



# D2.1 Review of the state of the art of mooring and anchoring designs, technical challenges and identification of relevant DLCs

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## 0 ABBREVIATION LIST

Abbreviation	Description
AHV	Anchor Handling vessel
ALS	Accidental Limit State
BoQ	Bill of Quantities
CA	Consortium Agreement
CAPEX	Capital Expenditure
CFS	Certificate on Financial Statement (audit report)
DLC	Design Load Case
EC	European Commission
EC - GA	(European Commission)-Grant Agreement
EIB	Exploitation and Innovation Board
EU	European Union
FLS	Fatigue Limit State
FOWT	Floating Offshore Wind Turbine
GAGA	General Assembly / Grant Agreement
GC	Gran Canaria
IAB	International Advisory Board
IPB	In-plane Bending
IPR	Intellectual Property Right
LCOE	Levelized Cost of Energy
LRFD	Load and resistance factor design
NDT	Non Destructive Testing
OPB	Out of Plane Bending
OPEX	Operational Expenditure
PC	Project Coordinator
PMO	Project Management Office
PR	Periodic Report
ROV	Remotely Operated Vehicle
SF	Safety Factor
SLS	Service Limit State
T&I	Transport and Installation
TLP	Tension Leg Platform
ULS	Ultimate Limit State
WAB	West of Barra
WP	Work package
WTG	Wind turbine generator

## 1 EXECUTIVE SUMMARY

This deliverable deals with defining current mooring and anchoring state of the art for floating wind projects currently installed or in construction phase. Aim is to ensure specifications and requirements to be developed within mooring Work Package 2 account for current industry status. This work package consists of a comprehensive literature survey, industrial engagement through network of contacts within the consortium and collation of findings to deliver a documentary summary report.

### 1.1 Station keeping system

Advantages and drawbacks of station keeping configuration are reviewed, design process is presented in section 3.1. Document then provides preliminary design guidelines and approach review versus Oil and Gas in section 3.4 complemented by industry examples in section 3.6. Design process is addressed in this section with target being to define appropriate DLCs for station keeping design. Detailed load case matrix will be addressed in deliverable related to WP2.2.

Market watch provided in section 4 identifies current floating wind projects in operation and associated technological choices with in particular: Mooring configuration versus water depth, floater type and installation methodology. The research has been performed for projects currently in construction phase and future planned projects. Main highlights are given versus projects in operation.

### 1.2 Installation & Inspection

Section 5 aims to describe installation and inspection techniques for semi-submersible and spar floaters. Installation and maintenance techniques are implemented according to procedures once mooring layout is fully defined, this procedure is focused on providing necessary information and instructions to perform these activities in a safe manner.

Installation techniques including preparation, site investigations, installation plan, vessel selection criteria and installation steps are described in section 5.1.

Section 5.2 provides a baseline of current state-of-the-art inspection and monitoring techniques for mooring systems of floating offshore wind turbines. Developers of foundations and mooring systems strive to design their products maintenance free. Even in case maintenance free design might be possible, it can be expected that this design will not be economically feasible. Hence, O&M activities will be required for future projects to ensure reliable operation throughout the lifetime. After a first evaluation on this topic following risks and challenges for operation, maintenance and monitoring are being identified.

### 1.3 Identification of constraints, critical design parameters, key performance indicators and technical challenges for the design of FOWT station-keeping systems

Section 9 identifies the constraints for the station-keeping systems based on the work of the previous sections. The constraints are divided in operational constraints, site constraints, anchor constraints, mooring line constraints, dynamic cable constraints and installation and maintenance constraints. The specific constraints for each case are identified and quantified where possible in order to facilitate their applicability in the optimization effort.

The critical design parameters are then summarized. These are the parameters or constraints that have bigger influence in the optimal solution of the mooring system design. The optimization problem must obtain the most reliable, cost effective, and easy installation station keeping solution for the life span of the structure. The critical design parameters are divided in design constraints, met-ocean data and life span of the mooring system.

The key performance indicators are finally provided. These measure the success of the optimization problem for the design of the station keeping system. The aim of the optimization problem is to find a cost-effective station keeping configuration that fulfills the design criteria of the FOWT. The key performance indicators are numbered as follows :

- % Cost reduction between solo solution vs wind park solution
- % Cost reduction of actual standard solutions vs Optimized ones
- Fulfillment of all constraints and design criteria

## 1.4 Outlooks

Following the state of the art, design constraints and key performance indicators review next section provides an outlook and discussion about some of the planned options and optimizations within COREWIND project :

### 1.4.1 [Numerical optimization](#)

The optimization problem for the station keeping design must be treated as a multi-objective optimization problem, because there are two objectives functions that have to be optimized simultaneously, the cost and the structural reliability of the mooring system. Minimizing the cost while maximizing the reliability for all the life span is the main goal of the design of the station keeping systems.

Within the framework of the project, the optimization problem can be divided in two parts, a sizing optimization problem and a topology optimization problem. The former aims to find an optimal design for the combination of parameters such as length, diameter, ancillaries' dimensions for a given mooring typology. The topology optimization objective is to find the optimal station keeping typology based on wind park constraints by modifying FOWT location and mooring line distributions as well as the number of line and the possibility of sharing anchors.

Within the project, it is planned to couple OrcaFlex (Finite Element software for mooring application) and a Design of Experiment software to allow automated screening of a large number of mooring configurations and automated acceptable solutions computation meeting selected criteria. The main targeted benefits are:

- Reduction regarding engineering man-hours to perform the mooring configuration definition thus reduce the overall engineering planning.
- Reduction in terms of cost.
- Ensure selected configuration is optimal versus selected criteria (station keeping capability, floater offset, fatigue resistance of mooring components, maximum peak load, payload on floater and its global cost).

### 1.4.2 [Integrated / combined Mooring / Dynamic cable design](#)

Maximum allowable offset for floater is usually limited by dynamic cable capabilities and thus significantly impacts mooring design and station keeping system. Aim of this task is to perform a combined mooring/dynamic cable configuration design loop with goal being to go up to maximum dynamic cable capabilities and thus relax mooring design.

### 1.4.3 [Breakthrough analysis / Technological benefits regarding peak loads reduction](#)

Aim of this task is to focus on peak load reduction. Reduction in peak loads and maximum tension will aim to define lower grade or lower capability (Minimum Breaking Load) equipment's thus lowering station keeping system cost. Several applications and technologies are foreseen to be tested numerically to assess benefit.

#### 1.4.4 [Investigations of tuning of the controller to reduce mooring fatigue](#)

This task will address the possibility to tune the wind turbine controller such that the mooring line fatigue loads in operational conditions are reduced. Multivariable controllers will be implemented in control-oriented models.

#### 1.4.5 [Design at farm level: use of shared anchors, shared mooring lines](#)

This solution will use conventional mooring materials. Two topics are planned to be addressed: Shared anchors and mooring lines.

## 2 INTRODUCTION

### 2.1 Introduction

Floating offshore wind is still a nascent technology and its LCOE is substantially higher than onshore and bottom-fixed offshore wind, and thus requires to be drastically reduced.

The COREWIND project aims to achieve significant cost reductions and enhance performance of floating wind technology through the research and optimization of mooring and anchoring systems and dynamic cables. These enhancements arising within the project will be validated by means of simulations and experimental testing both in the wave basin tanks and the wind tunnel by taking as reference two concrete-based floater concepts (semi-submersible and spar) supporting large wind turbines (15 MW), installed at water depths greater than 100 m and 200 m for the semi-submersible and spar concept, respectively. Special focus is given to develop and validate innovative solutions to improve installation techniques and operation and maintenance (O&M) activities. They will prove the benefits of concrete structures to substantially reduce the LCOE by at least 15% compared to the baseline case of bottom-fixed offshore wind, both in terms of CAPEX and OPEX. Additionally, the project will provide guidelines and best design practices, as well as open data models to accelerate further development of concrete-based semi-submersible and spar FOWTs, based on findings from innovative cost-effective and reliable solutions for the aforementioned key aspects. It is aimed that the resulting recommendations will facilitate the cost-competitiveness of floating offshore wind energy, reducing risks and uncertainties and contributing to lower LCOE estimates.

COREWIND aims to strengthen the European Leadership on wind power technology (and specially floating). To do so, the project consortium has been designed to ensure proper collaboration between all stakeholders (users, developers, suppliers, academia, etc.) which is essential to accelerate commercialization of the innovations carried out in the project.

### 2.2 Objective

This report focuses on defining current mooring and anchoring state of the art for floating wind projects currently installed or being engineered.

Aim is to ensure specifications and requirements to be developed within mooring Work Package 2 account for current industry status.

This task consists of a comprehensive literature survey, industrial engagement through network of contacts within the consortium and collation of findings to deliver a documentary summary report.

The state of the art will target to review the following components:

- Mooring configuration (catenary, taut, semi-taut, single point, spread),
- Number of mooring lines (3-leg, 4-leg, etc.)
- Material (chain, wire, synthetic rope)
- Anchor type

Following state of the art will be addressed the **identification of constraints, critical design parameters, key performance indicators and technical challenges for the design of FOWT station-keeping systems**. In order to provide a broad view on the required decisions for an optimized station keeping system, the definition of the optimization problem is performed in a first step. For this, the critical design parameters need to be identified as well as their constraints (such as defining a critical water depth level from which significant impact on mooring design feasibility and costing is expected). Also, key performance indicators need to be defined in order to evaluate a given design and compare it to other designs. The parameters outlining the design optimization are scrutinized. The potential of different innovations and breakthroughs to provide optimized solutions and the linked requirements are highlighted.

### 3 STATION KEEPING SYSTEM REVIEW

The station keeping system refers to the catenary or taut mooring systems of either chain, wire or fiber ropes for compliant support structures such as Deep draught floaters, or to the tendon systems of tethers for restrained support structures such as TLPs. The station keeping system is vital for keeping the wind turbine in position such that it can generate electricity and such that the transfer of electricity to a receiver can be maintained [11].

#### 3.1 Advantages and Drawbacks

There are two main types of mooring systems: catenary and taut mooring [1],[2], both are illustrated in Figure 3-1. For the catenary case, the motions of the floaters are limited by the weight of the lower section of mooring chain that rests on the seafloor. In the second case, stability is maintained by the high tension in the cables.

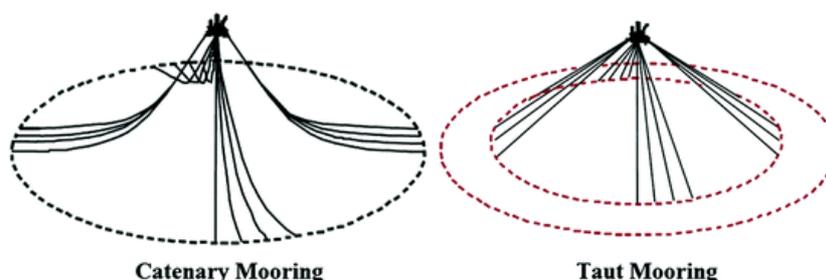


Figure 3-1 – Mooring systems [1].

The following table describes the two types of configurations and associated advantages and drawbacks:

	Catenary	Taut
<b>Connection to seabed</b>	Horizontal	Horizontal and vertical
<b>Loads on the anchor</b>	Reduced	Large, submitted to both horizontal and vertical forces
<b>Generation of the restoring force</b>	Weight of the mooring line	Elasticity of the mooring line
<b>Degrees of freedom</b>	Some degree of horizontal movement	Limited horizontal movement
<b>Seabed disruption</b>	Lower section of chain rests on the seabed, resulting in more disruption	Low disruption
<b>Common material</b>	Long steel chains and/or wires	Synthetic fibres or wire
<b>Usual applications</b>	Spar-buoy Semi-submersible platforms	Tension Leg Platforms

	Catenary	Taut
Main advantages	Low cost of anchors	Small footprint Adapted to higher depth (less mooring line needed)
Main drawbacks	Large footprint	High cost of anchor
Industry example	Hywind (Statoil)	Floatgen (IDEOL)

Table 3.1-1 – Catenary / Taut mooring comparison [3]

Taut mooring can also be designed with vertical cables, vertical tension mooring is thus a sub-category of the taut system. The footprint becomes smaller, the platform more stable and the system requires less mooring line. However, high vertical anchors forces will require more complex and costly anchors with limited anchoring options and the installation procedure becomes more complex [2]. See Figure 3-2 for current industrial concepts proposed for Taut mooring :mooring: Provence Grand Large (SBM) [9] or PelaStar [4].

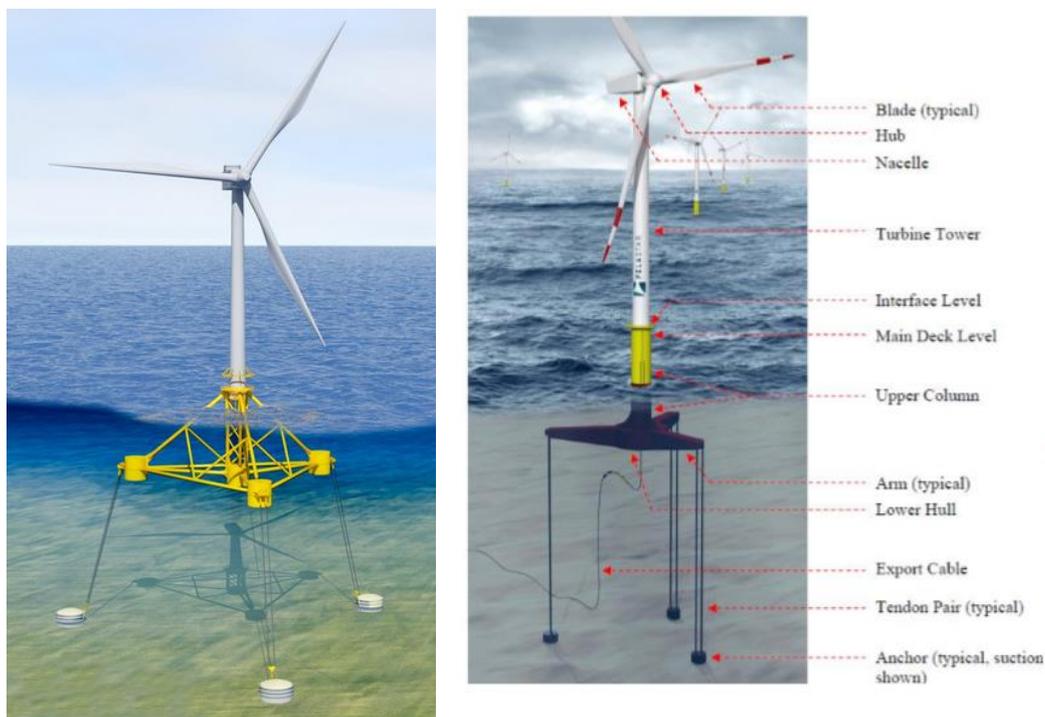


Figure 3-2 –SBM Taut mooring concept [9], PELASTAR Example for Taut mooring [4]

The catenary system can be complemented with clump weight or buoyancy modules. Clump weight are additional masses that increase the tension in the line and thus the restoring force applied to the floater. Buoyancy modules allow to reduce the dynamics of the mooring line and weight on the anchor. The Hywind project, for instance uses clump weights.

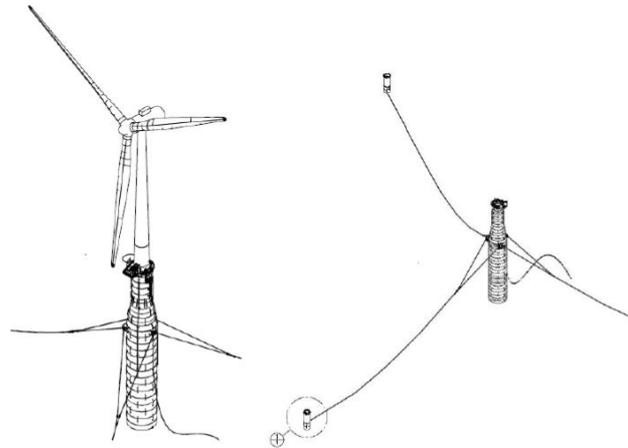


Figure 3-3 – OO-Star Example for catenary mooring [7], Hywind Scotland catenary mooring configuration [12]

Main configuration types are summed up in Figure 3-4. Materials (represented with colours on the schemes) are discussed in next sub-section.

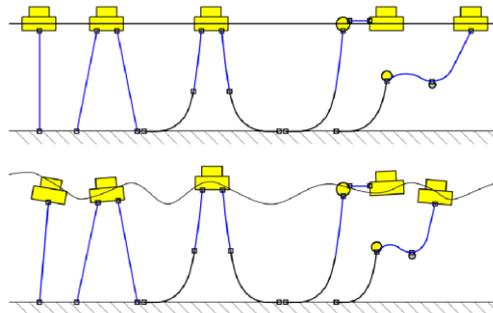


Figure 3-4 – Possible mooring arrangements [8]

Mooring systems can either be spread or single point. The spread system has multiple mooring lines, attached at various positions on the floater, connecting the floater to the seabed. The latter has one or multiple mooring lines connecting the floater's centre of rotation to the seabed, it is generally called a turret system (the X1Wind design for instance).

For FOWT, one of the main disadvantages highlighted of the usual single-floater turbine is the cost of anchoring. Hence, shared mooring or shared anchoring systems could help reduce those costs. To that goal, various possibilities are currently being explored such as the possibility of placing various small-scale turbines on one single floater or single-floater turbines with a shared-mooring system. These propositions are at a very early development stage.

All things considered, the most common mooring system among the existing or planned FOWT project is the catenary system for spar and semi-submersible platforms and taut systems for TLP. Other innovative ideas are under development.

### 3.1.1 [Design process and drivers for configuration selection](#)

Figure 3-5 provides an overview of mooring design process and main steps and criteria to be verified along the process:

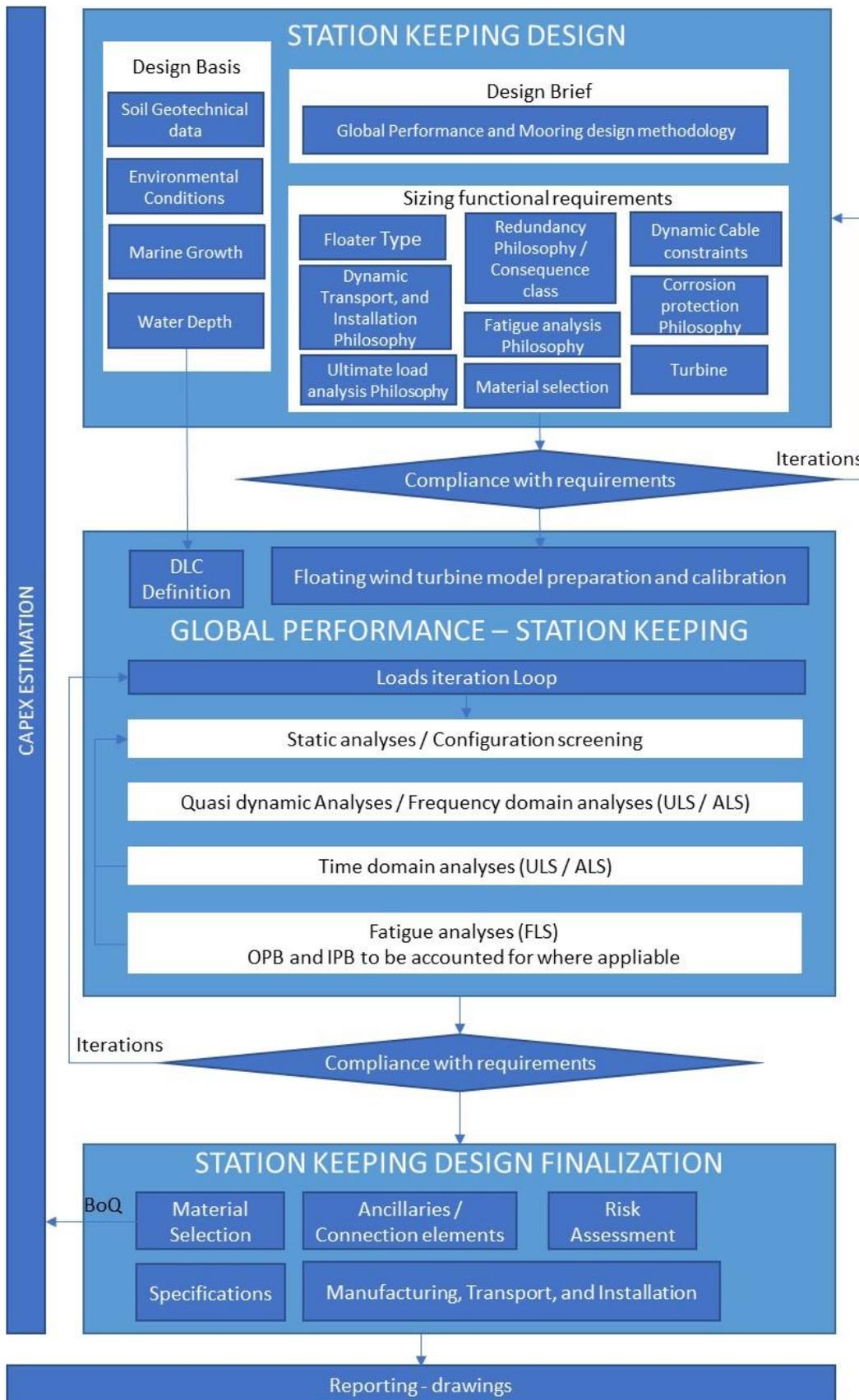


Figure 3-5 – Station keeping General design process

The mooring configuration must be designed to consider global response of floater integrating hydrodynamic / aerodynamic coupling.

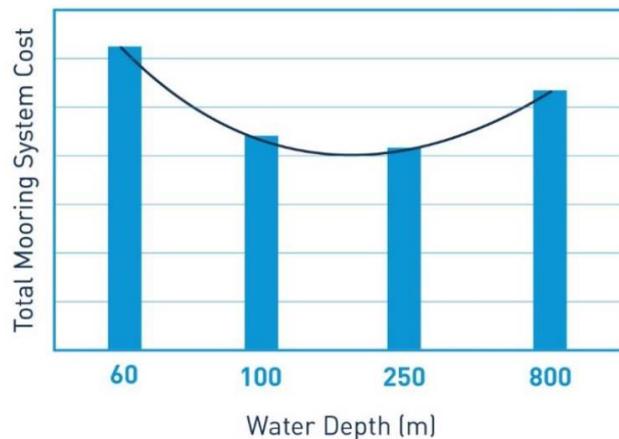
Main configuration design drivers are:

- Floater type & Environmental conditions
- Excursion limitations
- Water depth
- Marine Growth
- Fatigue response
- Mooring response and peak loads
- Loading at anchor
- Cost system including Ancillaries

**Floater response, configuration and hydrodynamic/aerodynamic coupling** is a key element for the mooring design and should be determined from global performance studies accounting for **environmental conditions** (Wind, waves and current particularly). Critical cases in terms of excursion obtained, tension in the mooring lines and line dynamics must be identified and applied to verify mooring components structural integrity. The spar buoy and the semi-submersible platform can assure stability on their own without relying on their anchoring systems. Mooring is thus only required for station keeping. Hence, both catenary and taut systems can be used. TLP platforms however rely on anchoring for stability and taut leg mooring is required. Besides the smaller footprint, taut leg configuration becomes more advantageous over catenary systems as water depth increases due to the lower requirement of mooring line. Taut leg also offers larger stability to the floater. However, cost for installation and anchoring increases [4].

