Deliverable 4.6:

Framework for the prediction of the reliability, economic and environmental criteria and assessment methodologies for Moorings and Foundations

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D4.6: Framework for the prediction of the reliability, economic and environmental criteria and assessment methodologies for Moorings and Foundations

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Abstract

This Deliverable reports on the framework for the prediction of the reliability, economic and environmental criteria and assessment methodologies for Moorings and Foundations.

Task 4.5, 4.6 and 4.7 are addressed and covered in this Deliverable. The main output of these three tasks represent the outcome of the three cross-cutting themes (i.e. Reliability, Economics and Environment) applied to moorings and foundations and are described in as many sections within the document, respectively Section 1, Section 2 and Section 3.

Furthermore this document can be considered complementary to Deliverable 3.4 where, in a similar fashion, the same cross-cutting themes have been applied to electrical infrastructure.

Section 1 reports on the reliability of moorings and foundation systems. The RAM analyses the type, quantity and hierarchical relationship of components and sub-systems (Reliability Assessment Sub-Module) and it is described in the context of Moorings and Foundation and two case study are shown.

The Economics analysis is described in Section 2. The DTOcean tool is capable to calculate a different number of array layouts, and the optimizations process will hinge around yielding the lowest LCOE (Levelized Cost of Energy). In this regard a correct prediction of CapEX and OpEX is of high importance.

Functions for estimating the cost of different types of moorings and foundations are described and two calculation examples applied to a fixed tidal turbine and a floating Wave energy device are shown.

Section 3 describes the different environmental functions developed within the EIAM (Environmental Impact Assessment Model) addressing different stages/phases of the Moorings and Foundations and their environmental assessment.

Moreover an introduction to each single section is provided.

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1 RELIABILITY OF MOORING AND FOUNDATION SYSTEMS

1.1 Introduction

Whilst a number of MRE device sea-trials have been conducted mainly for proof of concept, at the time of writing there have been no long-term (+5 year) deployments of MRE devices from which it is possible to derive reliable failure rate statistics. A general lack of convergence of device designs [1] has contributed to this issue. Adopting a cautious approach to mooring and foundation design, developers have mostly opted to specify components which have widespread use in the offshore shipping, oil and gas and aquaculture industries with prerequisite design approaches and factors of safety. Within these industries significant progress has been made to understanding the mechanisms of failure (i.e. corrosion, abrasion and fatigue) leading to suitable design codes and better manufacturing processes. This progress has led to a reduced rate of mooring line failures since the early 1980s [2]. Indeed, efforts are now underway to extend the lifetime of offshore platforms beyond the original 25 year period [3]. Despite the overall reduction in failures of offshore platform mooring lines (i.e. around 0.5 per annum for MODU mooring lines and 0.2 per annum for FPSO lines) failures still occur [4] due to a variety of causes [5].

In the absence of directly relevant reliability data, failure rate statistics can be adapted using application factors (covering aspects such as manufacturing quality, operating environment and conditions). Such factors are often used in the bottom-up statistical method to adapt failure rates from known to unknown scenarios with tabulated values found in well-cited documents such as MIL-HDBK-217F [6]. This extrapolation is arguably simplistic and not without limitations, particularly when there is a significant difference between two operating scenarios. Whilst such estimates can therefore have large levels of uncertainty associated with them [7] which must be acknowledged, this approach provides an initial assessment of system reliability before experience in the field has been accrued and hence is timely for the MRE sector.

1.2 Reliability assessment within the DTOcean Tool

1.2.1 Methodology

The assessment of design solution reliability occurs within the Reliability Assessment sub-Module (RAM), located within the System Control & Operation (WP6) module of the DTOcean Tool. A summary of the RAM is provided in this section and further details of the requirements, architecture and functionality of the RAM can be found in Deliverable 7.2 [8]. Given the current availability of failure rate (λ) statistics the bottom-up statistical method has been adopted within the RAM using failure rate statistics associated to each component within the database. The DTOcean Tool will be packaged with a set of components for use by the WP3 (Electrical System Architecture) and WP4 (Mooring and Foundation) modules. The RAM analyses the type, quantity and hierarchical relationship of components and sub-systems resulting from the Electrical System Architecture and Mooring and Foundation modules (e.g. Figure 1.1) and using the associated failure rates from the database calculates several reliability statistics recursively up through the hierarchical levels as outlined in the following subsections.

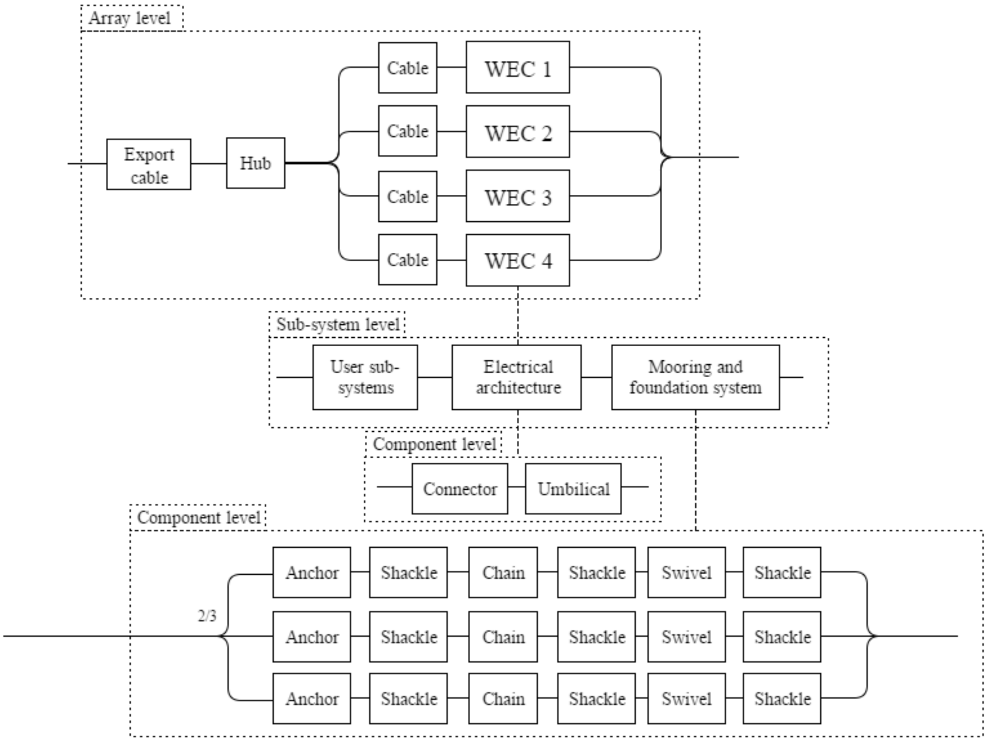

Figure 1.1: Example Reliability Block Diagram of four devices in an array

In the first instance the RAM processes the bill of materials and hierarchies generated by the Electrical System Architecture and Mooring and Foundation modules (and any user-specified elements) to construct a system level[1] list of components. The format of the module and user-

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[1] 'System level' is the top level which is the device array.

defined bill of materials and hierarchies is Python dictionaries, with nested lists used in the hierarchies to indicate to the RAM if the elements are connected in series and parallel (e.g. Table 1-1). The system level component list is also populated with ‘SER’ or ‘PAR’ flags to identify parallel or series nested lists.

Table 1-1: Mooring and foundation hierarchy[2] generated by the Mooring and Foundation module for the example shown in Figure 1.1

```
{'array': {'Hub foundation': ['pin pile', 'ultra high strength']},
'device001': {'Umbilical': ['submarine umbilical cable 6/10kV'], 'Mooring system':
[‘shackle’, ‘chain’, ‘shackle’, ‘swivel’, ‘shackle’], [‘shackle’, ‘chain’, ‘shackle’,
‘swivel’, ‘shackle’], [‘shackle’, ‘chain’, ‘shackle’, ‘swivel’, ‘shackle’]],
'Foundation': ['drag anchor', 'n/a']},
'device002': {'Umbilical': ['submarine umbilical cable 6/10kV'], 'Mooring system':
[[‘shackle’, ‘chain’, ‘shackle’, ‘swivel’, ‘shackle’], [‘shackle’, ‘chain’,
‘shackle’, ‘swivel’, ‘shackle’], [‘shackle’, ‘chain’, ‘shackle’, ‘swivel’,
‘shackle’]], 'Foundation': ['drag anchor', 'n/a']},
'device003': {'Umbilical': ['submarine umbilical cable 6/10kV'], 'Mooring system':
[[‘shackle’, ‘chain’, ‘shackle’, ‘swivel’, ‘shackle’], [‘shackle’, ‘chain’,
‘shackle’, ‘swivel’, ‘shackle’], [‘shackle’, ‘chain’, ‘shackle’, ‘swivel’,
‘shackle’]], 'Foundation': ['drag anchor', 'n/a']},
'device004': {'Umbilical': ['submarine umbilical cable 6/10kV'], 'Mooring system':
[[‘shackle’, ‘chain’, ‘shackle’, ‘swivel’, ‘shackle’], [‘shackle’, ‘chain’,
‘shackle’, ‘swivel’, ‘shackle’], [‘shackle’, ‘chain’, ‘shackle’, ‘swivel’,
‘shackle’]], 'Foundation': ['drag anchor', 'n/a']}}
```

1.2.1.1 Reliability at a user-specified time

The reliability at a user-specified time[3] (*T*) is calculated at each hierarchical level. This metric is within the range of 0 (not functional) to 1.0 (fully functional). Assuming that all components in the system have a constant failure rate (i.e. they do not degrade with time or wear out) and hence an exponential failure rate distribution is representative of component failures the following equation is used at the component level to calculate reliability at time *T*:

$$R(T) = e^{-\lambda T} \qquad (1)$$

---

[2] Note: Even though the Electrical System Architecture module is responsible for selecting the umbilical, for the purposes of reliability assessment it is grouped with the mooring and foundation system.

[3] This could be the required lifetime of the array.

Working up through the hierarchical levels of the system; assembly, sub-system, device, string and finally array reliabilities are progressively calculated by the RAM. The calculation scheme used is dependent on the relationship between elements at the same hierarchy level. For example using the example layout shown in Figure 1.1 it can be seen that each mooring line is composed of a number of components connected in series. In this case reliability of each line (or assembly) is calculated as the product of *n* component reliabilities:

$$R_{ser}(T) = \prod_{i=1}^{n} e^{-\lambda_i T} \qquad (2)$$

By default the RAM assumes that any parallel elements possess active redundancy (i.e. total failure occurs when all elements fail). In this case reliability is calculated differently from a series system, using the following equation:

$$R_{par}(T) = 1 - \prod_{i=1}^{n} (1 - R_i(T)) \qquad (3)$$

A third case analysed is also by the RAM; when failure of part of a parallel system is tolerated due to the provision of redundancy. The mooring system in Figure 1.1 falls into this category, where failure of one mooring line is permitted as part of Accident Limit State analysis [9]. The RAM has been programmed to accept this scenario as an *'m of n'* system (where *n* is the number of mooring lines and *m* = *n* – 1) using the following approach:

$$R_{mn}(T) = \sum_{r=k}^{n} \binom{n}{i} R_i^r(T)(1 - R_i(T))^{n-r} \qquad (4)$$

1.2.1.2 Mean time to failure (MTTF) in 10^6 hours

Mean time to failure is calculated as the reciprocal of component or (equivalent) assembly, sub-system, device, string or array failure rates, for example:

$$MTTF_{array} = \frac{1}{\lambda_{array}} \qquad (5)$$

The way in which equivalent failure rates are calculated for all hierarchical levels except the component level is dependent on the relationship between elements within the same level. For the mooring components within each mooring line in Figure 1.1, the equivalent failure rate of each line is calculated as the sum of individual component failure rates:

$$\lambda_{asy} = \sum_{i=1}^{n} \lambda_i \qquad (6)$$

The method of calculating equivalent failure rates for parallel systems with active redundancy is more complex than for series systems. In this case the RAM uses a binomial expansion of terms as follows:

$$MTTF_{array} = \sum_{i=1}^{n}\frac{1}{\lambda_i} - \sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\frac{1}{\lambda_i + \lambda_j} + \sum_{i=1}^{n-2}\sum_{j=i+1}^{n-1}\sum_{k=j+1}^{n}\frac{1}{\lambda_i + \lambda_j + \lambda_k} - \cdots + (-1)^{n+1}\frac{1}{\sum_{i=1}^{n}\lambda_i}$$

(7)

1.2.1.3 Pass/fail of system compared to reliability target

By default this will be based on relevant standards (e.g. for mooring systems DNV-OS-E301 specifies an annual probability of failure of 1×10^{-4} for Ultimate Limit State and Consequence Class 1 [9]). Alternatively the user will be able to specify a desired reliability target.

1.2.1.4 Risk priority numbers (RPNs),

Risk priority numbers (RPNs) are a metric incorporating probability of failure and consequence severity. Use of RPNs in the RAM is based upon NREL's *MHK Technology Development Risk Management Framework* [10] and can be thought of as a simplified way of carrying out integrity management. The analysis is conducted at a component level in order for the user to be able to readily identify at-risk components. The probability of failure is first calculated for each component and each value is allocated a corresponding frequency (*f*, with values provided in Table 1-2).

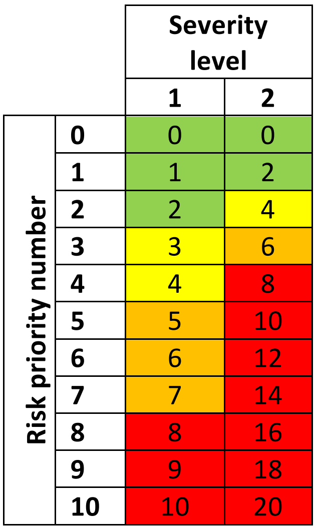
Table 1-2: Probability of failure bands and corresponding frequencies

Probability of failure/annum	< 0.01	$0.01 \le p < 0.1$	$0.1 \le p < 1.0$	$1.0 \le p < 10.0$	$10.0 \le p < 50.0$	$p \ge 50.0$
f	0.0	1.0	2.0	3.0	4.0	5.0

Once the corresponding frequencies have been assigned to each component, RPNs are calculated using the relevant severity level (*SL*) of the failure rate:

$$RPN = SL * f \qquad (8)$$

Where *SL* = 1 and 2 for non-critical and critical failure rates respectively. For visual representation of these values colour codes are assigned in the RAM as illustrated in Figure 1.2.



		Severity level	
		1	**2**
Risk priority number	**0**	0	0
	1	1	2
	2	2	4
	3	3	6
	4	4	8
	5	5	10
	6	6	12
	7	7	14
	8	8	16
	9	9	18
	10	10	20

Figure 1.2: Risk priority number colour codes

Due to the fact that the failure rates in the database may not be relevant to the application, or if directly measured data is available the user will be able to overwrite the values in the database. Furthermore in order to conduct whole system analysis the user will be able to populate other sub-systems not covered by the DTOcean design modules (e.g. to account for the power take-off system).

