern for aramid ropes, but not for polyester or HMPE ropes. However, Flory et al.[9] found axial compression fatigue to be the cause of failure for HMPE and nylon fibre ropes with long lay lengths of both ropes and strands. They concluded that “Nylon and polyester yarns demonstrate essentially no strength loss even after many thousands of cycles in the axial compression fatigue test method. But poorly designed ropes of these materials might fail under some circumstances.” Note that a stiff jacket may hinder or prevent rope compression.

3.9 External damage

Polyester lines are more easily damaged than the more commonly used steel cables. Examples of relevant external damage are fish bite[11], steel cables, or other kinds of abrasion. Situations that may lead to such damage are trawling, seismic surveys, installation, or tangling resulting from line breaks. Exclusion zones for fishery may be ignored, or the vessels may not know their exact position.

The consequence may be damage to the jacket as well as to the load bearing structure.

3.10 Marine growth

On marine growth, Weller et al.[4] state: “For MRE [Marine Renewable Energy] applications marine growth will not directly affect mooring ropes (unless hard-shelled species penetrate the rope interior), however a build-up of growth will increase the weight and drag of each line [3] which could adversely influence the response of the device.” They then go on to state that “The development of marine finishes and micron-level filtration screens (to prevent the ingress of abrasive material) have led to significant increases in the fatigue performance of synthetic ropes.”

The Metocean report for Buchan Deep[3] refers to the NORSOK Standard N-003 Section 6.6.1 and similarly state that “Marine growth may cause increased hydrodynamic actions, increased weight and increased hydrodynamic additional mass and may influence hydrodynamic instability as a result of vortex shedding and possible corrosion effects”. They also give information on expected marine growth thickness at different depths, saying that the thickness of marine growth may be assumed to increase linearly to the given values over a period of two years after the structure has been placed in the sea.

Spraul et al.[12] considered marine growth on floating wind turbine moorings, emphasizing the variation with site, time, position on the rope, and mooring rope surface. Biofouling for mooring of a wind energy converter (WEC) system was investigated by Yang et al. [13], who found that “for a WEC system which has been deployed for 25 years, biofouling can reduce the total power absorption by up to 10 % and decrease the fatigue life of the mooring lines by approximately 20 %.”

The influence of marine growth on the mooring’s mechanical and hydrodynamic properties is well-known and can be handled in the design phase, taking into account that the weight of marine growth is significantly lower in water than in air. A jacket around the rope will stop marine growth from penetrating into the rope, which would increase the abrasion inside the rope. Some rope manufacturers also work on making the rope surfaces hostile to marine growth, reducing the problem even further.

3.11 Biodegradation

According to plastic researchers and microbiologists in NORCE, biodegradation, i.e. enzymatic cleavage of plastic polymer material followed by mineralization of oligomers/monomers to CO_2 and CH_4 by microorganisms, is not expected to be a significant problem for conventional offshore mooring ropes. However, other processes, like mechanical damage and exposure to abiotic and biotic environmental factors may influence material properties and result in the release of microplastics to the environment. In this context, marine growth, or biofouling, may contribute to degradation processes through growth-associated physical and chemical effects, more so than through direct scission and digestion of the plastic polymers through biodegradation.

3.12 Summary

The various failure mechanisms and typical mitigation actions are summarized in Table 1.

Table 1. Failure mode summary

Failure mode	Relevant?	Handled by design?	Monitoring required?
Fatigue	Yes	Yes	Yes
Particulate ingress	Yes	Yes	No
Hysteretic heating	No		
UV light	Yes	Yes	No
Wet/dry cycling	Yes	Yes	No
High loads	Yes	Yes	Yes
Rope compression	Yes	Yes	No
External damage	Yes	Yes	Yes
Marine growth	Yes	Yes	Yes
Biodegradation	No		

4 Condition monitoring

According to Weller et al. in 2015[4], condition monitoring of fibre ropes mooring is done by periodic visual inspection, while in-situ methods are still at the prototype stage. In the following section, visual inspection as well as some in-situ methods are investigated in more detail.

4.1 State-of-the-art

4.1.1 Visual inspection

Weller et al.[4] mention inspection at regular intervals, referring to DNV GL and CI standards[14], [15]. The idea is to look for external damage, abrasion, or chain corrosion. Experience has shown that good quantitative criteria can be given to detect these failure modes. Visual inspection also serves as a safe fallback solution if more advanced sensor-based solutions fail.

Inspection may in principle be performed by divers, using underwater ROVs, or robots crawling along the ropes, similar to what is done for pipes. In practice, all visual inspection of mooring ropes is done by ROVs, due to a combination of legal regulations and cost. Typically, this kind of inspection is performed with a 5-year interval for chains. Special care must be taken to inspect end terminations, connections for buoys and weights, etc.

As for all rope inspection, a major disadvantage with visual inspection is that it is hard to learn anything about the rope interior, e.g. detecting fatigue damage. Jackets and marine growth aggravate this problem even further. Additionally, the cameras used for monitoring may experience marine growth, and must be cleaned accordingly. Some ROVs can clean the rope as part of the inspection procedure but note that on occasion ROVs may also damage the ropes. Transparent jackets could be possible, but compromises with other material properties may be required.

Communication with the ROVs is required both for ROV control and for data retrieval. The control centre can be aboard a surface vessel, the ROVs may connect to the wind park’s communication system, or autonomous solutions may be considered. The ROVs may be transported by a large surface vessel, or smaller ROVs can be transported by smaller vessels or even by drones. The latter may have a lifting capacity of 100 kg.

4.1.2 Modelling

A common way to follow the state of moorings, both ropes and chains, is numerical modelling, where initial statistical assumptions are gradually replaced by actual weather conditions, loads, etc. Pham et al.[16] are one of the authors recommending such an approach. Note that if data is available, this kind of modelling can also be done retrospectively to gain improved understanding.

The actual loads can either be input from measurements, or they can be calculated based on global navigation satellite system (GNSS) and motion reference unit (MRU) data.

The resulting information can be used to monitor both fatigue and creep, since longer lines will increase the platform movement at given weather conditions. However, there is still little long-term experience with offshore WTs, and the methods are mostly transferred from oil and gas, where other loads and requirements apply.

4.1.3 Load and angle measurement

Loads and angles of the mooring lines can be important input to fatigue monitoring, where different sensors may be required to monitor extreme and fatigue loads. For instance, load is measured for the polyester lines used in the Goliat platform mooring, and the results are used to monitor the rope state.

Bashir et al.[17] mentioned several condition monitoring systems developed by Pulse Structural Monitoring for chain or steel wire mooring[18], for instance MOORASSURE, a system for monitoring mooring lines angles for deducing their mean tension[19], Inter-M Pulse, a system for measuring line tension from strain gauges as inclinometers[20], and the more self-explanatory systems Load Cell Tension and Inclination Monitoring.

Since there is a risk of sensor failure over time, focus is on redundant sensors. For instance, data from angle sensors and load sensors at the point of mooring attachment can be correlated so that if one fails, the other can be used to follow the mooring's state. Smart sensor mounting and cabling will also contribute to increased lifetime, and such sensors are now made to last for 25 years[21].

Seasystems, one of the FIRM project partners, supplies tension sensors[22]. Their new H-Link tension monitoring consists of sealed-off units. Communication is via acoustics and power is by inductance. High resolution data sets, e.g. for fatigue, can be retrieved by ROVs. Data can also be compressed to e.g. min, max, and average, and data can be sent every 1-5 minutes. The communication is limited by bandwidth and by battery capacity. The sensor system can also be put to sleep and awakened on demand.

Huge amounts of data is generated, often these sensors have a sampling frequency of 2 Hz, which is the requirement for units with mobile mooring[23].

Line tension monitoring through load cells is unreliable and prone to failures, and may have limited measurement range compared to the full load spectre of the WT. Many of the currently installed systems, and those currently marketed, have been reported to be insufficient regarding accuracy and reliability. There appears to be little value in requiring the installation of a system whose accuracy and service life is questionable. Requiring failed line detection is, in many respects, more important, and certainly more practical[24]. The need for higher accuracy may trigger development of new load cells that are designed especially for mooring monitoring wrt. e.g. demanding environmental conditions, necessary measurement range/robustness and need for Remotely Operated Vehicles (ROVs) for installation, calibration and replacement.

4.1.4 Line rupture detectors

There are also sensors that will only give information if a rope breaks, and not about the rope state during normal operation. These may e.g. be mechanical or electrical sensors. Note that according to DNV GL[23], GNSS may not be sufficient if the excursion after a mooring line failure is limited.

4.1.5 Weather sensors

Weather data may be acquired from companies specializing in such information, or sensors may be placed in the WT park. Examples include wave sensors and sensors of pressure, temperature, rain, and humidity.