**Excursion limitations** are usually mainly driven by dynamic cable or the windfarm layout and will become one of the design drivers for mooring design.

**Water depth** is also a critical parameter for mooring design: the deeper the waters, the more expensive the material and the cost. According to [10], FOWT are considered to be viable for depth >40m. Above that limit, the mooring line cost for catenary mooring evolves as depicted in Figure 3-6. For shallow water sites (<100m), the restoring force required for the highly dynamic floater leads to more expensive systems. For deep water sites (>250m), added length to the mooring line adds to cost.



**Figure 3-6 – Costs for a conventional steel chain catenary mooring system (non-optimized) [10]**

Finally, the tension present in the mooring line, the anchoring and the fairleads are also design criteria parameters.

**Marine growth:** After prolonged duration in water, marine growth will start to form around the mooring system, including ancillaries. Marine growth can be critical for the mooring configuration linked to configuration pretension and is highly dependent of selected geographical zone. The added weight onto product and increased diameter impacts the configuration behaviour when fully developed.

Marine growth profile against water depth should be defined to properly account for the fact that marine is expected to be more prevalent near the surface of the ocean, where the water is oxygenated and warmer.

It should be emphasized that marine growth is site specific and project development should account for marine growth survey if not covered by actual specifications.

DNVGL-ST-0437 section 2.4.11 (Reference [21]) provides guidance regarding following geographical zones:

- Central and Northern North Sea (56° to 59° N)
- Norwegian Sea (59° to 72° N)
- Baltic Sea
- Gulf of Mexico
- Offshore West Africa

For other areas specific survey should be performed as this is a critical engineering input for dynamic cable configuration.

**Fatigue response :** As stated in reference [10] the coupled behaviour of floating wind turbines introduces new fatigue load characteristics (e.g. additional fatigue load cycles from transferred wind turbine loads or increased out-of-plane bending by increased yaw motions) that can have a material impact on the performance and reliability of the mooring system. In addition, reference [10] mentions that snap and shock loads in extreme conditions can have a significant influence on fatigue life.

**Loading at anchor:** limitations regarding loadings at anchor can significantly impact the mooring configuration line length thus global footprint. Particularly for catenary mooring lines associated to drag embedment anchors which have limited vertical load capacity. This can become the design driver for selected material weight and length resting on sea bottom.

**Mooring dynamics and peak loads:** Given the water depth and dynamic floater motions and line pretension mooring line can experience snap loads inducing high peak loads. Mooring components design will be driven by these peak loads occurring for extreme events. It is thus important to identify means to reduce these peak loads from a mooring line configuration point of view of technological components. Several companies are particularly investigating peak reduction load systems like Tfi [52] or Seaflex [53];

**Cost of system including ancillaries :** Ultimately, as explained in [2], the choice of configuration “may be a trade-off between the added complexity introduced by platform dynamics, the associated turbine cost, the added complexity and costs of the anchor system that determines the best option”.

## 3.2 Components and Ancillaries

### Chain

The most common product used for mooring lines is chain [13] which is available in different diameters and grades. Chains have been used for a long time for mooring applications. Diameters of chain available for commercial use range approximately from 25 to 180 mm typically. Different grades are available, depending on the quality of steel used, providing different strengths: Grade R3, K3, R3S, R4 and R5 are commonly used for offshore applications. Chains can be studlink or studless. Studlink chains are heavier, have a higher drag coefficient and resist better to fatigue. Chains are used:

- a) on the seabed section of a catenary mooring system, because of their weight which avoids excessive vertical loads on drag embedment anchors and because of their abrasion properties;
- b) in the water column, because of their bending properties, but their considerable weight may limit this application;
- c) near the water surface, in a highly dynamic zone, because of their bending properties. When using chains, corrosion needs to be considered.

### Wire ropes

Wire ropes are lighter than chain with the same breaking load and a higher elasticity, however they are more likely to be damaged or corroded [1]. They are made of steel. For offshore mooring applications, IWRC (Independent wire rope core) ropes are used due to their durability. For corrosion protection, a high-density polyethylene or polyurethane jacketing is employed [30].

### Synthetic fiber ropes

A recent development is the use of synthetic fibre ropes in mooring lines. Due to their light weight and high elasticity, they have become a widely used material. However, using synthetic material adds complexity and increase the cost of installation. A range of synthetic materials are available for different configurations and site conditions but the most widely spread is the Polyester rope. Nylon and HMPE (High modulus polyethylene) are also existing options. All these materials are detailed in [30].

Polyester being one of the most ancient synthetic rope, its suitability for offshore application has been proven in Oil and Gas application and is now widely used for FOWT applications. Polyester ropes are typically constructed of several smaller sub-ropes laid in a parallel construction. One of the major drawbacks of polyester ropes is that unlike wire ropes or chains, polyester ropes exhibit axial load elongation characteristics that are nonlinear, depending on loading type.

Amongst the other types of material, Nylon is the most classic. It is used when a high elasticity is required, usually for shallow water. It is thus particularly useful for FOWT systems. The durability of Nylon is said to be short, however recent advances extended that durability to be applicable to FOWT application. An application of Nylon is the Floatgen project.

HMPE has several properties superior to other fibre materials, such as excellent abrasion resistance, higher strength, and high stiffness. These properties make it an excellent candidate for floating wind TLP designs. Drawbacks of HMPE is that creep may increase and potentially cause relatively sudden rope failure.

The few examples using fibre ropes are the early DCNS Sea Reed design and the IDEOL Floatgen demonstrator. In these cases, nylon has been favoured over other fibres in order to insure sufficiently soft behaviour in very shallow water (30–40 m), where conventional arrangements become too stiff.

For catenary application, a combination of materials is often considered, for cost and weight reduction. Usually, chain is used on the upper part for floater connection to easily adjust the line length, to connect to the floater and to adjust the tension. At the bottom, only chain can be used since synthetic rope are not resistant enough to be dragged on the bottom. In-between, synthetic or wire is used for cost and weight reduction. The Hywind project for instance, uses a combination of steel chain and wire.

Regarding durability and fatigue the industry tends to agree that synthetic fiber is a fully qualified technology which has been used in several projects. This should be further investigated with product suppliers.

#### Other components: D-Shackle, H-Shackle, etc.

The D- shackle is a connector that is very common in the offshore industry. It is D-shaped and consists of a bow, which is closed by a pin. H-links (or H-shackles) serve to connect two lengths of mooring, independently of the material. This type of connector was introduced to avoid time-consuming handling that is associated with D-shackles and allows for mooring line segments with different sizes to be easily connected to one another.

#### Clump weights

Clump weights are cast steels that can be added to the mooring line. The clump weight will increase the vertical component and the total tension in the line, thus increasing the restoring force. It can thusly reduce the amplitude of tension peak that may occur on mooring lines in shallow waters.

#### Buoyancy modules

It is possible to attach a buoy to the mooring lines, creating an upward force. Such a layout is especially attractive for deep water applications, to limit the mooring line dynamics and reduce weight of mooring lines that must be supported by the platform. Buoyancy modules can also be used to create a hybrid or semi taut configuration to increase decoupling versus floater motions.

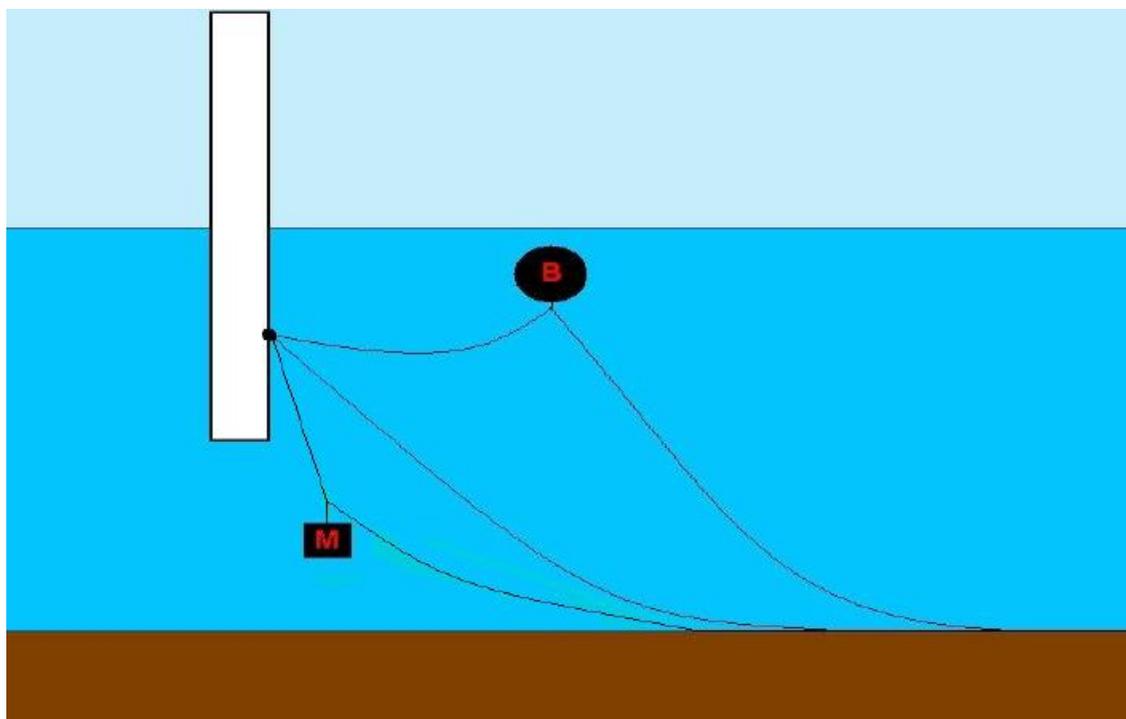


Figure 3-7 – Mooring system concepts with clump weights or buoyancy modules [18]

### Fairleads / chain stoppers

The connection between the mooring chain and the floating platform is ensured by a fairlead or chain stopper. Options regarding fairleads for floating wind floaters will be addressed in interfaces section 7.1.

### 3.3 Design methodology

As explicated in reference [14], COREWIND mooring design will be predominantly based on DNV recommendations. Main guidelines are recalled hereafter.

As per DNVGL-ST-0119 and DNVGL-ST-0126, the COREWIND platform shall be designed to Normal Safety Class, meaning the platforms is unmanned during severe environmental loading conditions. For initial design purposes, as a base case, a three-line mooring system shall be assumed. The system is considered redundant and Consequence Class 1 requirements are applicable.

The failure of a slack mooring line in the three-line system, will cause a large drift-off. It does not necessarily imply a system without redundancy. In such case, it may be necessary to carry out a qualification of the redundancy of the station keeping system.

To be qualified as a redundant system an ALS assessment will be performed to demonstrate the COREWIND is capable of withstanding loads in the damaged condition after an accident. For this purpose, characteristic environmental loads defined as 1-year loads can be assumed in conjunction with load factors for the ALS in the relevant safety class. If the platform cannot be qualified as redundant then a Consequence Class 2 in the mooring system design would be implemented.

The mooring line must be designed for the following limit states: ULS, FLS, ALS. The load factors as a function of safety class are listed in DNVGL-OS-E301 Chapter 2, section 2, subsection 4.2 & 4.3. Operating, Survival and Accidental design conditions are the most relevant situations to consider carrying out the mooring lines design.

The accuracy level required is Level I and therefore a Dynamic model is required. The model shall reproduce the real dynamics of the mooring lines. The buoyancy and the drag of the lines shall be included. Requirements for load factors in the ULS and the ALS are given in the next table as a function of safety class as done in DNVGL-ST-0119 section 8.2.2.6.

Load factor requirements for design of mooring lines			
Limit state	Load factor	Safety class	
		Normal	High
ULS	$\gamma_{mean}$	1.30	1.50
ULS	$\gamma_{dyn}$	1.75	2.20
ALS	$\gamma_{mean}$	1.00	1.00
ALS	$\gamma_{dyn}$	1.10	1.25

**Table 3.3-1 – Load factors for mooring design**

### Existing specifications for Station keeping design:

Here are the main standards that deal with mooring issues. The DNVGL-ST-0119 is highlighted and suggested as being the entry point and which will refer to the other applicable specifications.

	Guideline	Publication date
Det Norske Veritas	Floating Wind Turbine Structures: DNVGL-ST-0119	2018
	Position Mooring: DNV-OS-E301	2010
	Offshore Mooring Chain: DNV-OS-E302	2009
	Offshore Fibre Ropes: DNV-OS-E303	2013
	Offshore Mooring Steel Wire Ropes: DNV-OS-E304	2009
	Design and Installation of Fluke Anchors: DNV-RP-E301	2012
	Design and Installation of Plate Anchors in Clay: DNV-RP-E302	2002
	Geotechnical Design and Installation of Suction Anchors in Clay: DNV-RP-E303	2005
	Environnemental Conditions and Environnemental Loads : DNV-RP-C205	2010
Bureau Veritas	Classification of Mooring Systems for Permanent Offshore Units. NR 493 DT R02 E	2012
	Certification of fibre ropes for Deepwater offshore services. 2 <sup>nd</sup> edition. NI 432 CTO R01E	2007
	Classification and Certification of Floating Offshore Wind Turbines - NI 572 DT R01 E	2015
American Petroleum Institute	Recommended Practice for Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring: API RP 2SM	2007
	Design and Analysis of Stationkeeping Systems for Floating Structures API-RP-2SK	2015
American Bureau of Shipping	Guide for Building and Classing Floating Offshore Wind Turbine Installations	2014

Table 3.3-2 – Station keeping specifications

### 3.4 Comparison versus Oil and Gas applications

Design process and methodologies rely mainly on developments performed in the Oil and Gas sector. Offshore Oil and Gas utilizes floating platforms and thus station keeping systems for permanent structures. However

associated water depths are significantly higher in most cases. In addition, Oil and Gas floaters tend to have more limited motions than floating wind given their size particularly in the wave frequency range. Finally, safety factors considered for design account for the risk linked to fluids conveyed and associated human and environmental risks.

In addition, as noted in reference [16]

- The coupling effect and non-linear response of a FOWT could be so significant that the decoupled analysis, quasi-static analysis or frequency domain analysis that is normally acceptable for floating offshore oil and gas production installation may potentially introduce large error in case of FOWT.
- Non redundant or unconventional station keeping systems may be used in FOWTs. Special considerations of the design requirement are needed for those station keeping systems that are not commonly used by floating offshore oil and gas production installation.
- Overall safety level of a FOWT may be lower than that of a floating offshore oil and gas production installation. Reduced safety design criteria could be applied to the design of the station keeping system of a FOWT. Nevertheless, there are arguments indicating that the consequence of failure of a single station keeping system in an offshore wind farm with closely spaced FOWTs could lead to catastrophic chain reaction and, therefore, the high safety level may be necessary for the station keeping systems of FOWTs.

Main point addressed further in this section relates to these last points related to redundancy philosophy, mooring lines failure and design criteria. Reference [10] states that analysis statistics from oil and gas suggests that mooring line failures are not just possible but are likely to occur in large scale floating wind farms. Indeed, the failure rates observed are above target levels prescribed by industry standards. This suggest that floating wind units will need to factor in acceptable levels of redundancy or utilize advanced reliable designs, accounting for the floater-wind-specific load characteristics, to mitigate the probability of failure.

The main norms standards are compared for FOWT application on the following versus Oil and Gas DNV-GL-E301 [13]:

Norm	DNVGL-OS-E301 Position Mooring	DNVGL-ST-0119 Floating Wind Turbine Structures	NI 572 DT R01 E Bureau Veritas - Classification and Certification of Floating Offshore Wind Turbines
Return Period	100-year	50-year	50-year
Service Life	No minimum	No minimum	≥ 20-years
Intact SF Mean / Dyn.	Time domain analysis 1.2 / 1.9 Consequence class 2	Time domain analysis 1.3 / 1.75 Consequence class 1	1.67
Damaged SF Mean / Dyn.	Time domain analysis 1.0 / 1.45 Consequence class 2	Time domain analysis 1.0 / 1.1 Consequence class 1	1.25
Non-Redundant Penalty	1.2	Modification from Consequence Class 1 to 2 1.15 to 1.25 factor	1.2
Fatigue SF	10	5 for Consequence Class 1 10 for Consequence Class 2	3 For all line segments and other components of the line

**Table 3.4-1 – Specification comparison versus Oil and Gas**

The main differences are related to:

- Return period limited to 50 years for Floating Wind Turbines
- Redundancy philosophy. Non redundant mooring lines are usually not used in the Oil and Gas industry and tendency is to use more lines and reduce the individual line sizes to enable safer installation, higher reliability, increase procurement options.

Based on the above and given the number of lines foreseen for a full wind farm development redundant mooring lines may be preferred. It is foreseen that non redundant system will have a lower CAPEX cost however redundant system will have lower overall cost and no downtime [59].

### 3.5 Existing Anchor types

#### Advantages and Drawbacks

Reference [3] provides details regarding anchoring solutions available, depending on the mooring configuration, seabed conditions, and holding capacity required. The size of the anchor is also variable, with larger and heavier anchors able to generate a greater holding capacity.

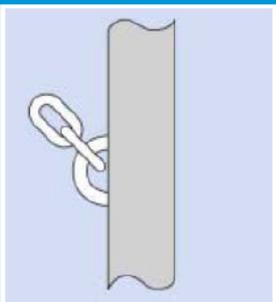
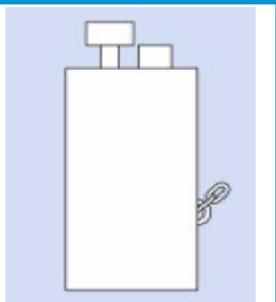
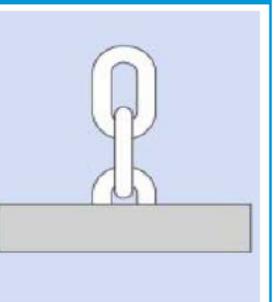
Drag-embedded	Driven pile	Suction pile	Gravity anchor
			
<ul style="list-style-type: none"> <li>• Best suited to cohesive sediments, though not too stiff to impede penetration</li> </ul>	<ul style="list-style-type: none"> <li>• Applicable in a wide range of seabed conditions</li> </ul>	<ul style="list-style-type: none"> <li>• Application constrained by appropriate seabed conditions - not suitable in loose sandy soils or stiff soils where penetration is difficult</li> </ul>	<ul style="list-style-type: none"> <li>• Requires medium to hard soil conditions</li> </ul>
<ul style="list-style-type: none"> <li>• Horizontal loading</li> </ul>	<ul style="list-style-type: none"> <li>• Vertical or horizontal loading</li> </ul>	<ul style="list-style-type: none"> <li>• Vertical or horizontal loading</li> </ul>	<ul style="list-style-type: none"> <li>• Usually vertical loading, but horizontal also applicable</li> </ul>
<ul style="list-style-type: none"> <li>• Simple installation process</li> </ul>	<ul style="list-style-type: none"> <li>• Noise impact during installation (requires hammer piling)</li> </ul>	<ul style="list-style-type: none"> <li>• Relatively simple installation, less invasive than other methods</li> </ul>	<ul style="list-style-type: none"> <li>• Large size and weight can increase installation costs</li> </ul>
<ul style="list-style-type: none"> <li>• Recoverable during decommissioning</li> </ul>	<ul style="list-style-type: none"> <li>• Difficult to remove upon decommissioning</li> </ul>	<ul style="list-style-type: none"> <li>• Easy removal during decommissioning</li> </ul>	<ul style="list-style-type: none"> <li>• Difficult to remove upon decommissioning</li> </ul>

Table 3.5-1 – Anchor examples [3]

#### Design criteria and drivers for configuration selection

The basic choice of the type of anchoring point is mostly determined by a combination of the water depth in which it is to be applied, the condition of the soil and the load that the anchor point needs to withstand. With the increase of water depth, remoteness of the mooring location from shore, environmental conditions, sea and soil conditions, the practicality of an anchor point or the cost of its transportation and installation become important selection criteria. In the illustration below it is shown the most principle anchor point types ranged

by water depth (shallow to ultra-deep water) and soil type (hard to soft soil). In the following subject it is described each of the typical anchor points.

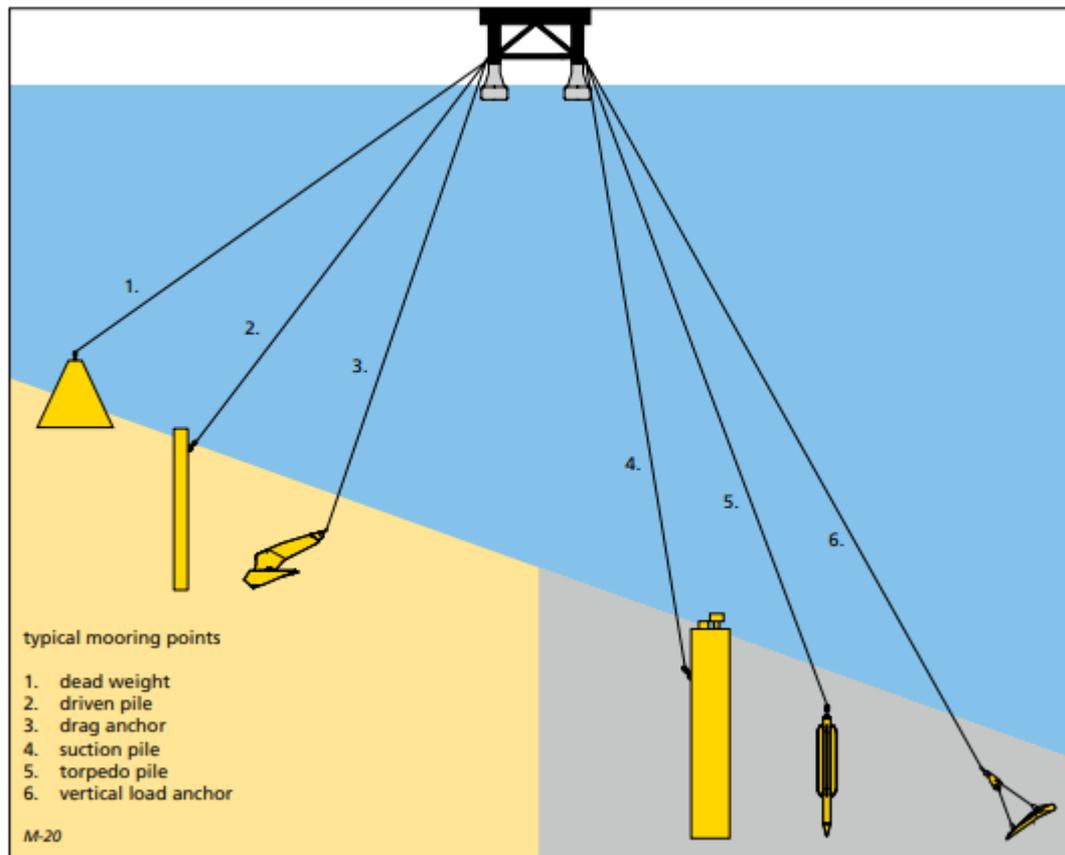


Figure 3-8 – Different anchor types for shallow and deep waters. Courtesy: Vryhof Anchor.