Each of the metrics introduced in this section will be presented to the user to identify critical parts of the system. Additionally component failure rates and equivalent sub-system failure rates will be used by the WP6 failure estimation module to conduct time-domain stochastic (Poisson process) simulations to plan maintenance actions. For further details the reader is directed to Deliverable 6.2 [11].

1.2.2 Data Requirements

The bottom-up statistical method is employed in the RAM, with component failures assumed to follow an exponential distribution which is used to represent the 'useful' or main portion of component life [7]. The method is suited to different system hierarchies (such as parallel and series relationships, and where active redundancy is built into the system). One shortcoming of this approach is that failures are assumed to occur independently and hence cascade failures aren't considered. On an assembly level this is an acceptable approach for mooring lines, because mooring line components are usually connected in series and hence the failure of one component usually results in loss of functionality of the entire line. In Ultimate Limit State design [9] the mooring system is analysed with all lines intact.

Often failure rates are specified as single values representing the mean of a set of analysed failure events. A single value does not provide information regarding the scatter of failures around the mean. In order to carry out confidence analysis if upper and lower failure rate bounds are known (i.e. exist in the database) the RAM will carry out analysis using these values to provide a measure of confidence in the reliability estimate.

The consequence of a failure occurring will range from total loss of functionality of the component or subsystem to a negligible reduction in performance. Within the OREDA Handbook [12] failures are categorised into three groups; *critical, degraded* and *incipient* failures. Given the current availability of reliability data for MRE devices, distinction will be made between *critical* and *non-critical* failures. Therefore if failure rate data is available for critical and non-critical failures in addition to upper, lower and mean failure rates the RAM will provide a total of six result sets. Similarly if only mean critical and non-critical failure rates are available two sets of results will be returned. The RAM will function on a minimum level of data, utilising mean failure rates and one severity level (i.e. critical failures).

1.2.2.1 Mooring line component failures

The component failure rates listed in Table 1-3 and Table 1-4 have been derived by Tension Technology International from reported failures of production and non-production mooring systems. The sources of data used for this review are provided in Appendix A1. Other reviews have been conducted (e.g [13],[14]) but these tend to be limited in terms of providing failure statistics or are specific to one particular platform or vessel type. A review conducted by Ma et al. in [4] concluded that based on mooring system failures reported between 2001 and 2011 the annual probability of multiple line failure is in the order of $3x10^{-3}$. A recent review by DNV GL [15] identified the following failure mechanisms:

- **Fatigue;** in particular tension-tension fatigue of chains in addition to out-of-plane bending and torsion induced fatigue. Fatigue crack growth and stress concentrations are also cited.
- **Wear;**
- **Corrosion**;

- **Overloading**;
- **Manufacturing Defects;**
- **Damage during installation and operation;**
- **Under-design**

Table 1-3:Failure statistics of mooring system components used in permanent production platforms

Component	**Chain**	**Wire rope**	**Polyester rope**[4]	**Connector**	**Component or mooring construction unknown**
Total number of failures	34	22	1	3	2
Number of years	30	30	20	30	30
Number of vessels	300	300	60	300	300
Failure rate (failures/annum)	3.78E-03	2.44E-03	8.33E-04	3.33E-04	2.22E-04

Details of the failure incidents are typically sparse or incomplete and often failures go unreported (i.e. due to ignored, faulty or non-existent alarms [5]). Therefore it can be reasonably assumed that over the time period analysed many more failures occurred globally than those reported in the tables. Non-permanent platforms such as Mobile offshore drilling units (MODUs) are often used in several locations perhaps with pre-emptive replacement of mooring system components during each deployment, hence the life of the mooring parts that have failed may not align with the duration of the installation.

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[4] The failure was caused by overloading of a polyester rope which had been damaged during installation [5].

Table 1-4: Failure statistics of mooring system components used in non-permanent platforms such as MODUs

Component	**Chain**	**Wire rope**	**Polyester rope**	**Connector**	**Component or mooring construction unknown**
Total number of failures	92	12	0	11	9
Number of years	30	30	15	30	30
Number of vessels	3370	3370	200	3370	3370
Failure rate (failures/annum)	9.10E-04	1.19E-04	0.00E+00	1.09E-04	8.90E-05

The failure of an anchor to provide a secure mooring line termination point can be classified in two ways: i) material or structural failure resulting in the loss of station-keeping contribution from the respective mooring line ii) dragging of the anchor resulting in an alteration of station-keeping ability of the mooring line and possibly entire mooring system. The former case is an issue for the manufacturing QC/QA as well as ensuring that an adequate design has been specified. In the latter case the anchor may re-embed but it is likely that this change in position will have a knock-on effect of mooring system performance (i.e. the overall stiffness of the mooring system or the possibility of 'out-of-plane' loading). Furthermore accurate positioning of anchors is notoriously difficult to achieve in practice. In general there is less information available for anchor failure events, especially material or structural failures and failures may be hidden in various reports of 'mooring line broke', or 'failed'. The survey indicates that mooring and anchoring planning and deployment procedures need to be further refined - including more detailed onsite examination of a mooring spread after it had been installed. The number of reported anchor failures is too low to derive meaningful failure statistics and for this reason it has been decided that general worldwide or UK Continental Shelf statistics will be used instead (5.78×10^{-3} failures per annum or 1.04×10^{-2} failures per annum respectively).

1.2.2.2 Foundation component failures

Failure data for MRE foundations is currently not available and for offshore foundations in general is sparse, with a few notable exceptions (e.g. [16],[17]). As with mooring system failures some knowledge can be gained from the offshore oil and gas industry which has investigated the causes and effects of foundation failures. Reviews such as [18] provide insight into possible failure modes, however most reported failures are not relevant to the DTOcean Tool (e.g. geotechnical failures of spudcan foundations [19]). One area which is relevant is the correct installation of pile foundations. Expensive buckling failures have resulted from driving piles into difficult conditions (e.g. hard calcareous layers, [17]), poor hammer performance or damage to the piles occurring during transportation.

A recent example of foundation failures concerns the grouted connection between the pile and transition piece of offshore wind turbines [20]. These failures resulted from an overestimation of the axial loading capacity of this connection. Other contributing factors included a lack of control over manufacturing tolerances and the abrasive wear of the grout due to the sliding of contact surfaces when subjected to large bending moments. Typical failure modes included dis-bonding, cracking, wear and compressive failure. As a result of these early failures DNV initiated a complementary joint industry project with the aim of updating existing knowledge of and design practices for grouted connections with shear keys. The JIP is now complete and the results have been published [21] and included in latest DNV standards (Design of Offshore Wind Turbine Structures DNV-OS-J101). The new knowledge is also expected to influence the design of large diameter grouted connections with shear keys [22]. Further discussion on this topic can be found in Deliverable 4.3 [23]. Although failure statistics cannot be readily obtained for this failure mode it was estimated that around 600 of Europe's installed offshore wind turbine were affected by this problem [24].

Due to the lack of derivable failure rate statistics a target level corresponding to the Recommended Practice of the American Petroleum Institute guidelines will be used of 1.0×10^{-4} failures / annum [25].

Despite the identified shortcomings of this data in addition to the fact that MRE mooring systems have different operating conditions, the approach introduced in previous sections is a first attempt to establish failure rates that may be applicable to MRE devices.

1.3 Example calculations

In this section RAM calculation results are presented for a single device mooring system comprising i) steel-only and ii) steel-synthetic components using failure rate statistics listed in **Error! Reference source not found.**. The mooring components feature in the RM3 system analysed in Deliverable 4.4 [26]. Both cases have been analysed on an '*m of n*' system, where *m* = *n* – 1 and failure of one mooring line is deemed as acceptable for ALS analysis. The difference between the two cases is that on each line the upper chain used in Case 1 is substituted for a polyester rope.

1.3.1 Case 1: Steel-only components

The hierarchy and block diagram for the steel-only mooring system are shown in Table 1-5 and Figure 1.3 respectively. It can be seen that each of the three lines comprises 14 components (including a drag anchor at the end of each line).

Table 1-5: Mooring and foundation hierarchy for a single device generated by the Mooring and Foundation module for Case 1

```
'device001': {'Umbilical': ['submarine umbilical cable 6/10kV'], 'Mooring system': [['shackle', 'chain',
'shackle', 'swivel', 'shackle', 'clump weight', 'shackle', 'chain', 'shackle', 'buoy', 'shackle', 'wire rope',
'shackle'], ['shackle', 'chain', 'shackle', 'swivel', 'shackle', 'clump weight', 'shackle', 'chain', 'shackle',
'buoy', 'shackle', 'wire rope', 'shackle'], ['shackle', 'chain', 'shackle', 'swivel', 'shackle', 'clump
weight', 'shackle', 'chain', 'shackle', 'buoy', 'shackle', 'wire rope', 'shackle']], 'Foundation': ['drag',
'n/a']}}
```

Table 1-6: Mooring and foundation bill of materials for Case 1

```
'device001': {'Umbilical': {'diameter [m]': 0.079, 'total weight [kg]': 660, 'umbilical type': 'submarine
umbilical cable 6/10kV', 'cost [euros]': 13750, 'length [m]': 55}, 'Mooring system': {'total weight [kg]':
121.20000000000002, 'mooring system type': 'catenary', 'line lengths [m]': [231.38492245606673,
231.38492245606673, 231.38492245606673, 231.38492245606673], 'total cost [euros]': 272.0, 'quantity':
Counter({'shackle': 3, 'chain': 3, 'swivel': 3, 'clump weight': 3, 'chain': 3, 'buoy': 3, 'wire rope': 3})},
'Foundation': {'foundation type': 'drag', 'grout volume [m^3]': 0, 'dimensions [m,m,m]': [2.14, 2.26, 0.56],
'total cost [euros]': 5600, 'total weight [kg]': 4540, 'grout type': 'n/a', 'quantity': 4}}}
```

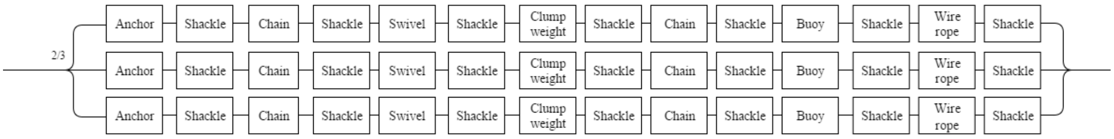

Figure 1.3: Reliability block diagram of the steel-only mooring system

1.3.2 Case 2: Steel-synthetic components

The hierarchy and block diagram for the steel-synthetic mooring system are shown in Table 1-7 and Figure 1.4 respectively. Whilst each line comprises the same number of components as in Case 1 the upper chain has been replaced with a polyester rope.

Table 1-7: Mooring and foundation hierarchy for a single device generated by the Mooring and Foundation module for Case 2

```
'device001': {'Umbilical': ['submarine umbilical cable 6/10kV'], 'Mooring system': [['shackle', 'chain',
'shackle', 'swivel', 'shackle', 'clump weight', 'shackle', 'polyester rope', 'shackle', 'buoy', 'shackle',
'wire rope', 'shackle'], ['shackle', 'chain', 'shackle', 'swivel', 'shackle', 'clump weight', 'shackle',
'polyester rope', 'shackle', 'buoy', 'shackle', 'wire rope', 'shackle'], ['shackle', 'chain', 'shackle',
'swivel', 'shackle', 'clump weight', 'shackle', 'polyester rope', 'shackle', 'buoy', 'shackle', 'wire rope',
'shackle']], 'Foundation': ['drag', 'n/a']}
```

