Deliverable 5.6: Report on logistical model for ocean energy and considerations

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D5.6: Report on logistical model for ocean energy array and considerations

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Abstract

This report presents the Deliverable 5.6 of the DTOcean project. It consists of a comprehensive description of the logistic functions and associated installation module (logistical model) forming the installation module developed within the frame of the global DTOcean tool. The overriding goal of Deliverable 5.6 is to disclose the structure and content of the computational installation module.

Deliverable 5.6 covers the entire scope of the installation phase by describing logistic functions dedicated for all array sub-components of an ocean energy project. Nine logistic phases responsible for the characterization and evaluation of assembly, transportation and installation of devices/components/sub-systems are detailed.

Specialized literature surveys and discussions with offshore experts, along with close communications with other module and database developers of DTOcean, have led to the transcription of highly complex and project specific logistic operations into standardized and yet flexible numerical procedure for their analysis. Each logistic phase is first analysed in terms of feasibility with respect to the maritime infrastructure. The assessment of feasible logistic solutions advances towards the performance appraisal.

A coherent computational package envelopes these logistic functions to supply a standalone application for the DTOcean global tool. Deliverable 5.6 also addresses the description of the logistic model. The context, requirements, architecture and functional specifications are detailed.

Lastly, the present report illustrates the use of the installation module by testing some realistic scenarios. Comparing with a high-level assessment exercise of a maritime contractor, validity of the results returned by the installation module are discussed. A section dealing with the sensitivity of some key input parameters to the results concludes the document.

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1 INTRODUCTION

1.1 OBJECTIVES

This report presents the Deliverable 5.6 – Report on logistical model for ocean energy array and considerations – which explains how the numerical tool supporting the assessment of the installation phase during a wave or tidal energy project was developed.

The objectives of D5.6 can be summarized as follows:

- Define the scope of the installation module, in particular by enumerating and describing the logistic phases developed to model the installation activities of all the elements considered by the DTOcean tool.
- Describe the logistic functions, and in particular, those associated with the installation module.
- Indicate the inputs from the different DTOcean modules required for the evaluation and accomplishment of the process.
- Describe the operation sequence behind each of the installation logistic phases, indicating the different steps and the different installation options.
- Indicate and evaluate the possible vessels and equipment required to accomplish the installation and their respective inter-matching, also together with the port.
- Evaluate the performance of the logistic phases on four different levels: time scheduling, cost assessment, environmental impact and risk analysis.
- Disclose the position of the installation module in the context of the global DTOcean software tool.
- Debug, test and verify partially the installation module by simulating relevant case studies as well as performing sensitivity analysis

1.2 SCOPE OF THE REPORT

Deliverable 5.6 builds upon the work previously carried out in the lifecycle logistics module, which can be summarized as follows:

- Deliverable 5.1 [1]: high level architecture and flow charts of the WP5 lifecycle logistics,
- Deliverable 5.2 [2]: extensive review of the logistic requirements associated with the installation of wave and tidal energy arrays
- Deliverable 5.3 [3]: construction of a database for maritime infrastructure
- Deliverable 5.4 [4]: Excel spreadsheets detailing the underlying logistic function of the installation module

The first three deliverables above have established the framework to program the installation module for the global DTOcean software package. This allowed the design and development of logistic functions under Deliverable 5.4 [4], forming the basis for the code development of the installation module in Deliverable 5.5.

The present report organizes and complements the results of Deliverables 5.4 & 5.5. The main focus of the report is on the installation module as part of WP5 while the logistic functions developed for the O&M module have only been briefly tackled in D5.6 (further depicted in D6.5 for details). Following the structure of the DTOcean global tool, the installation module is formulated around three core array-sub-components, namely: the electrical infrastructure, the moorings & foundations and the wave & tidal energy devices.

Starting from the mobilization and port assembly of sub-systems, the installation module comprises the transport from port to site plus the dedicated offshore operations to put in place the full ocean energy array. From the core sub-array components of ocean energy arrays: electrical infrastructure components (E), moorings & foundations components (M&F) and wave & tidal devices (D), Figure 1-1 depicts the ocean array elements considered within the installation module, which were selected based on the scope of upstream modules within the DTOcean global tool,