4.1.6 Destructive testing

Line removal allows destructive testing, e.g. testing for residual strength. This gives more definite answers than visual inspection, and the whole rope is tested, not just the visible surface. However, these tests are expensive, and are typically only done after decommissioning or to provide proof for changes in classification or in insurance cases. When fibre ropes for mooring were developed, these kinds of tests were more common. When new rope types, e.g. nylon, are now considered, line removal may again become more frequent.

4.1.7 User interface

All this information must be presented to the user in a way that ensures that the information is clearly perceived so adequate actions are taken. One example is Kongsberg Maritime's Mooring Load Radar, of which a sample screenshot is shown in Figure 11. The system gives a quick overview of the mooring status, and it allows the user to drill down to get e.g. trends of the tension in a specific mooring line the last 6 - 12 hours. This kind of system can also generate reports required for classing or insurance purposes.

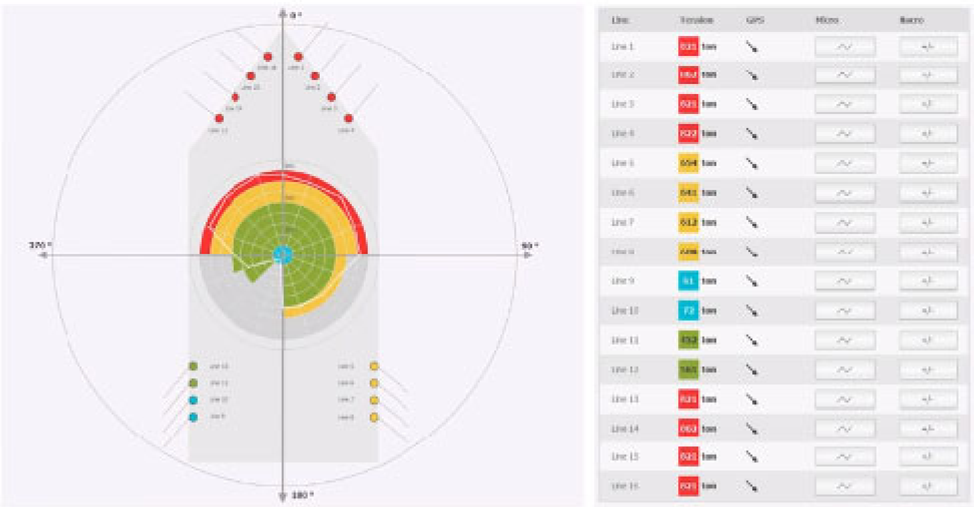

Figure 11. Example of Kongsberg Maritime's Mooring Load Radar system

4.2 Future developments

Developments in condition monitoring equipment may allow reduced safety margins without compromising the total safety of the construction. This section describes a few possibilities.

4.2.1 Magnetic and electrical measurements

Oland et al.[25] mention several magnetic and electrical measurement methods. The magnetic methods presented require insulation to be suited for use under water. The electrical methods are based on embedding conductive wires or thread. These may give global information on the rope state, as well as serve as detectors of broken lines.

4.2.2 X-ray and ultrasound

Oland et al.[25] also discuss X-ray methods, but these are not well suited for use under water. Ultrasound, on the other hand, can work under water. People at the University of Helsinki have successfully used ultrasound to detect defects in polymer samples[26], a fact suggesting that a similar technique may also be used for periodic inspection of fibre ropes.

4.2.3 Acoustic emission

Though more often used for steel wire ropes than for synthetic fibre ropes[27], acoustic emission may also be an option for fibre ropes in water, as discussed by Bashir et al.[17]. They found promising test results, with signals being related to bedding-in, slippage and failure.

4.2.4 Optical fibres

Bashir et al.[17] mention fibre optic strain gauges for steel wire ropes. This is a lot simpler in steel wire ropes than in polymer fibre ropes, most of all since polyester and nylon ropes exhibit far more elongation with time. However, knowledge of local strain in the wires would improve the condition monitoring.

The rope manufacturers Hampidjan[28] and Teufelberger[29] have both embedded optical fibres into some of their ropes, though for the purpose of communication. However, this shows that it is indeed possible to embed fibres in ropes and have them survive in harsh conditions.

Gordelier et al.[30] investigated the use of polymer fibre optic technology for monitoring of strain in synthetic mooring lines. This material is less fragile than silica fibres. For the optical fibre they tested, they concluded that “This results in an incompatible system for long term monitoring, whereby, at the point at which the PMMA [Polymethyl methacrylate] fibre can identify any strain, it will have suffered permanent damage. The system could be used as an ‘alarm system’ identifying a threshold breech, but it could not be used for continuous condition monitoring.” They then go on to suggest research directions to overcome this difficulty, either by changing the fibre material or the measurement technique. One option is to wrap the optical fibre in a helix around the core within a rope structure, giving a significantly lower fibre strain than rope strain with a known ratio between the two.

NORCE researchers comment that polymer optical fibres exhibit significant signal damping, making use of long polymer optical fibres a problem in practice. If the optical fibre is wrapped in a helix, measurement of local stress will be imprecise, and it is uncertain how the optical fibre will move relative to the rope. Temperature measurement in offshore mooring ropes is not very relevant, since the ropes are very well cooled by the surrounding water. If optical fibres can only be used as an “alarm system”, this can be achieved in cheaper ways, e.g. using embedded electrical conductors.

An interesting option is distributed acoustic sensing (DAS) by use of silica optical fibres, which is used in microseismic monitoring for CCS[31], [32]. The frequencies expected from single fibre yarns breaking is in the range of a few hundred Hz, which is very well suited for optical fibre transmission, and the silica material used here does not have the signal damping problems of polymer optical fibres.

4.2.5 In-situ sensors

Sensors placed on the ropes far below the surface may be localized strain gauges, but also accelerometers or sensors measuring depth and rope angle. All these give more detailed knowledge about the mooring state.

A problem with in-situ sensors is the signal transport through hundreds of meters of sea water. Presently wireless signal transmission is gaining reputation, see e.g. Figure 12 showing a wireless sensor from Volue (IoT Solutions). In these sensors, data is collected over a period of e.g. 15 minutes, when aggregated information like min, max, average and standard deviation is sent to the surface.

These sensors need battery replacements, typically every few years, a task which can be carried out by ROVs. The signal receivers, placed close to the surface, are influenced by marine growth, and should be cleaned yearly. Avoiding cabling may also be an advantage when sensors on the platform are on or close to moving parts to eliminate a source of failure.

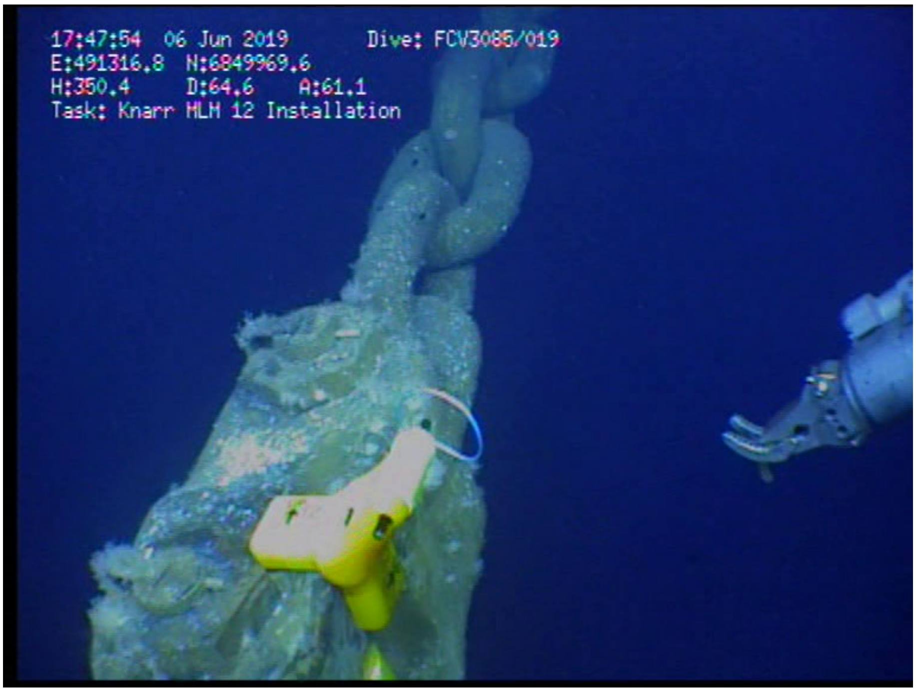

Figure 12. Example of wireless mooring monitoring system[33]

The NORCE-coordinated MarTERA UNDINA project (www.martera.eu/projects/2020/undina) investigates the use of underwater drones for a multimodal communication system. Acoustic communication is used for detailed, relative positioning between multiple drones. If the drones get close enough to the sensors and the water is clear, optical communication is used to increase the bandwidth compared to using other forms of communication.

SFI Smart Ocean (sfismartocean.no) is a centre for research-based innovation hosted by the University of Bergen. In this project, a statical sensor network consisting of wireless, autonomous, smart sensors is considered. To optimize the use of the small bandwidth available subsea, only small packages of aggregated data are communicated during normal operation. When an event occurs near a sensor, more data is transferred from this sensor, utilizing the distributed network. This architecture gives both redundancy and more evenly distributed traffic.