Table 1-8: Mooring and foundation bill of materials for Case 2

```
'device001': {'Umbilical': {'diameter [m]': 0.079, 'total weight [kg]': 660, 'umbilical type': 'submarine
umbilical cable 6/10kV', 'cost [euros]': 13750, 'length [m]': 55}, 'Mooring system': {'total weight [kg]':
121.20000000000002, 'mooring system type': 'catenary', 'line lengths [m]': [231.38492245606673,
231.38492245606673, 231.38492245606673, 231.38492245606673], 'total cost [euros]': 272.0, 'quantity':
Counter({' shackle': 3, 'chain': 3, 'swivel': 3, 'clump weight': 3, 'polyester rope': 3, 'buoy': 3, 'wire
rope': 3})}, 'Foundation': {'foundation type': 'drag', 'grout volume [m^3]': 0, 'dimensions [m,m,m]': [2.14,
2.26, 0.56], 'total cost [euros]': 5600, 'total weight [kg]': 4540, 'grout type': 'n/a', 'quantity': 4}}
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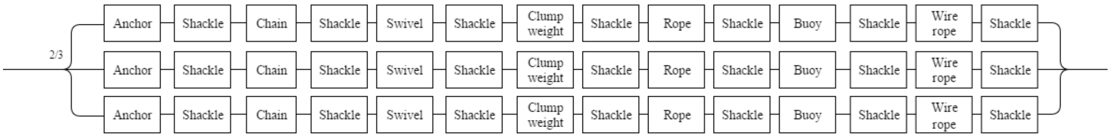


Figure 1.4: Reliability block diagram of the steel-synthetic mooring system

1.4 Results and discussion

Table 1-9: Calculated failure statistics for Case 1 and Case 2

Component	**Case 1: Steel-only**	**Case 2: Steel-synthetic**
Reliability at Mission Time (0.175×10^6 hours)	0.7654	0.8171
Equivalent failure rate (failures/annum)	0.0227	0.0191
Mean time to failure (years)	44.121	52.2784

The differences in mooring system reliability, equivalent failure rate and mean time to failure noted in Table 1-9 are due to the higher failure rate of chain (3.78E-03 failures/annum) compared to polyester rope (8.33E-04 failures/annum). This is reflected in the calculated RPNs shown in Figure 1.5 . The yellow markers, corresponding to high calculated RPNs and annual probabilities of failure represent the chains (0.377 %/annum), wire ropes (0.244 %/annum) and the drag anchors (0.576 %/annum) used in the mooring system. Common failure mechanisms for chains have been discussed in Section 1.2.2. Assuming that both configurations provide the same station-keeping characteristics and are fit-for-purpose in terms of expected design load cases, the results indicate that use of a steel-synthetic system would provide a longer service life. Indeed, unexpected steel component failure modes (e.g. 'out-of-plane' chain bending and early fatigue failures) have been investigated recently by the offshore oil and gas industry [5]. Although the approach used by the Tool is purely statistical and does not include the variability of reliability performance with (time-variant) operating conditions, these results give an initial indication of the effect of sub-system configuration on reliability performance. Any differences would be further exacerbated by the inclusion of more mooring lines and considering all devices in the array.

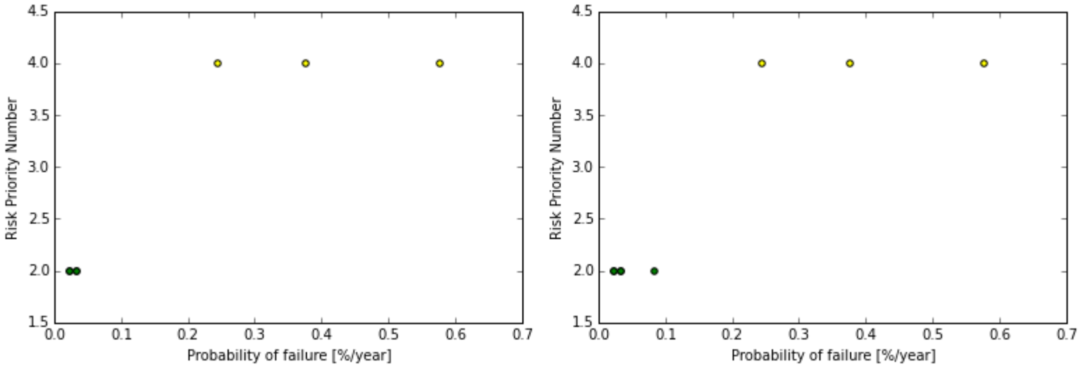


Figure 1.5: Risk Priory Number diagrams for (left) Case 1 and (right) Case 2

2 ECONOMICS OF MOORING AND FOUNDATION SYSTEMS

2.1 Introduction

Moorings and foundations systems need to be able to withstand the environmental loading, impact and operational procedures involved in keeping the devices on station, and to be sufficiently cost effective so that the overall economics of the project remain viable [36][37].

Although the industry of moorings and foundations is not limited to marine renewables, the approach for typical offshore structures is likely to be too expensive and often not appropriate to enable the device to convert efficiently power from the waves or currents. That isn't to say that some learnings can't be taken for Offshore Wind, and to some extent Oil & Gas, but it is important to note the difference in scale of the structures and, in the latter case, the depth of projects. Therefore, solutions tailored to marine renewables must be designed to ascertain that extreme environmental loads can be withstood, taking into account that different configurations and the use of different components can be associated with cost increases. These increases are not only related to the price of the components themselves, but also with their reliability (with implications in O&M costs), and the installation process they require [37][38].

Economies of scale can play a part in cost reductions in station keeping elements of marine renewable arrays, but these will most likely come from savings from bulk purchases/fabrication. Moorings and foundations are in the great majority of cases replicated for each device in an array. The sharing of moorings/foundations can bring more cost reductions, but these innovations still need to be proven, especially in the case of moored devices. Furthermore, the cost reductions associated with the sharing of support structures may be offset by higher installation costs or an increase of faults [36][38][39].

Both function and cost are mutually dependent – the installation of floating devices has different requirements than those with foundations. Replacing a foundation with a set of moorings raises a number of design challenges but allows deeper water, higher resource areas to be accessed. Installation of floating devices or platforms should be significantly cheaper than installation of bottom mounted devices [36][39].

Looking into reference studies on cost analysis for marine renewable energy, station keeping elements can represent between 5% or 15% of CAPEX ([36],[39],[40],[41],[42],[43],[44],[45],[46],[47]). Fixed foundations tend towards the higher end of the interval, but for both fixed and moored devices, the cost of station keeping is related to the depth at which the devices are installed [48]. Furthermore, the installation of moorings and foundations can also represent an additional 5% to 10% of the CAPEX [36][39][47]. This shows the need for optimized designs that are cost-effective at an array level.

2.2 Economic assessment within the DTOcean tool

2.2.1 Methodology

The economic assessment of arrays in the DTOcean tool uses the Levelized Cost of Energy (LCOE) as indicator, with the objective to obtain an array configuration that minimizes the LCOE. Each module, representing each technical work package, will aim to provide the least costly feasible solution, taking into consideration the requirements of the project set by the user and determined by other work packages. With this minimum cost per system as a starting point, the global tool will then run through an optimization routine to try to achieve a better solution for the global LCOE. This optimization routine will be defined in work package 7.

Prior to the optimization routine, the LCOE for the chosen layout based on the least costly feasible solution of each module, which is calculated using a list of all the components chosen by each module (Bill of Materials), their costs, and the estimated annual energy production (AEP). Even with the use of commercial prices it is important that the user is aware that these may not correspond to actual prices, as they are subject to variability. The causes of this variability can be simple to correct, such as inflation adjustment on past data, or currency exchange, to highly stochastic such as cost of raw materials (e.g., price of steel), market interactions (supply-demand), and bespoke components that are priced in a project by project basis. The LCOE calculated in this tool offers the end-user an approximation, or educated guess, to the real LCOE for the project.

The Bill of Materials and associated costs are to be retrieved from the local DTOcean database. This database will contain components listings, with detailed specifications and, when available, commercial prices. If prices are not available, best estimates can be derived from similar components, from cost functions developed specifically for each module/component, or the user can input their own values.

The calculation of the LCOE is defined as:

$$LCOE = \frac{\sum PV(Costs)}{\sum PV(AEP)} \tag{9}$$

Where the **PV(x)** function calculates the present value of the costs and the annual energy production. The present value is referenced to a year 0, which is assumed to be the year of the device installation and start of operation.

The present value function is defined as:

$$PV(x) = \sum_{y=y_0}^{Y} \frac{x}{(1+\ DR)^{y}} \tag{10}$$

Where ***x*** can be a cost or the annual electricity production; **y** is the year when the cost or the electricity relates to, starting in year 0, which corresponds to the commissioning year; and **Y** is the project lifetime. **DR** refers to the discount rate, which is to be a user input, and accounts for the time value of money and the perceived risk of the project. Due to this factor, initial costs such as procurement and installation of components have a higher impact on the LCOE than the operational and maintenance costs.

2.2.2 Data requirements

At work package level, only the costs are assessed. The impact on cost from WP4 is both direct and indirect: different components with different prices will yield a different overall cost of the station keeping infrastructure, but will also have implications in installation costs and in maintenance operation costs. For instance, the capital cost of a driven pile is considerably less (around 40% of equivalent capability anchors) but the associated installation cost is much higher – due to the vessels and equipment needed [37][49]. These costs are not included in work package 4, but will be detailed in work packages 5 and 6.

Within work package 4, the cost calculation takes into account the components selected and their dimensions, and through specific cost functions or commercial prices pulled from the global database. The cost associated with a specific component will be the product between its price and number of units. The number of units needed is determined by the technical requirements of the layout.

2.3 Overview of parameters with impact on Moorings and Foundations

2.3.1 Moorings

On floating designs, station keeping is provided through mooring lines connected to a foundation/anchoring system. The anchoring systems will be discussed on section 2.3.2. Mooring systems can be made of different materials: wire, chain, ropes, or a combination; and can be deployed in different configurations. Weights and buoys may be used to achieve different configurations and different loads distributions. A list of moorings configurations is detailed on Deliverable 4.1 [50].

For mooring lines, the price per meter is a function of its minimum breaking load (MBL) and of the base materials that compose them.

Chain and lines represent the largest cost factor (50 -70% of costs) for mooring designs [38]. Synthetic ropes however have a lower cost per unit length than steel chains or wires, and a much lower weight per unit of length. This means that lower capacity connecting components can be specified and the load bearing requirements of the moored structure are reduced which translates into indirect cost savings. Lighter components also require less specialized (and less costly) vessels for installation [51].

Results from Ridge et al. [52], and which were also presented on Deliverable 4.3 [51], highlighted the cost savings associated with the use of lightweight components for several single-line taut-moored and catenary configurations, including several anchor types. These costs are partially attributable to the specification of lower capacity components such as anchors and savings of this magnitude may not be achievable for all applications.

Table 2-1: Cost comparison carried out by Ridge et al. of different mooring configurations located in d=50 m water depth [52].

Mooring type/ geometry	Cable elements	Nominal size *(mm)*	Length *(m)*	Unit weight *(kg/m)*	Total cable weight *(tonnes)*	Cable Cost *(£)*	Anchor (drag embed. UOS) *(tonnes)*	Anchor cost *(£)*	Total cost Per leg *(£)*
Catenary									
catenary 5d	chain	81	250	152	38	74,733	12	66,784	141,516
catenary 8d	chain	60	400	82	32.8	62,933	8.5	47,482	110,415
Catenary with surface buoy									
chain/ polyester	chain polyester buoy	73 104 14.1 t *buoyancy*	250 50	123 8.25	30.75 0.41	58,213 3,300 6,800	5	29,486	97,799
chain/ nylon	chain nylon buoy	54 80 9.8 t *buoyancy*	250 50	66 4	16.50 0.20	31,466 1,722 4,900	2	13,027	51,115
Taut mooring									