A description of main anchors types is provided hereafter:

**Drag embedment anchor:** This is the most popular type of anchoring point available today. The drag embedment anchor has been designed to penetrate the seabed, either partly or fully. The holding capacity of the drag embedment anchor is generated by the resistance of the soil in front of the anchor. The drag embedment anchor is very well suited for resisting large horizontal loads, but not for large vertical loads although there are some drag embedment anchors available on the market today that can resist significant vertical loads.

**Pile / Driven pile:** The pile is a hollow steel pipe that is installed into the seabed by means of a piling hammer or vibrator. The holding capacity of the pile is generated by a combination of the friction of the soil along the pile and lateral soil resistance. Generally, the pile has to be installed at a great depth below the seabed to obtain the required holding capacity. The pile is capable of resisting both horizontal and vertical loads.

**Gravity Anchor / Dead weight:** The dead weight is probably the oldest anchor in existence. The holding capacity is generated by the weight of the material used and partly by the friction between the dead weight and the seabed. Common materials in use today for dead weights are steel and concrete.

**Suction anchor:** Like the pile, the suction anchor is a hollow steel pipe. But unlike the pile the suction anchor is closed at the top and generally has a much larger diameter than that of the pile. The suction anchor is forced into the seabed by means of a pump connected to the top of the pipe. When the water is pumped out of the

suction anchor this creates a pressure difference between the outside of the pipe and the inside forcing the anchor into the seabed. After installation the pump is removed. The holding capacity of the suction anchor is generated by a combination of the friction of the soil along the suction anchor and lateral soil resistance. The suction anchor is capable of withstanding both horizontal and vertical loads.

**Gravity installed anchor:** This anchor type is a hybrid system that combines significant vertical and horizontal load capacity. It installs itself due to its drop weight and requires no external energy or mechanical handling. It is therefore ultimately suited for ultra-deep water moorings.

**Vertical load anchor:** The vertical load anchor is installed like a conventional drag embedment anchor but penetrates much deeper. When the anchor mode is changed from the installation mode to the vertical (normal) loading mode, the anchor can withstand both horizontal and vertical loads. Although designed to suit deep water mooring application, its omnidirectional load capacity allows mooring objects in confined subsea infrastructures such as in vicinity of pipeline and cables.

### 3.6 Industry Examples

It is here chosen to develop three industrial examples: Hywind Demo , Fukushima MIRAI project and Floatgen project.

	Hywind Scotland	Fukushima – MIRAI	Floatgen
Floater type	Spar	semi-sub	Concrete damping Pool concept
Turbine capacity	5 x 6MW (Siemens Gamesa)	2 MW	2 MW
Water Depth	95—129 metres (105 m)	120	33
Mooring configuration	Catenary	Catenary	Catenary
Number of lines	3	6	6
Mooring length	Mooring line lengths are ranging from 700 to 900	450-480	Mooring line radius at aft (4 mooring lines): 400m.  Mooring line radius at fore (2 mooring lines): 850m.
Anchor type	Suction anchor (5m in diameter and 16m in height) made of steel weight of about 100 tonnes per anchor	Drag-embedded (Vryhof STEVSHARK)	Drag-embedded
Materials	Steel chain	Advanced steel chain (Nippon Steel 1 Sumito Metal)	Synthetic fiber (nylon) mooring rope and chain at both extremities of all mooring lines.
Mooring line characteristics	Offshore grade studless mooring chains.  Dimensions are between 132 and 148 mm in diameter.	132mm diameter	

**Table 3.6-1 – Industry examples**

**Table 3.6-2** provide some more insight / examples of products used on Floatgen and Hywind projects:

Floatgen project is an arrangement composed of chain, nylon ropes and specific ancillaries (Buoyancy modules and clump weight) to comply with low water depth (33 m) and Atlantic wave conditions.

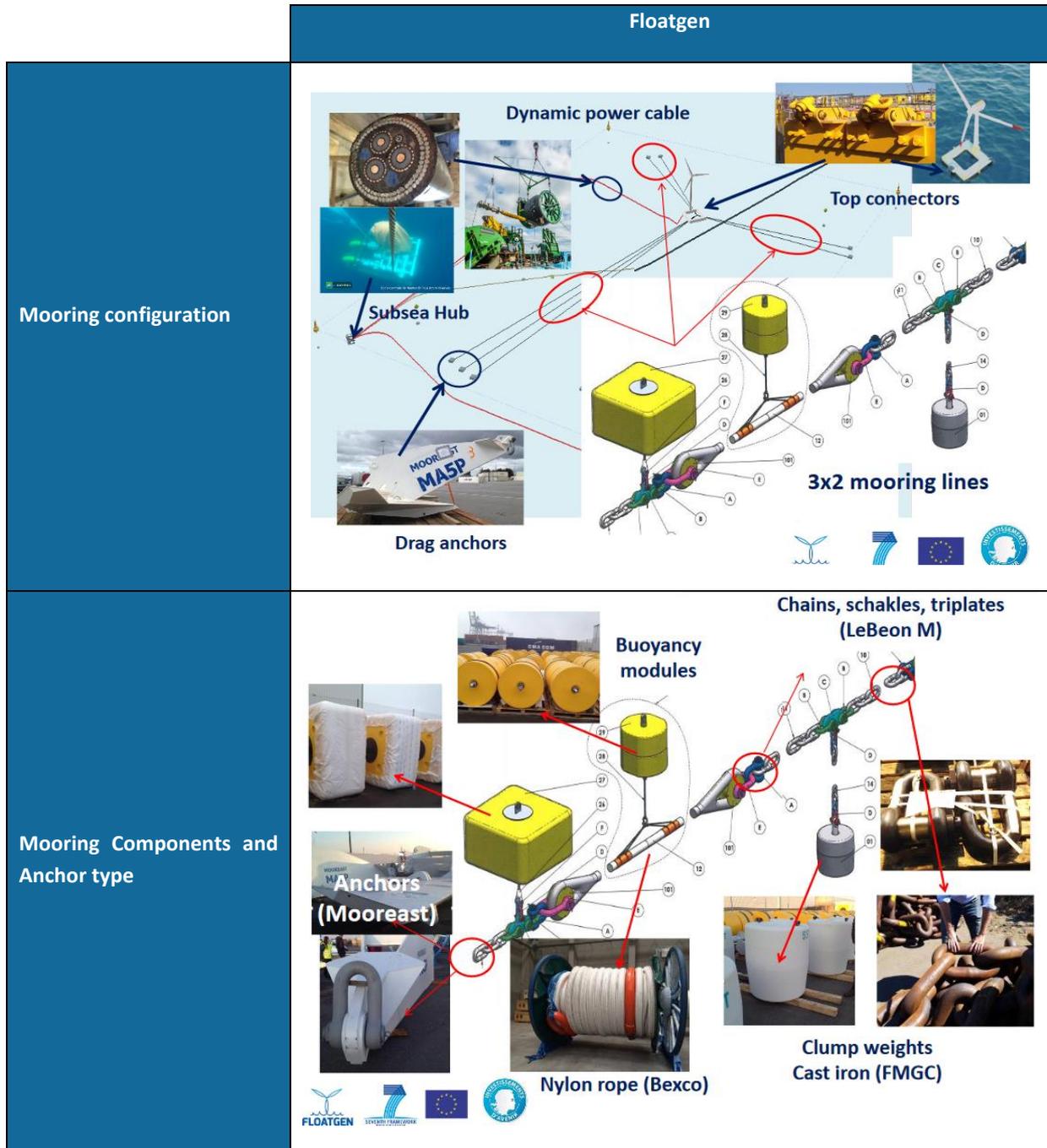


Table 3.6-2 – Industry examples – Pictures [27]

Hywind Scotland project is an arrangement composed of chain. Particularity lies mainly regarding anchor considered (suction anchor) linked to soil conditions and “crawfoot” type arrangement at floater connection to mitigate yaw motions of the floater.

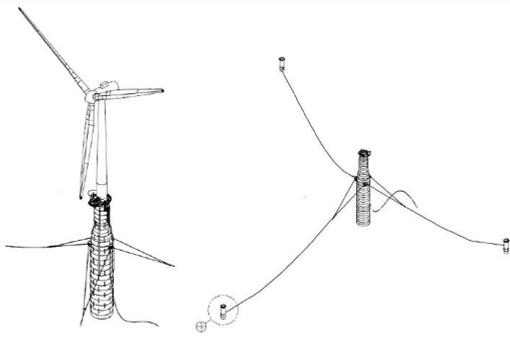
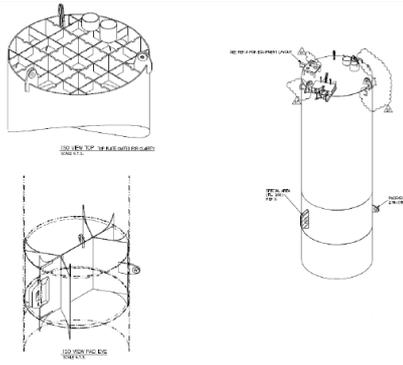
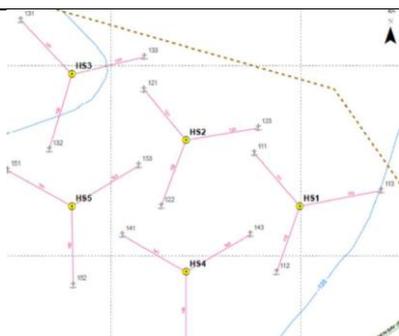
Hywind Scotland	
Mooring configuration	Spar
Mooring configuration	
Mooring Components and Anchor type	
Layout	

Table 3.6-3 – Industry examples – Pictures [12]

#### 4 MARKET WATCH OF MOORING IN FLOATING WIND INDUSTRY

Mooring lines are crucial for floating offshore turbines as it is the station keeping mechanism for the floating platform. Currently, the factors driving these choices are a combination of experience from the oil & gas sector, water depth, fabrication cost and innovations in design (i.e. weight, material, etc.).

The geometry of the floater has different impacts on lines tensions and hence on the mooring system design. However, the industry applications of mooring systems in operational floating projects have some trends. Spar or semi-submersible floater types have been mostly tested up to date. Therefore, in some cases it is also possible to see changes in the configurations as result of the lessons learned from the industry's experience.

A market watch has been performed within the consortium with main aim being to identify current floating wind projects in operation and associated technological choices in particular:

- Mooring configuration
- Number of Lines
- Mooring line length
- Materials
- Anchor Type
- Floater Design offset
- Installation Methodology

The research has been extended to projects currently in construction phase and future planned projects. Main highlights below mainly focus on projects in operation.

The following projects in operation have been mainly screened:

Status	Project	Ownership - Developer	Location	Total capacity (MW)	Development status	Region details	Installation
Construction	WindFloat Atlantic	WindPlus (EDP, Engie, Repsol, Principle Power) Floater designed by Principle Power	Portugal	25	wind farm (first turbine producing since 31-12-19)	Viana do Castelo	2020
	Kincardine	KOWL (Majority by Cobra Group)	UK	50	wind farm (in construction)		2021
Operation	Hibiki (is this also called Kitakyushu NEDO Next Generation Demo?)	IDEOL / NEDO	Japan	3	full-scale demonstrator	Kitakyushu	2018
	Floatgen (SEM-REV testing site at Le Croisic) 4C Offshore	FLOATGEN (includes IDEOL / Uni of Stuttgart / ECN / RSK Environment Ltd ) 4C Offshore	France	2	full-scale demonstrator	off St-Nazaire port	2018
	Kincardine Pilot	Pilot Offshore Renewables Limited	UK	2	first turbine	North Sea (Forth/Cromarty). 4C Offshore	2018
	Fukushima Mirai	Mitsui Sozen (Fukushima FORWARD)	Japan	2	full-scale demonstrator	Fukushima	2013
	Fukushima Shimpuu	Mitsubishi (Fukushima FORWARD)	Japan	7	full-scale demonstrator	Fukushima	2016

Status	Project	Ownership - Developer	Location	Total capacity (MW)	Development status	Region details	Installation
	Hywind Demo	UNITECH Offshore A/S - Equinor ASA (previously Statoil ASA), Siemens Wind Power A/S	Norway	2.3	2,3MW demonstrator	Karmøy	2009
	Fukushima Kizuna (Advanced Spar)	Japan Marine United (Fukushima FORWARD)	Japan	NA	full-scale demonstrator	Fukushima	2013
	Fukushima Hamakaze	Japan Marine United (Fukushima FORWARD)	Japan	5	full-scale demonstrator	Fukushima	2016
	Hywind Scotland Pilot Park	Equinor (75%) / Masdar (25%) - Hywind (Scotland) Limited	UK	30	Floating Pilot Park	Scotland, Grampian	2017
	Sea Twirl S1	Sea Twirl	Sweden	0.3	30kW demonstrator	Lysekil test site	2015
	Floatmast	Streamlined Naval Architects LTD, ETME, ERGOMARE S.A., and Enalios Diving Center	Greece	NA	full-scale demonstrator	Aegean Sea	2019
Planned	Sea Twirl S2	SeaTwirl AB, Colruyt, NorSea Group	Norway	1	full-scale demonstrator	Rogaland	2020
	TetraSpar Demo	Innogy SE, Shell New Energies, Stiesdal Offshore Technologies	Norway	3.6	full-scale demonstration	Rogaland	2020

Status	Project	Ownership - Developer	Location	Total capacity (MW)	Development status	Region details	Installation
	Pivot Buoy - PLOCAN (CHEF PROJECT)	X1 Wind (and financed by the European Union through Horizon 2020)	Spain		scale demonstrator	Islas Canarias	2020
	Groix & Belle-Ille	EOLFI -CGN	France	28.5	pilot farm		2021
	EolMed	Quadran - IDEOL	France	28.5	pilot farm		2021
	Provence Grand Large	EDF Renouvelable	France	24	pilot farm	Faraman zone	2021
	Golfe du Lion	ENGIE - EDPR	France	30	pilot farm		2022
	FLOTANT		Spain		scale demonstrator		2022
	Reedwood Coast	RCEA	USA	150	wind farm		2024
	Saipem Hexafloat Windpark	Plambeck Emirates LLC	Saudi-Arabia	500	wave tank tests / full-scale prototype is planned off Ireland		2030

Status	Project	Ownership - Developer	Location	Total capacity (MW)	Development status	Region details	Installation
	DemoSATH	Saitec Offshore Technologies S.L.U.	Spain	2	full-scale demonstrator	País Vasco	2021
	Hywind Tampen (supporting 2 o&g platforms)	Equinor (and partners at Gullfaks and Snorre) i.e. Petoro AS,OMV (Norge) AS,Equinor ASA (previously Statoil ASA),ExxonMobil Exploration and Production Norway AS,Idemitsu Petroleum Norge AS,DEA Norge AS,Point Resources AS	Norway	88	wind farm	Sogn og Fjordane (Norwegian Continental Shelf (NCS))	2022
	Dyfed Floating Energy Park	Floating Power Plant A/S,DP Energy Ireland Ltd	UK		full-scale demonstrator	Wales	

Table 3.6-1 – Market Watch – Projects in Construction, operating and planned regarding Floating Wind

The following subsections analyse the main configurations currently used by the industry. It examines these choices to evaluate the relationship with the floater type and water depth. The analysis also provides an overview of the relation between configurations and excursion range. This explains the 'level of freedom' of the system to move horizontally and how is influenced by the floater type, mooring line configuration and material properties. Finally, we provide an overview of the installation methods currently used by the floating wind industry.

## 4.1 Main configurations used currently in the industry

### 4.1.1 [Catenary mooring system](#)

The catenary mooring system is the most common mooring system in shallow waters currently used in the offshore floating sector. Through gravity, the catenaries, between the floating unit and the seabed, will show the typical shape of a free hanging line. The catenaries are hanging horizontally at the seabed. Therefore, the catenary lengths must be larger than the water depth and the anchor points in a catenary mooring system are subjected to horizontal forces [54].

The catenary mooring system is the easiest to manufacture and the mass works as a damper. Selecting materials for mooring lines will depend on the response you want from the mooring system and environmental factors – wind waves and currents. Fiber will dramatically change the response. Depending on the anchoring points and design the system could stand different loads, which usually makes drag-embedded a better choice over driving pile for floating offshore turbines. Regarding connectors, there are different concepts in the market and quick disconnection connectors are expensive. There are two factors to consider when designing the release system. The first is the geometry of the floater, as different geometries will have different responses. We could expect a spar system to have less resistance to move and the tetra-spar design to have even a lower resistance to wave motion. A contingency plan is needed for floating foundations with single mooring lines in case of line failure to avoid the unit moving away.

### 4.1.2 [Taut leg mooring system](#)

The taut leg system or taut system is characterized that the mooring lines are pre-tensioned until they are taut. A taut-leg system will usually have an angle of between 30 and 45 degrees. This means that in a taut leg mooring the anchor points are loaded by horizontal and vertical forces.

By the taut leg system, the restoring forces are created through axial elastic stretching of the mooring line rather than geometry changes. The restoring forces are determined by the stiffness and elasticity of the mooring line. The taut leg system has a much more linear stiffness than the catenary system that gives the advantage that the offsets under mean load better can be controlled and the total mooring line tensions are smaller. A further advantage of the taut-leg system is the better load sharing between adjacent mooring lines. The disadvantage of the taut-leg system is that the mooring line must have enough elasticity to absorb the vessel wave motions without overloading. For deep water the taut leg system is a better cost-effective solution than the catenary system [55].

The semi-taut system is a combination of the taut mooring system and catenary mooring system, wherein some parts of the mooring system are taut and other parts are catenary. The semi-taut and taut systems are better suited for deep water application than catenary system. The semi-taut system and taut system have shorter

mooring lines and require less seafloor space or seafloor spread than the catenary system. The shorter mooring lines result in material saving[55].

A single point moored buoy system consists of a permanently moored buoy. The buoy has a bearing system that allows a part of it to rotate around the moored geostatic part. When the offshore unit is connected to the buoy it will be able to rotate itself into the dominant environment. Consequently, the system will minimise the loads on the mooring system of the buoy [55].

#### 4.2 Configuration versus Floater type and water depth

The table below shows the different mooring configurations in relation to the different floater types currently used in the industry. As highlighted also in the previous section 4.1, the catenary mooring configuration is the most deployed for semi-submersible floaters (i.e. WindFloat, Fukushima Mirai, Fukushima Shimpuu, VoltturnUS), spar-buoy (i.e. Hywind, and Fukushima Kizuna), and barge (i.e. Floatgen), with the first topologies boasting the highest track record experience.

The taut configuration is currently used in the Floatgen (barge). Configuration could be considered taut given the use of clump weights however it is not similar to Taut system currently developed for “Provence Grand Large » for example. The single point mooring configuration was used in the Wind2Power (multi-turbine semi-submersible platform) project test.

Project	Floater type	Water depth (m)	Mooring configuration
Kincardine	Semi-sub	70	Catenary
Fukushima Mirai	Semi-sub	120	Catenary
Fukushima Shimpuu	Semi-sub	120	Catenary
Wind2Power [56]	Semi-sub	40	Single Point Mooring
Hywind Scotland	Spar	100-120	Catenary
Sea Twirl S1	Spar	35	Catenary
Goto	Spar	97	Catenary
Fukushima Kizuna	Spar	100-120	Catenary
Fukushima Hamakaze	Spar	120	Catenary
Hywind Norway	Spar	186-204	Catenary
Floatgen	Barge	33	Taut / Tensioned Catenary
Hibiki	Barge	55	Catenary

Table 4.2-1 – Water depth – Project examples

### 4.3 Excursion range

Little information has been extracted from the literature review about floater excursions used as input for station keeping configuration design. Current position on COREWIND is to take a varying value with respect to water depth function of selected sites:

- For 100 m case, 30% of water depth is defined based on on-going projects feedback.
- For Deepwater case (870 m), and based on O&G standard, excursion limitation is function of water depth and ranges between 5% to 12% typically (for Intact and damaged cases respectively) which gives an upper bound of 104 m approx.
- For the intermediate case (250 m), an intermediate value 60 m (2 x 30 m) is proposed (24% Approximately of water depth).

This is a starting point and target for mooring design and dynamic cable design but will be determined precisely within further WP2 and WP3 tasks.

### 4.4 Installation methodology

The installation process of the anchoring points will depend on the type of anchors. Usually the drag embedded are the most used due to its compatibility with catenary configuration and lower installation cost. According to industry interviews, other mooring design such as driven piles, can be around 50% more expensive during installation phase because of the vessel support required.

Installation methodologies for existing projects (mostly catenary) are commonly divided into two phases. First, the mooring lines are pre-installed before the hook-up of the floater, depending on the project timeline this can vary between few months up to a year. Anchors are also installed in the seabed during this phase and can remain at seabed for months. Usually it is possible to install one mooring line every 8 hours.

Once the anchoring points are installed in the seabed it is possible to hook up the pre-assembled floating wind turbine to each anchor, leaving the mooring lines wet stored in tension on seabed. In the case of the taut system there's an extra step where nylon is laid down and stretched just before leaving the mooring lines tensioned.

## 5 INSTALLATION AND MAINTENANCE TECHNIQUES

Installation and maintenance techniques are meaningful for cost reduction in offshore floating farms, even relevancy is growing due to the fact that deeper waters are explored and distance to shore is higher. Installation and maintenance techniques are implemented according procedures once mooring layout is fully defined, this procedure is focused on providing necessary information and instructions to perform these activities in a safe manner. This section aims installation and maintenance techniques for semi-submersible and spar floaters since COREWIND project only address ACTIVEFLOAT floater (semi-submersible) and WindCrete floater (spar). Therefore, tension leg platforms are considered out of scope.

Installation and maintenance techniques require detail procedures describing operations, which follow standards and codes. Some of them have been identified in following table.

Document reference	Document title
API RP 2SK	API, Design and Analysis of Station keeping Systems for Floating Structures
DNV-OS-H202	DNV, Sea transport operations
ABS-195	Guide for building and classing Floating Offshore Wind Turbine Installations
DNVGL-SE-0122	Noble Denton marine services - certification for towing vessel approvability
DNVGL-ST-N001	Marine Operations And Marine Warranty
DNVGL-OS-E301	DNV, Position mooring
BV-NR493	Classification of mooring systems for permanent offshore units

Table 4.4-1 – Reference code and standards for installation techniques

### 5.1 Installation techniques

#### 5.1.1 [Preparation](#)

Preparation includes not only several technical onshore activities (storage space, procurement, transport, auxiliary means, etc.) but also administrative activities before installation are necessary to manage permits with competent authorities related to use of harbor (port and marine operations) and environmental impacts. Likewise, Health and Safety plans must be provided to guarantee that onshore and offshore activities are carried out under safe conditions.