4.2.6 Microplastics detection

Microplastics is found in the sea, in fish gills, and sometimes in marine life intestines, see e.g. Haave et al.[34]. Recent research[35] shows a significant increase in microplastics release from abrasion of marine polypropylene ropes as the ropes age. It was also found that the microplastic fragments produced were irregular, and not fibrous, as expected. The reported tests related to rope hauling. While less abrasion is expected for mooring ropes, the general trends found still apply.

Current regulations on microplastics is on primary usage, e.g. in cosmetics, and not on e.g. abrasion over time[36]. There is no standard method for microplastics monitoring, but NORCE is doing work that may lead towards standardization[37], [38], using the methods μ-infrared imaging (μFTIR, useful for identifying shapes of particles) and mass estimation (pyrolysis-GCMS) to analyse sediments, sea water and suspended matter[39]. One may also, more indirectly, monitor organisms native to the area, e.g. mussels, sessile filter feeders acting as natural collectors of particles including plastic particles[40].

Microplastics related to offshore WTs may not all originate in the mooring but may also come from e.g. plastic based marine paints. Also, the plastic pollution is everywhere, so plastics will also be detected in the site considered as “reference” (a site far from or not affected by the offshore wind power production site). Consequently, comparisons between sites must always be made to understand the pattern in the levels, shapes, type of polymer etc.

As a starting point, microplastic in the surrounding sea could be measured yearly. A monitoring plan should include water column and sediments monitoring considering sampling sites placed in orthogonal transects centred on the main orientation of the main currents. The sampling sites should be placed at increasing distances from the WT platform.

Microplastic monitoring could be included in a monitoring program assessing the impact of other environmental contaminants released within the offshore wind power production

4.3 Mooring assessment process

Operational phase mooring assessment should follow the general framework recommended by DNV[41], as illustrated in Figure 13.

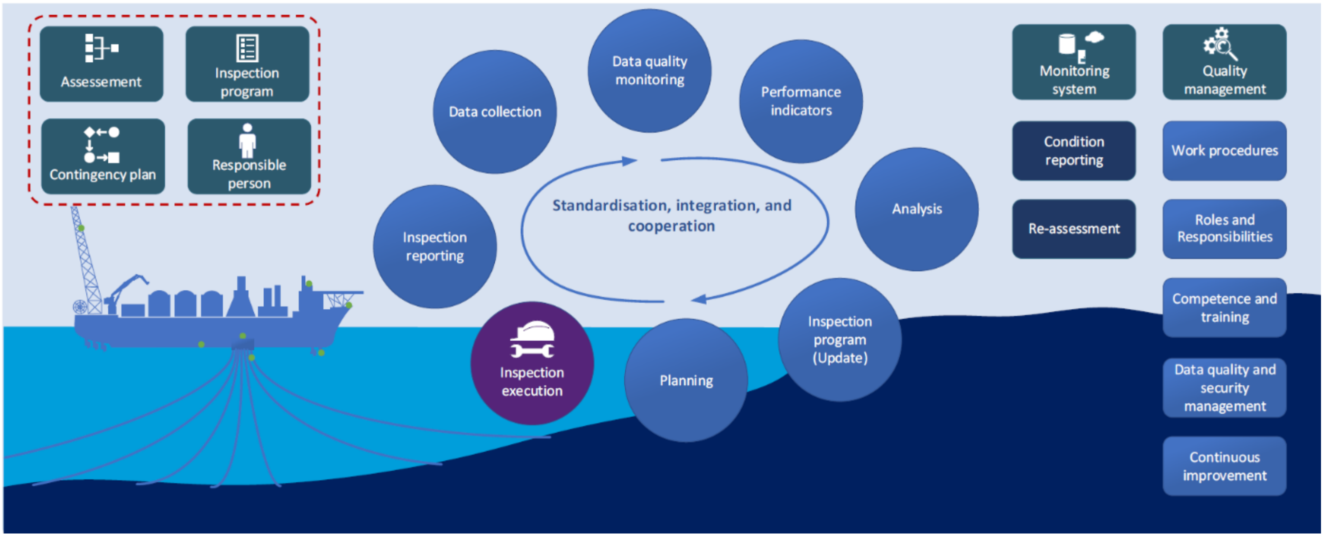

Figure 13. Mooring Assessment Process illustrated by DNV[41]

This process has much in common with the mooring assessment process by ABS[42] presented in Figure 14.

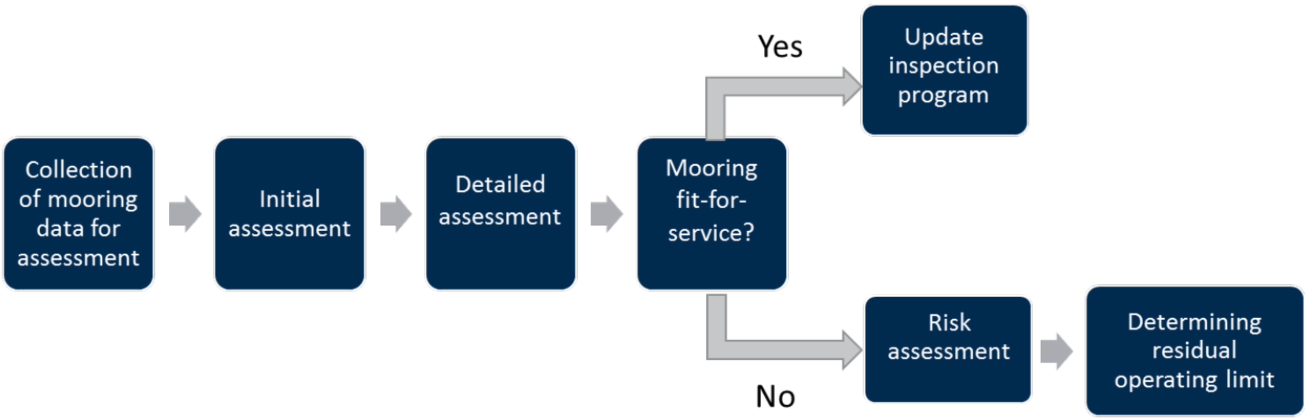

Figure 14. Mooring Assessment Process illustrated by ABS[42]

The strategy proposed in the present report does not treat the whole mooring integrity management (MIM) plan but is limited to the monitoring part. The process is normally periodic or ad-hoc e.g. through risk-based inspection (RBI), triggered by a detected anomaly or change in the mooring condition. Such conditions may include:

- Mooring component updates
- Metocean environmental condition variations
- Changes to the seabed
- Any other possible changes affecting the mooring responses.

The proposed scheme is summarized in the process flow diagram seen in Figure 15. It starts with a pre-assessment after installation through inspection and collection of sufficient amounts of baseline data. The data is then processed to provide condition indicators for designed rope features to be monitored. Based on statistical methods thresholds are produced for comparison of future rope features. In the operational phase data is collected and processed in similar way and compared with the threshold. If features exceed the threshold an assessment process is initiated. The process includes manual assessment of the data to uncover the root cause of threshold crossing which may be input for an ad-hoc inspection to verify the findings. If the rope is assessed as fit for continuing operation, the threshold should be assessed. Either the monitoring process can continue under current thresholds but with intermittent manual inspection of the rope features to detect either sudden deviations in or ramping up of features. Alternatively, the thresholds can be automatically recalculated based on the more recent data points or manually adjusted based on experience and the results of the condition assessment. If the rope is deemed as unfit for service, it will trigger an action that can include maintenance, repair, or replacement. The action will trigger another assessment to check if the rope is fit for service.