taut (vertical lift anchor)	steel wire rope nylon	52 80	21 49	11.1 4	0.23 0.20	480 1,687	VLA 5m^2	67,973	70,140
taut GBA (concrete/ steel)	steel wire rope nylon	52 80	21 49	11.1 4	0.23 0.20	480 1,687	600 GBA	250,000	252,167

Looking at the catenary example in the table above, it is shown that even though the required length of chain almost doubled from the 5d to 8d cases, there are savings coming from using chains with smaller diameters. These savings will have to be balanced with environmental and operational constraints regarding the footprint of each device.

The weight – and the cost – of the mooring chains changes with the square of the diameter. Lorenzo et al. [53], using functions provided by Vicinay Cadenas, defines the weight per length, in kg/m, of a chain as:

$$Weight_{Chain} = diameter^2 \times K \tag{11}$$

with K = 0.02 for studless chains, and K=0.0219 for studlink chains. The diameter is expressed in mm.

Similarly, Ryo et al. [54], has expressed the weight of R4 studless chain using a similar formula, but assuming a K value of 0.0195 (for dry weight).

The calculation of the cost of the chain is then simply obtained by multiplying this weight by the value of cost of steel:

$$Cost_{Chain} = Weight_{Chain} \times Cost_{Fab.Steel} \qquad (12)$$

In Lorenzo et al. the value used was 2.6 €/kg. In Ryo et al. the value was 3.24 USD/kg, which corresponds to 2.75 €/kg. Figure 2.1 shows the variation of chain costs based on the previous functions and with data provided by suppliers.

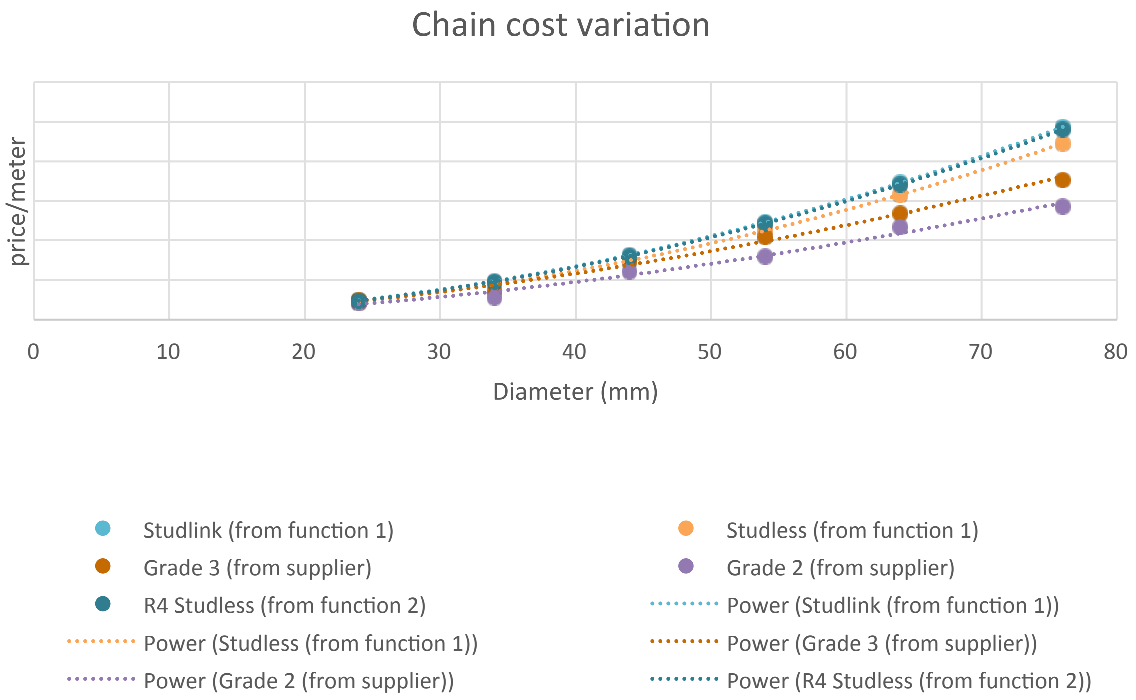


Figure 2.1: Chain cost variation with diameter (function 1 corresponds to data from [53] and function 2 to data from [54])

For wire ropes Ryu et al. defines a similar weight function [54]:

$$Weight_{Wire} = A \times diameter^{B} \qquad (13)$$

with A=0.0065 and B=1.9582 for dry weight and A=0.0045 and B=1.9871 for wet weight.

This function matches well with data from suppliers, although differences exist from different wire types.

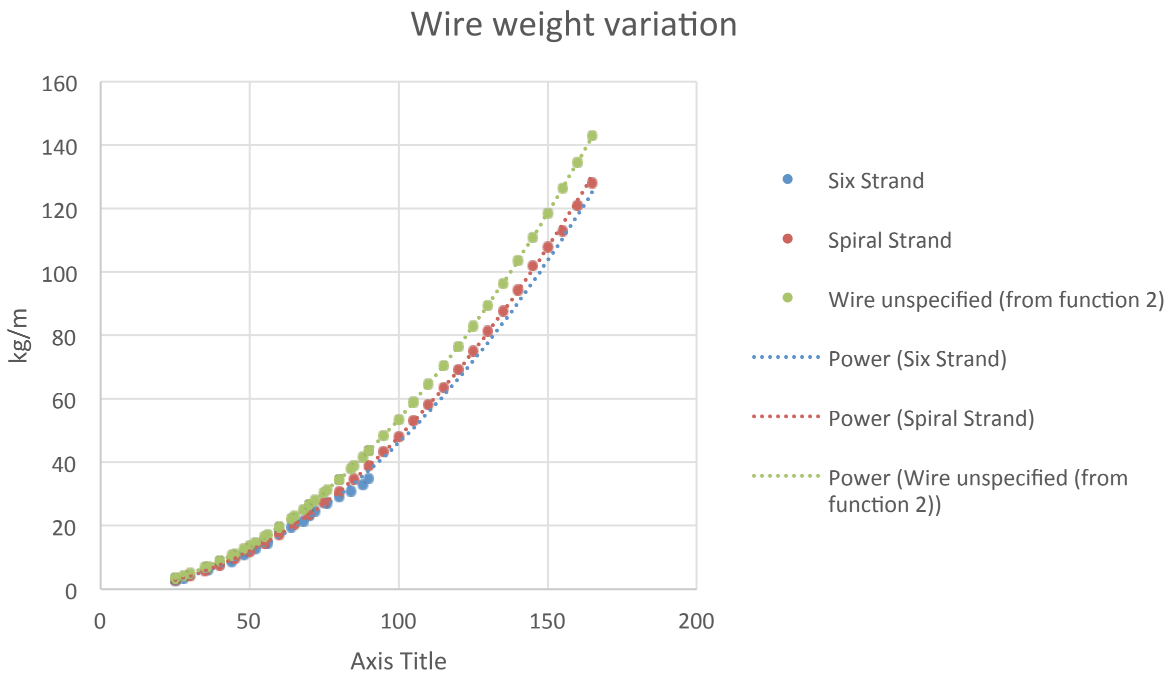


Figure 2.2: Wire weight variation (function 2 is equation (13))

Unlike the chain moorings, the cost of wires is not a simple function of the cost of fabricated steel. The cost function provided by Ryo et al. results in a cost of fabricated steel varying between 5.3 €/kg and 5.8 €/kg [19].

$$Cost_{Wire} = diameter^{2} \times 0.03415 \qquad (14)$$

However, the data provided by suppliers shows different cost trends, with cost of steel decreases for higher diameter wires. The wire cost variation is show in the figure below.

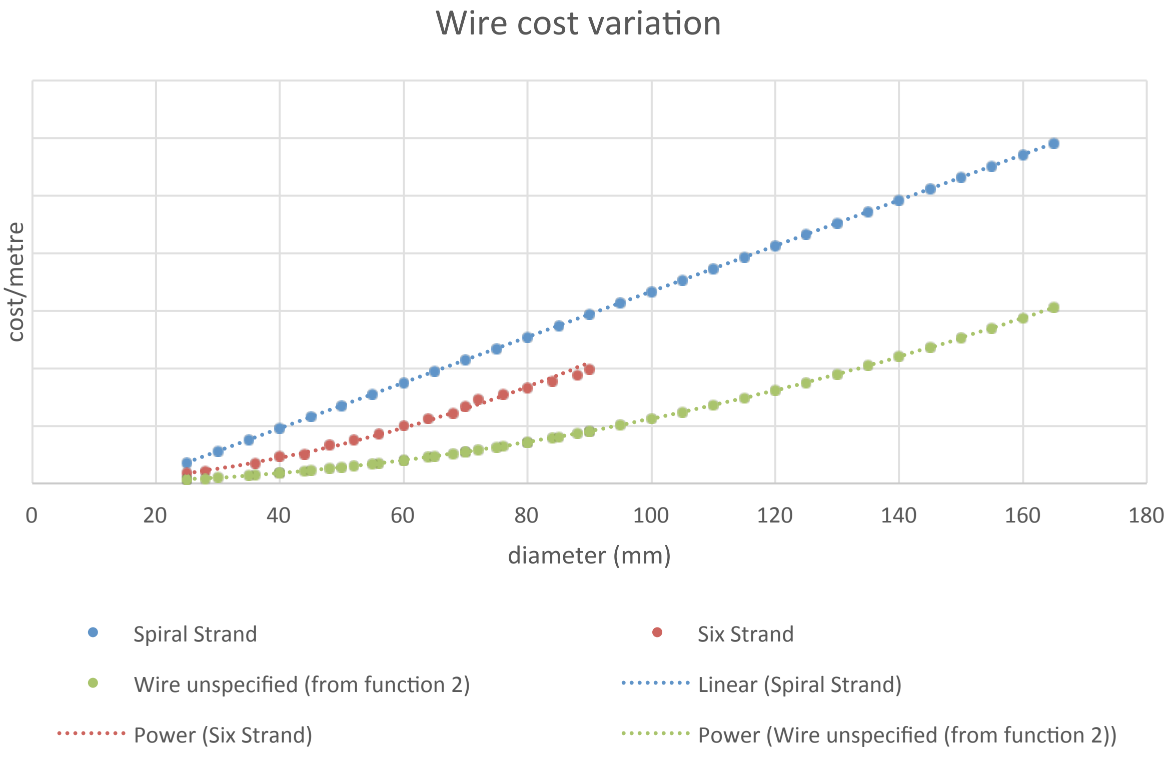


Figure 2.3: Wire cost variation (function 2 is equation (14))

For synthetic ropes, the cost calculation provided by suppliers is more complex than simply a price of steel. Different materials will, of course, have different associated costs (Figure 2.4). While Nylon and Polyester ropes have similar costs in relation to their diameter, HMPE costs are much higher, and increase more rapidly.

Furthermore, the cost per weight is banded by MBL. This can be seen in Figure 2.5, especially for the HPME case, as there is a “jump” at MBL values of 4000 kN and 8000 kN. For Nylon and Polyester ropes, although there is also this banding, it works in the inverse with cost per kg decreases for higher capacity ropes.

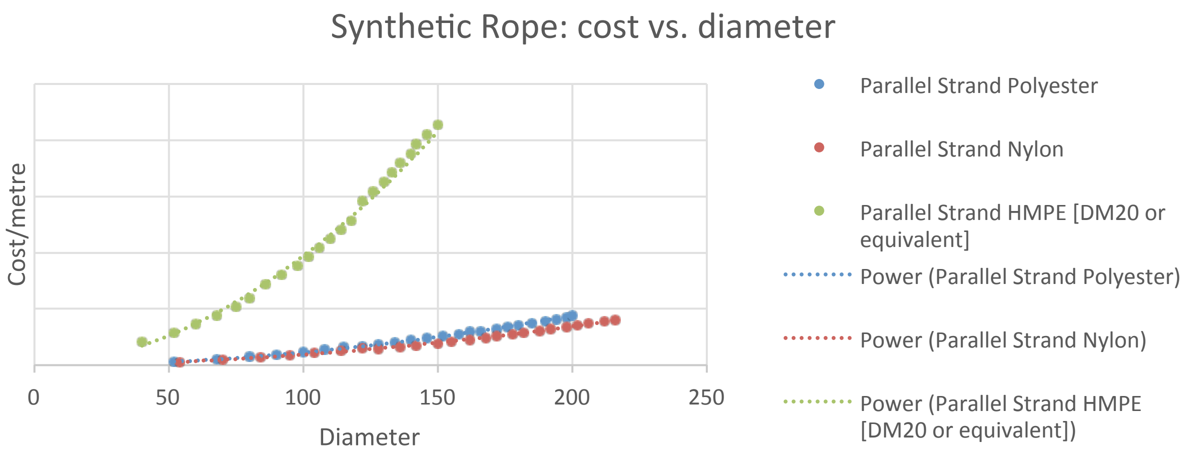


Figure 2.4: Synthetic Ropes cost variation with diameter

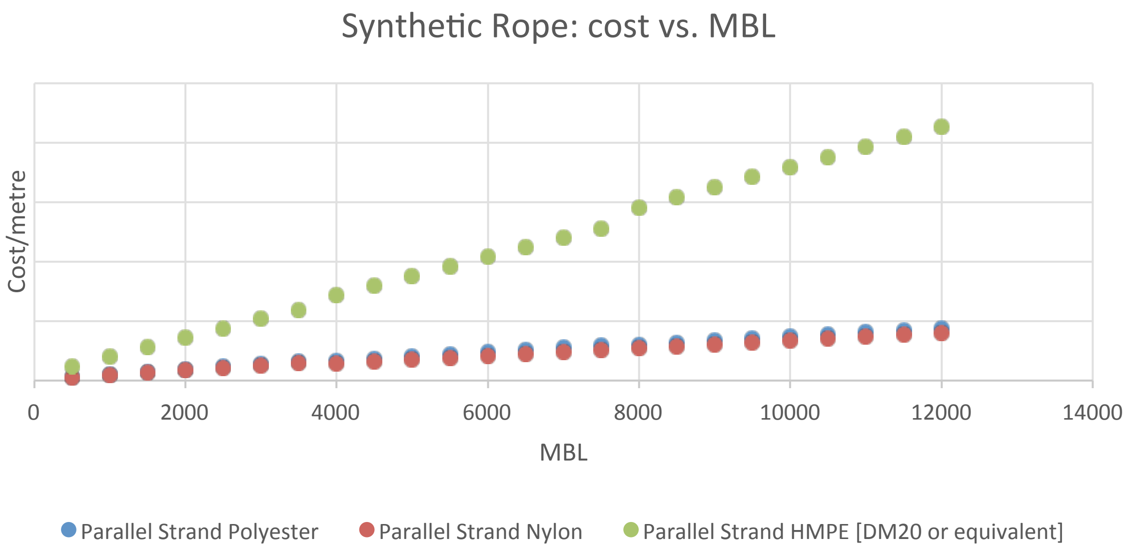


Figure 2.5: Synthetic Ropes cost variation with MBL

However, there are other costs associated with synthetic ropes:

- Cost of splicing

- Cost of protection
- Cost of coatings
- Inclusion of thimbles
- Surcharges for low volume orders

These have a high impact on the final cost of the rope, as it can be seen on Figure 2.6

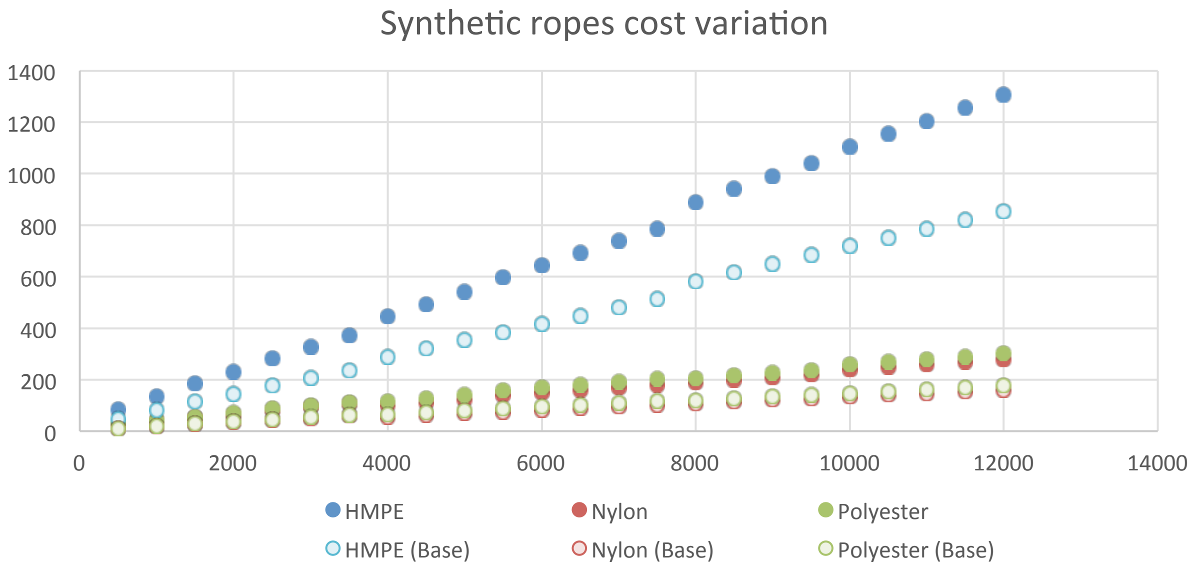


Figure 2.6: Final cost variation for synthetic ropes

2.3.2 Foundations and anchoring elements

While mooring elements were related only with floating devices, foundations are applicable to all devices.

For fixed devices the foundations are usually divided into 3 types [36]:

- Piled
- Gravity Base
- Suction piles

As these structures are also be found in offshore wind, their associated costs are also well known. In the case of offshore wind, due to the size of the structures they must support, the cost of foundations is an important contributor to the LCOE, and there is a great deal of effort into decreasing these costs.

These systems are designed for a specific project, and device location in mind. Although fabricators will provide piles in certain sizes, according to their manufacturing capabilities, these can be cut-to-size to match the needed embedment. Custom sized piles can be manufactured, by suppliers may input additional costs for non-standard dimension.

Generally the costs for fixed foundations are expressed as a function of the amount of material needed to fabricate the structured, modified by the complexity of the fabrication process [55]. This is of extreme importance for Offshore Wind, as Jacket structures are more prevalent. For marine renewables, and as in the case of DTOcean only the embedded structure is analysed, jacket structures are not used. However, the complexity factor is important to determine the full price of the structure, which is calculated according to equation (15).

$$Cost_{Foundation} = Weight_{main\ material} \times Cost_{main\ material} \times (1 + Complexity\ Factor) \tag{15}$$

If the foundation is a combination of materials, the cost will be the sum of the costs for each material. The complexity factor for steel piles is usually between 0.8 and 1.5, although, for both gravity base and piles is common to use the value of 1 ([55],[56],[57],[58],[59]).

In terms of cost of the materials, concrete prices are generally much less volatile than steel and the price per ton is much lower than steel. However the structures used are also much heavier and the total costs, including installation, increase exponentially with depth ([60],[61],[62],[63]).

The cost of anchors is dependent on the required holding power and weight, which is sensitive to subsurface geotechnical conditions. For example - sand is better than clay with cost of anchors being approximately 25% for clay deployment. The capital cost of a driven pile is considerably less than that of equivalent capability anchors (around 40%). However, installation costs for piles are much higher (vessels types time and spreads). For suction piles, both the capital cost and installation cost increase [38][49]. According to [64], total production costs for suction pile anchors can range between 9.5 and 11 k€/ton.

Drag embedded anchors are one of the lowest cost anchor types and based on data from [52]and [64], the cost follows a linear progression with the anchor weight (Figure 2.7).

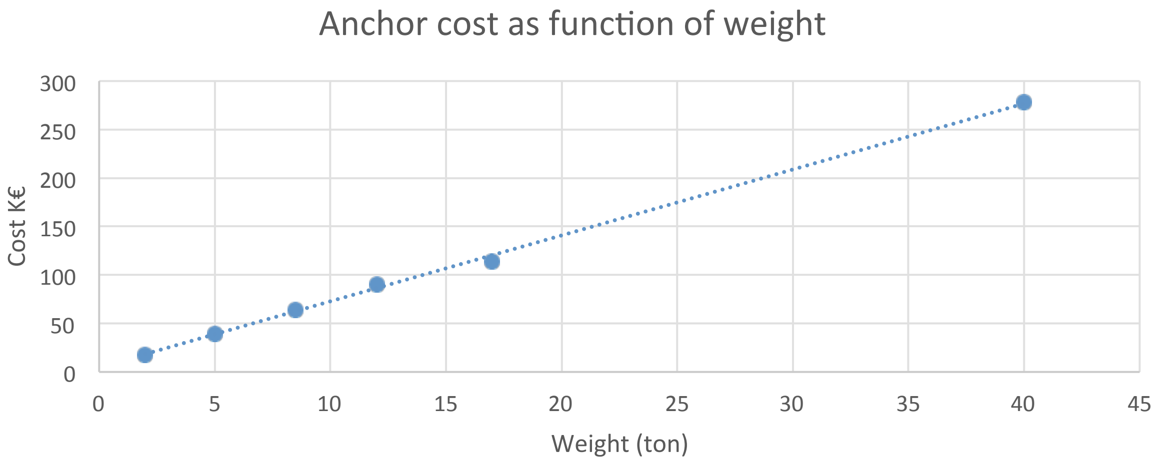


Figure 2.7: Anchor cost as function of weight [37][64].

2.4 Example calculations

2.4.1 Case 1: Alstom 1MW tidal turbine

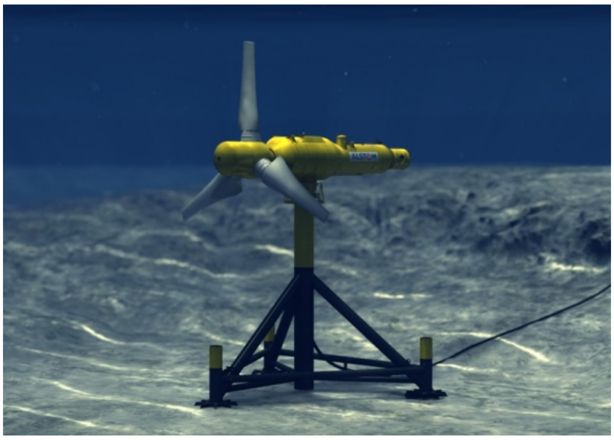


Figure 2.8: Alstom 1 MW turbine

18m diameter rotor, 22m long nacelle, 150 tonnes weight

Foundation: 3x open-ended tube piles (3m diameter, 0.12m thick, 10m long) positioned 10m radius from centre of support structure. Basic stress calculations carried out using S355 grade steel.

Based on these dimensions, each pile has a volume of 10.86 m^3. Assuming a density of 7850kg/m3, the mass of each pile is 85.23 ton.

Using a base cost of steel of 1 €/kg, and a complexity factor of 1, the fabricated cost of steel is 2 €/kg. For 1 device the cost of the foundation is 511.38 k€.

To look into what this figure represents in terms of LCOE, the following parameters were used to calculate the contribution of the moorings to the LCOE:

Table 2-2: Parameters for LCOE calculation

Parameter	Value
Capacity Factor	30%
Availability	90%

Discount Rate	10%
Project life	20 years

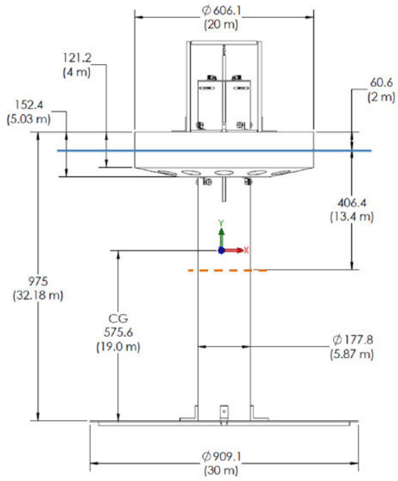
The calculated contribution to LCOE is 25.40 €/MWh. Using the projected values for second arrays in [46], this represents between 7% and 16% of the LCOE, which matches the published figures for the contribution of station keeping elements to the LCOE.

As the price of steel is volatile, the table below shows how the contribution to the LCOE changes for different values of the cost of fabricated steel.

Table 2-3: Variation of contribution to LCOE with changes in cost of fabricated steel

Cost of fabricated steel	1	1,5	2	2,5	3	3,5	4	*€/kg*
Contribution to LCOE	12,70	19,05	25,40	31,74	38,09	44,44	50,79	*€/MWh*
Percentage of LCOE	*4% - 8%*	*5% - 12%*	*7% - 16%*	*9% - 20%*	*11% - 24%*	*13% - 28%*	*14% - 32%*	

2.4.2 Case 2: RM3 point absorber device



20m diameter, 32.2m long, 1639.7 tonnes weight, 286 kW

Mooring system: 3 x mooring lines comprising: wire rope (20m long)-buoy-nylon rope (267m long)-clump weight-anchor chain (130m long)[5]

Table 2-4: Case 2 Moorings description

Mooring Line	Fairlead (m,m,m)	Anchor (m,m,m)
1	2.94,0,-3.5	443.0, 0, -70.0
2	-1.47, 2.54, -3.5	-221.5, 383.65, -70.0
3	-1.47, -2.54, -3.5	-221.5, -383.65, -70.0

	Volume (m^3)	Mass (te)	Height (m)
Clump weight	0	25	1.471
Subsea buoy	2.361	1.5	1.652

---

[5] Connecting hardware not included.

Type	Effective diameter (m)	Dry mass per unit length (kg/m)	Minimum break load (kN)
Diamond blue wire rope[6]	0.0534	19.3	3670
Nylon Braidline rope[7]	0.1156	11.35	4089
Studlink chain[8]	0.1701	189.0	4090

Foundation: 3x gravity base anchors (width: 2.4m, length: 2.4m, height: 0.6m) each comprising 2.93m^3 of steel and 0.53m^3 of concrete.

For the mooring lines, the calculation for each segment was based on different criteria:

Table 2-5: Parameters used to calculate costs, and costs for each mooring line segment

Type	Effective diam.(m)	Dry mass (kg/m)	MBL (kN)	Cost (€)	Cost per metre (€/m)
Diamond blue wire rope	**0.0534**			1655,47	82,77
Nylon Braidline rope			**4500 (4089)[1]**	25726,38	96,35
Studlink chain		**189.0**		638,82	4,91

[1] *Value chosen was the next in the specification list*

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[6] http://www.bridon.com/uk/oil-and-gas-ropes/downloads/diamond-blue.pdf

[7] http://www.bridon.com/uk/oil-and-gas-ropes/downloads/viking-braidline-nylon.pdf

[8] http://www.saxtonmarine.co.uk/kenter_shackle_chain_weights.html

Using a base value of 2 €/kg for the clump weight and for the subsea buoy, the cost for 1 mooring line is 82.07 k€.

For the gravity base foundation, a concrete cost of 450 €/m^3 [65] was assumed. The steel price was assumed to be 1 €/kg, and the steel density 7850 kg/m^3. A fabrication factor of 1 was also applied. The cost of each GBA is 46.48 k€. This brings the total cost of the moorings and anchoring system for 1 device to 385.65 k€.

Following the same rationale as before, Table 2-6 shows the parameters used for the calculation of the contribution to the LCOE.

Table 2-6: Parameters for LCOE calculation

Parameter	Value
Capacity Factor	30%
Availability	93% [66]
Discount Rate	10%
Project life	20 years

The contribution of the moorings and anchors to the LCOE is 64.71 €/MWh, which represents between 13% and 41% percent of LCOE. This value is higher than what would be expected, especially as no connecting elements were included. However, the capacity of the device considered is a result of a different study [66], in which the device dimensions do not match the ones presented here. Adjusting the device rating will bring changes in the LCOE, as the costs are offset by more electricity production (Table 2-7).

Table 2-7: Variation of contribution to LCOE with changes in device rating

Device rating	100	200	286	500	750	1000	1250	*kW*
Contribution to LCOE	185,07	92,54	64,71	37,01	24,68	18,51	14,81	*€/MWh*
Percentage of LCOE	*37% - 118%*	*18% - 59%*	*13% - 41%*	*7% - 24%*	*5% - 16%*	*4% - 12%*	*3% - 9%*	

3 ENVIRONMENTAL ISSUES FROM MOORING AND FOUNDATION SYSTEM

3.1 Introduction