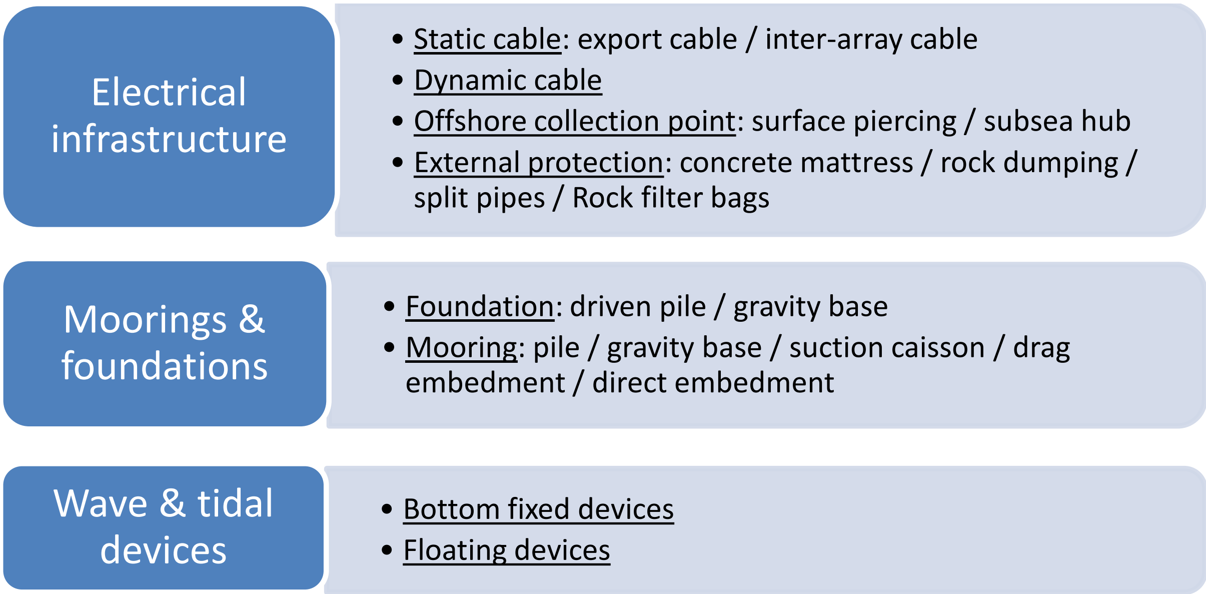


Figure 1-1 Array components covered by the DTOcean WP5 installation module

1.3 METHODOLOGY

Since Deliverable 5.6 consists of a comprehensive report relying on the work of tasks 5.4 and 5.5, it is relevant to present herein the approach employed to carry out these two tasks. The path of task 5.4 was to relate the logistic requirements - identified in D5.2 - with the parameters of the maritime infrastructure database (D5.3).

For this purpose, a set of logical and mathematical functions was developed around four areas:

- Feasibility functions (sub-task 5.4.1): functions to assess feasibility/suitability of a certain infrastructure (port, vessel or equipment) to perform a specific activity (e.g. weight of component A ≤ lifting capacity of vessel B) and if applicable the number of infrastructure units needed to complete it,

- Performance functions (sub-task 5.4.2): functions to determine time and costs of each logistic activity as a function of the infrastructure specifications, array logistic requirements and site characteristics,
- Risk functions (sub-task 5.4.3): functions to identify, analyze and assess the main risk associated with marine operations,
- Environmental functions (sub-task 5.4.4): functions to determine the potential environmental impact of specific logistic activities.

The above four categories can be split into two subsets: the dedicated logistic functions and the transversal logistic functions. The former are grouped around individual logistic phases sharing common characteristics, while the latter are transversal to all logistic phases. Figure 1-2 illustrates this arrangement. Once these functions are established, the next step consists of integrating them together to form a coherent model. Additional features are introduced to assemble these functions. Ultimately, the aim is to obtain a code capable of providing logistic solutions in response to any array layout configurations that may be designed by the upstream modules (hydrodynamics, electrical infrastructure and moorings & foundations) and the end-user specifications.