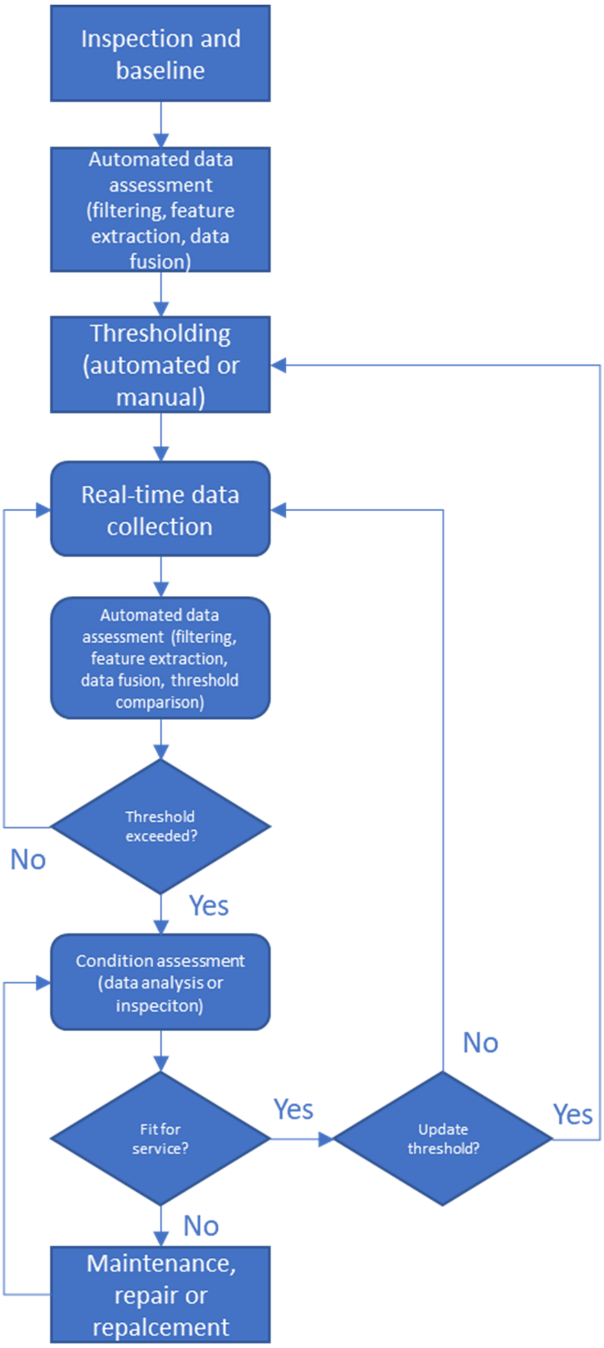

Figure 15. Mooring monitoring and assessment process

To achieve global monitoring capability of the mooring lines it is suggested to combine the data collected with a set of physics-based models. First step is to define a set of indicators to be monitored that are inherently linked to the condition of the fibre rope. These indicators may include, but are not limited to:

- Level of creep
- Rope stiffness coefficient (static/dynamic)
- Platform dynamic motion
- Catenary parameters (static/dynamic)

- Fatigue (tension-tension/bending)
- Marine growth (added mass)
- …

For each indicator a model is developed using the available measurements. Physics-based models can either be implemented on computational fluid dynamics (CFD), fine element modelling (FEM) or lumped models, depending on model complexity. For efficient real-time monitoring, lumped models are often preferred where applicable. There will also be need of models mapping input data such as meteorological and SCADA data into physical inputs for the model in terms of e.g. forces and moments. The models can also be used to compare expected performance with real performance, to detect anomalistic behaviour, e.g. comparing expected platform dynamic motion with estimated dynamic. Moreover, the models can be used to design observers or as part of model-based filters, e.g. extended or unscented Kalman filters, for noise rejection in measurement data.

For thresholding it is proposed to apply the process of estimating the probability distribution function of the nominal condition indicators. It is expected that they follow particular distributions (typically normal distribution or Rayleigh distribution depending on the design of the indicators) and a chi-square distribution if concatenating several indicators. The threshold can then be determined by choosing a confidence level and solved through the inverse cumulative distribution.

Prognostic models can be developed on top by trending the rate of change in the condition indicators and solve for the time until threshold is reached. The models can either be data driven such as autoregressive integrated moving average (ARIMA), Bayesian-based or physics-based, but such models will require further research to develop.

One of the many challenges with currently installed systems is that each monitoring solution depends on the specific floating system, implying considerable increase of cost and lead time, since any system must be designed ad-hoc[43]. A baseline data source plan can be proposed, based on a standard set of sources that are applicable for both types of mooring solutions evaluated in the FIRM project. Likewise, for the data processing and model development it is suggested to develop and implement a library of standardized models that can be combined effectively for different mooring solutions, to keep cost down and lead time down, where common models can be used interchangeably in addition to required specific models. It is advisable to seek a high level of design standardization for the different monitoring solutions and to achieve high level of model parameterization (depth, environmental conditions, turbine size etc.) to minimize the need of delicate model redesign in future floating wind power projects.

The types, complexity and number of models is a design choice and should be analysed based on technical requirements and through cost-benefit analysis. Models can be costly to establish, but if well designed, parameterized and modularized, they can be simple to adapt. The models will have specific inputs and outputs either from sensors, other models or in combination (multiple input – multiple output) forming a functional diagram as exemplified in Figure 16.

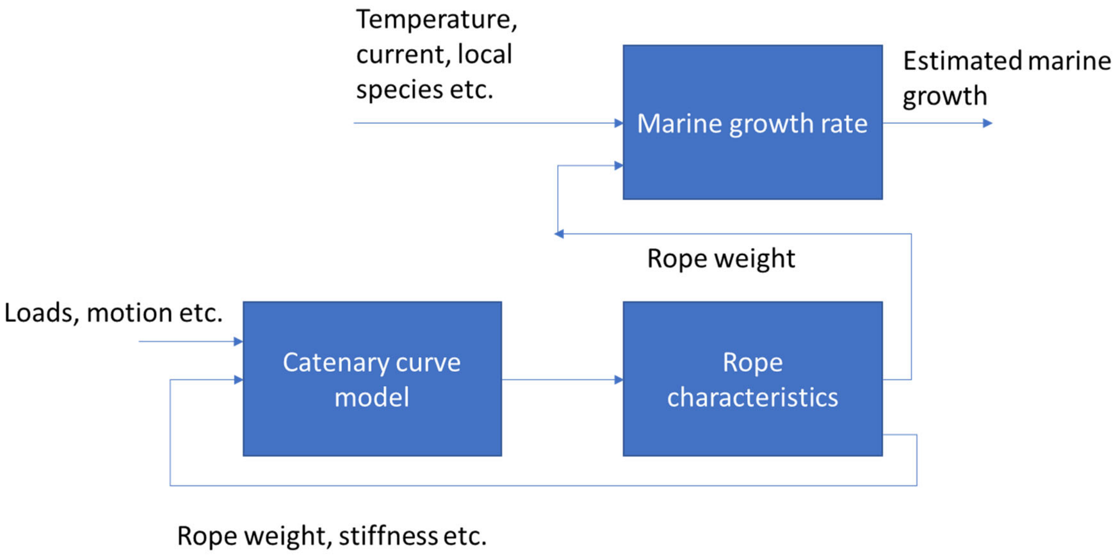

Figure 16. Illustration of model diagram with sensor inputs, inter relations and outputs

DNV's recommendations for annual condition reporting is illustrated in Figure 17[41].

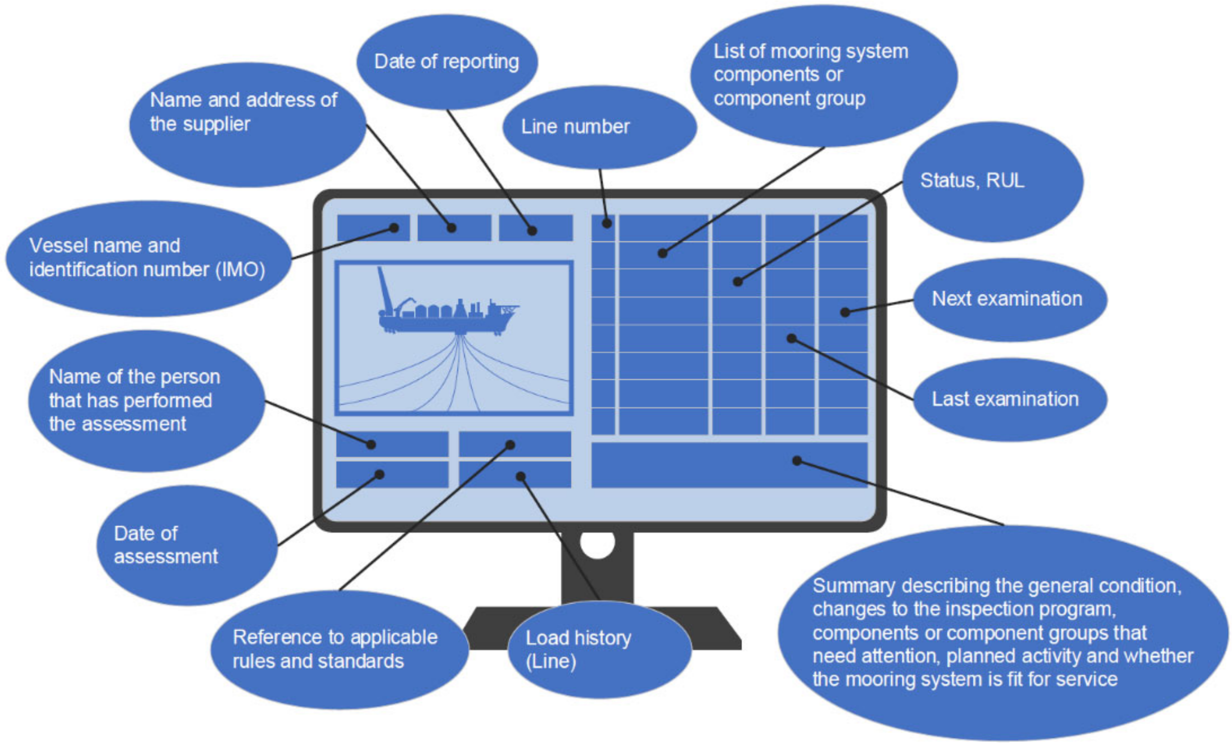

Figure 17. Annual reporting on condition, as recommended by DNV[41]

Re-tensioning

By comparing metocean data, platform motion (GNSS/MRU), rope tension and catenary curve based on inclination measurements, the rope length can be estimated and used as input for assessing need of and quantification of level of re-tensioning to be applied.