Health and Safety plans must define at least risks and Personal Protection Equipment (PPE) such as boots, coveralls, hat, glasses, etc. In addition, risks assessment must identify tasks and event within the work plan to assign job hazards such as work with ropes under tension, lift heavy equipment, deck operation on board, winches operations or work with divers. H&S plan must identify sequence of operations, site conditions and mitigation measures as well.

Furthermore, toolbox talks are arranged between Project managers, Project supervisor and vessels crew representative before starting any operation or shift change to coordinate every action plan.

### 5.1.2 [Site investigations](#)

Site investigations include onshore and offshore working areas to implement any installation activity. Onshore areas require to define close harbours, required storage space for mooring lines and anchors, cranes working area and vessels preparation. Regarding offshore site should be noted that location and available marine areas are essential, i.e., conditions such as shore distance, harbour distance, wind turbines to be installed or extension.

Also, equipment previously installed on site must be taken into account, since it could interfere in mooring and anchoring installation, for instances export cables are usually laid on seabed in advance. Furthermore, available corridors for mooring lines must be clearly identified to ensure that no damage appears.

Site environmental data are crucial to define action plans, mooring lines position and anchoring solution selected. Environmental data should consider soil, wind, waves, tidal currents and accurate weather forecast allowing to define weather windows and suitable conditions to implement marine operations.

### 5.1.3 [Installation plan](#)

Installation plan must summarise main information related to the floating platform and wind turbine (e.g. sizing, shape, fairleads position, power, weight and operation draft). On the other hand, mooring configuration is detailed in terms of number of lines, mooring lines and anchoring position, materials and components. In particular, mooring lines information is provided paying special attention to lines lengths, weights, diameters, connectors, ropes, and materials.

Furthermore, installation plan varies according anchoring system selected since it depends if the system is based on anchors, deadweight or piles. The example used as reference for this document are hold anchors, which is the most common system currently used.

Within installation plan, operation time is estimated step by step since it allows to evaluate required weather window through meteorology forecast. It is recommended to define both necessary time by task and available time to face contingencies. For example, the reference used foresee a duration of 48 hours for mooring lines hook-up, which contingency time is roughly 40%.

To define an accurate installation plan is relevant to count with reliable weather forecast since it would allow cost reduction though decreasing down times. Although it is not limited to waves, wind and current, operating limiting criteria defines maximum current (<1,5 knots), maximum significant wave high (1,5 metres), maximum wind speed (20 knots) and wave period should be also considered. Limiting criteria for pre-lay is a little bit higher than for hook-up.

Contingency and emergency plans should be annexed to the procedure in order to have an action plan related to equipment failures such as pick-up lines, buoy system, intermediary line, winches, vessels and observation remote operated vehicles.

### 5.1.4 [Vessels\[43\] &\[44\]](#)

Based on real experiences and literature review, mooring installation requires at least three different vessels: anchor handling tug supply vessel, observation class remote operated vehicle and guard vessel.

Anchor Handling Tug Supply Vessels are used to install mooring lines and anchoring. These vessels are selected mainly evaluating bollard pull, brake horsepower, clear deck space and winch line pull, nevertheless the following parameters allow to select the correct one:

Criteria	Characteristics
Dimensions and capacities	Length, breadth, depth, draft, clear deck area, deck strength, deck cargo, fuel consumption, potable water and ballast water
Machinery	Engines, thruster, generator, auxiliary generator and emergency generators
Towing and anchor handling	Bollard Pull, winches dimension and capacity, drum dimension and capacity and stern roller
Deck equipment	Tuggers, capstans, windlass, smit towing bracket and cranes

**Table 5.1-1 – Anchor handling tug supply vessels**

These vessels incorporate not only electronics navigation tools but also specific dynamic positioning system, acoustic devices as well as survey spread to locate mooring and anchoring in accurate positions, monitor vessels on site and provide survey report.

Observation Class Remote Operated Vehicles are used for visual inspection and light intervention tasks during the operation. These vehicles should commit with operation requirements in terms of:

Depth rated, power, thrusters, dimensions and weight.

Speed, pay load capacity and bollard pull

Likewise, observation class remote operated vehicles include electronic, mechanics and control systems to implement specific tasks.

Guard vessel is mobilised on site during operation in order to ensure safe and efficient operations since this is mobilised to ensure that no vessels are entering into the installation zone.

### 5.1.5 [Installation Steps](#)

Steps for installation depend on harbor and site characteristics, thus it is an ad-hoc procedure that must be adapted to every project or wind farm. However, offshore wind farms already under operation allows to distinguish three groups of operations: pre-assembly, mooring line pre-lay and mooring line hook-up.

Under pre-assembly is considering mobilisation of mooring lines, connectors and anchors. This step is carried out on harbour and it may be executed according availability of equipment and installation aids being necessary the following: forklift, mobile crane, personnel, anchor handling vessel and hand tools.

Mooring line pre-lay main steps are shown in next figure:

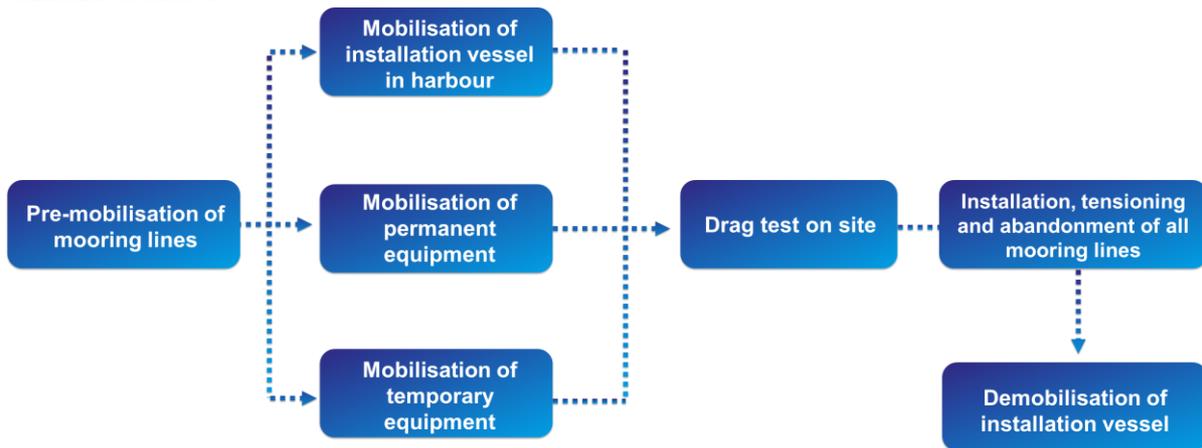


Figure 5-1 – Mooring line pre-lay steps

Mooring line hook-up main steps are summarized in next figure:

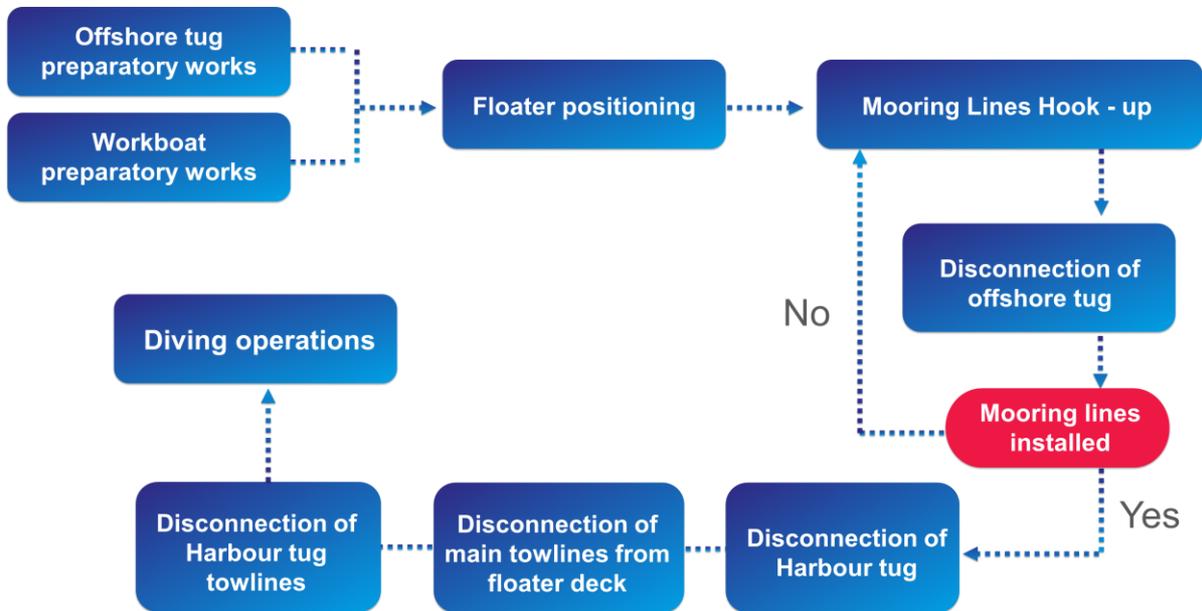


Figure 5-2 – Mooring line hook-up steps

Regarding mooring line hook-up, the three last steps are limited by weather permitting, thus they could be postponed until weather conditions allow execution. However, they shall be completed before next winter season from installation date.

## 5.2 Inspection and Monitoring

This subchapter provides a baseline of current state-of-the-art inspection and monitoring techniques for mooring systems of floating offshore wind turbines. Developers of foundations and mooring systems strive to design their products maintenance free. Even in case maintenance free design might be possible, it can be expected that this design will not be economically feasible. Hence, O&M activities will be required for future projects to ensure reliable operation throughout the lifetime. After a first evaluation on this topic following risks and challenges for operation, maintenance and monitoring are being identified:

- Calculation or determination of all mooring line tension loads is essential to guarantee optimized mooring system behavior.
- Excessive corrosion and wear
- Pre-emptive maintenance activities
- A concept for removal of mooring lines for inspection or maintenance purpose needs to be developed.
- Lack of system knowledge and inadequate training for operators
- Dropping lines / re-tensioning of lines
- Reusing mooring components: Suction anchors are not re-usable so if the floater is required at another location, new anchors need to be installed.
- Lack of proper monitoring systems
- There is a demand for the real-time monitoring of mooring systems both in their deployment and to track their condition. A lack of monitoring and tracking can lead to mooring line replacement or failure.
- Effective monitoring and data management – ideally without the need for costly maintenance or subsea sensors—is necessary to detect mooring line failure and ensure continued mooring systems integrity for the lifetime of the asset.
- Assessment of new technologies such as Advanced Distance and Positioning System (ADAPS) and Device Tracking and Control Systems (DTAC) – supports monitoring real-time drag anchor positioning and potentially eliminates the need for ROV work during prelay operations.
- Synthetic fibers shall not get into contact with the seabed at any time during operation.
- Quality and efficiency of offshore inspections if required
- Deferral of inspections if required

### 5.2.1 [Inspection Schedule](#)

Similarly, to inspection schedules for dynamic cables, which are discussed in COREWIND deliverable D3.1 “Review of the state of the art of dynamic cable system designs”, mooring system inspection schedules are distinguished as described in the following.

#### 5.2.1.1 [As-built inspection](#)

To verify that the completed installation work meets the specific requirements and to identify the first mooring conditions an as-built survey should be performed. The survey is primarily conducted to confirm that the anchor legs are connected as designed, to check for damages that occurred during installation, and to ensure that the twist in the anchor legs is within the design margins. Most as-built surveys are conducted by visual inspections from anchor to fairlead (mostly by video-capable ROVs). Those recordings should be saved with comments made by the inspector. In general, every damage and any discrepancy between the actual as-built-status and the nominal planned state should be addressed with enough detail and documented in a report in order to facilitate future inspections. Additionally, a detailed list of all components can be attached including manufacturer, serial number and/or other identification [30].

### 5.2.1.2 Long-Term Inspections

After the installation procedure and the following as-built survey has been accomplished and the mooring system has been in service for a while, the planned maintenance and inspection activities should be executed. General subjects of those planned activities include [30]:

- Visual inspections/surveys
- Survey of subsea crossings with cables or other equipment
- Inspection of the chain
- Inspection of connection points (e.g. chain and winches)
- Removing of marine growth

The frequency of undertaking those planned inspections considers several aspects, as for example, the requirements of the authority and the mooring supplier, the probability and consequences of failure, and the results of previous inspections as well as changes in the operational conditions. Hence, critical sections of the mooring system that are prone to damage or that undergo major changes in their service life should be at least inspected at adequate periods of time.

Maintenance can be distinguished into three different types which each differ from the trigger of the maintenance work. In following figures the different types and their classification are illustrated while their effects on the condition of the object to be inspected can be seen in Figure 5-3. These figures and maintenance techniques can also be seen in D3.1 “Review of the state-of-the-art of dynamic power cable design” since they are generally applicable to maintenance.

Figure 5-3 – Classification and Types of Maintenance [40]

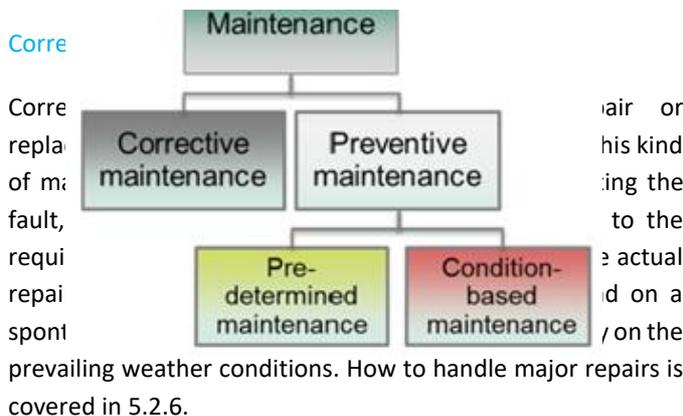
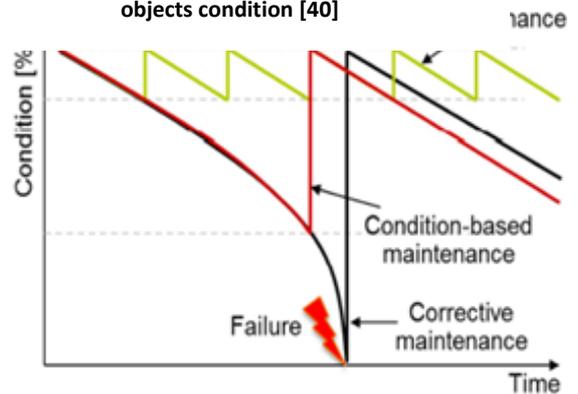


Figure 5-4 – Effects of maintenance types on inspected objects condition [40]



#### Predetermined Maintenance

Also known as “Time Based Maintenance” (TBM), predetermined maintenance performs preventive maintenance based on a specified time schedule. This kind of maintenance is often the basis and is carried out as offshore surveys [30], distinguishes here in annual, intermediate and special surveys. Annual surveys are normally restricted to mooring components above the waterline. Special attention should be paid to connection points of the chain with winches, chainstoppers and fairleads, especially if they are located in way of the splash zone. Intermediate surveys should be undertaken every 2-3 years. They may take the form of an in-water survey



and usually provide useful information about the mooring condition. While annual and intermediate surveys are restricted to relatively easily accessible components, special surveys (every five years) are paying attention to mooring components at or near the touchdown-point or to prior noted damage. If possible, it is suggested to raise the mooring equipment to the surface for a detailed inspection and for an efficient removal of marine growth. Additionally, condition and performance tests of any corrosion protection can be undertaken. As the observed condition is steady and no significant changes over several inspections can be seen the period between inspections can be increased. In the case of condition worsening the TBM may result in the next maintenance type.

### Condition Based Monitoring

The Condition Based Maintenance (CBM) is performed upon the condition of the mooring system and not with a fixed time interval. This allows pre-emptive repairs to minimize lost generations and allows the inspector to take advantage of predictable future surveys. Due to the larger distances from shore which floating offshore wind farms (FOWF) make accessible since they are easier to install in deep waters, travel time will increase significantly. Hence, a high-quality Operations & Maintenance plan and a decreasing number of visits is important in order to work economically. The challenge here is to predict the remaining lifetime of the mooring component concerned. Good starting points are the observations at TBM activities and also are provided by monitoring the mooring system's condition. These tests are not "fail or pass" measurements like at the as-laid inspections, but their purpose is to follow the evolution of the mooring system and to plan appropriate maintenance activities.

In the next subsection, the inspection and maintenance requirements by selected classification societies are listed.

## 5.2.2 [Regulatory Requirements](#)

### 5.2.2.1 [Class NK](#)

Class NK [31] requires the following components of a mooring system to be inspected in intermediate and special surveys:

#### Intermediate surveys

- Mooring line stoppers
- Tensioning equipment
- Measurement of mooring line departure angles to check if the line tensions remain within the permitted limits. Other verification methods may also be applied.
- Mooring line above water to identify wear and tear
- Mooring components above water to identify wear and tear
- Turret mooring system bearings if applicable (including the lubricating system)
- Check of abnormalities in the operation of the mooring equipment (winches, windlasses etc.)

#### Special surveys

- Connecting points to the platform and the anchor (remove marine growth in advance)
- Mooring lines and tendons in their complete length including all connections
- Detailed inspection of areas where high corrosion and wear is to be expected (seabed, splash zone)

- NDT (see section 5.2.3.3) of chain and chain stoppers above sea level (remove marine growth before testing)
- Examination of turrets and related equipment and measurement of thickness due to corrosion
- MEP (see section 5.2.3.4) at representative locations in the mooring line
- Check of abnormalities in the operation of the mooring equipment

Occasional inspections have to be executed in case of loads acting on the structure exceeding the design assumptions and the results have to be reported to the classification society. If essential parts of the substructure are damaged, the operator needs to apply for an occasional survey.

#### 5.2.2.2 [DNVGL](#)

In general, the time interval for periodic inspections will be five years, if the Design Fatigue Factor (DFF) is applied as specified in Section 7 of (DNV GL, 2018). The interval for periodic inspections can be increased if the DFF is modified according to DNV requirements.

DNVGL (DNV GL, 2016) allows for inspection programs based on a risk based approach in case of large numbers of turbines in a wind farm. It needs to be noted that the standard accounts for offshore wind turbines in general and is not specifically developed for floating substructures. Non-inspectable items need to be designed with sufficient durability for the entire operation lifetime.

For critical items of the substructure, DNVGL recommends inspection intervals of less than one year, [33].

#### 5.2.2.3 [Bureau Veritas](#)

Bureau Veritas (BV) [34] requires the determination of inspection intervals on a case-to-case basis., However, it recommends a 5-year inspection interval. The items to be accounted for, the methods chosen, the sampling rate, the inspection intervals and the personnel requirements of all inspections must be listed in an inspection and test plan which needs to be approved by BV. The inspection plan is continuously updated to address new experiences from R&D and other floating foundations. Revisions are to be approved by BV.

#### 5.2.3 [Inspection methods](#)

Inspections are understood as the determination of the status and/or condition of a mooring system or a mooring component at a specific point in time. The identified status and/or condition of the mooring system or component is compared to the status/condition according to design prediction. In case the predicted values are exceeded, more detailed investigations or corrective measures/replacement are to be initiated. Usually, inspections are carried out by skilled personnel often under use of inspection equipment. Inspection intervals are set in the design phase but can also be adjusted based on findings of previous inspections. The inspections need to be executed by a company certified by the classification society, [31] and utilized survey robots also need to be approved. For underwater inspections remotely operated vehicles with mounted camera are suggested; diver operations shall be omitted whenever possible. The required scope of inspection can vary significantly from one individual component to the other.

After a definition of the term “inspection” is given in the following, this section will deal with different inspection methods that can be conducted. To differentiate “inspection” from the later used term “monitoring” (see 5.2.5) following definition is used. **Inspection is when human action (offshore or onshore) is required and executed**

**to obtain condition data from site.** 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, based on [35].

### 5.2.3.1 [General Visual Inspection](#)

General visual inspection (GVI) is the most common inspection method for mooring lines by carrying out a continuous slow ROV flight along the mooring line in order to evaluate and assess the structural integrity and completeness of the mooring line and components. It is obvious that a GVI can only assess the overall condition of the mooring lines and give indication for areas which should be inspected in more detail. Although time consuming, removal of marine growth might be necessary for specific areas. A GVI can be executed according to e.g. DIN EN 13018, [36]. The viewing distance shall be selected appropriately for the inspection.

The scope of a general visual inspection is to assess:

- Damage to the structure and components such as dents and deformation(s)
- Missing or loose parts
- Distorted elements

Necessary tools for the inspections:

- Digital camera with flash (for those accessible components above water)
- Tape measure (for those accessible components above water)
- Writing instrument
- ROV (for those components underwater)
- Chain survey robots (for those components underwater)

The GVI of a mooring line can be performed by use of support equipment as ROVs or chain survey robots according to DNVGL, [33]. These support tools check the whole mooring system for its integrity.

According to Ma et al., (Ma, Shu, Smedley, l'Hostis, & Duggal, 2013)<sup>[33]</sup> the most critical areas to be inspected are the following:

- Top chain at fairleads and chain stoppers
- Rope terminations
- Connectors
- Seabed touchdown area

### 5.2.3.2 [Detailed Visual Inspection](#)

Detailed visual inspections (DVI) can only be carried out for the mooring components located above water if diver operation is not allowed. Detailed inspections of critical areas underwater can be done with e.g. scanning methods. A DVI can be executed according to e.g. DIN EN 13018, [36]. A DVI is required for a more precise investigation whenever needed. The viewing distance and angles are defined in standards like [36]. Mirrors may be used to improve the angle of vision, and aids such as a magnifying lens, endoscope and fiber optic may be used to assist testing.

The scope of a detailed visual inspection is to assess:



- Material degradation
- Condition of issues from previous periodical inspections
- Connectors, anchors and chain stoppers
- Corrosion
- Pitting
- Cracks
- Indication for weld defect

Necessary tools for the inspections:

- Digital camera with flash
- Tape measure
- Writing instrument
- Mirror tool or endoscopic camera
- Diver

According to DNVGL [33], diver operation could be required in order to carry out a DVI.

### 5.2.3.3 Non-destructive Examination Techniques (NDT)

Due to findings by the GVI or the DVI or other requirements a more detailed inspection might be needed. Multiple NDT methods are available. The NDT method that has to be chosen depends on multiple factors (e.g. type of damage to be investigated, part and accessibility, operational aspects) and shall be chosen by the NDT person of the executing company.

Surface preparation is required in most cases. Manual (brush, scraper) or high-pressure cleaning of the investigated area might be necessary in addition.