Moorings and foundations are essential parts of Marine Renewable Energies (MRE) devices as they allow devices to be held on station in harsh conditions like high tidal flows, strong winds, heavy waves loads or a combination of all. Most common foundation types are gravity bases, monopiles, jacket foundations or mooring anchors. Most common moorings are usually wire rope, chain, synthetic or hybrid composed as single and multiple lines, basic catenary system, catenary system with auxiliary surface buoy and lazy wave system with subsea floater and sinker [67]. Considering water depth and seabed type, design concepts are often dictated by limitations to construction, transportation, installation, structure design life, safety class/group as well as cost [68].

Different stages/phases can be considered within the lifecycle of foundations and moorings:

- preparation of the ground (optional)
- remedial activities
- settlement of the foundation
- operation and decommissioning (if required)

Overall, the main associated effects to these stages are:

- bathymetry modification potentially having effects on wave and tide
- sediment / rock removal potentially altering benthic habitat and communities
- turbidity modification potentially altering benthic habitat and communities
- sediment transport with fine particles deposition potentially altering benthic habitat and communities
- noise with potential disturbance/damage and displacement of fish, marine mammals and birds
- collision and entanglement risks potentially affecting marine megafauna (including mammals)
- indirect consequences related to vessel traffic and/or damage to existing marine infrastructures such as cables, pipelines etc..

In the above context, this document describes the environmental impacts of moorings and foundations in the marine environment with a particular focus on adverse issues related to seabed footprint, collision risks, noise, but also reef effect usually considered as positive issue (Figure 3.1). The last section of this document gives a description, for each environmental issue cited above, of the developed functions from the Environmental Impact Assessment Module (EIAM). This module has been designed to assess the environmental impacts generated by the various technological choices of arrays of wave or tidal devices.

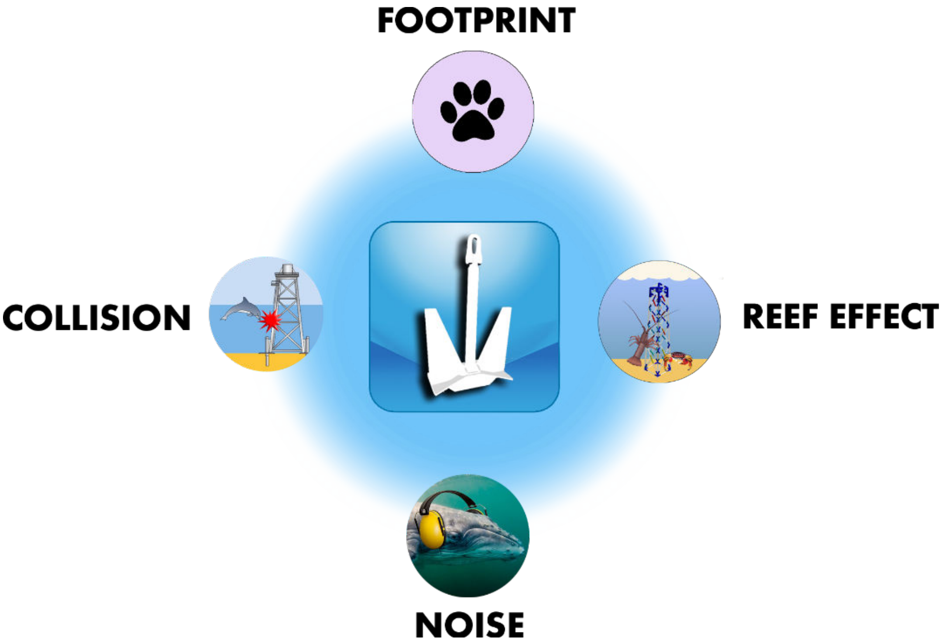


Figure 3.1: Considered environmental impacts for Moorings and Foundations for DTOcean tools

3.2 Environment assessment within the DTOcean Tool

3.2.1 Methodology

The whole Environmental Impact Assessment Module (EIAM) is based on several scoring principles detailed in Deliverable 7.2. Briefly, the use of the environmental functions allows the EIAM to generate numerical values that will be converted in environmental scores (EIS - Environmental Impact Score). The conversion from the function' scores to the environmental scores is made through calibration matrices. Each function is associated with one calibration matrix (or several depending of the complexity of the function) in order to qualify the initial pressure score. Calibration matrices are based on literature data or empirical when no sensible data are available.

The scoring allocation system developed within the framework of DTOcean is generic for each environmental function and based in three consecutive main steps shown in Figure 3.2:

The main principle for the different steps is summarized below:

- STEP 1: qualification and quantification of the 'pressure' generated by the stressors

- STEP 2: basic qualification of the occurrence (or absence) of receptors potentially affected by the stressors. If receptors chosen in the basic receptor data availability are also in the red list, the Receptor sensitivity score doesn’t use the standard qualification of the score, but takes the maximum score 100.

- STEP 3: qualification refinement of receptors e.g. definition of slot of occurrence during the year where receptors are sensitive (i.e nesting seasons for birds, breeding seasons for mammals...).

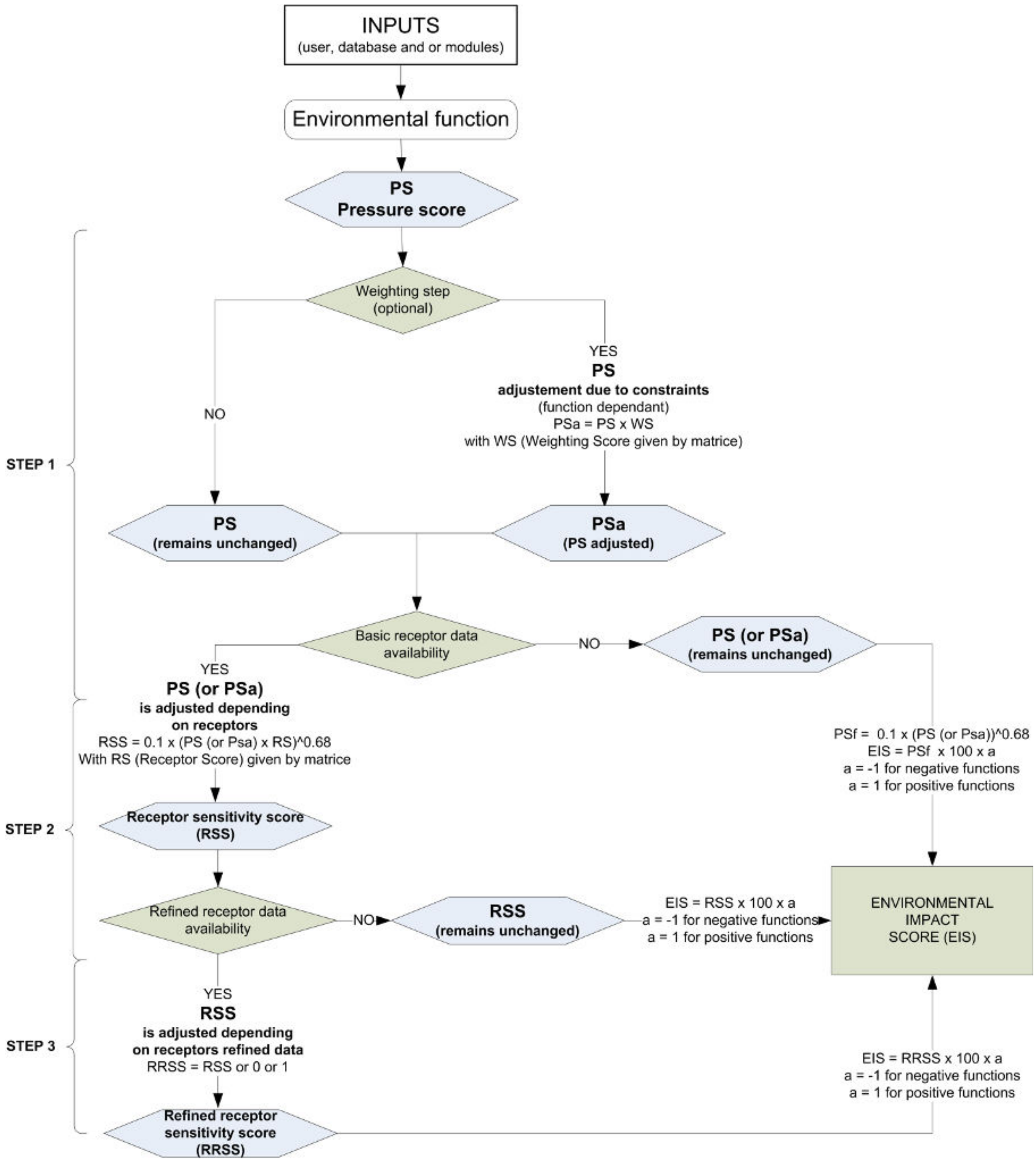


Figure 3.2: Architecture of decisional flowchart for the DTOcean Environmental Impact Assessment Module (EIAM)

3.2.2 Data Requirements

3.2.2.1 Perimeter

The environmental impact associated to the WP4 "Mooring and foundations" is largely driven by the types and the number of moorings and foundations. The period and the time of installation (or decommissioning) of these moorings and foundations are driven by the WP5 and WP6 and is not treated in this document. Based on the database of moorings and foundations of the WP4, four environmental potential impacts have been selected over the set of eleven anticipated in the DTOcean project. These four potential environmental pressures which can create negative (or positive) impacts are:

- The footprint (created by the foundation and moorings area on the seabed)
- The collision risk (due to the presence of structures in the water column)
- the underwater noise (due mooring line chafing on seabed)
- the reef effect (created by new hard substrate in the water column)

To define the potential impacts, some data are required and will be provided by the user or the other DTOcean modules. These data are about:

- Design of foundations
- Number of foundations and moorings lines
- Substrata surface covered by mooring and foundation
- The chafing surface area
- The total surface lease area
- The total volume of mooring lines and foundations in the water column

The calibrations of the various functions use as much as possible values based on bibliographic references. However, sometimes there is no quantitative information about environmental processes. In such cases, calibration values are given using an empirical or a 'best guess' approach. Note that In this report is described the environmental effects relates to parts associated to mooring and foundations. Only the operational phase is considered here, as environmental issues related to moorings and foundations during installation and maintenance phases are treated by the DTOcean Lifecycle Logistics module. Therefore, adverse environmental effects are somewhat restricted to footprint, collision risks (mainly entanglement) and noise (produced by mooring chafing). Reef effect is also considered as a positive environmental effect.

3.2.2.2 EIAM functions

Here is presented all the parameters that are involved in the environmental processes. Stressors create the pressure and receptors are the sensitive animal and vegetal species that are impacted by the stressors. The environmental function use inputs to produce results. As shown in Figure 3.2, a weighting can also occur in the first step of the evaluation process to better qualify the pressure.

3.2.2.3 Footprint

Background:

One of the main environmental impacts is directly related footprint generated by foundations but also moorings. Seabed can be degraded due to the foundations themselves and the dragging of the moorings lines. In this case, the main risk is the destruction of local habitats and associated communities. The environmental impact of foundations is directly related to the area of seabed contact under the footprint of the foundation structure. But it is also acknowledged that the area covered by the over shadowing foundation structure itself can also alter the seabed. This shadowing effect is presented on Figure 3.3.

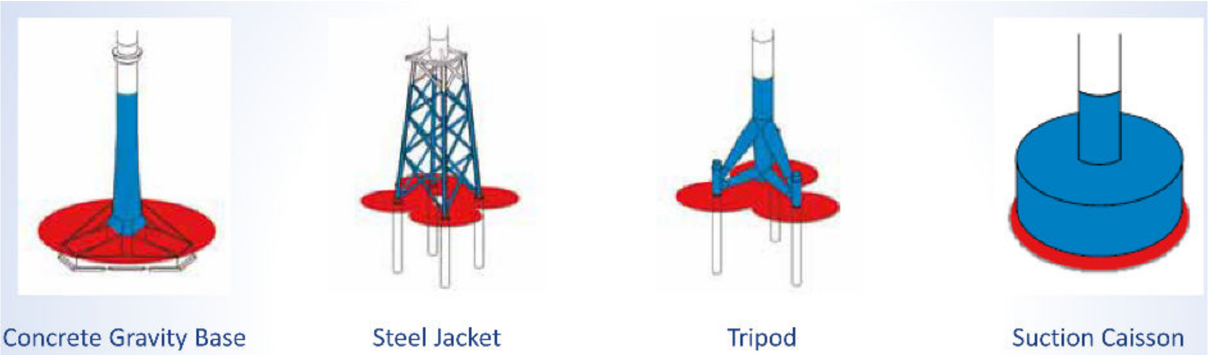


Figure 3.3: Shadowing effect of different type of foundations (Reach et al. [69])

Direct and indirect physical effects are expected through the placement of the foundation itself and the modification of the hydrodynamics and related sediment transport. Most of the data and reviews come from the offshore wind sector [70][71][72]. These reviews show that the seabed can be directly affected by the nature of the foundations as well as their placement that ultimately modify the local hydrodynamism and therefore the sediment transport. Besides, regarding the direct footprint area of foundations, protective measure such as scour can also increase the footprint area changing usually local seabed to rock substrate [73].

The main direct biological effect of foundations and moorings on seabed is the habitat removal affecting infauna (organism living within the sediment) for mobile sediment (usually sands), epifauna (organism attached to coarse sediments and rock) for coarser sediments like gravels, pebbles and cobbles. Infaunal communities consist of species that mainly burrow below the surface sediment. Energy exposure and sediment granulometry are the main factors that determine the nature of the infaunal communities. Thus muddy sands will host bivalves, urchins or polychaete worms, as gravels and coarse sands will tend to host larger species such as mollusc, anemones and other polychaete worms. Epifauna can be composed of polychaete worms, barnacles, colonial ascidians, anemones; ophiuroids, sponges, bryozoans or hydroids within subtidal coarse (gravels) and mixed sediments (gravels, sands and muds) (Figure 3.4). The loss of these communities affect indirectly the surrounding ecosystem with in particular an effect on the mobile and errant species like crustaceans, molluscs, echinoderms and pisceans as they prey upon infauna and epifauna.

Figure 3.4: Examples of sediment habitats (from left to right: Fine sand sediments with polychaetes, coarser sand and sandy gravel sediments with polychaete and bivalve and coarse gravel sediments supportingcalcareous tube worms, and urchins)

As most infaunal and epifaunal species live respectively in the top layer of the sediment (0.5m) and on the surface of the sediment, any process such as abrasion, subsurface penetration and disturbance, that will affect this sediment layer will have an effect on these communities. Recovering time after alteration may vary from months to years. Hill et al. [74] estimated that biotopes can recover within a period ranging from 6 to 24 months for high energy environment with medium fin sediment. Biotopes associated with coarser sediment are expected to recover over longer times ranging from 8 to more than 15 years [72]. Dernie et al. [75] also studied recovery rates of benthic communities following physical disturbance. These authors showed that clean sand communities had the most rapid recovery rate following disturbance, whereas communities from muddy sand habitats had the slowest physical and biological recovery rates.

Stressors:

Stressors are the physical anthropogenic element that generates the 'footprint' pressure. In the WP4, the footprint is induced by moorings, anchors and foundations. The type of foundations can substantially influence the footprint. The footprint is here considered as the total surface area occupied by mooring and/or foundation systems.

Receptors :

Receptors are all the biological (fauna and flora) species which can by impacted by the stressor. Regarding footprint the major species that can be impacted are the benthic species (living on the hard and soft substrate) and some other species as fishes classified in the ecosystem group (hard and soft substrate).

Aim :

The footprint function aims at evaluating the pressure on the seabed occupied by moorings and/or foundations on the benthos and some other species of this ecosystem living on the sea bed.

Inputs:

To quantify the pressure and the impact, some inputs re required, provided either by the WP1 database or by the user. These inputs are:

- Total surface area occupied by mooring and/or foundation system Scouring surface area (Configuration seafloor footprint area from 'Moorings and Foundations' module)
- Total surface of the lease area

Function's formula :

The 'footprint' function is calculated as follow:

Footprint = (Chafing surface area + scouring surface area)/total surface of the lease area

Rule :

If the function's formula result is near to 0 then the impact is minor. It becomes major if the ration is close to 1.

Weighting step :

The weighting step helps to better qualify the pressure calculated by the function's formula. In this specific case, there is no weighting step.

Calibration :

Step1

To qualify scores and calibrations for footprint, an empirical approach has been carried out. This approach is based on 4 ration ranges of footprint areas vs. lease area (see Table 3-1).

Table 3-1: Footprint Pressure Scores

Formula Score (FS) - Footprint ratio	Pressure Score (PS)
0.01	1
[0.01-0.1]	2
[0.1-0.3]	3