Marine growth

By comparing metocean data, platform motion (GNSS/MRU), rope tension and catenary curve based on inclination measurements, the rope weight and drag coefficient can be estimated and used as input for assessing need of marine growth removal. The estimated catenary curve can be applied to estimate the marine growth distribution along the mooring line. A dedicated model for estimating level of marine growth based on variables such as ocean currents, rope surface characteristics, calendar, local marine species, and temperature can be implemented separately. Then, the added weight and drag estimates can be fused with the marine growth estimate to increase estimation accuracy. Note that[12] concluded that the increase in mean tension is quite negligible in case study of large pre-tension compared with the breaking of taut mooring lines but shifts the natural frequency towards larger periods thus increasing response (motion amplification factor) to wave load.

5 Maintenance

According to Weller et al.[4], many polyester mooring systems have been in use for 20 years, and cases of residual strength of 96 % after 12 years of service have been reported. Even so, the WTs are specified to last for 20-25 years, so there is need for clear strategies for maintenance, which are discussed below.

5.1 Rope replacement

The DNV–OS–E303[44] standard states that disposal is necessary if loads exceeding 70 % MBL have been measured in-service. A description of a replacement of a polyester mooring line at 2 700 m depth was given at OTC 2021[45].

When used for lifting, a damaged part of a fibre rope can be cut out and the remaining rope spliced, but this is harder for offshore mooring. One can imagine loosening the rope tension somewhat on one side and then have a specialized ROV cutting out a piece of the rope and splicing the remaining rope, while all the time holding both ends of the rope to keep the tension sufficiently high. This is clearly a complicated and expensive procedure.

As illustrated by the H-link problems at Martin Linge[46], unplanned marine operations can be very demanding and costly. Plans must therefore be made for replacing or splicing ropes at all relevant positions, e.g. near the platform, near the sea floor, and at connections with buoys or clump weights.

5.2 Marine growth removal

For marine growth, periodic removal may be necessary, even with anti-fouling coatings in place. However, the Metocean Buchan Deep report[3] states that if marine growth exceeds the values for which the installation is documented, cleaning may be omitted if a new analysis shows that the structure has sufficient strength.

According to Restivo and Brune[47], the most common methods for marine growth removal are brushes, abrasives, and high-pressure water jets. An example of such a brush, most suitable for soft growth, is shown in Figure 18.

Figure 18. Brush for marine growth removal[47]

Abrasive pads are better suited for hard growth, and typically consist of nylon mesh with embedded abrasives. Since both abrasives and high-pressure water jets may damage any protective coating, Restivo and Brune[47] present an alternative ROV-mounted cavitation water jet solution.

5.3 Re-tensioning

Depending on the mooring solution requirements and on the rope creep, re-tensioning may be required. For the FIRM project's base case mooring this is less critical and may be avoided altogether due to the clump weights and buoys. Retightening gives extra cost and additional equipment that must be monitored and maintained. For polyester bedding in or pre-tightening may be sufficient, but for nylon ropes this is less probable. Tests performed as part of the FIRM project will give more information here.

5.4 Wind turbine maintenance

While wind turbine maintenance is outside the scope of the present project, the mooring system must allow transport of wind turbines to shore or near-shore for maintenance. If this happens, the mooring ropes may be placed on the seabed, or they may be attached to a buoy. In the former case, the ropes may have to withstand sand, silt, or sharp objects several years after installation.

For the Honeymooring solution, a specific solution is required if WTs inside the grid is to be transported out of the WT park, as illustrated in Figure 19. For the other mooring designs in the present project, each WT is independent, so no specific solution is necessary.

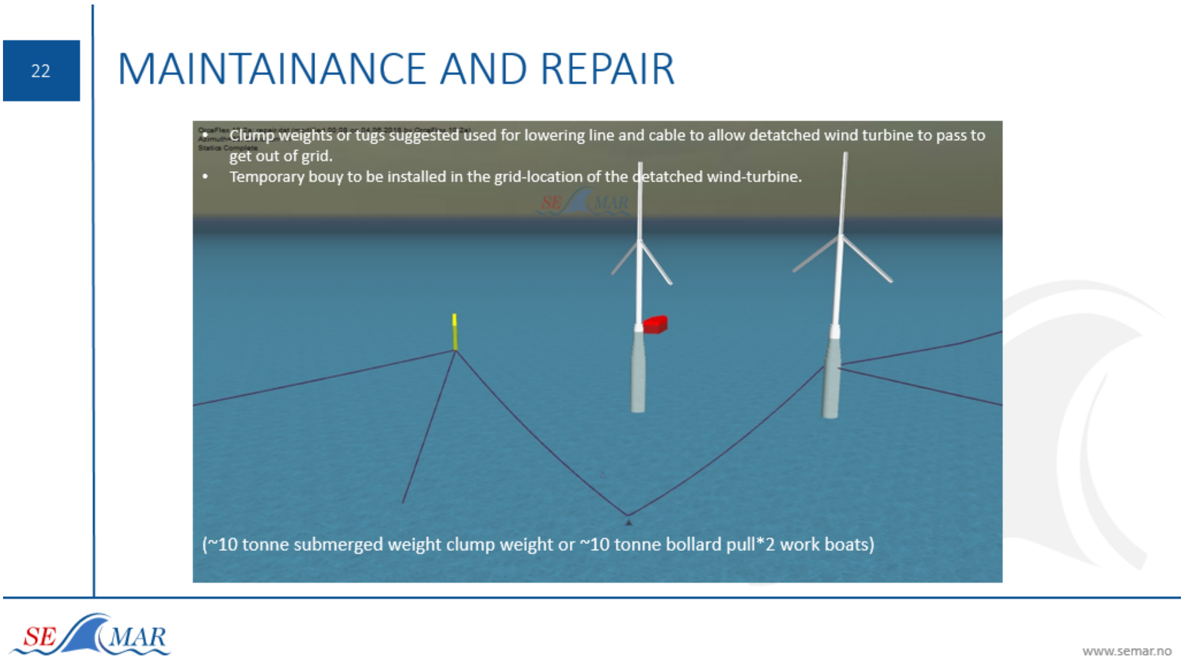

Figure 19. WT replacement in the Honeymooring solution

5.5 Rope recycling

Lankhorst has recycling operative[4], but this is mostly relevant for ropes for ship mooring, which is made of polyolefins, not polyester or nylon. The recycling mostly takes place in the Netherlands, where ship mooring rope material can be recycled to brushes.

5.6 Chain maintenance

Chain links can be replaced one by one based on their state. Typically, the links in contact with the fairlead and the chain link stoppers suffer most damage. As for rope replacement, such operations should be planned for already in the design phase, to avoid costly, demanding ad-hoc procedures.

6 Condition monitoring and maintenance in the FIRM project

This section takes the general topics from the previous sections to concrete plans for condition monitoring and maintenance for the FIRM project mooring solutions. The proposed solutions rely on components available in the market today that can be shared for both main mooring cases. The present designs focus on the fibre rope part of the solution. Any condition monitoring and maintenance of anchoring, chains, clump weights, buoys, power cables, tension limiting systems, etc. are therefore not treated in detail.

6.1 Method

In an ideal world, the ropes and other parts of the mooring were all fully understood, and one could design based on this knowledge. Since this is not the case, compromises must be made between cost and risk and between the well-known and the more forward-looking, choices which will direct the concrete designs for condition monitoring and maintenance.

In the FIRM project, these choices were be discussed in a workshop held October 14th, 2021. Input to the workshop was:

- Draft designs for condition monitoring and maintenance for base case mooring and taut leg mooring, both at 150 m depth in the North Sea
- Indications of how these designs will change with greater depth and if subject to typhoons and higher temperatures
- Regulations and recommendations for microplastics pollution control
- Cost of relevant sensors, sensor installation, and condition monitoring systems, including data storage
- Cost of maintenance procedures like ROV inspection, microplastics survey, and marine growth removal.

Issues that were discussed at the workshop are listed below.

Sensors
Questions to be answered:

- Number of sensors (one per rope, duplication for redundancy, or several placed along the mooring)
- Type of sensors (strain, load, angle, accelerometer, weather, …)
- Placements of sensors (on platform, under water, …)
- Should fatigue calculations be updated from direct sensors and/or from indirect measurements of position, weather, and accelerometer data?
- Should the sensors be cabled or use wireless communication?
- How, where, and for how long should the data be stored?
- How do these choices influence safety factors and costs of the rest of the mooring design?