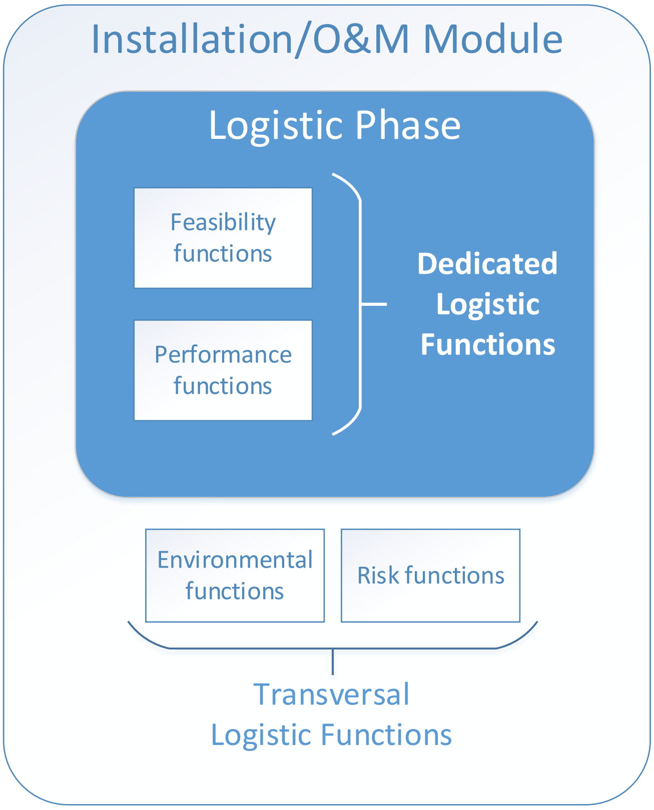


Figure 1-2 Framework of the Logistic models

Finally, the last step of tasks 5.4 and 5.5 concerns the testing and verification exercise. This crucial step should start with thorough debugging work to ensure the smoothness of the simulation regardless of the inputs (as long as they are within meaningful ranges). In parallel, a testing phase should be conducted with the objective to make a critical assessment of the outputs generated by the installation module. In short, the three step process previously described can be seen graphically, as presented in Figure 1-3.

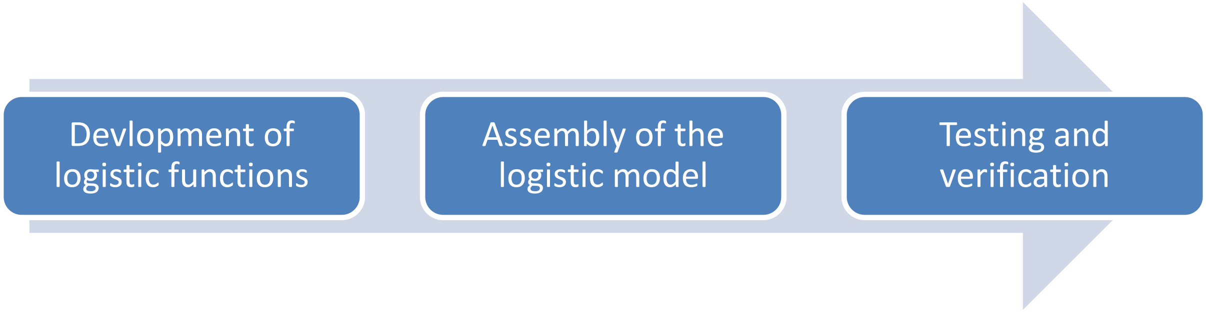


Figure 1-3 Three steps procedure to carry out the work in tasks 5.4 & 5.5

1.4 OUTLINE

This report is articulated around three core content-oriented chapters following this introduction:

- Chapter 2 describes the logistic functions as developed in task 5.4,
- Chapter 3 depicts the structure and functional organization of the installation module,
- Chapter 4 reports the results obtained through the testing and verification exercise of the installation module.

2 LOGISTIC FUNCTIONS FOR OCEAN ENERGY ARRAYS

Chapter 2 relates to task 5.4 of the DTOcean project. In the following sections, the logical and mathematical formulations delivered for this task will be presented.

2.1 FRAMEWORK FOR THE DEVELOPMENT OF THE LOGISTIC FUNCTIONS IN THE DTOCEAN TOOL

Having identified the critical logistic requirements governing the selection of the most suitable maritime infrastructure in D5.2 and constructed a customized database of ports, vessels and equipment in D5.3, the natural following step was to establish a meaningful link between these two outcomes with the view to have a flexible systematic approach to simulate marine operations. This led the logistic module developers WP5 leaders to draw an Excel template mimicking the logical formulation of a computer program.

2.1.1 SCOPE AND ARCHITECTURE OF THE LOGISTIC FUNCTIONS

In this section, we introduce the reader to the structure of the above mentioned Excel spreadsheets. Each Excel sheet is composed of six tabs as summarized in Table 2-1. One Excel spreadsheet must be drawn for each logistic phase. Kicking off with the exhaustive list of required inputs necessary to run the logistic functions in the installation module, each subsequent Excel tab incrementally poses the foundations for the definition and assessment of a logistic phase. Each input is identified with the module where it comes from, its description, its Python name, and its unit of measurement, its format and some additional comments for further description.

Table 2-1 Description of the tabs forming the Excel template for the logistic functions

Tab name	Tab content
Inputs	List of expected inputs from upstream WPs and the global database
Operation sequence	Flow-chart breakdown of the logistic phase into individual logistic operations and decision-making trees from mobilization to demobilization
Vessel & Equipment (V&E) combinations	List of vessel(s) types and equipment types combinations that can carry out this logistic phase
Feasibility functions	Relationship between array physical parameters and requirements for the port, vessels and equipment specifications
Matching	Compatibility check for the port/vessels and vessels/equipment
Performance functions	Methods employed for the schedule time assessment and the cost assessment

The extensive literature review in D5.2 [2] served as a basis to fill out these Excel sheets. However, in comparison to the content of D5.2, important adaptations to the design and structure of the DTOcean software have been meticulously considered. In particular, most of the effort was to enter in a close dialogue with the database developers and the upstream design module developers to ensure the communication of inputs-outputs would be smooth.