>0.3	5

Step2

The ecosystem in hard substrata is potentiality more vulnerable because the number and the variability of species are richer than in soft substrata and that these species are less mobile. The types of benthic species are more diversified in hard substrate. This is the reason why we have assigned the score of 3 for species living in hard substrata and 1 for species in soft substrata. The receptor scores (Table 3-2) are based on the nature of the ecosystem.

Table 3-2: Footprint Receptor Scores

Soil group	Soil types	Receptor Score (RS)
Ecosystem living in hard substrate (cemented to hard rock soil types)	Firm clay	3
	Stiff clay	
	Cemented	
	Soft rock coral	
	Hard glacial till	
Ecosystem living in soft substrate (cohesion less soil group)	Loose sand	1
	Medium sand	
	Dense sand	
	Very soft clay	
	Soft clay	

After selecting the appropriate Receptor Score (RS), The Receptor Sensitive Score (RSS) can be obtained using the formula:

$$\mathbf{RSS = 0.1 \times (PS \times RS)^{0.68}}$$

This formula ensures that RSS fits in the final Environmental Impact Scoring scale.

Step3

The final step (STEP 3) takes into account the seasonal distribution of the receptors. If data are available (provided either by the user or the database), RSS will be adjusted to a new value called RRSS (Refined Receptor Sensitivity Score) using a new matrix containing the information of the receptor monthly absence or occurrence. In the case where the receptor is 'regulatory protected', the DTOcean database should be able to identify it during this STEP and then assign the maximum negative EIS score (-100). In summary during STEP3 and for a specific receptor, there are only two cases:

- **RRSS = RSS (occurrence of the receptor) or 0 (absence of the receptor)**
- **RRSS = 1 as the receptor is 'regulatory' protected.**

Finally, fo Step 1, 2 or 3, the final Environmental Impact Score is ultimately calculated as follow (Figure 3.2):

EIS - Environmental impact score = A x 100 x a

With

A = PS, RSS or RRSS if the process stops in STEP 1, 2 or 3 respectively

a = -1 or 1 for negative and positive functions, respectively

3.2.2.4 Collision (entanglement)/based on volume swept calculation

Background:

The collision risk is qualified with the following definition: “an interaction between a marine vertebrate and a marine renewable energy device that may a result in a physical injury to the organism” [76]. Entanglement can be defined as the inadvertent capture or restraint of marine animals by strong, flexible materials of anthropogenic origin [77]. Regarding this issues, two types of species are usually considered: marine birds and marine megafauna. For marine birds, collisions generally appear when birds fly and collide either with devices in the air (mostly for offshore wind farm) or in the water depth [76]. In the water, the risk of collision with the foundations themselves is relatively limited compared to the devices. Indeed foundations are usually deeper and beneath the devices and therefore, collision risks with birds are not taken into account in the DTOcean EIAM for moorings and foundations. Similarly, as foundations are usually minor in term of occupied volume compared to the converters themselves, collisions with foundations are not taken into account. Only entanglement will be taken into account.

Marine megafauna may be affected by MRE tidal and wave devices in term of entanglements. Indeed the future development of MRE arrays raises the potential interactions between mammals

and these structures that include amongst other parts mooring lines. European waters are populated by a substantial number of marine mammals including seals and cetaceans. To date, a substantial amount of studies examining the potential impacts of MRE on marine mammals have been carried out, see for example [78][79].
Entanglement is considered as a potential significant problem for marine megafauna and remains a significant source of mortality and injury [80]. The Figure 3.5 gives an example of entanglement resulting in injuries.

Figure 3.5: Example entanglement effects of seal and whale

There is a wide range of species subject to entanglement. Even if most of the cases involves actual fishing gears (nets, seines, weirs, etc.), whether active or derelict, many records of marine magafauna involve cetaceans like large whales that appear to be vulnerable due to their size and bulk [77], and several dolphin species. Pinnipeds such as seals and sea lions can also suffer from entanglement events. Details about locations and species are given in the review written by Benjamins et al. [77]. Several causes of entanglement events have been put forward even if this issue is still controversial. Entanglement could be related to the absence of line detection or simply through a voluntary contact with the line. In any case, specific environmental conditions (highly turbid waters, low light…) could decrease the animal’s capability to detect lines or ropes and therefore increase the probability of contact. Some other reasons are also evocated such as distraction during preying, range of detection or even juvenile stage (less experience than adult).

The effects of entanglement are diverse and have been reported by Moore and van der Hoop [81] and Cassoff et al. [82]. They can result in drowning, infecting tissues, causing severe loss of weight, and affect animal natural moving capabilities due to drag effects. Overall, there is still of high level of uncertainty regarding whether entanglements, as well as collision might impact mammals at population level [83].

As for mammals, fish are characterized by a wide range of hearing structures, resulting in different capacity and sensitivity to noise. They use biological noise to gain information about their

Stressor:

Stressors are the physical anthropogenic element which causes collision and entanglement. In the WP4, only entanglement is considered through moorings lines. Mooring system can contribute to a risk of entanglement [84].

Receptors:

Receptors are all the sensitive species that can by impacted by the stressor. Regarding entanglement risks, the major species that can be impacted are mainly marine mammals. Birds can be also affected with interactions with mooring lines when diving.

Aim:

The goal of this function is to evaluate the collision risk, and entanglement between fauna (marine mammals and birds) with moorings lines.

Inputs:

To quantify the pressure and the impact, some parameters or inputs are required. They are provided by either the DTOcean database, the other modules or the user. These inputs are:

- Total volume occupied by mooring and/or foundation system (given by the 'Moorings and Foundations' module - Configuration volume)
- Total water column lease volume

Function’s Formula:

The 'collision risk' function is calculated as a ratio of occupied by mooring and/or foundation system by the total lease volume area.

Collision risk = (occupied by mooring and/or foundation system) / total lease volume

Rule:

0 ≤ Collision risk ≤ 1

0 means that the impact is minor and 1 means that the impact is major.

Weighting step:

The weighting step helps to better qualify the pressure calculated by the function's formula. In this specific case, there is a weighting step based on the study "assessment of entanglement risk to marine megafauna due to offshore renewable energy mooring systems" [84]. More details are given in the calibration section.

Calibration:

Step1

Due to the lack of data about the risk of collision between megafauna and moorings and foundations, an empirical and best guess approach has been implemented. Based on the result of the function's formula, three ranges have been defined as presented in Table 3-3.

Table 3-3: Collision Risk Pressure Scores

collision risk	**PS**
[0-0,1]	0.5
[0,1-0,20]	1
[>0,20]	1.25

Weighting scores have been assigned based on Harnois et al [84]. This paper considers the potential risk of entanglement of marine megafauna between mooring lines and floating devices. They developed a methodology to evaluate the risk from different mooring systems. Physical parameters of mooring affecting the risk of entanglement are the tension, the swept volume ratio and the mooring line curvature. They did a summary of risk assessment for different mooring parameters (Table 3-4):

Table 3-4: Summary of risk assessment for the different mooring parameters from [84]

Mooring type	Tension characteristics	Swept volume ratio	Curvature	Total score
catenary & chains	2	2	2	6
catenary & chains & nylon ropes	3	2	2	7
catenary & chains & polyester ropes	2	2	2	6
taut	1	1	1	3
catenary & accessory buoy	3	2	2	7
taut & accessory buoy	3	1	2	6

For fitting the EIS scale, the weighting scores have been modulated as shown in Table 3-5 below.

Weighting score (Table 3-5)

Table 3-5: Collision Risk Weighting Scores (WS)

	Score Harnois et al.[84]	**DTOcean Weighting Score (WS)**
catenary & chains	6	3
catenary & chains & nylon ropes	7	3.5
catenary & chains & polyester ropes	6	3
taut	3	1.5
catenary & accessory buoy	7	3.5
taut & accessory buoy	6	3

Depending of the mooring configuration, the pressure score (PS) is then modulated/adjusted using the following formula:

PS adjusted (PSa) = PS x WS

Step2

The next step (STEP 2) is to consider if there are some species in the area and their degree of sensitivity though a coefficient (Receptor score) that will lead to the Receptor Sensitivity Score (RSS). Receptor Scores (RS) were obtained from the literature and other European regulations.

According to Lejart et al [85], in Europe, marine mammals have a specific protected status. Cetaceans and pinnipeds are protected by numerous international regulations and texts, such as the Washington convention [86], Berne convention, Convention on migratory species [87], OSPAR etc. They are also directly protected by international agreements such as ASCOBANS [88], ACCOBAMS [89] or the International Whaling Commission [90].

At the European level, the Habitats Directive [91] also mentions many species of marine mammals in Annexes IV (species protection) and II (protection of species and their habitats). The finally, the Marine Strategy Framework Directive [92] also shows a close interest in marine mammals and the human activities that threaten them.

Given all these regulations, it is not relevant to give the same scores for all marine mammals. It was decided to also take into account maneuverability and feed depth of marine mammals. Maneuverability is a specific criterion for collision risk. Focusing on the size of the marine mammals and their behavior helps determine a high or a low RS (Receptor Score). Finally another parameter influencing the behavior of marine mammals is the feeding depth. Indeed the risk of collision is higher for species that use to feed at the bottom increasing the risk of collision with moorings and foundations (Table 3-6).

Table 3-6: Collision Risk Marine Mammals Receptors Scores

Species	**RS-Receptor Score**
seals	3
porpoises	3
dolphins	3
pinnipeds	3
mysticetes	4
large odontocetes	4

Regarding birds, collision risk has also to be considered [93]. The quantification of RS for birds has been based on the methodology published in the ICES Journal of Marine Science [93]. In this research they create a species vulnerability index for wave and tidal devices impacts. The index involves several factors such as diving ability, benthic foraging, feeding range or disturbance by ship traffic for tidal and factors such as disturbance by structure benefit from fish attraction device for wave. It allows a classification ranging from minimal risk of mortality to very high risk of mortality. More details about the index calculations can be found in the original paper [93]. Based on this work, receptor score have been established for birds. An example of RS values are presented in the table below (Table 3-7)

Table 3-7: Some examples of Collision Risk Birds Receptor Scores

Receptor	**turbine**	**species**	**RS-Receptor Birds**
birds	tidal turbine	black guillemot	4
		great nothern diver	3
		velvet scoter	2
		roseate tern	1
	Wave	black-thoated diver	3
		common eider	2