Procedures
Questions to be answered:

- Is removal of marine growth from the mooring or from any sensors necessary? How often and how should it be done?
- Is 5-yearly inspection of rope status sufficient, or is yearly inspection required?
- Is 5-yearly inspection sufficient for the chain segments?
- How should the results be analysed and reported?
- What are the criteria for re-tightening?
- How do these choices influence safety factors and costs of the rest of the mooring design?

Reliability, Availability, and Maintainability
Questions to be answered:

- What are reasonable estimates for replacement time and annual failure rate for the different mooring components?

The mooring
Questions to be answered:

- Is a jacket as protection against UV, marine growth and mechanical damage needed for the whole rope, or only for certain parts?
- Is filter tape that lasts for several years required, e.g. to allow later contact with the seabed due to WT maintenance?
- What shall the rope replacement procedure be?
- Is equipment for re-tightening required, and if so of which kind?

Microplastics
Questions to be answered:

- How often shall monitoring be performed?
- What type of sampling grid, with how many samples are required? The answer depends on local oceanographic conditions.

6.2 Design for maintenance

As summarized in section 3.12, all relevant failure mechanisms are handled through design. Some problems can even be fully solved by suitable design choices, not requiring dedicated condition monitoring in operation. Some choices deemed particularly important for the FIRM project are discussed below.

6.2.1 Rope material

Polyester is well-known, but relatively short polyester ropes will make shallow water mooring too stiff, leading to undesired long mooring lines at these depths. To avoid that kind of design, an effective “damper” that can make mooring line “softer” in stiffness will be useful. For that purpose, SeaSpring (TFI), or Smart Buoy (Dunlin Offshore, see section 2.1.3), or even a segment of carefully constructed nylon rope could be used.

Polyester is currently used in Spain and UK for offshore wind. For nylon there is no experience with long term use in mooring

6.2.2 Rope protection

Jackets and filter tape are needed for the whole line length, and they should last for the whole lifetime of the line. This gives protection both during installation and during maintenance, as well as from fishery and other external damage.

There are many alternatives for jacket material on the market including Ultra High Molecular Weight PolyEthylene (UHMWPE). For instance, Equinor’s Åsta Hansteen has a double Dyneema jacket, which protects against light, pelagic trawling. More robust alternatives exist.

A relevant question here is if a robust jacket can make bottom chains unnecessary, making the buoy of the base case mooring solution obsolete. To answer this question, the various reasons for using a bottom chain should be considered:

- Seabed contact. Jackets can be produced that can protect the mooring ropes from dynamic seabed contact during the whole wind turbine design lifetime. Note, however, that jackets protecting from overtrawling and jackets protecting from dynamic seabed contact have different design requirements and damage modes.
- Mechanical compliance. The weight of the chain (along with buoys) provides mechanical compliance by bending the line under influence of gravity (catenary). A mooring system without such mechanically induced compliance must be designed so that sufficient compliance is introduced in other ways to minimize dynamic, wave-driven, load peaks.
- Weight for anchoring. Drag embedment anchors hold best when load is only applied horizontally. Ground chain is used to ensure only lateral loading. Other anchor types are capable to resist vertical loads as well, and these could eliminate ground chain entirely.

6.2.3 Power cables

Well-designed routing of power cables will reduce the consequences of the failure of one cable. A quick-release upon predicted mooring line failure could also avoid further damage.

6.3 Data sources

The proposed solution relies on multiple data sources. The focus has been on choosing data sources typically already available at the wind turbine (WT) in combination with sensors that are easy to install also for retrofitting. Keeping the HW cost down has also been prioritized.

- Required data:
  - Metocean: waves, wind, currents, temperature etc.
  - Operations: Supervisory Control and Data Acquisition (SCADA)
  - Positioning: Global Navigation Satellite Systems (GNSS) and Motion Reference Unit (MRU)
- Nice-to-have data for production sites:
  - Line tension: Load cells, one for each mooring line e.g. at the fairlead.
  - Inclinometers: Multiple, spaced along each mooring line. The number of inclinometers should depend on the mooring line length and the needed granularity
  - Accelerometers on the ropes: These are found useful for monitoring vibration in tidal energy applications[48], and can give direct information on changes in the ropes' response to wind, waves, and current.
- Nice-to-have data not relevant for production sites:
  - Sonars: either fixed underneath the WT or at seabed to spatially localize the individual mooring lines in real-time.
  - Acoustic emissions: local methods that would need multiple sensors to localize the degradation processes. Water provides a good transfer function for acoustic signals.
  - Integrated fibre optics in rope: established technology with good signal quality but is considered too expensive.

Monitoring 3-6 lines per wind turbine for a whole park of e.g. 300 wind turbines can be done, but it will be costly and generates a large amount of data. There are, however, special political and environmental risks related to the first installation. If the mooring fails, further funding will be hard to obtain. The first deployment instrumentation could therefore be more extensive and used to learn, while later deployments will require less monitoring. Alternatively, one can e.g. monitor every 5th unit with the sensors described as "Nice-to-have data for production sites", and/or one could only use these data sources during special periods of time, e.g. during installation, during extreme events, or for model calibration.

6.4 Visual inspection

According to DNV-ST-0119 Floating wind turbine structures, a general visual inspection should be performed at least every 4-5 years, as shown in Figure 20. Note that details on this inspection is not given, and exceptions may be granted. It is also not stated how tension and temperature for fibre ropes shall be monitored.

Section 15 In-service inspection, maintenance and monitoring

15.1 Introduction

15.1.1 General

15.1.1.1 The provisions set forth in DNV-ST-0126 Sec.9 for in-service inspection, maintenance and monitoring shall apply. General visual inspection (GVI) should be performed at least every 4-5 years on items which are linked to degradation modes of the structure such as deformations, corrosion protection systems or bolt pre-tension. For inspection of fatigue cracks, see DNV-ST-0126 [9.3.2.2].

15.1.1.2 For corroded steel structures, inspections shall include measurements of plate thicknesses by ultrasonic testing to document the degradation.

15.1.2 Anchors, mooring chain and steel tendons

The provisions set forth in DNV-OS-E301 for in-service inspection, maintenance and monitoring shall apply.

15.1.3 Fibre ropes, tethers and tendons made from synthetic fibre yarns

15.1.3.1 The provisions set forth in DNV-OS-E303 for in-service inspection, maintenance and monitoring shall apply.

15.1.3.2 The in-service condition management program shall be based on tension monitoring and control of temperature in order to manage the 3-T margins throughout the design life.

Figure 20. DNV-ST-0119 floating wind turbine structures

DNV-OS-301 refers to DNV-RU-OU-0300 Ch.3 Sec.4 [4.2.4], as shown in Figure 21.

12 Survey during installation

12.1 General

12.1.1 For floating production and/or storage units and CALM buoys a surveyor shall be present during installation of anchors and during hook-up and pre-tensioning of the mooring lines.

12.1.2 Prior to start of mooring system installation the installation procedures shall be submitted for approval. The installation procedures shall describe how the mooring system is to be installed as per design, without risk to the line assemblies. Acceptance criteria shall be included.

12.1.3 Upon completion of the installation process a comprehensive documentation package demonstrating that the mooring system design specifications are met shall be subject to approval prior to issue of the **POSMOOR** notation. This installation documentation shall comprise all change handling (e.g. management of change), be complete with certificates for installed components and include the documentation from the post installation survey. The documentation shall describe the 'as-installed' mooring system. This documentation shall be used as basis for the in-service follow-up of the mooring system, see DNV-RU-OU-0300 Ch.3 Sec.4 [4.2.4].

Figure 21. DNV-OS-301

DNV-RU-OU-0300 Ch.3 Sec.4 [4.2.4] contains a table of survey schemes, shown in Figure 22. The present report describes (parts of) a MIM, meaning the last row of the table is the relevant one.

Table 1 Applicable survey schemes with reference to survey requirements

	Survey requirements 5), 6)				
	General requirements		Additional requirements	Additional requirements for thruster assisted systems 7)	
	Annual 4)	Complete	Complete	Annual	Complete
1) Systems designed before 1996 (no fatigue analysis and corrosion allowance)	[4.4]	[4.7]	[4.8]	[4.6]	[4.11]
2) Systems designed with a fatigue design life factor of 3	[4.4]	[4.7]	[4.9]	[4.6]	[4.11]
3) Systems designed with a fatigue life factor of 5-8 or greater	[4.4]	[4.7]	[4.10]	[4.6]	[4.11]
Systems with an approved mooring integrity management programme (MIM)	[4.12]				

1) All lines required to be inspected on an onshore/offshore facility in a five year period cycle.
2) At least two lines required to be inspected on an onshore/offshore facility in a five year period cycle.
3) All lines inspected in-water on location.
4) For 1st annual after installation, the additional requirements of [4.5] apply.
5) Recordings from installation survey and the expanded 1st annual survey may require inspections below the waterline between the 5 yearly surveys. This additional inspection scope can also be triggered by special design solutions requiring a more frequent survey interval.
6) Incidents where damages, or suspected damages occur shall be reported to the Society i.l.w. Ch.1 Sec.3 [1.2]. These incidents may require additional inspections.
7) These requirements are applicable for **POSMOOR(TA)**, **POSMOOR(TAR)**, **POSMOOR(ATA)**, **POSMOOR(ATAR)** and **POSMOOR(HC)**.