The flow of inputs-outputs circulating in the logistic functions is schematically represented in Figure 2-1. From top to bottom, the logistic functions progressively carry out:

- The definition of the logistic phase in terms of operation sequencing and default vessel(s) & equipment combinations
- The characterization of the logistic requirements (first step of the feasibility functions)
- The selection of the suitable maritime infrastructure (second step of the feasibility functions)
- The performance assessment of all feasible logistic solutions in terms of time efficiency, cost and environmental impact.

On the left side of Figure 2-1, one can find all “external” inputs originating from the end-user or generated by upstream computational modules (including the array hydrodynamics, the electrical sub-system and the moorings & foundations modules). On the right side, the “internal” inputs accounting for the maritime infrastructure database and default values are placed. Unlike “external” inputs, “internal” inputs are established by the developers of the logistic functions and the installation module. Details of these inputs, intermediate outputs and final outputs will be provided in the remainder of the present document.

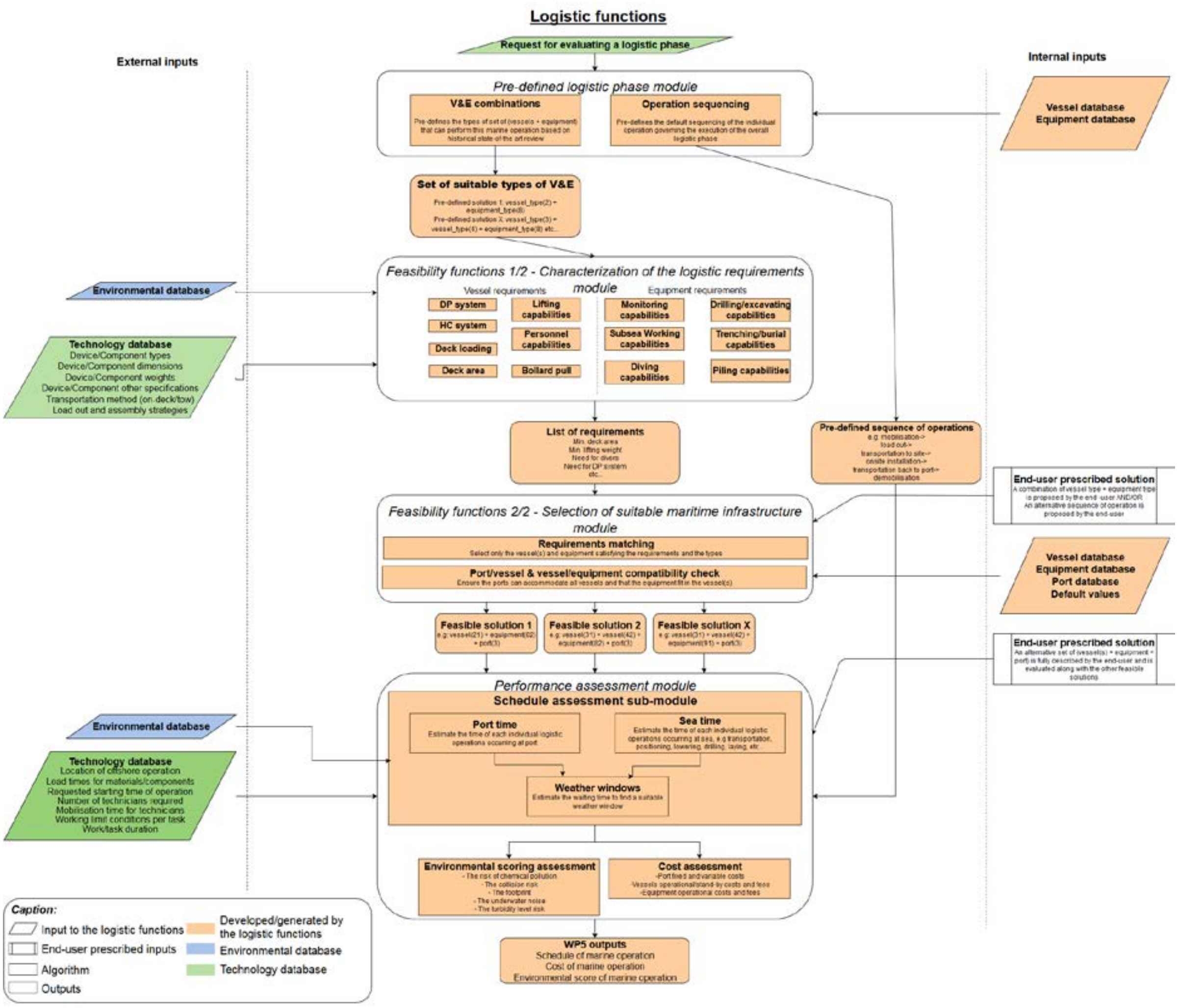


Figure 2-1 Flow chart representing the architecture of the logistic functions and their respective I/O communication

2.1.2 DEFINITION OF A LOGISTIC PHASE: OPERATION SEQUENCING AND VESSEL(S) & EQUIPMENT COMBINATIONS

It was necessary to standardize some aspects of the logistic phase assessment to facilitate the code development and future integration into the global DTOcean suite of tools. For instance, it was decided to implement a common set of individual logistic operations in the sequence breakdown and Figure 2-2 illustrates this standardization. Any logistic phase shall start with the same first three operations, namely: mobilization, assembly at port and vessel preparation & loading. Following these port activities, other operations occur at sea which are specific to each logistic phase. Finally, the demobilization is always concluding the sequence once the vessel, equipment and personnel have returned to port.