After selecting the appropriate Receptor Score (RS), the Receptor Sensitive Score (RSS) can be obtained using the formula:

$$\mathbf{RSS = 0.1 \times (PSa * RS)^{0.68}}$$

This formula ensure that RSS fits in the final Environmental Impact Scoring scale.

Step 3

The final step (STEP 3) takes into account the seasonal distribution of the receptors. If data are available (provided either by the user or the database), RSS will be adjusted to a new value called RRSS (Refined Receptor Sensitivity Score) using a new matrix containing the information of the receptor monthly absence or occurrence. In the case where the receptor is 'regulatory protected', the DTOcean database should be able to identify it during this STEP and then assign the maximum negative EIS score (-100). In summary during STEP3 and for a specific receptor, there are only two cases:

- **RRSS = RSS (occurrence of the receptor) or 0 (absence of the receptor)**
- **RRSS = 1 as the receptor is 'regulatory' protected.**

As shown in Figure 3.2, the final Environmental Impact Score is ultimately calculated as follow:

EIS - Environmental impact score = A x 100 x a
With
A = PS, RSS or RRSS if the process stops in STEP 1, 2 or 3 respectively
a = -1 or 1 for negative and positive functions, respectively

3.2.2.5 Underwater Noise

Background:

The quantification of underwater noise due to the wave and tidal devices is poorly known and documented. In particular, the noise generated by ‘moorings and foundations’ after being installed is mostly restricted to the sounds of moorings lines chafing on the seabed. This has been identified by Robinson et al [94].

Environmental effects related to noise is expected on marine life through different ways. Marine mammals can adapt to a wide variety of natural sound and have adaptive mechanism to many anthropogenic sounds. The frequencies that can be heard from marine mammals range from less than 100 Hz up to 180 kHz, making predictions of potential effects challenging. However when anthropogenic sounds are excessive in level, frequency or even duration, they might exceeds the mammals adaptive capacity and then cause the following main effects (see details in: Marine Mammals and noise, A Report to Congress from the Marine Mammal Commission, 2007 and reference therein) [95]:

- Physical injuries: with permanent threshold shifts or loss of hearing sensitivity resulting from either a brief exposure to very intense sounds or a longer duration to moderately intense sounds, or intermittently but repeatedly to sounds sufficient to cause temporary threshold shifts [96]
- Physiological Reactions: with sound exposure that cause non-auditory physiological effects such as stress and tissue injury
- Masking: when sounds are more difficult to hear because of added noise affecting mammal's behavior in detection and interpretation. Masking may affect (1) reproduction if a female

cannot hear potential mates vocalizing at a distance, (2) mother-offspring bonding and recognition if the pair cannot communicate effectively, (3) foraging if animals cannot detect prey or animals that hunt cooperatively cannot communicate, and (4) survival if an animal cannot detect predators or other threats.

- Behavioral responses: following the detection of sounds, mammals can change in habitat use to avoid areas of higher sound levels, modify patterns such as diving and surfacing or vocalizing for example.

As for mammals, fish are characterized by a wide range of hearing structures, resulting in different capacity and sensitivity to noise. They use biological noise to gain information about their surrounding environment in order to locate their prey and predators or even communicate. Noise may generate physical injury, hearing loss and behavioral changes. In their review paper on several European fish [97] indicated that fish that receive high intensity sound pressures (i.e. close proximity to the MRE construction) may be negatively impacted to some degree, whereas those at distances of 100s to 1000s of meters may exhibit behavior responses. However, the impact is unknown and will be dependent on the received sound. During operation there may be more subtle behavioral effects that should be considered over the life time of the MRE development. Slabbekoorn et al. [98] also stated that very loud sounds of relatively short exposure, can harm nearby fish.

For birds, noise is considered as an indirect effect. Indeed it may cause a reduction in fish abundance and therefore reduce food resources. For both mammals and fish, displacement is also another potential effect generated by noise where devices are deployed, but this effect is hardly quantifiable.

Overall noise produced by mooring lines is expected to be low in level. To our knowledge, there is no data available. Therefore within DTOcean, a qualitative approach will be used considering both the nature of moorings (i.e. taut vs. catenary) and the nature of the sediment (i.e. soft or hard substrata)

Stressor:

Stressors are the physical anthropogenic elements that generate the environmental pressure. In the WP4, underwater noise is induced by moorings lines through chafing. The noise created during the installation phase of foundations and anchors is taken into account in the 'Lifecycle Logistic' module.

Receptors:

Receptors are all the species (fauna and flora) that can by impacted by the stressors. Underwater noise produced by mooring lines chafing is a physical pressure that can affect marine mammals and fishes.

Aim:

The goal of this function is to evaluate the impact of underwater noise produced by the mooring lines on the seabed on marine species.

Inputs:

To quantify the pressure and the impact, inputs are required and given by either the DTOcean database, the different modules or the user. These inputs are:

- Threshold sensitivity of species underwater noise (DTOcean database)
- Underwater noise produced by mooring lines (user, or database by default)

Function's Formula:

The 'underwater noise' function consists of a comparison between the threshold sensitivity of species and the underwater noise level produced by the mooring lines during chafing.

Underwater noise = comparison between threshold sensitive of species underwater produced by lines

Rule:

The noise induced by the mooring lines is compared to the sensitivity threshold of species to identify if they overlap (or not). If they overlap the risk is major.

Weighting step:

The weighting step helps to better qualify the pressure calculated by the function's formula. In the case of this function there is no weighting step.

Calibration:

Step 1

Underwater noise calibration is based on available data for different existing type of device. We have no information about the underwater noise dues to the chafing lines. Tree ranges of underwater level of noise are presented (Table 3-8):

Table 3-8: Under water noise Pressure Scores

Underwater noise Function Score (FS)		**Pressure Score (PS)**
no concordance of data (Noise stressor < Sensibility receptor)		0.5
concordance of data (Noise stressor ≥ Sensibility receptor)	[< 100 dB re 1µPa]	1
	[100 dB re 1µPa-150 dB re 1µPa]	2
	[150 dB re 1µPa-200 dB re 1µPa]	3
	> 200 dB re 1µPa	5

Step 2

To discriminate in term of sensibility, Step 2 involves three expected type of effect:

- behavioral modification of species,
- TTS - temporal threshold shift,
- PTS - permanent threshold shift.

Behavior effect is considered as a moderate effect unlike TTS and PTS that are considered as major effects because of the potential physiological issues they can generate. So receptor scores are based on the following assignment:

- Behavioral modification: score 3
- TTS: score 5
- PTS: score 5

Values in each level (Behavioral, TTS and PTS) are also species specific. Some examples are given in Table 3-9.

Table 3-9: Example of underwater noise Receptor Scores assigned to different marine species

Groups	Species	Sensitivity threshold	Effect	RS
Cetaceans	Porpoise, Delphinids, Mysticetes	[90-143] dB re 1µPa	behavioural	3
		[143-224] dB re 1µPa	TTS	5
		>224 dB re 1µPa	PTS	5
Seals	Pinnipeds	<160dB re 1µPa	behavioural	3
		[160-200] dB re 1µPa	TTS	5
		>200 dB re 1µPa	PTS	5
Fishes	Bony fish	[75-205] dB re 1 µPa	behavioural	3
		>205 dB re 1µPa	TTS	5
		> 205 dB re 1µPa	PTS	5

After selecting the appropriate Receptor Score (RS), the Receptor Sensitive Score (RSS) can be obtained using the formula:

$$\mathbf{RSS = 0.1 \times (PS \times RS)^{0.68}}$$

This formula ensures that RSS fits in the final Environmental Impact Scoring scale.

Step 3

The final step (STEP 3) takes into account the seasonal distribution of the receptors. If data are available (provided either by the user or the database), RSS will be adjusted to a new value called RRSS (Refined Receptor Sensitivity Score) using a new matrix containing the information of the receptor monthly absence or occurrence. In the case where the receptor is 'regulatory protected', the DTOcean database should be able to identify it during this STEP and then assign the maximum negative EIS score (-100). In summary during STEP3 and for a specific receptor, there are only two cases:

- **RRSS = RSS (occurrence of the receptor) or 0 (absence of the receptor)**
- **RRSS = 1 as the receptor is 'regulatory' protected.**

As shown in Figure 3.2, the final Environmental Impact Score is ultimately calculated as follow:

EIS - Environmental impact score = A x 100 x a
With
A = PS, RSS or RRSS if the process stops in STEP 1, 2 or 3 respectively
a = -1 or 1 for negative and positive functions, respectively

- **RRSS = RSS (occurrence of the receptor) or 0 (absence of the receptor)**
- **RRSS = 1 as the receptor is 'regulatory' protected.**

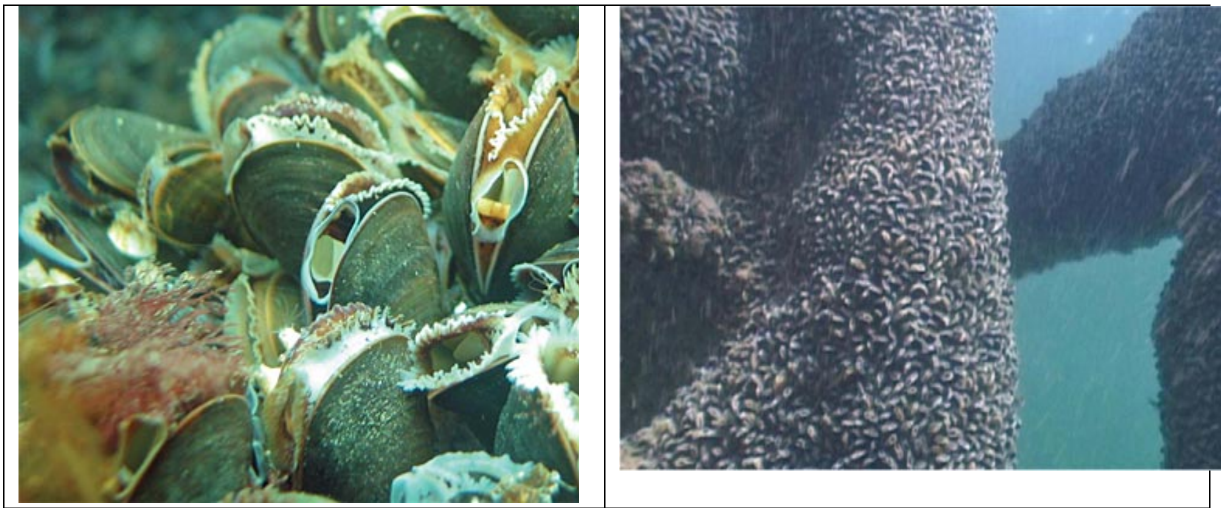
3.2.2.6 Reef effect

Background:

Marine renewable developments on the bottom can provide new hard substrate to marine organisms for colonization, thus playing the role of "artificial reefs". As such they can generate new or enhanced existing habitats with an increased heterogeneity in the area important for species diversity and density. This is particularly true for foundations parts.

Despite the need of more research about advantages of these new habitats, there seems to be a consensus about the positive effects for marine organisms. Indeed new habitats increase the available area for habitats, attract marine life in search of food, hence providing prey for mammals. Langhamer [99] indicates that a positive reef effect is dependent on the nature and the location of the reef and the characteristics of the native populations.

Figure 3.6 and Figure 3.7 show examples of colonization on different MRE structures including foundations. Pictures on fig.6 show advanced colonisation by mussels (*Mytilus Echilij*) on protective structure of the Horn Rev offshore wind farm (Denmark) [100][85]. Pictures on fig. 7 shows the diversity of hard substrate benthic population, observed on the tidal stream turbine site at Paimpol Bréhat, after several months during the BREBENT Campaign; the picture (a) shows unidentified proliferating sponge, the (b) unspecified social ascidians .



www.ens.dk/offshorewind Danish Offshore Wind – Key Environmental Issues

Figure 3.6: colonization of offshore wind pile

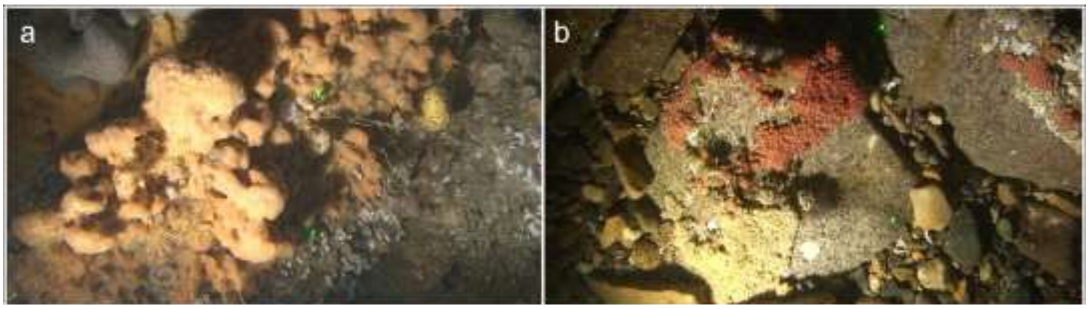


Figure 3.7: Overview of the diversity of hard substrate benthic populations observed on the tidal stream turbine site at Paimpol-Bréhat (© Ifremer, BREBENT-01 campaign)

The introduction of artificial hard substrates can also promote the establishment of introduced species (including invasive species), or promote their geographic expansion by playing the role of "bridgehead" [101].

This "reef" effect was highlighted on the bases of offshore wind turbines [102]. There may also be a "refuge" effect for some species, which find favorable habitats between the artificial structures. Certain protective structures for the laid cables can accommodate benthic species that are of potential interest from a heritage or commercial perspective (large crustaceans [103]. Some new investigations in the tidal site of Paimpol-Bréhat (France) seem to show that concrete mattress could be used as a new habitat by crustaceans (Carlier, pers. Comm.).