Figure 22. DNV-RU-OU-0300 Ch.3 Sec.4 [4.2.4]

As shown in Figure 22, section 4.12 in DNV-RU-OU-0300 describes requirements for a MIM, and for which part of the mooring a MIM will replace fixed-interval inspections. Note that visual inspections can be part of a MIM, both for «Data collection» and «Fit for service», see Figure 14 and Figure 15.

4.12 Mooring integrity management

4.12.1 General

Mooring integrity management (MIM) is a systematics established as a continuous process to assure that the mooring system maintain the integrity throughout the service life. The process shall identify hazards that may lead to a mooring system failure and provide measures to prevent or eliminate them.

When MIM is applied for a vessel in the operation phase (in-service) it is used as an alternative to the regular inspection and maintenance approach following a fixed five (5) years cycle.

MIM is applicable for a vessel with long term mooring systems, comprising all components between the interface at the vessel structure and the soil interface at the anchor, covered by the additional notation **POSMOOR**. MIM does not cover equipment permanently installed on the vessel used to ensure the interface and connection of the mooring system, e.g. fairleads, turret, winches, etc.

When approved and implemented for a vessel, the MIM shall replace the requirements described in [4.5], [4.8], [4.9], and [4.10].

Guidance note:

See also DNV-RP-E308 for additional information on MIM.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

Figure 23. Section 4.12 in DNV-RU-OU-0300

As seen in Figure 24, DNV-OS-303 does not give specific requirements for monitoring, but rather that the plans for monitoring will part of a certification process.

4.4 Request for certification

The request for certification should be sent to DNV by e-mail. The following information should be included:

- manufacturer name, plant location and reference to manufacturer-approval certificate
- production and delivery schedules for fibre-rope segments and termination hardware
- testing facilities, location and foreseen testing schedule
- type of application
- scope of delivery
- any requests for deviations or test waivers, fully documented
- dimension, breaking strength of the line, including type of fibre and rope construction.

Additional information for long term mooring systems:

- in-service condition assessment scheme
- key results from analysis in order to decide the load levels to be used in the certification test program and determine the rope length in production.

Figure 24. DNV-OS-303

6.5 Microplastics

The sampling sites should be placed in orthogonal transects according to the main current direction at the site. An earlier example for gas platform pollution monitoring is shown in Figure 25, where reference sampling sites are marked K1-K4.

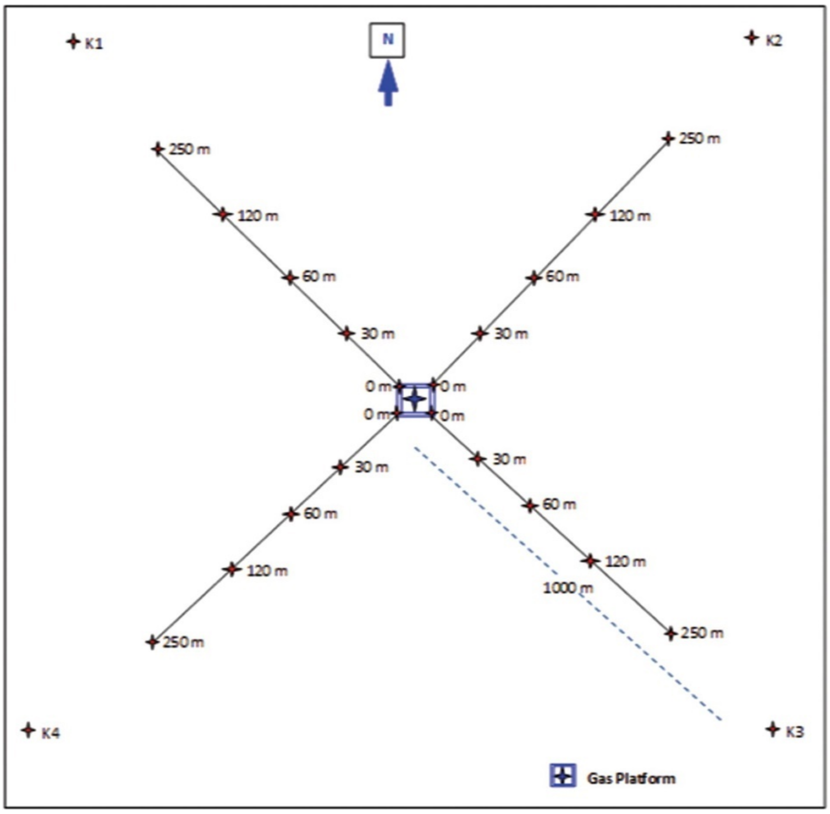

Figure 25. Example of sampling grid, from Gomiero et al.[49]

For the FIRM project, a wind turbine park of 50 turbines of DTU's reference 10 MW turbines is assumed. This turbine has rotor diameter 178.3 m. Assuming the turbines are laid out as 5 rows of 10 turbines with 8 rotor diameters between the rows and 4 rotor diameters between the turbines in each row, the total area is 5.7 km × 6.4 km. This corresponds to the small square at the centre of Figure 25.

Suggested distances from the "corners" of the wind turbine park are 0 m, 200 m, 1 km, and 5 km plus 4 reference sites placed 10-20 nautical miles from the WT park, resulting in 20 sampling sites in total. For the Buchan Deep site, the metocean report[3] indicates that the main current direction is north-south, so the sampling grid should be oriented accordingly. For the Donghae site, the currents are not known. Particle distribution modelling should be performed before the site positions are fixed.

Annual inspection is recommended.

NORCE has developed a sampling device with a total weight of 30 – 40 kg, which can easily be shipped around the world. After sampling, an interior metal filter is collected, placed in a standard petri dish, and shipped by normal post for analysis.

6.6 Mooring maintenance process

6.6.1 Mooring line replacement

An annual failure rate of 10^{-4} per line is the target value for oil & gas, the achieved value is closer to 10^{-3}. If a wind farm employs in the order of 1000 mooring lines (e.g. 300 wind turbines with 3 lines each), it can therefore be assumed that about 20 mooring lines might experience a failure during their 20 years of service life

Mooring line replacement is a standard service offered by multiple offshore service suppliers. The operation might require an anchor handling ship. The replacement time can vary from 1-2 days to weeks for one line. For replacing all 3 lines of the base-case mooring, subsequent re-tensioning is required, meaning more time is needed.

6.6.2 Replacement of other components

This topic has not been discussed in detail within the project, but it needs further attention.

6.6.3 Marine growth removal

Marine growth removal is not recommended on polyester ropes. The procedure may push growth into the jacket and/or cause direct damage.

Marine growth removal on chains is probably not harmful.

The initiation should be applied based on need from thresholding based on the proposed models. ROV-operated mooring line cleaning service is a standard service offered by multiple offshore service suppliers.

6.6.4 Re-tensioning

Re-tensioning is a contingency action, and not planned for normal operation.

The initiation should be applied based on need from thresholding based on the proposed model.

The operation will depend on the chosen mooring solution but can include changing level of buoyancy and weight or having an In Line Mooring Tensioner (ILMT) system installed, requiring a surface installation vessel or similar. Re-tensioning is a standard service offered by multiple offshore service suppliers.

6.7 Cost estimates

Costs can only be accurately estimated once the designs are completed. The following sections shall therefore only be considered as draft estimates. Costs for condition monitoring and maintenance can be divided into:

One-time cost:

- Sensors
- Model building for data assessment
- Inspection plan
- Data storage (onshore)

Periodic costs:

- Inspection
- Data assessment

Infrequent costs:
- Maintenance or replacement of sensors
- Maintenance or replacement of mooring parts
- Unplanned maintenance

6.7.1 One-time costs

Sensors
Representative unit costs are given in Appendix A, taken from the report “Mooring System Integrity Management Technologies”[50], one of the deliverables from the MooringSense project[51]. These costs are available for the following condition monitoring equipment:
- GNSS receivers
- Load cells
- Inclinometers
- Optical strain sensors

Assuming median cost sensors, one GNSS receiver per wind turbine and one load cell and three inclinometers per mooring line, with three lines per wind turbine, a rough estimate for these sensor costs is EUR 31 000.

In addition, the following sensors would be useful for the condition monitoring:
- Meteorology, one sensor per site giving information on e.g. wind, waves, current, and temperature. Are these standardized?
- Sensors used by SCADA system, which are not installed with condition monitoring as the main purpose
- MRU, e.g. from Kongsberg
- Compass

Finally, an installation costs must be included.