Mobilisation

- Until arrival of the vessel(s) + equipment at the requested port

Assembly at port

- Any assembly work of sub-systems and components at port

Vessel preparation & loading

- Include any out-fitting and re-engineering work, loading of components & equipment on vessel deck, sea-fastening, crew preparation and boarding

… specific logistic operations …

- Specialized logistic operations to be detailed separately for each logistic phase such as transportation, positioning, cable laying, pile hammering, etc.

Demobilisation

- Ensure the vessel(s) and equipment are ready for another mission

Figure 2-2 Standardized operation sequence of all logistic phases

In the Excel tab dedicated to the “vessel & equipment (V&E) combinations“ it was imposed to select maritime infrastructure among the vessel types and equipment types included in the logistic database. It should be noted that these vessel and equipment types have suffered minor changes since the delivery of D5.3 [3]. This is due to rearrangements based on discussions with other DTOcean module developers as well as recommendations from industrial partners of the project. Table 2-2 and

Table 2-3 provide the updated list of vessel and equipment types respectively.

Table 2-2 List of vessel types considered in DTOcean

Vessel Class	**Vessel type (Acronyms)**	
Heavy Lift Installation	Jack-up	Jack-up Vessel (JUPV)
		Jack-up Barge (JUPB)
	Heavy lift (no jack- up)	Crane Vessel (CV)
		Crane Barge (CB)
	Construction Support Vessel (CSV)	
Offshore Service	Cable installation	Cable Laying Vessel (CLV)
		Cable Laying Barge (CLB)
	Dredger	
	Rock Dumping Vessel (RDV)	
	Anchor Handling Vessel (AHV or AHT or AHTS)	
	Tugboat	
Offshore Support & Maintenance	Multicat (Workboat)	
	Crew Transfer Vessel (CTV)	
	Accommodation	Accommodation Barge (AB)
		Accommodation Vessel (AV)
	Platform Support Vessel (PSV)	
	Helicopter	
Standby Cargo	Barge	
Other	Fit-For-Purpose Vessel (FFPV)	

Table 2-3 List of equipment types in DTOcean

Equipment Types	
ROV Systems	Inspection
	Workclass
Offshore Diving Teams	
Cable Burial Tools	Cable Burial ROVs
	Cable Burial Ploughs
	Tracked Cable Burial Vehicles
Subsea Excavating Tools	
External protection equipment	Concrete Mattress
	Split Pipe
	Rock Filter Bag
Pilling equipment	Hammer
	Drilling Rigs
	Vibro-driving

2.1.3 FEASIBILITY FUNCTIONS AND SAFETY FACTORS

Having defined the combinations of vessel(s) and equipment that are suitable for carrying out one logistic phase, it should be ensured that the specifications of the maritime infrastructure selected satisfies the physical and technical characteristics of the sub-systems or components to be installed. This task corresponds to the establishment of logistic requirements as initiated in D5.2. In the logistic functions Excel template, two successive tabs tackle this issue, respectively: the "feasibility functions" and "matching".

The feasibility functions relate inputs to the parameters of the vessel, port and equipment databases. Simple mathematical and Boolean formulations filter out the maritime infrastructure non-complying with the logistic requirements. While the feasibility functions only deal with the interactions between maritime infrastructure and physical elements of the ocean energy array, the "matching" tab goes one step further. In fact, this worksheet verifies the compatibility within the maritime infrastructure. In other words, it consists of new feasibility functions which ensure that there is no conflict in using the couples port/vessel and vessel/equipment together.

While constructing these feasibility functions, it transpired that it was necessary to make assumptions in order to simplify the process's complexity while maintaining physical meaningfulness. For instance, the available inputs to the installation module cannot inform us about the accurate optimal deck layout when transporting components/sub-systems together with the required equipment to site. Therefore, if nothing is mentioned, it was assumed that all elements are stacked together and laying on their two principal dimensions with only one layer possible vertically (i.e. no piling of component/equipment).

Beyond these simplifications, it was acknowledged that the offshore industry often uses safety factors to reflect such uncertainties and also to account for a margin of error in a harsh environment. Following this recommended practice, safety factors on most of the simplified feasibility functions implemented in the logistics installation module have been applied. Table 2-4, Table 2-5 and Table 2-6 summarize the core aspects scrutinized during the feasibility functions and their associated safety factors for the port, vessels and equipment respectively.