Necessary tools for the inspections depend on the following parameters:

- Inspection method
- Type of defect
- Material which shall be inspected

An NDT is in general possible for those elements above the water surface, but difficult for the emerged components. It might be required for high wear and tear areas in the platform chain or for mooring equipment as the chain stoppers and winches. In case an NDT inspection for emerged components is initiated, the results should be treated carefully (defects are often further below the surface and may not be detected, critical areas are often inaccessible etc.).

Non-destructive testing may be one of the following (the NDT methods described below are based on [38] and have been partly adapted to fit into the floating wind specific context):

#### Mooring Line Dimension Measurement

Certain measurements of mooring components may be required during periodic inspection. Mooring chain measurement systems that have been used include simple diver-deployed manual calipers, a prototype stand-alone robotic system, and ROV-deployed systems. Some dimensional checks, particularly those that involve measurement over multiple chain links, become difficult or impossible to perform underwater. But some ROV-



deployed systems include both mechanical caliper and optical caliper systems that appear to be practical and effective.

### Magnetic Particle Inspection (MPI)

MPI is commonly used during manufacture and installation, including most of the chain surface if equipment is supplied allowing good access to the chain intrados. MPI is normally used to detect surface breaking or near surface breaking crack indications but it should be noted that the rough surface of most chain links may create false indications. In-service inspection could include MPI, but noting that moving components around to allow thorough inspection is generally not feasible. For most chain, MPI of the flash butt welded area would be possible, but only for surface breaking or near surface breaking cracks.

### Ultrasonic Testing (UT)

UT is often used to examine the flash butt weld area of chain. The great advantage that UT has is that it can detect both surface breaking and subsurface defects. This is particularly important in the flash butt weld area where incomplete fusion can result in subsurface defects. The technique is straightforward to use above water and underwater with divers. For ROV applications, it may be necessary to develop a special tool to hold the probe(s).

### Electro Magnetic Detection (EMD)

EMD is an old technology that has been used for many years for the inspection of wire ropes. The method can detect surface breaking defects through non-conductive coatings. One of the biggest problems with the technology is that it is not good at detecting defects close to the wire rope termination, probably the area of greatest interest in mooring wires. For many years there has been discussion about moving the existing, relatively mature, technology underwater, but so far little progress has been made.

### Dye Penetrant Testing (PT)

PT can be used on metallic and non-metallic materials. Only surface breaking defects can be detected. PT requires the surfaces and possible surface-open discontinuities to be clean. It is only applicable above water.

### Radiography Testing (RT)

RT for mooring chain and wire rope produces a picture of mainly volumetric discontinuities, provided these are favorably oriented with respect to the direction of the applied X- or gamma radiation. Two-dimensional flaws can be difficult to reveal and the defect height, which often is the most critical parameter, is normally impossible to assess by radiography. The radiation hazard can limit the applicability of the method.

#### 5.2.3.4 Measurement of electrochemical potential (MEP)

Measuring the electrochemical potential of the steel surfaces can be required in order to ensure that sufficient cathodic protection has been achieved.

Its scope is to assess:

- The polarization of steel surfaces (protective potential)

Necessary tools for the inspections:

- Reference electrode (vs. Ag/AgCl)



- Voltmeter
- Cables for electrical connection
- ROV

### 5.2.3.5 Scour Protection

The method of survey, (e.g. sonar, ADCP or ROV) is up to the operator’s choice, most likely depending on cost and availability. Though, it is important to obtain survey data with sufficient accuracy to identify changes of the prescribed dimensions.

The scope of the inspection is:

- To assess dimensions of eventually occurring cross sectional changes
- To serve as a basis for efficient rectification measures (if required).

Measurement errors and tolerances must be considered. In general, scour will only occur around suction piles, driven pile anchors and drilled pile anchors.

### 5.2.3.6 Marine Growth Measurement (MGM)

Measuring the marine growth thickness is carried out in order to ensure that the operational limits as considered in the design are not exceeded.

Its scope is to assess:

- Thickness of marine growth

Necessary tools for the inspections:

- Measuring probe or folding ruler

Corrective measures are to be taken in case the maximum allowable marine growth thickness is exceeded.

### 5.2.4 Failure Mechanism of Mooring Systems

After introducing diverse inspection methods which can be used to determine the state of the mooring system, this chapter will explain common failures and their locations on mooring components. It is required to be considered in order to successfully inspect the mooring system.

Table 5.2-1 extracted from [38], briefly highlights the areas that need to be inspected, what is being looked for, and some of the difficulties of inspecting those areas.

What to Inspect	Where to Inspect Chain	Difficulties with Inspection
General inspection	All over chain	Need to clean chain and access difficulties at and below mudline
Tension-tension fatigue	Half crown Half-crown intrados (most common location)	Very difficult to see or get any access to the area as it obstructed by the

What to Inspect	Where to Inspect	Difficulties with Inspection
<b>Chain</b>		
		adjacent link
	Crown extrados (another relatively common location)	Reasonable access, particularly in studless chain when the adjacent link is not as obstructive
	Flash butt weld (occasional location for fatigue)	Good access to outside, but more difficult on intrados.
Out-of-plane Bending Fatigue	Chain link at the bell-mouth	Access impaired by bellmouth in most cases. Can be either in-air or under water, depending on the design.
General corrosion	All over chain	Visual gives some information. Measurements can be taken if needed.
Pitting corrosion	All over chain	Good from visual
Interlink wear	Contact point between links	Need to measure the double diameter of the two links at the contact point. Need baseline dimensions. Chain bar stock ovalizes during fabrication.
Dimensional anomalies	Length over a number of several adjacent links	Need baseline for results to be meaningful. Can be difficult to measure relatively large distances with sufficient accuracy
Mechanical or installation damage	All over chain	No significant problems if there is sufficient visibility
Twist in chain	All over chain	Need reasonable visibility to be able see twist over number of links
<b>Synthetic</b>		
Mechanical damage	Splice	Generally good visual, but access to termination limited
	Body of rope	No significant problems if there is sufficient visibility
Internal damage		Not possible with available technology
<b>Wire rope</b>		
Fatigue of wire rope	All over – sheathed rope	Not currently technology, but possible in the future
	All over – un-sheathed rope	Visual of surface only
Corrosion	All over	Visual, but can be difficult to interpret. Measurements of diameter feasible if wire not sheathed
Fatigue of rope termination	Body of termination	Similar access problems as with chain
<b>Connectors</b>		
Misalignment	Between connector and connected	Visual normally adequate (see also

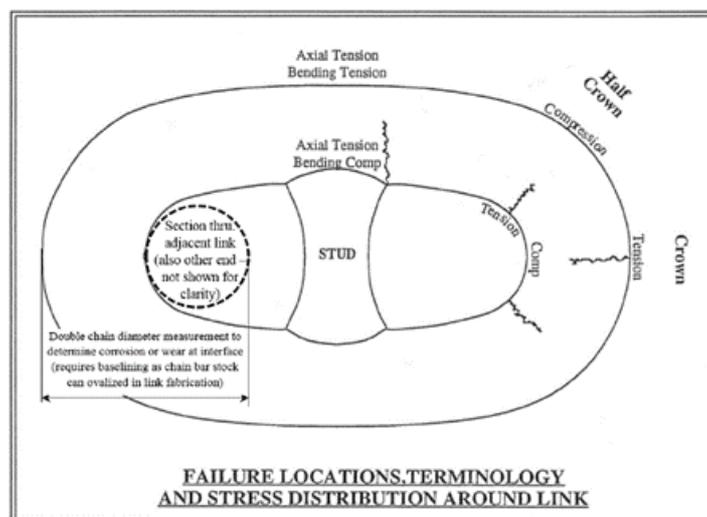
What to Inspect	Where to Inspect	Difficulties with Inspection
<b>Chain</b>		
	components	discussion below this table)
Corrosion	All over	Similar to chain (see also discussion below this table)
Inter-component wear		Similar to chain interlink wear
Loose pins, lost retainers, etc.	Visual	Inspectors need to know what the component should look like (in order to see defective condition)

**Table 5.2-1 – Outline of mooring components for inspection [38]**

Critical areas for which more detailed inspections may be beneficial are the fairlead region, the splash zone, the seabed touchdown area, the connectors and the rope terminations. Another area where failures are likely are parts of the mooring line where weight discontinuities occur leading to additional bending and wear. The following are some of the reasons that connectors are of special interest during inspections of existing installations, based on [38]:

- Tolerances: Connectors are designed and fabricated within specified tolerance limits to help ensure that the components being connected will fit into the connector. However, if the connector tolerances are, for example, at their maximum, and the components being connected are at their minimum, then there can be appreciable play in the system, potentially leading to out of alignment loading. This issue is being considered for inclusion in a new draft API document, but there are currently no industry-based guidelines.
- Materials: Another issue that has been discussed at some length by the group developing the draft connector guideline is that of material compatibility: different types of steel have resulted in increased corrosion rates.
- Design Details: Missing retaining pins, nuts, etc. has been a problem on connectors, often due to failure of design details.

Figure 5-5 has been included to help to explain the tension-tension fatigue crack locations on a common (stud link) chain. The locations are similar on a studless link.



**Figure 5-5 – Terminology and Tension-Tension Fatigue Crack Locations on Common (stud link) Chain [38]**

## 5.2.5 [Monitoring](#)

For reducing O&M cost and implementing advanced O&M strategies, monitoring systems are a key enabling technology. (Continuous) monitoring systems indicate mooring line failures in real time or at least on short term, whereas inspections will only detect mooring line failures on pre-set inspection intervals or after major events. Since FOWT mooring systems are and will be designed with lower level of redundancy and safety than the mooring systems of O&G substructures, detection of mooring line failure should be possible within a short time window. Thus, it is likely that the significance of monitoring will be higher than the significance of inspections of FOWT mooring systems in order to detect mooring line failure.

The purpose of monitoring can be to identify mooring line loss, to validate design assumptions or to gain information on possible structural optimization and hence reduce cost of future projects. It is possible to use monitoring in order to collect data on fatigue damage (and remaining structural lifetime), extreme loads as well as on specific issues like chain bending characteristics around fairleads and chain stoppers. Monitoring of mooring lines improves reliability and optimizing operation and maintenance of floating support structures leading to reduced costs. State-of-the art sensor devices are able to monitor chain bending characteristics in chain stoppers and fairleads. An analysis of the monitoring data can indicate whether chain wear at these hot spots has developed and also chain failure. Wear is often present at fairleads in the splash zone. Inspection might be possible by de-ballasting the foundation and monitoring may support the decision-making process for such inspections.

To prevent confusion between inspection and monitoring following definition of the term “monitoring” is given: **Monitoring is defined as an automated inspection being a subset of inspection.** 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 of offshore human operation, based on [35].

### 5.2.5.1 [Monitoring Equipment](#)

In the following an overview about current technologies for monitoring is presented based on [38] with partial adaptations to fit into the floating wind specific context.

#### Simple Sonar Probe

A simple sonar probe system has been applied under offshore conditions. Horizontal scanning single beam or multi beam sonars are typically deployed from centre of the turret or moonpool or over the vessel side. The sonar head is usually submerged down to approximately 15 to 20 meters below the hull. The sonar reflections are processed in real time to detect if a line is missing or has moved outside its maximum allowable design envelope, the system can automatically trigger an alarm notifying the operator. The illustrated system is simple and easy to repair if something does go wrong with it. But if a line breaks in the mud, still having some tension/catenary, the signals from the sonar probe may not be sufficient enough to indicate that a line has failed. This technology has limited application and long-term field performance data will help assess its reliability and accuracy.

<b>Maturity</b>	Has been used in a limited number of applications (O&G)
<b>Intent</b>	Detect failed mooring line only – no tensions. If not permanently deployed, then no real time feedback on a failure

<b>Application</b>	All types of facility, but easiest on a turret moored system
<b>Deployment</b>	New and existing units (O&G)
<b>Advantages</b>	Can be retrofitted; low technology; probes easily repaired if damaged
<b>Disadvantages</b>	Only failed line detection when system deployed. Possible problems detecting failure on seabed if it does not result in significant mooring line angle change at turret. No mooring line tension data gathering

**Table 5.2-2 – Sonar Probe [38]**

### Inclinometer

A simple inclinometer could measure mooring line departure angles. Using analysis tools, the current mooring line tensions can be estimated. In calm weather, if any of the mooring line angles have changed to a significant extent, there is a possibility of a line failure. Such inclinometers could be checked using “football” sized ROVs, which can be deployed directly from the deck of the vessel itself. Installation is easy and the technology is relatively cheap and robust. Simple inclinometers overcome the difficulties sometimes encountered with damage to power and signal distribution cables on more complex systems as inclinometers installed under water usually come with an acoustic signal link. A challenge is the limited battery lifetime. Measurement accuracy is not optimal, and a continuous error might be present due to calibration errors. The readings are not continuously monitored. Inclinometers have been applied in several O&G projects under offshore conditions.

<b>Maturity</b>	Has been used in a limited number of applications (O&G)
<b>Intent</b>	To measure mooring line angles for the use of detecting line failure or as input to the mooring line load assessment
<b>Application</b>	All types of mooring systems
<b>Deployment</b>	New and existing units (O&G)
<b>Advantages</b>	Direct measurement of line angle and not affected by other parameters. Relatively simple system with low cost
<b>Disadvantages</b>	No continuous monitoring. Line angle for each mooring line may be recorded at different times and could cause inaccurate line load assessment

**Table 5.2-3 – Inclinometer [38]**

### Load Cell

In theory, mooring line load monitoring is the most straightforward way to detect mooring line failures. Direct in-line load cells have been used widely under offshore conditions and this method is a proven technology in order to determine line tensions, [39]. There are systems that use fixed chain stoppers, which have been outfitted with load cells underneath their base. Next figure illustrates a load cell at chain stopper. There are also load cells installed in mooring lines (e.g. between the bar stocks of studless chain elements) with the limitation that data transfer is only possible by hardwired cables leading to increased need of repair or replacement, [39]. Long term application of these strain gauges can be questioned due to decreasing signal quality evoked by loose connections due to corrosion. Figure 5-6 shows an instrumented load pin. A third option is to determine the natural frequencies of chain segments in order to calculate the load acting on it. However, experience in O&G application has indicated that the accuracy, reliability and robustness are major issues using load monitoring systems, especially for underwater where access to the mooring line and instrument is very difficult if not possible. The power and signal transmission cables are areas of particular weakness for systems exposed to long term offshore loading conditions. Acoustic data transmission overcomes these weaknesses but seems to be a complex solution as well. A new development in recent years is the use of in-line load cells housed in a protective casing, making it better suited for offshore installation. Data transfer is conducted via an acoustic transmitter. See ref. [38] for further information.

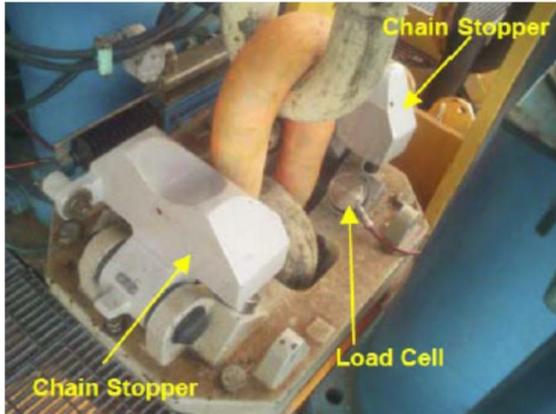


Figure 5-6 – Instrumented Load Cell at Chainstopper (courtesy of FPS mooring integrity JIP) [38]

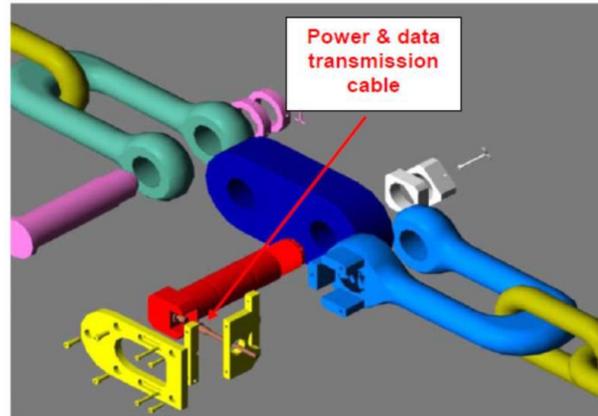


Figure 5-7 – Instrumented Load Pin (courtesy of BMT/SMS) [38]

Load cells have been found to be unreliable when used in mooring system monitoring being sensitive to weather and lightning. Part of the problem is that they are required to be operational for extended periods of time with little opportunity for recalibration or suitable replacement (especially for the load pin option). Signal drift can be detected up to a point; however, it is not always possible to determine what is due to instrument drift versus what is a slow change in the real mooring line load. Another problem can be the system losses between the chain stopper, where the load cell is installed, and the mooring line tension away from the facility. Not only is it difficult to ascertain the frictional losses, but they may not be fixed over time. Again, this can introduce an unexplained signal drift.

<b>Maturity</b>	Has been used in number of applications (O&G)
<b>Intent</b>	Monitor mooring line load for the detection of line failure, over loading, or fatigue assessment
<b>Application</b>	All type mooring systems; difficulty for submerged turret mooring system
<b>Deployment</b>	New and existing systems (O&G). For inline load cell; retrofit is difficult
<b>Advantages</b>	Long time, very well used method for load measurement. Relatively simple system, low cost.
<b>Disadvantages</b>	Measurement is not reliable especially when the mooring line load is not very high. Many other factors affect the output of the measurement, such as frictions, temperature, signal drafting, recalibration, durability of transmission cables, etc

Table 5.2-4 – Load Cell [38]

Table 5.2-5 illustrates a global positioning system. Theoretically, the abnormal changes of the offset of a floating substructure should be able to indicate the failure of a mooring line. Some O&G units have installed GPS/Differential Global Positioning System (DGPS) for position monitoring which makes this system a proven offshore technology. However, the effectiveness of using offset monitoring to detect mooring line failure depends upon many factors, such as the characteristics of the mooring system, water depth, monitoring of environmental conditions, and reliability of GPS and Gyro. But in general, overall offset monitoring and recording using GPS and Gyro is cheap. The offset information combined with knowledge of environment and mooring system behavior could, at least, provide indications for further inspection.

<b>Maturity</b>	Has been used in a number of applications (O&G)
<b>Intent</b>	To monitor and measure vessel locations and hence to derive the mooring line load
<b>Application</b>	All types of mooring systems
<b>Deployment</b>	New and existing systems (O&G)
<b>Advantages</b>	Easy to install and relatively low cost. Equipment on board the vessel and easy to maintain
<b>Disadvantages</b>	The relationship between vessel’s position and mooring line load needs to be carefully studied to have a clear understanding between the measured positions and mooring line load. Environment measurement (wind, wave, and current) may be necessary

Table 5.2-5 – Global positioning System (GPS) and Gyro [38]

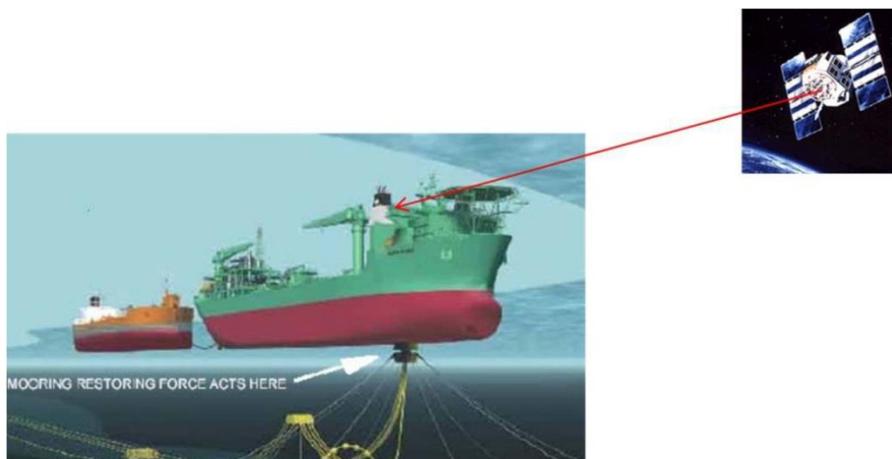


Figure 5-8 – Global Positioning System (courtesy of FPS mooring integrity JIP); Source: (ABSG Consulting Inc., 2015)

Indirect in-line tension monitoring (moorASSURE)

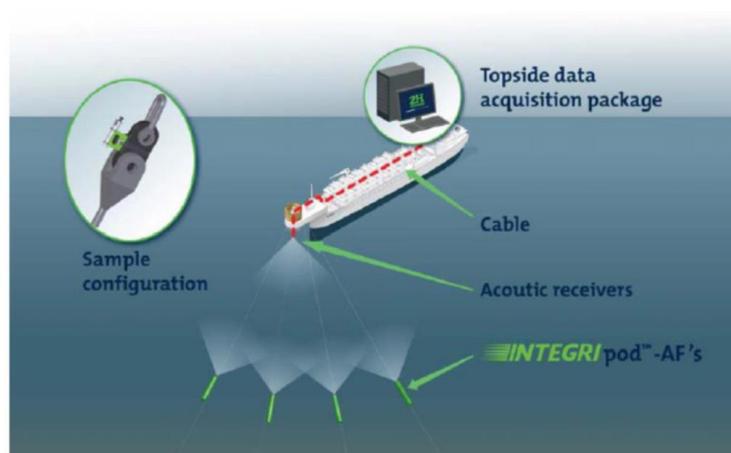
The moorASSURE monitoring system monitors the mean angle of mooring lines and vessel’s position. On each mooring line, an inclinometer is attached to measure its mean angle. The measured angle is periodically transmitted to vessel mounted acoustic receivers using hydro-acoustic data link. The acoustic inclinometer is placed in a holder to allow its retrieval and installation by ROV or diver. The logger holders can be attached to chain links or on the chain follower below the chain table. A number of hull-mounted acoustic receivers are

connected using electrical cables to an industrial rack mounted data acquisition system located on the topside (see Figure 5-9).

The measured mooring line angles are collected by a topside data acquisition system. The mean mooring line tension is derived using the measured mooring line angles and vessel's position data. The calculated mooring line tension is displayed and compared with predefined thresholds. Where measurements exceed the threshold, alarms are raised by the software. The system has already been installed under offshore conditions in O&G industry.