Model building for data assessment
Technical requirements must be specified to make a cost estimate. It is recommended to start with a simple model and develop it as more data and experience is gained.

Inspection plan
Inspection of shackles, buoys, chains, etc., and of their connection to the ropes: standardized plans can be used.

For microplastic sampling, particle distribution modelling should be performed. Depending on the amount of source data available and the desired accuracy, this can take from x to y months, resulting in a cost of z.

Data storage
The following sensors are assumed per wind turbine:
- One MRU giving three values for acceleration and three values for angular velocity
- One GNSS giving three values for position
- One compass giving one value for angle
- Three lines with one load cell and three inclinometers per line

Assuming all data is stored with 8 bytes per value at the frequency of 2 Hz used in Oil & Gas, the required storage generated per wind turbine per year can be found from the number of sensors and the number of values stored per sensor. As discussed in section 4.2.5, data aggregation can and should be performed before data is stored, e.g. to a level of four values from each sensor value per 15 minutes. The optimal degree of aggregation is site specific and depends on communication between sensor and wind turbine, between wind turbine and shore, and on the condition monitoring requirements.

Typical cost for cloud storage is USD 10 per month per TB of storage. The cost for processing power can be expected to be higher, but of the same magnitude. The advantage of using the cloud is that additional resources to detect and remedy any hardware problems are not required.

6.7.2 Periodic costs

Inspection
Condition monitoring is expected to transfer some of the periodic inspections to ad hoc inspections, to an increasing degree as the model experience increases.

Appendix A contains representative unit costs for ROV inspections, taken from the report "Mooring System Integrity Management Technologies"[50]. Assuming average costs and no specialized equipment, a 7-day survey costs about EUR 210 000.

For an annual microplastic survey per site, a sampling device can be rented for about EUR 1000 per week[52], and the sampling itself can be performed by the ROV doing other inspection tasks. The sample analysis cost is estimated to EUR 800 per sample[52], including extraction, analysis, and reporting for μFTIR and pyrolysis-GCMS. With 20 sampling sites the annual cost will be of magnitude EUR 20 000 if no extra ROV inspection days are required.

Data assessment
The data assessment happens automatically once the model is built. Model updates are included in "Model building".

If a problem is detected, time is required to identify the problem and determine if manual action is required. The amount of time depends strongly on the type of event.

6.7.3 Infrequent costs

Maintenance, calibration, and replacement of sensors

Based on lifetime and inspection costs

Battery change of inclinometers

Maintenance or replacement of mooring parts

Based on lifetime + inspection costs

Unplanned maintenance

A defined method must be used to estimate this cost

6.8 Summary

Condition monitoring for the mooring lines in the FIRM project shall as much as possible be based on sensors installed for the daily operation of the wind turbines. This includes sensors for position, motion, wind, waves, and current. A digital twin can then be used to detect line breakages, and preferably also to predict line breakages.

It is recommended to monitor any microplastics pollution from the wind farm.

Visual inspection can be useful for bolts, buoys, coupling elements etc, and will be risk-based.

Mooring line replacement will be required during the lifetime of the wind farm, while removal of marine growth is not recommended. Re-tensioning shall be possible, but is seen as a mitigation action, rather than being part of normal operation.

7 Directions for further research

In order to design and build safe and reliable fibre rope mooring systems for offshore wind platforms, the present work has shown that further research would be useful within the following topics:

- Nylon rope properties
- Acoustic emission as condition monitoring method, possibly in combination with optical fibres
- Optical fibres to gain localized information on strain
- Lifetime of rope filters against particle ingression
- The value of detailed locational knowledge of stresses, strains, angle, movement, etc. in the ropes
- The uncertainty of stress calculations based on data on position and weather

More specifically for the FIRM project, answers to the following questions are required:

- How early must a prediction be available to give time for useful actions?
- Can a robust jacket make the bottom chain unnecessary, thereby making the buoy of the base case mooring obsolete?
- How relevant is the failure mode of wet/dry cycling, and how can the consequences be monitored?
- What are relevant procedures for monitoring and replacing components like buoys, connectors, etc.?

8 Conclusion

Failure modes, condition monitoring and maintenance relevant for the FIRM project's mooring solutions have been investigated. Based on the findings, condition monitoring and maintenance schemes for the concrete mooring solutions are suggested together with directions for further research.

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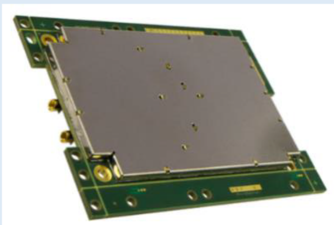
Appendix A. Costs

This appendix contains unit costs taken from the report "Mooring System Integrity Management Technologies"[50], one of the deliverables from the Mooring Sense project[51]

Table A-1. GNSS receiver costs[50]

GNSS receiver		Price	Features
Novatel OEM 7700		5 K€ 6 K€ (with access to corr. service)	Multi-constellation: all Multi-frequency: all available Tracking channels: 555 L-band channel: Yes Corr. Services: Terrastar Interference mitigation Accuracy*: 1.2 m (L1/L2)
Septentrio AsteRx4		5 K€	Multi-constellation: all Multi-frequency: all available Tracking channels: 544 L-band channel: Yes, dual Corr. Services: Marinestar Dual antenna (heading) Integrity monitoring Interference mitigation Accuracy*: 1.2 m
Septentrio AsteRx-m2		3 K€	Multi-constellation: all Multi-frequency: all available L-band: Yes Corr: Sapcorda ready Integrity monitoring Interference mitigation Accuracy*: 1.2 m
Trimble BX992		4 K€	Multi-constellation: all Multi-frequency: all available L-Band: Yes, Tracking channels: 544 L-band channel: Yes, dual Corr. Services: Omnistar, Trimble RTX Integrity monitoring Multipath mitigation Accuracy*: 1 m

NVS NV08C		200 €	Multi-constellation: GLONASS, GPS, GALILEO, BEIDU, SBAS Multi-frequency: L1, L2 Tracking channels: 96 L-band: No Corr. Services: No Integrity monitoring Multipath mitigation Accuracy*: 2.5 m
**** Horizontal accuracy, standalone (without correction services, RTK, etc.)***			

Table A-2. Load cell prices[50]

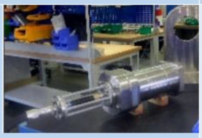
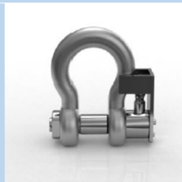
	Scotload-Strainstall	Scotload-Strainstall	LCM Systems - LCM4487	LCM Systems - LCM3511	LCM Systems - LCM4570
Product type	Load Shackle	Tension link load cell	Load Pin	Bow Shackle Load Cell	Load Shackle
Photo					
Price	55T - 2793€ 120T - 3968€ 150T - 4400€	50 T - 1316€ 120 T - 5350€	120T–1569€	120T - 4195€	120T - 3168€
Industrial uses	Strainstall's specialist mooring system starts monitoring at Hywind [145]	SSE utilises SmartLoad® load monitoring technology during power cable installation [146]	Load Pins for Anchor Chain Load Measurement in Norway [147]	-	Mooring line monitoring of fish farm tanks [148]

Table A-3. Inclinometer prices[50]

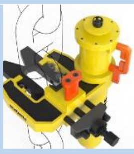
	Seatools - SINCLINO 200	**Seatools - TWINCLINO 1000**	**Seatools - MoorMate**
Product type	Single-axis	Dual-axis	System based on the inclination measurement
Photo			
Price (aprox.)	1210€	2386€	Unknown
Industrial uses	Seatools to Supply Dredging Monitoring Sensors [158]	-	In 2018 Seatools successfully delivered a remote offshore monitoring system for the Ocean Cleanup [155]

Table A-4. Optical strain sensor prices[50]

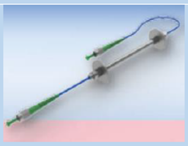
	HBM - FS62	**HBM - OL/OL-W**	**HBM - FS22DI-ST**
Product type	Optical Strain Sensors	Optical Strain Gauge	Interrogator - Data acquisition system
Photo			
Price	215€	Optical fiber with multiple Fiber Strain Gauges: 1700€	10000-20000€ (Depending on characteristics like the number of optical connectors)
Industrial uses	Although there is still no application of this type of sensors to mooring lines, other industrial applications that have been found for this type of sensors are: - Tunnels Structural Monitoring - Wind Blade Load Monitoring - Monitoring of fiber ropes - Characterization of Railway Traffic and its Effect on Structures Monitoring Method for The Rope Of A Lifting Device [165].		

Table A-5. ROV inspection costs[50]

	Average day rates [€/day]
Support Vessel	10,000 – 30,000
Inspection class ROV	3,000-5,000
ROV crew (*)	1,000
Other inspection equipment (**)	1,000-10,000

(*) cost per person. Gnerally 4-6 people required for 24hr operation

(**) depends on the type of inspection