Table 2-4 Port feasibility functions and safety factors

	Port parameter verified (unit)	Methodology	Safety factor (in %)
Terminal/Dock capabilities	Terminal dock size area (m²)	Ensure the largest sub-system can individually fit in the dock size area	20%
	Max. terminal load bearing (t/m²)	Ensure the maximum loading one individual sub-system can apply on the terminal does not exceed the max. terminal load bearing specified in the port database	20%
Load out capabilities	Marine slipway (yes/no)	Ensure the availability of the appropriate load-out equipment at port depending on the transportation method and load-out strategy of the device	N/A, 20% on the dimensions of the dry-dock
	Dry dock (yes/no and dimensions)		

Table 2-5 Vessel feasibility functions and safety factors

	Vessel parameter verified (unit)	Methodology	Safety factor (in %)
Deck capabilities	Deck size area (m^2)	Ensure that as many sub-systems as possible to be transported fit the deck size area	20%
	Max. Deck loading (t/m^2)	Ensure the loading of one sub-system does not exceed the one of the vessel deck	20%
	Maximum cargo (t)	Ensure the total weight on the deck does not exceed the maximum payload	20%
Lift capabilities	Onboard crane capacity (t)	Ensure the maximum weight of one individual sub-system does not exceed the on-board max. lifting capacity	20%
Towing capabilities	Bollard pull (t)	Verify that the mass of the element to be towed is inferior to the vessel bollard pull	20%
Turntable capabilities	Turntable/reel - loading capacity [t]	Ensure the turntable/reel loading capacity of the cable laying platform is sufficient for the sum of cable weights to be loaded	20%
	Turntable/reel - inner diameter [m]	Ensure the inner radius of the turntable/reel is higher than the cable minimum bending radius	20%
Dredging capabilities	Dredge Depth [m]	Ensure the dredging depth capabilities of the dredger vessels is higher than the bathymetry within the cable route	20%
Anchor handling capabilities	Winch rated pull [t]	Ensure the winch pulling capabilities of the anchor handling vessels are sufficient to perform the installation of the mooring systems	0%
	Winch drum capacity [m]	Ensure the winch drum capacity of the anchor handling vessels are sufficient to perform the installation of the mooring systems	0%
Jack-up capabilities	Maximum payload (t)	Ensure the total weight on the deck does not exceed the maximum payload	20%
	Leg max. operating water depth (m)	Ensure the leg max. operating depth is suitable for the working site bathymetry	20%

Table 2-6 Equipment feasibility functions and safety factors

	Equipment parameter verified (unit)	Methodology	Safety factor (in %)
ROV	ROV manipulator max. grip force (N)	Verify the suitability of the ROV arm manipulator for performing wet mate connections.	20%
	Depth rating (m)	Ensure the depth rating of the onboard ROV inspection class is superior to the maximum operating water depth.	0%
Diver team	Depth rating (m)	Ensure the depth rating of the diving team is superior to the maximum operating water depth	0%

Piling equipment	Max. pile sleeve diameter (m)	Ensure the piling equipment has a sleeve diameter exceeding the maximum diameters of ALL piles to be installed at site	20%
	Max. pile weight capacity (t)	Ensure the piling equipment has a weight capacity exceeding the maximum individual weight among ALL piles to be installed at site	20%
	Depth rating (m)	Ensure the depth rating of the piling equipment is superior to the maximum water depth of the foundations	0%
Cable Burial Tool	Max. Trench depth [m]	Ensure the max. trench depth of the cable burial tool is superior to the maximum burial depth within the cable route	0%
	Max. Cable diameter [mm]	Ensure the max. cable diameter of the cable burial tool is superior to the maximum cable cross section diameter	0%
	Min. Cable bending radius [m]	Ensure the min. bending radius of the cable burial tool is superior to the min. bending radius of the cable	0%
	Max. Operating depth [m]	Ensure the depth rating of the cable burial tool, is superior to the maximum water depth of the cable route with burial requirements	0%
Split Pipes	Max. Cable size [mm]	Ensure the max. cable size of the cast-iron pipes is superior to the maximum cable cross section diameter	0%
	Min. Bending radius [m]	Ensure the min. bending radius of the cast-iron pipes is superior to the min. bending radius of the cable	0%

2.1.4 PERFORMANCE FUNCTIONS AND CONCLUSION

The last tab of the logistic functions Excel template intends to describe the methods to estimate the time per individual operation and their associated costs.