<b>Maturity</b>	Used in limited number of applications (O&G)
<b>Intent</b>	Continues monitoring and measuring mooring lines angles and predicts mooring line load based on line angles or detects mooring line failures
<b>Application</b>	All types of mooring systems
<b>Deployment</b>	New and existing units (O&G)
<b>Advantages</b>	Real time monitoring, acoustic transmission, less maintenance
<b>Disadvantages</b>	Need careful calibration for the model of mooring line angles and mooring line load. Data management and alarm setting criteria

**Table 5.2-6 – Indirect in-line tension monitoring (moorASSURE) [38]**



**Figure 5-9 – Indirect Line Tension Monitoring System (courtesy of 2H) [38]**

Integrated Monitoring and Advisory Systems (IMAS) have been installed in O&G industry in the past. It includes monitoring system, forecast system and data acquisition system. The monitoring system monitors wind, wave and current conditions, vessel motions and mooring load. The forecast system includes the prediction of vessel motions and mooring line load. It also provides advisory on optimum loading conditions. The hardware used includes DGPS, Inertial Measurement Unit (IMU), Acoustic Doppler Current Profilers (ADCP), inclinometers, accelerometers, Fiber Bragg Gratings (FBG) sensors.

<b>Maturity</b>	Has been used in a limited number of applications (O&G)
<b>Intent</b>	Monitor and detect mooring line overloading, failure, and provide operation advisory
<b>Application</b>	All types of mooring systems
<b>Deployment</b>	New and existing units; could be difficult for existing units (O&G)
<b>Advantages</b>	Comprehensive system for real time monitoring and provide advisory for operations
<b>Disadvantages</b>	Relatively expensive with the measurements systems. The system is relatively new and the effectiveness of the advisory system is not yet known.

**Table 5.2-7 – Integrated Monitoring and Advisory System [38]**

### 5.2.5.2 [Post-processing](#)

Since a huge amount of data is generated by all monitoring sensors in a wind farm (considering that sensors are not only installed in the mooring lines, but also in the wind turbine, on the turbine substructure and on the substation), data storage and transmission is a huge challenge.

The data is collected in the onshore SCADA centre and needs to be evaluated and assessed which requires skilled personnel. The evaluation software and the personnel need to be able to identify a mooring line failure from a false alarm within a short time frame since repair or replacement measures should be initiated shortly. It is necessary not only to track and assess the real time data, but also to identify any trends comparing actual data with historic data in order to e.g. identify slow changes in mooring line tensions. Data storage is also a challenge since the large amount of sensors will generate a huge amount of data that needs to be stored. This also indicates the need to clearly define the purpose and the amount of sensors that are needed to gain the target parameters. Even though the cost of the sensors itself may decrease in the future, server space for storage of large data may be the critical parameter.

## 5.2.6 [Repair Methods and Procedures](#)

### 5.2.6.1 [Mooring Line Replacement Procedures](#)

In the design phase of the substructure and the mooring system, a mooring line replacement concept shall already be worked out, since O&G experience showed that mooring line failures during operation are quite probable. Close collaboration to the installation contractor is beneficial since line failures can be installation induced. In general, redundancy or safety levels applied in the design should keep the probability of a mooring line failure as low as economically possible. However, if one mooring line breaks, it should be ensured by design (consideration of damaged and transient conditions in the mooring analysis) that the remaining mooring lines and anchors are not overloaded and that the structure will not break free completely. After a mooring line

failure, it might be reasonable to not tow back the substructure into the port, but replace the mooring line at site. A procedure for mooring line replacement using an AHV in O&G industry is given in [39]. and is described below:

The replacement of an in-service mooring line presents some unique challenges. Failed mooring lines could be replaced either by derrick barge or by large Anchor Handling Vessels (AHV). Mooring line replacement feasibility using AHVs was evaluated with an objective to develop an effective and economic line replacement option. Original installation in O&G typically uses large derrick barges as a part of a more comprehensive installation scope. However, using a derrick barge for a limited mooring replacement campaign is not practical as they are difficult to obtain a lease on short order and are much more expensive.

AHVs may require modifications to be able to perform the job of construction vessels. Depending on the scope of mooring component replacement, special installation aids such as a Subsea Chain Table may be required to make subsea cutting and joining of mooring line. Further requirements on the AHV capabilities regarding the equipment and procedures to apply can be found in [39]. This includes step-by-step procedures, and requirements for suction pile installation, rope installation and amount of AHVs needed.

#### 5.2.6.2 [Tow-In for Major Repair Work](#)

Disconnection and reconnection for major maintenance is not a proven procedure. While detailed investigation of the benefits and disadvantages of such maintenance schemes was not performed in this study, because it is very site and design dependent, some general statements are possible: It is likely that most repairs to the extent possible will be performed offshore. If a repair cannot be performed offshore, the disconnection procedure will have high demands regarding weather windows and given that both a tow-in and tow-back transport is required, the downtime will be significant. This risk is increased if considering that in such a case, a suitable port facility with appropriate crane lifting capacities is also required, usually connected with additional mobilization time. To overcome this and reduce transport distance, a tow-in to sheltered areas and the use of a traditional jack-up barges for the repairs might be a viable option – however feasibility of this option is site dependent. Regarding the mooring design, the top connector design is most relevant for the operation. Quick connectors (e.g. ball-taper bearings) make this process easier, but have the risk of being expensive; also their robustness over the whole lifetime is a challenge, i.e. ensuring that the mechanism still works after 20 year lifetime and accumulated corrosion and marine growth. Other, simpler connector systems using e.g. only links, could still be disconnected, but then likely involve either more complex marine operations and larger vessels, or if the links are simply cut, result in the additional cost, both for the component and the re-installation of the connector.

## 6 MODELS FOR OPTIMIZATION

DNVGL-ST-0119 [11] and DNVGL-RP-0286 [19] are the top-level design codes for this project. Analysis is performed using recommended practices detailed in this code. Dynamic mooring line modelling is planned as per [19].

Modelling will include Static Configuration Checks, Extreme Event (ULS) Analysis, Fatigue Analysis (FLS) and Interference checks when needed. These will be undertaken as detailed in D1.2 report.

Next Table provides a list of tools extracted from [20]. Set of tools used in WP2 are highlighted in blue.

	Aerodynamics	Hydrodynamics	Structural dynamics	Mooring line dynamics	Controller modelling
WAMIT	N/A	FD PT	RB or Modal	GSM	N/A
AQWA	N/A	FD PT or TD CE+MD	RB or FEM (TD)	GSM or QSM or FEM	N/A
WINDOPT	N/A	FD PT	RB	QSM or FEM	N/A
FAST	(BEM or GDW) + DS + DI	TD ME or TD CE + MD	Modal or MBS	GSM or QSM or FEM	DLL or UD or SM
BLADED	BEM + DS + DI	TD ME or TD CE + MD	Modal or MBS	GSM or QSM or FEM	DLL
OrcaFlex	Coupled to FAST	TD ME or TD CE + MD	Coupled to FAST	GSM or QSM or FEM	Coupled to FAST
3DFloat	BEM + DS + DI	TD ME or TD CE + MD	FEM	GSM or FEM	DLL or UD
Flex5	BEM + DS + DI	TD ME or TD CE + MD	FEM/Modal/Shape	QSM	UD
HAWC2	BEM + DS + DI	TD ME or TD CE + MD	MBS/FEM	GSM or QSM or FEM	DLL or UD
SIMA (SIMO/ RIFLEX)	BEM + DS + DI	TD ME or TD CE + MD	MBS/FEM	GSM or QSM or FEM	DLL or UD
Sesam/ Wadam	N/A	FD PT + ME	RB	GSM	N/A
Simpack	(BEM or GDW) + DS + DI or FVM or CFD	TD ME or TD CE + MD	MBS	GSM or QSM or MBS	DLL
SLOW	ACP	Reduced TD CE or ME	Modal or MBS	GSM or QSM	SM
<i>Aerodynamics</i> BEM – Blade Element Momentum GDW – Generalised Dynamic Wake (induction model) DI – Dynamic Inflow DS – Dynamic Stall CFD – Computational Fluid Dynamics FVM – Free-wake Vortex Model ACP – Actuator Point Model  <i>Hydrodynamics</i> FD – Frequency Domain TD – Time Domain PT – Potential Flow CE – Cummins Equation MD – Morison Drag term ME – Morison Equation			<i>Structural &amp; mooring line dynamics</i> RB – Rigid Body MBS – Multi-Body System formulation FEM – Finite Element Method GSM – Global Stiffness Model QSM – Quasi-Static Model  <i>Controller Modelling</i> DLL – Dynamic Link Library UD – User Defined SM – Simulink-MATLAB interface		

Table 5.2-1 – Software examples for hydrodynamic, mooring and coupled simulations [20]

## 6.1 OrcaFlex Analysis Software

OrcaFlex, published by Orcina, is the 3D, non-linear, time domain finite element analysis program which will be used to simulate realistic mooring lines and cables in the Corewind project. Wave structure interaction can be modelled using different schemes, from simple imposed motions to second order potential flow analysis with multi-body interactions. It is commercially available software which has been successfully applied to both dynamic deep-water Oil and Gas applications and shallow relatively static renewable cable applications.

OrcaFlex can model a wide range of objects including:

- Lines (Fully coupled bending, torsion and axial stiffness, Bend Stiffener / Tapered Stress Joint model generation, etc.)
- Vessels;
- Subsea structures;
- Winches;
- Turbines.

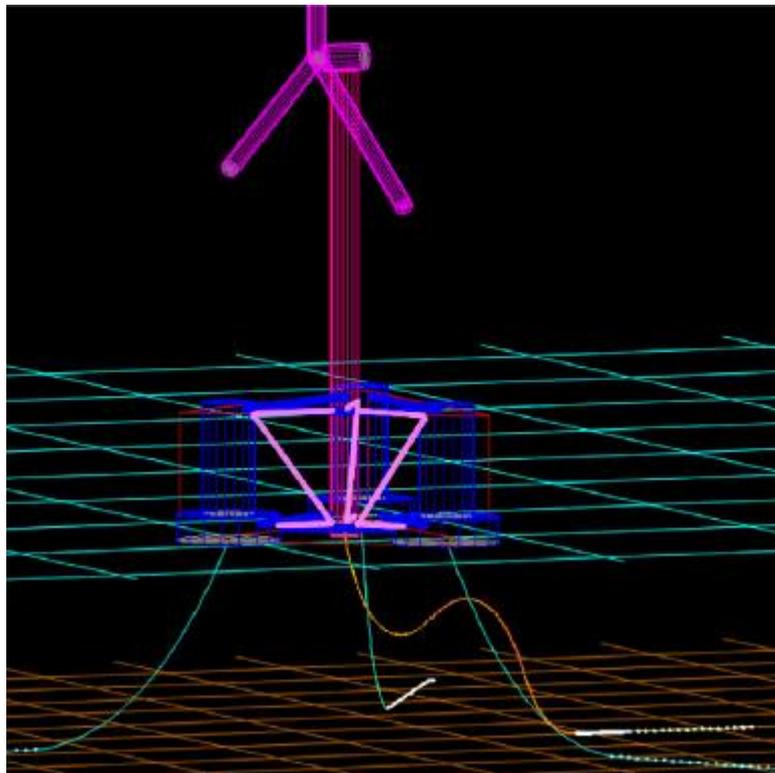


Figure 6-1 – View of OC4 model set-up with Orcaflex [46]

FAST is NREL's open source tool for simulating the coupled dynamic response of wind turbines. FAST joins aerodynamics models, hydrodynamics models for offshore structures, control and electrical system (servo) dynamics models, and structural (elastic) dynamics models to enable coupled time-domain nonlinear aero-hydro-servo-elastic simulation.

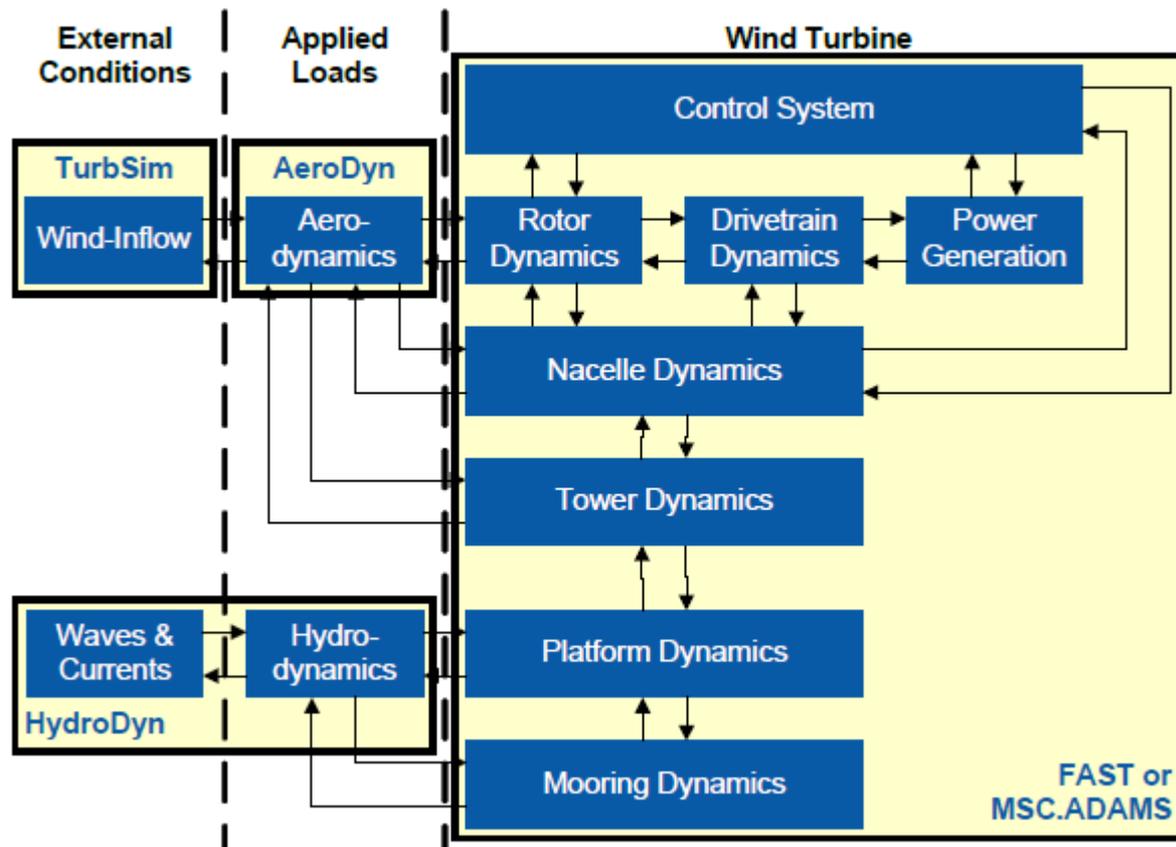


Table 6.2-1 – FAST Modules description [45]

FAST is based on different modules responsible for different parts of the simulations:

- **AeroDyn** is an aerodynamics software library (module) for use by designers of horizontal-axis wind turbines. It is designed to be interfaced with FAST for aero-elastic analysis of wind turbine models. The aerodynamics model in AeroDyn is a detailed analysis that includes Blade Element Momentum (BEM) theory (with modifications to improve accuracy in yawed flow).
- **InflowWind** is a FAST module that allows to process wind-inflow, either steady wind model internally calculated or using various types of input files (uniform, binary TurbSim full-field, binary bladed-style FF, binary HAWC wind files).
- **Elastodyn** is a structural-dynamic model for horizontal-axis wind turbines based on modal superposition theory. It includes structural models of the rotor, drivetrain, nacelle, tower and platform.
- **HydroDyn** is a time-domain hydrodynamics module that has been coupled with FAST to enable aero-hydro-servo-elastic simulation of offshore wind turbines. HydroDyn allows for multiple approaches for calculating the hydrodynamic loads on a structure: a linear potential-flow theory solution, a strip-theory solution, or a combination of both. Hydrodyn requires importing the hydrodynamic database in

frequency domain obtained by a potential flow solver (e.g. NEMOH).

- **ServoDyn** is a control and electrical-drive model for wind turbines. It includes control and electrical-drive models for blade pitch, generator torque, nacelle yaw, high-speed shaft brake and blade-tip brakes. ServoDyn can use an external controller defined by a DLL, so-called “Bladed-style” because it uses the same communication scheme as DNV GL’s Bladed.
- The **Mooring Analysis Program (MAP++)** is a library designed to model the steady-state forces on a Multi-Segmented, Quasi-Static mooring line. This model is developed based on an extension of conventional single-line static solutions. Conceptually, MAP++ solves the algebraic equations for all the mooring elements simultaneously with the condition that the total force at connection points sum to zero. Seabed contact, seabed friction, and externally applied forces can be modelled with this tool. This allows multi-element mooring lines with arbitrary connection configurations to be analysed.
- The **TurbSim** stochastic inflow turbulence tool has been developed by NREL to enable the numerical simulation of a full-field flow that contains coherent turbulence structures. The purpose of TurbSim is to provide the wind turbine designer with the ability to drive FAST simulations of advanced turbine designs with simulated inflow turbulence environments that incorporate many of the important fluid dynamic features known to adversely affect turbine aero-elastic response and loading. TurbSim is used in pre-processing, before FAST simulations.
- **BModes** is a finite-element code that provides dynamically coupled modes for a beam. The beam can be a rotor blade, rotating or non-rotating, or a tower. Both the blades and tower can have a tip attachment. The tip attachment is assumed to be a rigid body with mass, six moments of inertia, and a mass centroid that may be offset from the blade or tower axis. In addition to the tip inertia, the tower can also have tension-wire supports. Both the tip inertias and tension-wire support can substantially influence the coupled modes mentioned earlier, especially for a tower. BModes is used in pre-processing, before FAST simulations.

FAST will be used for the station keeping simulations coupled with Orcaflex in particular for the floater global performance and part of the software package to evaluate the floater excursions.

### 6.3 WAMIT:

WAMIT as described in [20] is a commercial numerical tool originally developed at MIT and now licensed by WAMIT, Inc. for analyzing wave-structure interaction for offshore and ship structures(WAMIT, 2015).It is based on potential flow theory and solves wave-structure interactions problems in the frequency domain, although transformation of results into the time domain is also possible. WAMIT is capable of evaluating second order potential flow hydrodynamic forces and allows for the modelling of complex sub-merged geometry and flexible substructures.

WAMIT hydrodynamic database including excitation and damping loads will be used for the coupled simulations as input to Orcaflex software.

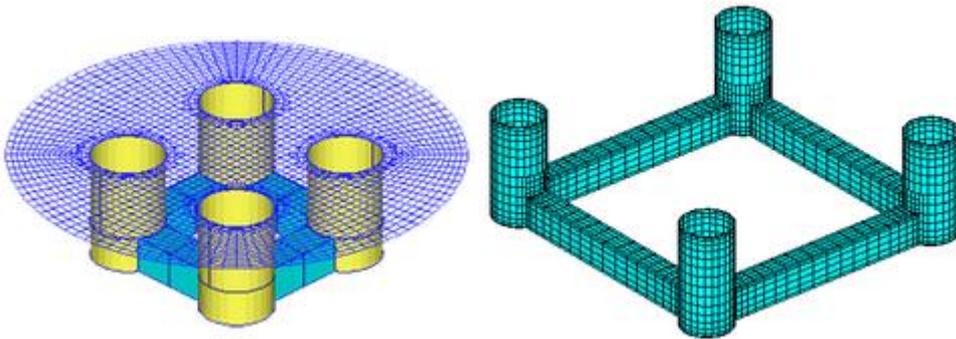


Figure 6-2 – View of floaters / Examples of structures for WAMIT application [47]

## 7 MOORING INTERFACE CONSTRAINTS

### 7.1 Mooring interface with the floater

Interface with floater is particularly critical as it will be submitted to extreme and fatigue loadings. Load transmission to floater is also essential based on the type of floater addressed (Concrete or steel). Mooring interfaces are also particularly operated during mooring line installation phase.

Two main components are screened hereafter:

- Pulling-in system
- Fairlead / Chain stopper

A typical Installation process involving main equipment is described hereafter [51] to put in perspective the use of different elements.

Assuming a chain stopper is installed on each mooring line and that no mooring line section is pre-installed on the substructure, an AHV picks up the upper end of the mooring line. The upper end is connected to a chain stopper.

The AHV approaches the FOWT structure close to one fairlead. A messenger line which is connected to the platform chain is shot over from the FOWT and the platform chain stopper is activated.

The messenger line is connected to the deck winch of the AHV and the platform chain stopper is deactivated. The AHV winch starts hauling in the messenger line and the platform chain. A specified length of the platform chain is stored on the AHV deck. The platform chain stopper is activated. The platform chain is released from the messenger line and connected to the mooring line.

The platform chain stopper is deactivated, and the platform winch starts hauling in the platform chain until a pre-defined line tension is reached. The chain stopper is once again activated.

This process is repeated until all mooring lines are connected to the FOWT.

In case the winching equipment is temporary, the winching equipment and power supply is dismantled and installed on the next platform. In case no chain stoppers are used, a modified procedure is applied, e.g. using a winch to generate the required pre-tension in the line, then using a shackle to connect the line and disconnecting the excess part of the chain.

Pull-in winch is a general term used to describe the various types of winches involved in pull-in operations, such as the riser pull-in and mooring line pull-in. Various ancillary equipment, for instance trolleys and turndown sheaves are often involved in operations such as the riser pull-in [48].

The winch can be operated from the floating platform considering a permanent or removable system.



**Figure 7-1 – The movable windlass is a concept designed to operate multiple mooring lines within the same area. Normally, one windlass skids along a special foundation to operate one mooring line at a time [48]**



**Figure 7-2 – Example of Mooring Winch [48]**

#### Fairlead / Chain stopper

As defined in reference [11] fairlead is the device that guides a mooring line near the point where the mooring line is connected to the floater. Fairlead should be designed against fatigue and extreme loads in particular (IPB/OPB) should be scrutinized as described in [22] and [23]. For some concepts sufficient restoring stiffness in yaw may be required like “Crawfoot configuration” [23].

The evaluation of combined fatigue at top chain connection is to be performed when the pretension in mooring lines at intermediate draft is higher than 10% of the Minimum breaking strength of a chain of the same diameter in Oil Rig Quality (ORQ) grade and when the design life onsite is higher than 2 years [23].

Chains in mooring lines are designed to resist tension loads in line with chain direction. Far from connection points, the angular variation between two chain links is negligible and the assumption of pure tension loading is valid. However, at connection points such as chain stoppers, when one link is forced to rotate with regards to the adjacent link, higher bending moments are imposed in the first following links, generating additional fatigue damage. At fairlead/chain-stopper location, the motions and rotations of the vessel are imposed to the fairlead and the link retained in fairlead pocket whereas the motions of the mooring lines, following mooring line catenary, are imposed to the adjacent chain links. Due to the angular differences between fairlead and chain and to friction between links, high bending moments are imposed to the first links of the top chain [23].

Aim in this section is to assess the type of connection envisaged regarding FOWT concepts to minimize these phenomena.