Stressor:

Stressors are the physical anthropogenic element that causes the pressure footprint. In the WP4, the reef effect is generated by all foundations and anchors that are not buried.

Receptors:

Receptors are all the marine species that can be impacted by the stressor. Regarding reef effect, the major species potentially impacted (positively) are benthic communities living on hard substrate. Indirectly, this effect can also enhance the marine ecosystem in the vicinity of artificial reef.

Aim:

This function evaluates the intensity of the 'reef effect' due to the colonized surface of 'moorings and foundations' system.

Inputs:

To quantify the pressure and the impact, inputs are required and given by either the DTOcean database, the different modules or the user. These inputs are:

- Total surface of the lease area
- Surface of foundations and other hard substrate (not buried)

Function's Formula:

The function reef effect is calculated as a ratio of the surface of foundation and anchors (not buried) by the total lease surface area.

Reef effect =(Surface of the foundations not buried and anchors) / total surface of the lease area

Rule:

0 ≤ ratio ≤ 1

0 means no positive impact as increasing values means a higher positive impact.

Weighting step:

The weighting step helps to better qualify the pressure calculated by the function's formula. In the case of this function there is no weighting step.

Calibration:

Step 1

The reef effect is considered positive. New hard substrate can potentially create new habitats and host specific benthic communities, mainly composed of fixed and encrusting organisms. The pressure score (PS) is empirically given and presented in Table 3-10:

Table 3-10: Reef Effect Pressure Scores

Reef effect range	**PS - Pressure score fitting in reef effect range**
[0-0.01]	0.5
[0.01-0.1]	1
[0.-0.3]	1.5
>0.3	2.5

Step 2

To discriminate the reef effect, two level of positive effects have been considered:

- Occurrence of benthic communities (biological ecosystem only restricted to the hard substrate),
- Enhanced ecosystem living in the vicinity of the reef effect,

Table 3-11: Reef Effect Receptor Scores

Receptors	RS-Receptor Score
Benthic communities	3
Enhanced ecosystem	5

After selecting the appropriate Receptor Score (RS), the Receptor Sensitive Score (RSS) can be obtained using the formula:

$$\mathbf{RSS = 0.1 \times (PS * RS)^{0.68}}$$

This formula ensure that RSS fits in the final Environmental Impact Scoring scale.

Step 3

The final step (STEP 3) takes into account the seasonal distribution of the receptors. If data are available (provided either by the user or the database), RSS will be adjusted to a new value called RRSS (Refined Receptor Sensitivity Score) using a new matrix containing the information of the receptor monthly absence or occurrence. In the case where the receptor is 'regulatory protected', the DTOcean database should be able to identify it during this STEP and then assign the maximum negative EIS score (-100). In summary during STEP3 and for a specific receptor, there are only two cases:

- **RRSS = RSS (occurrence of the receptor) or 0 (absence of the receptor)**
- **RRSS = 1 as the receptor is 'regulatory' protected.**

As shown in Figure 3.2, the final Environmental Impact Score is ultimately calculated as follow:

EIS - Environmental impact score = A x 100 x a
With
A = PS, RSS or RRSS if the process stops in STEP 1, 2 or 3 respectively
a = -1 or 1 for negative and positive functions, respectively

- **RRSS = RSS (occurrence of the receptor) or 0 (absence of the receptor)**
- **RRSS = 1 as the receptor is 'regulatory' protected.**

3.3 Example calculations

3.3.1 Case 1: West Wave Killard Site (Deliverable 4.6 case of studies)[104]

3.3.1.1 Example of function collision risk

Type of device:

RM3 point absorber device

Specifications:

- Mooring system: 3 mooring lines comprising: wire rope (20m long)-buoy-nylon rope (267 m long)-clump weight-anchor chain (130 m long).
- Foundation: 3 gravity base anchors (width: 2.4m, length: 2.4m, height: 0.6m).

Step 1: Pressure score (PS)

Result of the function

- [0-0.1] = 0 to 10 % space occupied by mooring and foundations

PS: 0.5

Weighting step

- Mooring system: wire rope + nylon rope + chain

WS: 3.5

Pressure adjusted score is

PSa = PS x WS = 1.75

Step 2: Receptor sensitivity score (RSS)

Receptors

- **Location**: West Wave Killard Site
- **Marine mammals**: Occurrence of harbour porpoise, bottlenose dolphins, grey seal, harbour seal (Table 3-12) [104]
- **Birds**: Occurrence of common shag, cormorant, northern gannet, northern fulman, puffin, common gull, razorbill etc. (Table 3-13) [104].

Table 3-12: Example of risk of collision: Marine Mammals Receptor Score (RS)

Receptor marine mammals	**RS-Receptor Score**	**Killard site**
seals	3	x
porpoises	3	x
dolphins	3	x
pinnipeds	3	x
mysticetes	4	
large odontocetes	4	

Table 3-13: Example of risk of collision: Birds Receptor Score (RS)

receptor	**turbine**	**species**	**RS- Receptor Score**	**Killard site**
	Wave	black-thoated diver	3	
		great nothern diver	3	
		razorbill	2	x
		common goldneye	2	
		nothern gannet	2	x
		roseate tern	2	
		common eider	2	
		long-tailed duck	1	
		great skua	1	
		great-crested grebe	1	
		artic skua	1	
		little auk	1	
		nothern fulmar	1	x
		european storm-petrel	1	
		common gull	1	x

Receptor sensitivity score (RSS) is:

RSS marine mammals = $0.1 * (PSa * RS)^{0.68} = 0.1*(1.75 * 3)^{0.68} = 0.31$

RSS birds = 0.1 * (PSa * RS) $^{0.68}$ **= 0.1*(1.75 * 2)**$^{0.68}$ **= 0.23**

Step 3 : Refined Receptor Sensitivity Score

1. Identification of species in the red list (Table 3-14**)**

Table 3-14: Table Red List

Red 'regulatory protected' list		RS-Receptor Score
Mysticetes	Sei whale Fin whale North Atlantic right whale	5
Delphinids	Long-finned pilot whale Risso's dolphin Killer whale Striped dolphin Rough-toothed dolphin Common bottlenose dolphin	
Large odontocetes	Sperm whale	
Porpoise	Harbour porpoise	
Diadromous bony fish	Sturgeon	
Zostera noltii beds		
Maerl beds		
Zostera marina beds		

Presence of: harbour porpoise, bottlenose dolphin (protected species in the red list) in the Killard site area.

RSS marine mammals changes to RSS = 0.31 to RSS= 1

2. Receptor seasonal data availability:

Presence of marine mammals is around all year long: **RRSS = 1**

EIS marine mammals (collision risk) = RRSS x 100 x (negative function: -1) = -100

Birds: migratory species. EIS birds varies as

- Feb to April RRSS = 0
- August to November RRSS = 0
- April to June RRSS = 0.23

EIS birds (collision risk) = RRSS x 100 x (negative function: -1) = -23

In that specific case, the EIAM aims at keeping the worst EIS. So the presence of protected marine mammals constitutes serious issues in term of environmental and in particular for collision risks.

4 CONCLUSIONS

The assessment of offshore structure and equipment reliability is a complex and multi-variate problem which demands a considerable level of detailed performance data in order to achieve accurate predictions of component, sub-system and system life. Based on operational experience, gained often in unforgiving environments, well-established industries such as those involved in offshore oil and gas extraction have gone to great lengths to establish a means of recording failures and sharing data (i.e. the OREDA consortium). The MRE industry is still in its infancy and the lack of deployment hours means that relevant data is sparse, or for some designs, non-existent. At present, reliability predictions have to be based on data from other sectors with the understanding that more accurate assessments will be possible once more experience has been accrued.

With this in mind a statistical approach to reliability assessment is used within the DTOcean Tool in the first instance to generate failure statistics for the various hierarchical levels of an MRE array and relationships between components, assemblies, sub-systems and systems. These results are then used to generate stochastic failure events in order to plan suitable maintenance intervals. Within this report a summary of the statistical calculation method has been summarised, including the sources of 'default' failure statistics that will be included in the Tool database. It is envisaged that these values can be updated by the User if more relevant values are known. In order to highlight the influence of individual failure rates on sub-system performance, two example case studies have been presented, comparing the respective failures of two different mooring configurations.

With regard to the Economics moorings and foundations have a big impact on the farm final LCOE, with implications throughout the project lifecycle, in terms of procurement, installation and O&M costs. Therefore, it is necessary to understand how the cost of these components changes according to the project characteristics. Although device characteristics will define whether the choice is for moorings or foundations, there are design choices for each that will depend on site characteristics, with an associated cost.

It's the aim of DTOcean to provide a low LCOE technically feasibly solution for the deployment of a marine energy array. This deliverable presented the procurement cost variations for the most relevant components of the moorings and foundations subsystem, which will be used to determine the cost of the solution produced by the Work Package 4 module.

The final aspect taken into consideration in this deliverable is the Environmental Impact Assessment Module (EIAM) which is designed to take into account environmental issues within the DTOcean tool. It is based on several functions and logical pathways to assess the main environmental issues generated by wave and tidal arrays. This report describes the environmental effects relates to parts associated to mooring and foundations. Only the operational phase is considered here, as environmental issues related to moorings and foundations during installation and maintenance phases are treated separately and linked to the DTOcean 'Lifecycle Logistics' module. As such, considered adverse environmental effects are therefore footprint, collision risks (mainly entanglement) and noise (produced by mooring chafing). Reef effect is also considered as a positive environmental effect. Overall, a generic architecture has been designed to implement the environmental assessment. It is based on three main steps that allow the user to get environmental impact score depending about the details of environmental data provided (by the user or the DTOcean database). Specific functions and calibrations were developed for each environmental effect associated to mooring and foundations based on bibliographic data when available or on empirical or 'best guess' approaches otherwise. This set of functions feeds the EIAM to ultimately provide environmental impact scores (EIS).

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6 ACRONYMS

MRE	Marine Renewable Energy
MODU	Mobile Offshore Drilling Unit
FPSO	Floating Production, Storage and Offloading
RAM	Reliability Assessment sub-Module
MTTF	Mean Time To Failure
RPN	Risk Priority Number
OREDA	Offshore and onshore Reliability Data
DNV	Det Norske Veritas
QC/QA	Quality Control/Quality Assurance
RM3	Reference Model 3
AEP	Annual Energy Production
CAPEX	Capital Expenditures
DR	Discount Rate
HMPE	High Modulus Polyethylene
MBL	Minimum Breaking Load
LCOE	Levelized Cost of Energy
O&M	Operations and Maintenance
EIAM	Environmental Impact Assessment Module
EIS	Environmental Impact Score

PS	Pressure Score
PSa	Pressure Score Adjusted
WS	Weighting Score
RSS	Receptor Sensitivity Score
RRSS	Refined Receptor Sensitivity Score
WP	Work Package
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CMS	Convention on Migratory Species
ASCOBANS	Agreement of the Conservation of Small Cetaceans in the Baltic North East Atlantic Irish and North Seas
ACCOBAMS	Agreement of the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic Sea
MSFD	Marine Strategy Framework Directive

7 APPENDIX A1

References for mooring component failure statistics.

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