Inevitably, the exercise of populating this Excel logistic functions template for all logistic phases involves the adaptation and simplification of complex and highly project specific issues. In practice, a project developer would face challenging multi-factorial decision making processes. This is why the key ambition of the DTOcean installation module is rather to eliminate unrealistic logistic solutions than providing a decision making tool suitable in any conditions. Yet, valuable feedback received from industrial experts bestows the acceptability of the underlying assumptions. One should also keep in mind that the methodology to assess one logistic phase allows significant flexibility for the end-user. In fact, it is expected that all assumed default values for evaluation can be overwritten. Furthermore, additional logistic phases or customization of the ones already implemented should be accessible to the advanced user due to the open-source nature of the DTOcean global tool.

In the following sections, the 9 logistic phases as part of the scope of the installation module will be described in detail following the Excel sheets that were delivered in D5.4 [4]. The equivalent 8 logistic phases for the O&M module have been characterized in Deliverable 6.5 [5]. Due to the open source aspect of the tool, In the future, a developer can improve existing or develop additional logistic phases, to extend the scope or detail the further the description of each task in a logistic phase.

2.2 INSTALLATION OF DEVICES

This logistic phase is related to the installation of wave and tidal devices (Figure 2-3). In this section, the reader will find a description of how the devices are transported, positioned and connected at the desired location using the logistic phase framework:

- Listing of the required inputs from the upstream modules (section 2.2.1),
- Description of the operation sequence during installation (section 2.2.2),
- Possible combinations of vessels and equipment (section 2.2.3),
- The minimum requirements associated with the maritime infrastructures (section 2.2.4).
- The time and met-ocean limit conditions associated to each operation (section 2.2.5).

Figure 2-3 Wave and tidal device installation

2.2.1 INPUTS

The list of inputs from the different WPs and their corresponding format and unit, for the installation of moorings is the following (Table 2-7):

Table 2-7 List of inputs required for the installation of devices logistic phase

#	Module	Parameter	Python name (panda name: parameter name)	Unit	Format
1	Data base	Points of the grid coordinate system in the lease area	site: x coord	[m]	float
2			site: y coord	[m]	float
3			site: zone coord	[-]	string
4		Bathymetry	site:bathymetry	[m]	float
5		Seabed Conditions - Geophysics/Geotechnics	site:soilt type	[-]	string
6		Date and time of the measure met-ocean historical data	met-ocean:year	[-]	integer
7			met-ocean:month	[-]	integer
8			met-ocean:day	[-]	integer
9			met-ocean:hour	[-]	integer
10		Resource met-ocean data (wave): (Hs, Tp)	met-ocean:wave Hs	[m]	float
11			met-ocean:wave Tp	[s]	float
12		Resource met-ocean data (wind): wind speed	met-ocean:wind speed	[m/s]	float

13		Resource met-ocean data (tide): tidal speed	met-ocean:tide speed	[m/s]	float
14		Device dimensions	device:dimensions	[m]	float
15		Device dry mass	device:dry mass	[t]	float
16		Sub-system list	device:sub system list	[-]	string
17		Sub-system dimensions	device:sub system dimensions	[m]	float
18		Sub-system dry mass	device:sub system dry mass	[kg]	float
19		Assembly Strategy of the sub-systems of one device	device:assembly strategy	[-]	text
20		Estimated assembly duration of one device	device:assembly duration	[h]	float
21		Load-out strategy	device:load out	[-]	string
22		Device and/or sub-assembly transportation method	device:transportation method	[-]	string
23		Required towing bollard pull of the device/sub-assembly	device:bollard pull	[t]	float
24		Estimated overall duration of positioning and connection to moorings/foundations	device:connect duration	[h]	float
25		Estimated overall duration of disconnection	device:disconnect duration	[h]	float
26		Operational Limit Conditions during the device positioning and connecting/disconnecting operation	device:max Hs	[m]	float
27			device:max Tp	[s]	float
28			device:max wind speed	[m/s]	float
29			device:max current speed	[m/s]	float
30		Device sub-system ID	sub_device:id	[-]	string
31		Device sub-system dimensions	sub_device:length	[m]	float
32			sub_device:width	[m]	float
33			sub_device:height	[m]	float
34		Device sub-system dry mass	sub_device:dry mass	[kg]	float
35		Assembly location of the device sub-system	sub_device:assembly location	[-]	string
36		Estimated assembly duration of the device sub-system	sub_device:assembly duration	[hour]	float
37	Hydro dynamic	Position of devices in the UTM grid coordinate system	device:x coord	[-]	float
38			device:y coord	[-]	float
39			device:zone	[-]	string
40	M&F	Foundations/anchors coordinates	found:location X coord foundation	[-]	float
41			found:location Y coord foundation	[-]	float

42	Logistics	Vessel database	vessels:	various	floats and strings
43		Equipment database	equipments:	various	floats and strings
44		Port database	ports:	various	floats and strings

2.2.2 LOGISTIC PHASE SEQUENCING

In Figure 7-1 in Appendix 7.1.1 the high level operation sequence required to conduct this specific logistic phase is presented. After mobilization of the device(s) and required gear, depending on the transportation method, on deck or towed, the assembly can be either done at a quay or at a dry-dock.