Figure 7-3 – View of floaters / Examples - Extract from reference [15] to illustrate floater / mooring interface for Floatgen



Figure 7-4 – View of Fairlead/ Examples - Pusnes eccentric chain fairlead from Mac Gregor [48]

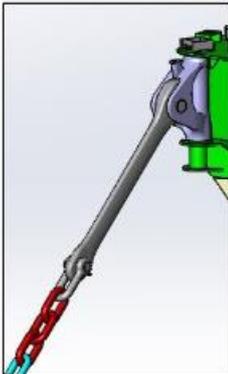


**Mooring equipment**

Photo: Statoll

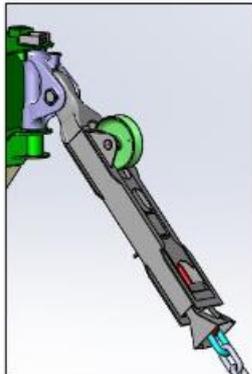
**Fixed Mooring Strongpoints**

- 4 on each Turbine
- 132 mm R4S chain
- Chain tension and bending monitoring on two turbines



**Adjustable Fairlead Chain Stoppers**

- 2 on each Turbine
- 132 mm R4S chain
- Chain tension and bending monitoring on two turbines



**Mooring Brackets**

- 3 on each Wind Turbine

**Tools**

- Chain pull-in tool
- ROT (Remote Operated Tools)

**Schedule**

- Equipment June 2016 to Jan. 2017
- Offshore installation 2017



Figure 7-5 – Example Equinor / Hywind Scotland – Mooring Connection design [50]

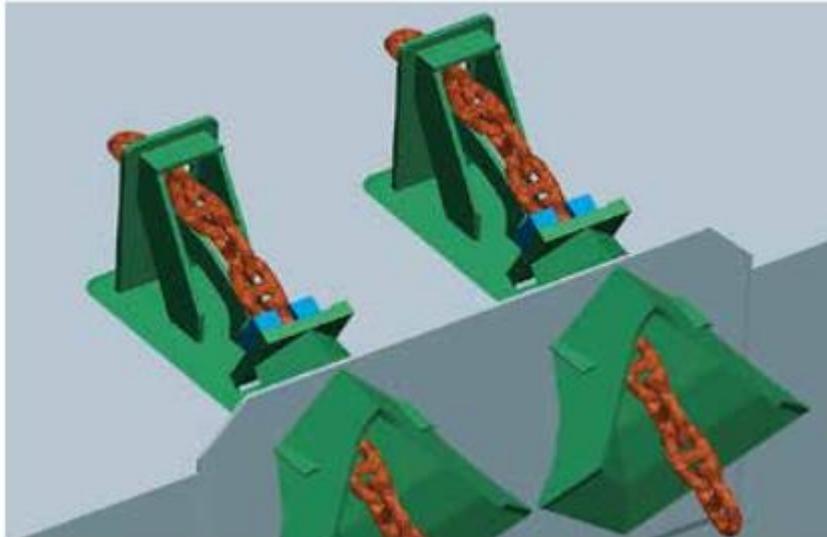


Figure 7-6 – Example Chain stopper [48]

MacGregor developed a fairlead chain-stopper system for Hywind with special features to prevent mooring line fatigue induced by out-of-plane bending (OPB). Also, as the system does not use any winches to ‘pull-in’ and deliver tension on the spar, pre-tension was achieved by externally pulling the mooring lines with anchor handling vessels [49].

## 7.2 Mooring interface with the seabed

Mooring will interface with the sea ground at the cable touch down point and when laid onto the seabed. Sensitivity to soil stiffness will be strongly linked to dynamic configuration selected and ability to decouple floater motions from soil contact area. For example, a simple catenary configuration will strongly interact with soil given. In case of catenary mooring lines abrasion should be investigated, particularly for synthetic material for which abrasion is usually not allowable.

Regarding mooring global analysis and performance assessment, the seabed reaction force is the sum of a penetration resistance force in the seabed normal direction and a friction force in the direction tangential to the seabed plane and towards the friction target position as defined in [26]. The penetration resistance force depends on the choice of seabed model used. OrcaFlex software for example provides a simple friction model that can give an approximate representation of contact friction. This is commonly used to model seabed friction. Soil-Structure horizontal load law is illustrated in this case in next figure with  $D_{crit}$  evaluated with the following formulae:

$$D_{crit} = \frac{\mu R}{k_s a}$$

with:

- $\mu$  the friction coefficient;
- $R$  the contact normal reaction force;
- $k_s$  the shear stiffness;
- $a$  the contact area.

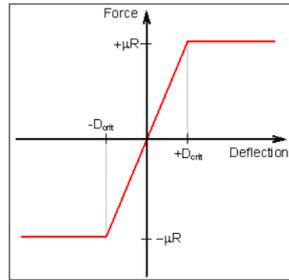


Figure 7-7 – Soil-Structure interaction horizontal loading law [26]

### 7.3 Mooring and dynamic cabling

In comparison to the floating structure and mooring system, the cable is relatively light and flexible and therefore it has very little influence on the moored structure when connected compared to the significant influence the structure and mooring have upon the cable.

As described in D3.1 the dynamic cable configuration is strongly linked to floating structure station keeping performance. The mooring system is required to limit the excursions of the floating structure induced under environmental loading. The allowable excursion for each project scenario should always be defined, accounting for station keeping and dynamic cable constraints.

The second main consideration for the cabling system is the potential risk of interference / clashing. The cables are not designed to withstand impact of collisions with mooring lines and thus no collisions are acceptable as defined in reference [25]. Dynamic Cable configuration should thus be verified versus mooring layout and structure to avoid clashing.

For established mooring solutions of floating Oil and Gas structures, typically the mooring system designers provide a 3D spatial envelope which can accommodate reasonable cable configuration movement to avoid clashing with the floating structure and mooring lines.

Mooring connection points on floating structures are predominantly driven by effective platform offset control and minimization of system costs (installation and O&M). This typically is managed considering floating structure stability, strength, and effective mooring performance. Where mooring systems are applied to floating wind, the size, number and placement of the mooring lines relative to the scale of the 3D envelope provided to the dynamic cable movement to avoid clashing is likely to become of greater importance in upfront considerations.

This is likely to be more challenging for shallow to medium water depths for floating wind. This is because the mooring line connection placement on the smaller structures, combined with desired lower cost relaxed mooring lines, may mean much smaller envelopes for cable approaches to the structure to avoid clashing than current system configurations have been utilized. This may also be of greater importance where Offshore wind structure sizes are reduced driven by lower cost requirements and quicker installation requirements for viable commercial scale farms compared to the oil and gas systems in existence.

Careful consideration of the cable entrance point declination, azimuth and location into to the structure, as detailed in D1.2 for the Corewind project, should be paired with consideration of this cable movement envelope to ensure the cabling angles and motion is carefully controlled near the structure. In order to minimize the requirement for interference checks within the Corewind project, the mooring system model from WP2 will provide a 3D spatial envelope the cable will need to operate to avoid possibility of clashing.

## 8 REVISION OF COST EVALUATION

In this section, a summary of some cost functions for mooring and anchors are presented. From the analysis and review of such functions and cost parameters, the most appropriate will be selected to be implemented within the LCOE evaluation tool within WP6.

It is worth noting that due to lack of information and data in floating wind power market, it is extremely difficult to compute exact cost for different concepts.

Two main references are being used for cost estimation functions. Both treat in a different manner the binomial Mooring and Anchor.

In this regard, the deliverable 2.2 from LIFES50+ [41] functions currently applied at FOWAT LCOE tool) split their costs as Mooring line and anchor:

- **Mooring Line:** The price of mooring lines depends on the both material and type. Due to this, the cost of a single mooring line depends on the weight of the line and can be computed as:
  - $C_{ML} = C_m * l_{ML} * m_{ML}$ ; where  $l_{ML}$  is the length in meters,  $m_{ML}$  is the mass (kg/m) and  $C_m$  is the cost of the mooring line in €/kg.

The most common materials used are steel chains, steel fiber wires or synthetic fiber ropes.

- **Anchor:** In this case, as on the mooring line, the cost may vary depending on the type of anchor. However, a unit price is considered for simplifications.

These functions are presented for individual type (mooring line or anchor), but the total cost of them must be multiplied by the number of turbines, and the number of mooring lines.

On the other hand, Reference [42] introduced two general functions as well as some cost values for the anchor and mooring costs depending on the technology where:

- $Chain\ cost = (0.0591 * MBL - 89.69) * L$ ;
- $Drag-embedded\ anchor\ cost = 10.198 * MBL$ ;

Where MBL stands for Minimum breaking load. Such functions calculate the costs based on chain tension (not the holding capacity). In the following, some values based on other references are given:

Source	(Bjerkseter & Ågotnes, 2013)	(Hurley & Nordstrom, 2014)	Average cost (£)
Type	Drag-embedded	Driven pile	-
Anchor cost (£/anchor)	97 000	160 000	-
Mooring cost (£/anchor)	34 000	41 000	36 000

Table 7.3-1 – Mooring elements cost references

## 9 IDENTIFICATION OF CONSTRAINTS, CRITICAL DESIGN PARAMETERS, KEY PERFORMANCE INDICATORS AND TECHNICAL CHALLENGES FOR THE DESIGN OF FOWT STATION-KEEPING SYSTEMS

### 9.1 Identification of Constraints

This section identifies the constraints for the station-keeping systems based on the work of the previous sections. The constraints are divided in operational constraints, site constraints, anchor constraints, mooring line constraints, dynamic cable constraints and installation and maintenance constraints. The specific constraints for each case are identified and quantified when is possible in order to facilitate their applicability in the optimization problem. The specific constraints are presented in tables giving the characteristics, the constraint values and comments associated with.

#### 9.1.1 [Operational and design constraints](#)

The operational and design constraints are based on the requirements of the FOWT and wind farm performance during operation. These constraints are the maximum surge offset, the surge design period, the yaw design period. Within the mooring design itself, the number of mooring lines and its behavior in case of failure of one line determine the level of redundancy of the mooring system. Moreover, shared anchors and maximum footprint allowed are other constraints that will affect on the FOWT distribution and separation. It has to be highlighted, that mooring lines of adjacent FOWT may not cross to each other to avoid chain failures in a floating wind park.

Constraint	Definition	
<b>Maximum surge offset</b>	<b>Depths</b>	<b>Values</b>
	60m-100m	30 m
	100m-250m	30 m to 60 m
	>250m	Percentage of water depth : 5 to 12%
<b>Surge/Sway design period</b>	Surge and sway motions are governed by the mooring stiffness and the overall mass of the platform. These degrees of freedom can be highly excited by the second order waves forces and the low frequency wind loads. Larger platforms will need stiffer mooring systems to ensure a certain level of compliance in the surge/sway motion.  Surge/Sway periods use to be in a range between 100-150 s.	
<b>Yaw design period</b>	Yaw degree of freedom is also governed by the inertia of the platform and the stiffness of the mooring system. The stiffness of the mooring system in the yaw degree of freedom depends on the number of lines, the tension of the lines, the radius to anchor, and different connection topologies like delta lines.	

Constraint	Definition	
	Yaw periods used to be in a range between 7-14 s for spar designs and in a range between 60-80 s for semisubmersibles.	
<b>Redundancy of mooring lines</b>	Reference is made to discussion included in section 20	
<b>Shared anchors</b>	The anchor must provide multidirectional holding capacity	
<b>Maximum footprint (radius to anchor)</b>	<b>Depths</b>	<b>Values</b>
	60m-100m	7D Apart(Typical value)
	100m-250m	7D Apart(Typical value)
	>250m	Water Depth will influence mooring layout. This should be further investigated.

**Table 9.1-1 –Operational and design constraints**

### 9.1.2 [Site constraints](#)

The site constraints are mainly related to water depth. A mooring line can incorporate chain, wire rope, synthetic fiber rope, or a combination of these depending on the water depth.

**In shallow water**, chain is used extensively, which many refer to as an “all-chain” design. It is a simple and effective design taking advantage of the fact that chain is sturdy, has a good resistance to seabed abrasion, and provides added holding capacity to the anchor. To enhance the station-keeping performance, some mooring designers fit clump weights on ground chain near the touch down point. The additional weight can increase the restoring force of the mooring system.

**In deeper water**, an all-chain system may become too heavy. The weight of chain causes the catenary shape to dip (i.e., sag), the angle at the top of a mooring line becomes steeper. The result is a less-efficient mooring system that provides a reduced restoring force to the floating platform. On top of that, the added value chain weight must be carried by the floating platform thus reducing the platform’s payload capacity. This is where wire ropes can be utilized in a mooring system. Because of its lighter weight, wire rope alleviates the weight challenge found with all-chain designs. Meanwhile it offers a higher restoring force at the same given pretension because of the less-steep catenary shape of lighter mooring lines. As such, wire rope was introduced to the offshore mooring industry and become popular when drilling and production vessels went to deeper water. They have also been used for mobile offshore drilling unit (MODU) and buoys.

For platforms stationed in **deep or ultradeep water**, polyester rope has been increasingly favored over wire rope due to its much lighter weight and lower stiffness. Polyester rope is not only highly competitive in cost, but also offers longer fatigue life than wire rope. Thus “chain-polyester-chain” designs have become a standard configuration for mooring systems in ultradeep water. To reduce weight, designers continue to extend the polyester segment as much as possible by minimizing the lengths of both top and bottom chains.

The protected areas at borders of the wind farm may ban any activity in this area as well as the use of certain types of anchors. Drag anchors need a certain drag excursion to be buried within the soil which may not be reached if the final anchor position is close to a protected area.

Constraint	Definition	
Sea depth	<b>Depths</b>	<b>Mooring system typology (Three, Multiple, ...)</b>
	60m-100m	The catenary mooring system can adopt the “all-chain” design that is commonly used in the oil and gas industry.
	100m-250m	In this range of water depth, it is also possible to use a taut-leg (or semitaut) mooring design for floating wind turbines. In order to provide the compliance to floater dynamic responses, it may be a good option to incorporate synthetic fibers. Wire rope has a lighter weight and a higher elasticity than chain when compared to chain of the same breaking load.  Another option is to use a hybrid mooring system combining chain and rope and fitting clump weights on ground chain near the touch down point in order to add additional weight.
>250m	In deep and ultradeep water a mooring based on synthetic fiber ropes with taut and semitaut configurations can be a promising solution due to its light weight and high elasticity	
Seabed typology	<b>Typology</b>	<b>Constraints</b>
	Rock	Do not allow to install drag embedded nor plate anchors
Protected zones at borders	Protected zones at borders may ban the use of certain types of anchors due to the possibility of damage of the seabed.	

Table 9.1-2 –Site constraints

### 9.1.3 [Anchor constraints](#)

#### 9.1.3.1 [Overview: Available anchor types](#)

Moored floating structures impose a variety of loading conditions on the anchor system. These loads range from the horizontal load for a catenary mooring line, the combination of the horizontal and vertical load for a semi-taut and taut leg mooring line, to the vertical uplift load for a tension-leg platform (TLP). Also, soil conditions for the anchors can vary in type and properties, such as soft clay, stiff clay, sand, gravel, etc. Comprehensive

engineering analysis is required to select the anchor type and to design the anchor configuration based on the loading and soil conditions.

### 9.1.3.2 [Anchor design considerations](#)

The anchor constraints are related to its properties and characteristics. Industry is in continuous development of new designs to improve the properties of the anchors. The main properties that define the anchor constraints are the expected maximum holding capacity depending on the soil type, the durability in terms of life span and the installation requirements like the sea depth constraints, burial excursion, or handling operations. There are several attributes of an anchor which are crucial in assuring its effective performance:

- The anchor must offer a high holding capacity; a result of the fluke area and shank design in combination with penetration and soil type.
- The design of the anchor should be such that the anchor is capable of being used successfully in practically all soil conditions encountered over the world, ranging from very soft clay to sand, corals and calcarenites.
- The fluke/shank angle of the anchor should be easily adjustable, allowing the anchor to be quickly deployed in different soil conditions.
- The design must be so conceived and produced that the high loads common in practice can be resisted.
- The anchor must be designed so that it can be easily handled, installed, retrieved and stored.
- The penetration of an anchor depends upon its shape and design. Obstructing parts on the anchor should be avoided as much as possible.
- The stability of an anchor encourages its penetration and, consequently, its holding capacity. Efficient stabilizers are an integral part of a good anchor design.
- The shank must permit passage of the soil.
- The surface area of an anchor fluke is limited by the required structural strength of the anchor.
- The anchor design must have optimal mechanical strength to fulfil requirements and stipulations of the classification societies.
- The anchor should be designed to ensure an optimum between structural strength of the anchor and holding capacity.
- The anchor should be streamlined for low penetration resistance.

For anchor design and installation, the availability of good soil data is of utmost importance as the soil has great influence on anchor behavior. The following are influenced by the soil conditions encountered:

**Anchor type** - some anchors are more suited for soft soil conditions (soft clay), while others are more suited for hard soils (sand and hard clays), although there are a number of anchor types on the market that are suited for most soil conditions encountered.

**Holding capacity** - in hard soil, like sand and clay, the maximum attainable ultimate holding capacity with a certain anchor type and size, is higher than the attainable ultimate holding capacity in very soft clay.

**Penetration and drag** - in very soft clay the anchor will penetrate deeper than in harder soil like sand. Therefore, the drag length of the anchor will also be longer in very soft clay than in hard soil.

**Retrieval forces** - when an anchor is installed in very soft clay, the required retrieval forces will be higher than in hard soil, like sand. For example, in very soft clay the required retrieval force of an anchor can be equal to 80%-90% of the installation load, while in hard soil (sand) the retrieval force might only be 20%-30% of the installation load.

Constraint	Definition		
Anchor Properties	Anchor type	Property	Value / comments
	Drag embedded:	Holding Capacity	<p><b><u>Very soft clay (mud):</u></b></p> <p>Fluke/shank angle: 50°.</p> <p>Holding capacity between depending on the anchor weight:</p> <ul style="list-style-type: none"> <li>- <b>Weight: 1 – 10 t Holding Capacity: 70 t</b></li> <li>- <b>Weight: 10 – 25 t: Holding Capacity: 150 t</b></li> <li>- <b>Weight 25 -50 t: Holding Capacity: 450 t</b></li> </ul> <p><b><u>Medium Clay:</u></b></p> <p>Fluke/shank angle: 41°.</p> <p>Holding capacity between depending on the anchor weight:</p> <ul style="list-style-type: none"> <li>- <b>Weight: 1 - 10 t: Holding Capacity: 100 t</b></li> <li>- <b>Weight: 10 – 25 t: Holding Capacity: 250 t</b></li> <li>- <b>Weight 25 -50t: Holding Capacity: 520 t</b></li> </ul> <p><b><u>Hard clay and sand:</u></b></p> <p>Fluke/shank angle: 32°.</p> <p>Holding capacity between depending on the anchor weight:</p> <ul style="list-style-type: none"> <li>- <b>Weight: 1 - 10 t: Holding Capacity: 140 t</b></li> <li>- <b>Weight: 10 – 25 t: Holding Capacity: 300 t</b></li> <li>- <b>Weight 25 -50 t: Holding Capacity: 800 t</b></li> </ul>
		Installation	<p>-Can require specaled handling</p> <p>-Not self-righting: must be placed on seabed with flukes oriented down</p>

Constraint	Definition		
			<ul style="list-style-type: none"> <li>-Suited to piggyback configuration</li> <li>-Simple recovery by chain chaser</li> <li>-Can be disassembled for transport</li> </ul>
Plate Anchors / Vertical load anchor	Holding Capacity		Capacity depends on anchor area and soil characteristic. For a 15 m <sup>2</sup> anchor: <b>Soft Clay:</b> 250 t <b>Medium clay:</b> 450 t <b>Hard Clay and Sand:</b> 750 t
	Installation		<ul style="list-style-type: none"> <li>-Installed similar to drag anchor</li> <li>-Easy recovery by pulling from an auxiliary tail cable.</li> <li>-Configurations for permanent and temporary mooring applications: wire for permanent applications to enable deep burial and chain for temporary applications</li> </ul>
Pile Anchors	Holding Capacity (HC)		It has great adaptability to any load requirements by modifying the penetration length and diameter.  Holding capacity can reach more than 1000 t
	Installation		<ul style="list-style-type: none"> <li>-Requires specialist drilling and installation equipment</li> <li>-Installation methods driven or drilled and grouted</li> <li>-Pipe piles resist bending in any direction</li> </ul>
Suction Piles	Holding Capacity		For a medium size suction pile in normal consolidated clays, it can be considered 300 t of pure vertical load capacity. Reduced to 200 t when 150 t lateral load is acting.  Large suction piles can reach holding capacities above 1000 t
	Installation		<ul style="list-style-type: none"> <li>-Suitable for taut, semi-taut and catenary mooring</li> <li>-The system is recoverable.</li> <li>-The system requires specialized install equipment and positional control during installation.</li> <li>-A suction pile does not require an external pull test.</li> <li>-Suction piles are only suitable for clay soils.</li> </ul>

Constraint	Definition		
Dead Weight Anchor	Holding Capacity	<p>The resistance mechanism is friction for lateral loads and selfweight for vertical loads.</p> <p>Lateral capacity in sand can be assumed to be around 50% of the effective weight.</p> <p>Surface effective cohesion in clays may be low rounding 5 to 10 kPa. The lateral capacity will depend on the area of the dead weight anchor.</p>	
	Installation	-Relatively easy to deploy, but requires large weight and is subject to dragging.	

Table 9.1-3 –Operational and design constraints

#### 9.1.4 Mooring Line constraints

The mooring line constraints are bases on its properties and characteristics. Like anchors, industry is improving the capacities of materials like the steel grade of chains, increasing the line diameters or improving the coatings and materials for a larger life span. Mooring line characteristics are high correlated with its dimensions, then the characteristics of the largest capacity line type are presented. The following section is currently limited to chain but will be further extended during project.

Constraint	Definition		
Line Characteristics	Line Type	Property	Value (Typical)
	Chain	Maximum Diameter	180 mm
		Maximum Mass	0.645 Tons / m
		Break Load	2680 Tons

Table 9.1-4 –Mooring line constraints

#### 9.1.5 Installation and maintenance constraints

Installation and maintenance constraints are related with the operations, techniques, required time and planification of the installation and maintenance process during the life span of the FOWT.

Constraint	Definition
Fairlead depth	Fairlead positions far from the center of rotation of the structure may cause an increase of the fairlead range tensions due to the coupling of pitch and surge motions.

Constraint	Definition
	On the other hand, deep fairlead connections will be required different installation process than platforms with fairleads located at shallow or above mean sea level locations.
<b>Installation</b>	The installation constraints depend on the different mooring systems types which may require different installation techniques, installation time or different installation vessels. The properties of the mooring system that can effect on the total installation costs are the mooring system type (catenary, taut, semi-taut), the initial pretension, the number of lines to be installed, the type of mooring lines that require different degrees of execution (chain vs synthetic lines) and the type of required anchor.
<b>Maintenance</b>	The maintenance constraints are related with the periodic inspections needed for each element. Longer periods may require larger Design Fatigue Factors as defined in section 5.2.2.2. which may compensate the cost increase of more reliable designs. Moreover, the maintenance and the design reliability must prevent failure of one mooring line which will suppose the stop of the production of the FOWT.

**Table 9.1-5 – Installation and Maintenance constraints**

## 9.2 Critical design parameters

The critical design parameters are the parameters or constraints that have bigger influence in the optimal solution of the mooring system design. The optimization problem must obtain the most reliable, cost effective, and easy installation station keeping solution for the life span of the structure. From the analysis of this document, the critical design parameters are divided in design constraints, met-ocean data and life span of the mooring system.

### 9.2.1 Design constraints

The design constraints are the ones related with the design parameters selected. The design parameters define the characteristics of the FOWT and the characteristics of the mooring system itself. Moreover, the site constraints, are one of the main design parameters, as the depth will affect the mooring typology and the total length of the lines.

- **Platform design:**

The main platform design characteristics that influences the mooring system design are the mass, inertia and the fairlead locations. The surge/sway and yaw natural frequencies depend on the stiffness of the mooring system and the mass/inertia of the platform.

Semi-submersible platforms usually have large yaw damping sources, which allows to the mooring system to be more compliant. Whereas spar platforms, have very low yaw damping sources which usually leads to stiffer mooring systems in the yaw DOF by using special connection systems like crowfoots.

- **Station keeping typologies:**

The main mooring system typologies for a spar and a semi-submersible are the catenary, the semi-taut and taut mooring shapes. For each configuration, the number of lines, the number of line sections and the anchor typology must be defined in order to assess the optimum design. The combination of these parameters will lead to many possible solutions. In addition, the condition of shared anchors or shared mooring lines must be defined. The assessment is done using numerical models in order to achieve the most economical and robust mooring system. Also, the excursion ranges allowed (section 3.1.2) play a role on the length and configuration of the mooring system.

Moreover, the use of more than three mooring lines effects on the redundancy classification.

- **Mooring line component design characteristics:**

The mooring line characteristics as the weight, mass, axial stiffness, bending stiffness and bearing capacity are the main design constraints for its design verification.

- **Site constraints:**

The main site constraints are the depth and the space available. The depth is a key parameter that influences the final solution of the mooring system because is directly related with the length of the mooring lines. Moreover, deepest seas will increase the installation costs of certain types of anchors due to the complexity of the operations.

The space available per turbine is also a constraint that can affect very much on the mooring system design especially for the catenary systems that needs long segments resting on the seabed. Interference between mooring systems of adjacent platforms should be avoided to reduce the risk of chain reaction that could represent the failure of several FOWTs.

### 9.2.2 [Metocean data](#)

The met-ocean data of the selected location will provide the loads that the FOWT has to resist during its life span. The main loads that affect the FOWTs, and hence the mooring systems, are the wind, waves, and currents.

The wind in conjunction with the wind turbine design is the responsible of the mean excursion of the structure by the thrust and tower loads, which has to be balanced out by the mooring system. Furthermore, wind gusts can affect the low frequency range of the FOWT close to mooring system frequency response. Wave loads are responsible for the dynamic tension of the lines. As well as the wind gust, second order waves forces can fall in the surge/sway natural frequency range and increase the total excitation of the system. The currents also effect on the mean excursion of the platform which can be very important for large draft platforms like spars.

### 9.2.3 [Life span](#)

The life span of the mooring system is very important because the operation costs are an order of magnitude above the material costs. Thus, a mooring system reliable for the whole life span of the FOWT could be more cost effective than a mooring system that requires a replacement of the lines at half of the life span of the FOWT. Then, the service life of the materials used must be considered in order to assess the total cost of the mooring system for all its life span, considering possible replacements.

### 9.3 Key performance indicators

The key performance indicators measure the success of the optimization problem for the design of the station keeping system. The aim of the optimization problem is to find a cost-effective station keeping configuration that fulfills the design criteria of the FOWT. However, the optimization model will be based on simplified tools in order to speed up the calculations and to allow the assessment of as much possible combinations. Moreover, full design processes require to analyze many load cases for the Ultimate and Fatigue limit state which is unviable to perform in the optimization problem. Thus, the key performance indicators are defined to ensure the solutions of the optimization problem fulfill all the prescribed requirements and proper solutions are obtained. The key performance indicators are numbered following.

#### 9.3.1 % Cost reduction between solo solution vs wind park solution

The cost reduction between a single-FOWT solutions against the wind park solution per FOWT is defined to characterize the influence of placing several FOWTs in a wind park. Shared anchors and moorings are expected to reduce the cost of the station keeping systems for FOWTs, but limitations of the space between FOWTs may affect negatively on the performance of catenary shape mooring lines.

#### 9.3.2 % Cost reduction of actual standard solutions vs Optimized ones

The cost reduction of an actual standard park solution against optimized solution key performance indicator assesses the improvement of the computed solution against a reference frame. This comparison will help to initially estimate the CAPEX reduction, because the reduction of the LCOE is one of the main goals of the project.

#### 9.3.3 Fulfillment of all constraints and design criteria

Design criteria of the mooring system like the proof load or break load of the mooring line materials cannot be fully assessed during the optimization problem due to the large amount of feasible solutions. Design criteria can be applied in the optimization problem through simplifications by the problem constraints. However, because of the simplifications of the models used, the actual behavior can be both underestimated and overestimated, and thus the solution could not be feasible or more optimal solutions may be refused. Then, detailed analysis must be carried out in order to check the fulfilment of the constraints and design criteria and evaluate if adjustments are needed to the simplified tools to obtain more realistic solution from the optimization problem.

## 9.4 Technical challenges for the design of FOWT station keeping systems

### 9.4.1 [Anchors](#)

As per today, there are no recognized design methods to compute the anchor capacity in various soils. Anchor holding capacity is difficult to estimate for the design purpose. Guidelines used here are:

- OPL “Oilfield Seamanship” – Barge Mooring.
- S0300-A7-HBK-010 “U.S. Navy Salvor’s Handbook”
- Vryhof Anchor Manual
- API-RP-2SK

Soil conditions may vary in the field significantly. Conservative assumptions need to be made in order to ensure enough holding power during the design phase. Piggy-back as back-up solution are possible, when drag anchors are considered.

Resistance verification of (fluke) anchors is often difficult to accomplish since corresponding test load needs to be not less than the maximum line tension in intact operation condition.

- This load may be several hundred tons for long term moorings (50-year return period environmental loads).
- As an alternative, additional drag (drift of the anchor) at higher loads may be estimated and the risk of damage to adjacent structures is to be investigated.

### 9.4.2 [Moorings](#)

Mooring systems consist mostly of chain, wire and synthetic components. When designing the system following points shall be considered:

#### *Chain:*

- Mooring chain is generally heavy and for the installation campaign the required vessels, lifting gear and equipment shall be accounted for.
- Corrosion allowance is to be considered and as such different specific submerged weights during the lifetime are to be expected. This in turn has an influence on the restoring forces and as such an impact on the dynamic behavior in waves.
- Large water depths result in large vertical (weight) loads at limited horizontal pretension of the mooring system.
- Depending on the mooring layout and geometry of the mooring design, horizontal forces (mean and dynamic) acting on the floating foundation may introduce large downward vertical forces at the mooring connection point. This in turn may lead to different average floating conditions specifically in pitch and draft when dealing with foundations with small water plane area (semi-sub, spar).

#### Wire:

- Must not twist under tension. May easily be damaged by external forces.

#### Synthetics:

- Stiffness (modulus of elasticity) is not constant for different average loadings. Average and conservative stiffness properties difficult to identify and should be covered in additional simulation cases.

Regarding maintenance, the accessibility required for

- Periodic inspection,
- Exchange of components,

shall be considered.

### 9.4.3 [Rules and regulations](#)

Rules and regulations covering the design of mooring systems are mainly, but not limited to, the following. It shall be noted, that for the design purpose a hierarchy of applicable codes shall be agreed:

American Petroleum Institute (API)	
API RP 21	In-service Inspection of Mooring Hardware for Floating Structures
API RP 2MIM	Mooring Integrity Management
API RP 2SK	Design and Analysis of Stationkeeping Systems for Floating Structures
API RP 2SK 4th Edition	An Updated Stationkeeping Standard for the Global Offshore Environment
API RP 2SM	Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring
API Spec 9A	Wire rope
API Spec 2F	Mooring chain
International Organization for Standardization (ISO)	
ISO 19901-7	Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units
ISO 18692	Fiber ropes for offshore stationkeeping – Polyester
American Bureau of Shipping (ABS)	
ABS-39	
ABS-90	Guidance Notes on the Application of Fiber Rope for Offshore Mooring
ABS-286	Guidance Notes on Nearshore Position Mooring
ABS-292	Guide for Position Mooring Systems
ABS-294	Guidance Notes on Mooring Integrity Management
Bureau Veritas (BV)	
BV-NR493	Rules for the classification of mooring systems for permanent and mobile offshore units
DNVGL	
DNVGL-OS-E301	Position mooring
DNVGL-OS-E302	Offshore mooring chain
DNVGL-OS-E303	Offshore fibre ropes
DNVGL-OS-E304	Offshore mooring steel wire ropes
DNVGL-RP-E304	Damage assessment of offshore fibre ropes for offshore mooring

DNVGL-RP-E305	Design, testing and analysis of offshore fibre ropes
DNV-RP-E303	Geotechnical Design and Installation of Suction Anchors in Clay
DNVGL-ST-N001	Marine operations and marine warranty

**Table 9.4-1 –Operational and design constraints**

## 10 CONCLUSIONS AND OUTLOOK

This deliverable dealt with defining current mooring and anchoring state of the art for floating wind projects currently installed or in construction phase. Aim is to ensure specifications and requirements to be developed within mooring Work Package 2 account for current industry status. This work package consists of a comprehensive literature survey, industrial engagement through network of contacts within the consortium and collation of findings to deliver a documentary summary report.

### 10.1 Station keeping system

Advantages and drawbacks of station keeping configuration are reviewed, design process is presented in section 3.1. Document then provides preliminary design guidelines and approach review versus Oil and Gas in section 3.4 complemented by industry examples in section 3.6. Design process is addressed in this section with target being to define appropriate DLCs for station keeping design. Detailed load case matrix will be specified before the end of month 8 and addressed in deliverable D1.3, with the floaters models development. This load case matrix will be specified along with WP1 and WP3 participants to assess floater and dynamic cable design, respectively.

Market watch provided in section 4 identifies current floating wind projects in operation and associated technological choices with in particular: Mooring configuration versus water depth, floater type and installation methodology. The research has been performed for projects currently in construction phase and future planned projects. Main highlights are given versus projects in operation.

### 10.2 Installation & Inspection

Section 5 aims to describe installation and inspection techniques for semi-submersible and spar floaters. Installation and maintenance techniques are implemented according to procedures once mooring layout is fully defined, this procedure is focused on providing necessary information and instructions to perform these activities in a safe manner.

Installation techniques including preparation, site investigations, installation plan, vessel selection criteria and installation steps are described in section 5.1.

Section 5.2 provides a baseline of current state-of-the-art inspection and monitoring techniques for mooring systems of floating offshore wind turbines. Developers of foundations and mooring systems strive to design their products maintenance free. Even in case maintenance free design might be possible, it can be expected that this design will not be economically feasible. Hence, O&M activities will be required for future projects to ensure reliable operation throughout the lifetime. After a first evaluation on this topic following risks and challenges for operation, maintenance and monitoring are being identified.

### 10.3 Identification of constraints, critical design parameters, key performance indicators and technical challenges for the design of FOWT station-keeping systems

Section 9 identifies the constraints for the station-keeping systems based on the work of the previous sections. The constraints are divided in operational constraints, site constraints, anchor constraints, mooring line constraints, dynamic cable constraints and installation and maintenance constraints. The specific constraints for each case are identified and quantified where possible in order to facilitate their applicability in the optimization effort.

The critical design parameters are then summarized. These are the parameters or constraints that have bigger influence in the optimal solution of the mooring system design. The optimization problem must obtain the most



reliable, cost effective, and easy installation station keeping solution for the life span of the structure. The critical design parameters are divided in design constraints, met-ocean data and life span of the mooring system.

The key performance indicators are finally provided. These measure the success of the optimization problem for the design of the station keeping system. The aim of the optimization problem is to find a cost-effective station keeping configuration that fulfills the design criteria of the FOWT. The key performance indicators are numbered as follows :

- % Cost reduction between solo solution vs wind park solution
- % Cost reduction of actual standard solutions vs Optimized ones
- Fulfillment of all constraints and design criteria

## 10.4 Outlooks

Following the state of the art, design constraints and key performance indicators review next section provides an outlook and discussion about some of the planned options and optimizations within COREWIND project :

### 10.4.1 [Numerical optimization](#)

The optimization problem for the station keeping design must be treated as a multi-objective optimization problem, because there are two objectives functions that have to be optimized simultaneously, the cost and the structural reliability of the mooring system. Minimizing the cost while maximizing the reliability for all the life span is the main goal of the design of the station keeping systems.

Within the framework of the project, the optimization problem can be divided in two parts, a sizing optimization problem and a topology optimization problem. The former aims to find an optimal design for the combination of parameters such as length, diameter, ancillaries' dimensions for a given mooring typology. The topology optimization objective is to find the optimal station keeping typology based on wind park constraints by modifying FOWT location and mooring line distributions as well as the number of line and the possibility of sharing anchors.

Within the project, it is planned to couple OrcaFlex (Finite Element software for mooring application) and a Design of Experiment software to allow automated screening of a large number of mooring configurations and automated acceptable solutions computation meeting selected criteria. The main targeted benefits are:

- Reduction regarding engineering man-hours to perform the mooring configuration definition thus reduce the overall engineering planning.
- Reduction in terms of cost.
- Ensure selected configuration is optimal versus selected criteria (station keeping capability, floater offset, fatigue resistance of mooring components, maximum peak load, payload on floater and its global cost).

### 10.4.2 [Integrated / combined Mooring / Dynamic cable design](#)

Maximum allowable offset for floater is usually limited by dynamic cable capabilities and thus significantly impacts mooring design and station keeping system. Aim of this task is to perform a combined mooring/dynamic cable configuration design loop with goal being to go up to maximum dynamic cable capabilities and thus relax mooring design.

### 10.4.3 [Breakthrough analysis / Technological benefits regarding peak loads reduction](#)



Aim of this task is to focus on peak load reduction. Reduction in peak loads and maximum tension will aim to define lower grade or lower capability (Minimum Breaking Load) equipment's thus lowering station keeping system cost. Several applications and technologies are foreseen to be tested numerically to assess benefit.

#### 10.4.4 Investigations of tuning of the controller to reduce mooring fatigue

This task will address the possibility to tune the wind turbine controller such that the mooring line fatigue loads in operational conditions are reduced. Multivariable controllers will be implemented in control-oriented models.

#### 10.4.5 Design at farm level: use of shared anchors, shared mooring lines

This solution will use conventional mooring materials. Two topics are planned to be addressed: Shared anchors and mooring lines.

- [1] Harnessing offshore mooring experience and anchoring technology for the floating renewable energy systems, Vryhof – lecture
- [2] Feasibility of loading platform platform systems for wind turbines. Musial, W., Butterfield, S. & Boone, A. ASME wind energy composium 2004
- [3] Floating Offshore Wind: Market and Technology Review / Prepared for the Scottish Government - June 2015
- [4] “UK-floating-offshore-wind-power-report” - The Crown Estate – UK Market Potential and Technology Assessment for floating offshore wind power - An assessment of the commercialization potential of the floating offshore wind industry Public Version – 2012
- [5] Connolly, P. and Hall, M. Comparison of pilot-scale floating offshore wind farms with shared moorings, 2019
- [6] LIFE50+ - Deliverable D4.5 State-of-the-art models for the two LIFES50+ 10MW floater concepts
- [7] LIFE50+ - Deliverable D4.2 Public Definition of the Two LIFES50+ 10MW Floater Concepts
- [8] Weller, Davies, & Johanning. The influence of load history on synthetic ropes response. EWTEC 2013
- [9] <https://www.sbmoffshore.com/news/sbm-offshore-selected-edf-energies-nouvelles-provide-floating-wind-systems-solution-pilot-offshore-france/>
- [10] Floating Wind JIP - Summary Report Phase 1 - Carbon Trust. Key findings from Electrical Systems, Mooring systems and Infrastructures and Logistics studies
- [11] DNVGL-ST-0119. Edition July 2018 - Floating wind turbine structures
- [12] Decommissioning Programme for Hywind Scotland Pilot Park C178-HYS-Z-GA-0002
- [13] Offshore standards, DNVGL-OS-E301. Edition July 2018 - Position mooring
- [14] D1.2 Design Basis – COREWIND Deliverable
- [15] Friends of Floating Offshore Wind, March 2018
- [16] Floating Wind Turbines, May 2012, ABS Final report
- [17] [https://www.kivi.nl/uploads/media/5ae711f5178c0/SOZ-KIVI\\_lecture\\_-\\_Anchoring\\_Technologies\\_for\\_FOWT\\_by\\_Vryhof\\_Anchors.pdf](https://www.kivi.nl/uploads/media/5ae711f5178c0/SOZ-KIVI_lecture_-_Anchoring_Technologies_for_FOWT_by_Vryhof_Anchors.pdf)
- [18] MSc Thesis of Design of Mooring for FOWT - NTNU 2011
- [19] DNVGL-RP-0286 Coupled analysis of floating wind turbines
- [20] LIFE50+ - Deliverable D4.4 Overview of the numerical models
- [21] DNVGL-ST-0437 - Loads and site conditions for wind turbines
- [22] NI 572 DT R01 E Bureau Veritas - Classification and Certification of Floating Offshore Wind Turbines
- [23] Qualen et al. CFD Simulation of a Floating Offshore Wind Turbine System Using a Quasi-static Crowfoot Mooring-Line Model, 2014
- [24] Bureau Veritas - Guidance Note NI 604 DT R00 - Fatigue of Top Chain of Mooring Lines due to In -plane and Out-of-plane Bendings
- [25] DNVGL-RP-F203 Riser interference
- [26] Orcina – Orcaflex software Online help
- [27] [https://www.weamec.fr/wp-content/uploads/2017/10/4\\_SEM-REV-WeAMEC-Corrosion.pdf](https://www.weamec.fr/wp-content/uploads/2017/10/4_SEM-REV-WeAMEC-Corrosion.pdf)
- [28] SWIRE PACIFIC OFFSHORE, "swirespo.com," SWIRE PACIFIC OFFSHORE, [Online]. Available: <https://www.swirespo.com/>. [Accessed 29 01 2020]
- [29] SWIRE PACIFIC OFFSHORE , "https://www.swirespo.com/," SWIRE PACIFIC OFFSHORE , [Online]. Available: <https://www.swirespo.com/Fleet/Fleet>. [Accessed 29 01 2020]
- [30] K.-T. Ma, Y. Luo, T. Kwan and Y. Wu, Mooring System Engineering for Offshore Structures, Gulf Professional Publishing, 2019
- [31] Class NK, *Guidelines for Offshore Floating Wind Turbine Structures*, 2012.
- [32] DNV GL, DNVGL-ST-0119: Floating wind turbine structures, 2018.

- [33] DNV GL, DNVGL-ST-0126: Support structures for wind turbines, 2016.
- [34] Bureau Veritas, Classification of Mooring Systems for Permanent and Mobile Offshore Units, NR 493 DT R03 E, 2015.
- [35] A. Kolios, U. Smolka, C. B. Ramdane, T. Lorena and J. Robert, "ROMEO, Deliverable D4.1 Monitoring technology and specification of the support structure monitoring problem for offshore wind farms," 2018.
- [36] DIN, "DIN EN 13018: Non-destructive testing - Visual testing - General principles," 2016.
- [37] K.-T. Ma, H. Shu, P. Smedley, D. l'Hostis and A. Duggal, "A Historical Review on Integrity Issues of Permanent Mooring Systems," in *Offshore Technology Conference*, 6-9 May, Houston, Texas, USA , 2013.
- [38] ABSG Consulting Inc., "Study on Mooring System Integrity management for Floating Structures," Bureau of Safety and Environmental Enforcement (BSEE), Arlington, 2015.
- [39] S. Bhattacharjee, D. Angevine and D. Smith, "Permanent Mooring Reliability & Mooring Risk Management Plan (MRMP): A Practical Strategy to Manage Operational Risk," in *Offshore Technology Conference*, 04-07 May, Houston, Texas, USA, 2015.
- [40] D. Coronado and K. Fischer, "Condition Monitoring of Wind Turbines: State of the Art, User Experience and Recommendations," Fraunhofer IWES, 2015.
- [41] Deliverable 2.2. LCOE tool description, technical and environmental impact evaluation procedure", Tech. Report:2016 [https://lifes50plus.eu/wp-content/uploads/2016/10/GA\\_640741\\_D2.2-internal.pdf](https://lifes50plus.eu/wp-content/uploads/2016/10/GA_640741_D2.2-internal.pdf)
- [42] <https://mdh.diva-portal.org/smash/get/diva2%3A1128321/FULLTEXT01.pdf>
- [43] SWIRE PACIFIC OFFSHORE, <https://www.swirespo.com/>
- [44] SWIRE PACIFIC OFFSHORE – FLEET, <https://www.swirespo.com/Fleet/Fleet>
- [45] Model development and Load Analysis of a Wind Turbine on a floating Offshore Tension Leg Platform, January 2009, D. Matha, T. Fisher, M, Kuhn (University of Stuttgart), J. Jonkman (NREL)
- [46] Design Optimization of dynamic inter-array cable for floating offshore wind turbines, September 2019, M. Rentschler, F.Adam (University of Rostock), P. Chainho (WavEC)
- [47] <https://www.wamit.com/structures.htm>
- [48] <https://www.macgregor.com/globalassets/picturepark/imported-assets/81909.pdf>
- [49] <https://www.macgregor.com/news-insights/news-articles/2018/specialist-mooring-solution-secures-first-floating-wind-farm/>
- [50] <http://www.norcowe.no/doc//konferanser/2016/SMI%20Stavanger%20presentasjoner/Hovik%20%20MCG%20Norway%20-%20Mooring%20System%20For%20Hywind%20Scotland%20-%20Public.pdf>
- [51] [https://lifes50plus.eu/wp-content/uploads/2015/11/GA\\_640741\\_LIFES50\\_D7.5.pdf](https://lifes50plus.eu/wp-content/uploads/2015/11/GA_640741_LIFES50_D7.5.pdf)
- [52] [https://www.oceanologyinternational.com/\\_novadocuments/450596?v=636562139223830000](https://www.oceanologyinternational.com/_novadocuments/450596?v=636562139223830000)
- [53] <http://www.seaflex.net/products/seaflex-mooring-system/>
- [54] <http://abc-moorings.weebly.com/mooring-systems.html>
- [55] <http://dredgingengineering.com/moorings/lines/Offshore%20mooring%20lines%20mooring%20system.htm>
- [56] Scale prototype (1:6). Water depth corresponds to PLOCAN test facility.
- [57] Vryhof Anchor Manual



- [58] ABS Technical Report: Offshore Anchor Data for Preliminary Design of Anchors of Floating Offshore Wind Turbines, August 2013
- [59] Mooring system failures impact on dynamic cabling system – A risk mitigation study (Vryhof / Aker Solutions)