If it is transported on deck, the assembly should be at a quay and two different load out methods exist. The gear can be either lifted onto the vessel deck before seafastening or placed on a steel rail or trailer and translated onto the vessel deck before seafastening. After adequate seafastening, the gear is transported on the vessel deck for positioning.

If it is transported by towing, two assembly options exist: assembly at a quay or assembly at a dry-dock. The assembly at quay is similar to the one when the device is transported on deck but instead of being placed on the vessel it is placed in the water ready to be transported. If the assembly is done at a dry-dock, it is only necessary to flood the dry-dock before transportation by towing to site once assembly is completed.

After being transported the positioning and connection phase begins. Depending on whether it is a floating or fixed bottom device it will be either connected to the moorings or the foundations respectively. Finally, the connection to the electrical system is performed before demobilization.

2.2.3 VESSEL AND EQUIPMENT TYPE COMBINATIONS

The different possible vessels and equipment to be used are presented. They reflect the different possible methods presented before and the necessary operation equipment to accomplish the logistic phase. Depending on the transportation mode different vessels combinations are considered suitable. A Multicat is assumed as a support vessel together with an inspection class ROV.

Table 2-8 Vessel and Equipment combination for the Installation of devices

#	Transportation Mode	Vessel 1 - Installation		Vessel 2 - Support		Equipment 1 – Support	
1	On deck Transportation	1x	Crane vessel	1x	Multicat	1x	Inspection Class ROV
2		1x	Jack-up vessel	1x	Multicat	1x	Inspection Class ROV
3		1x	Construction Support Vessel	1x	Multicat	1x	Inspection Class ROV
4		1x	Fit for Purpose (FIT)	1x	Multicat	1x	Inspection Class ROV
5		1x	Crane barge + Tugboat	1x	Multicat	1x	Inspection Class ROV
6		1x	Jack-up barge + Tugboat	1x	Multicat	1x	Inspection Class ROV

7	Tow Transportation	1x	Anchor Handling Vessel	1x	Multicat	1x	Inspection Class ROV
8		1x	Tugboat	1x	Multicat	1x	Inspection Class ROV
9		1x	Fit for Purpose (FIT)	1x	Multicat	1x	Inspection Class ROV

2.2.4 FEASIBILITY FUNCTIONS

The feasibility functions are used to translate the inputs into maritime infrastructure parameters. It reflects the minimum infrastructure requirements regarding the inputs for ports, vessels and equipment. These are calculated considering that at least one device is required to be installed per trip. The actual number of devices installed per trip is obtained during the performance assessment, which varies depending on each suitable vessel characteristics. It's also assumed that all devices requires an installation vessel with positioning capabilities (Dynamic Positioning or Jack-up legs).

Also relevant for computing the area, load and lifting capabilities required, is the assembly strategy. In particular for devices with support structures where the overall weight and dimensions to be considered, may vary considerably whether these are assembled together at port, or at site. The definition of the assembly strategies is specified in Table 7-14.

Table 2-9 Port infrastructure requirements

	PORT			
	Upstream inputs	**Function**	**Eval.**	**Logistic parameter**
Area / Load capabilities	Sub-system (SS) Dimensions [m]	$SUM(SS\ lenght\ \times\ SS\ width)$	≤	Terminal dock size area [m²]
	Device (DEV) Dimensions [m]	$\frac{DEV\ dry\ mass}{1000 \times DEV\ lenght \times width}$	≤	Max. terminal load bearing [t/m²]
	Device (DEV) dry mass [kg]			
	Device (DEV) and/or sub-systems (SS) transportation method (-)			
	Load-out Strategy (-)			
	Sub-system (SS) dry mass [kg]			
Dry-dock capabilities	Device (DEV) and/or sub-systems (SS) load-out strategy (-)	If transportation == 'tow' and Load-out Strategy == 'lift away': *Terminal = Dry-dock* or *Terminal = Quay, Dry-dock*	==	Type of terminal [Quay/Dry-dock]
	Load-out Strategy (-)			

Table 2-10 On-deck transportation vessel requirements

	CRANE BARGE / CRANE VESSEL / CONSTRUCTION SUPPORT VESSEL / JACK-UP BARGE / JACK-UP VESSEL			
	Upstream inputs	**Function**	**Eval**	**Logistic parameter**
Area / Load capabilities	Device (DEV) Dimensions [m]	if AS is ([A,B,C,D]) : $DEV\ lenght \times width$	≤	Free deck space [m²]
	Sub-system (SS) dimensions [m]			
	Assembly Strategy (AS)			

		if AS is ([A,B,C],D) : max[1] $(SS\ lenght \times width)$		
	Device (DEV) dry mass [kg] Sub-system (SS) dry mass [kg] Assembly Strategy (AS)	if AS is ([A,B,C,D]) : $\frac{DEV\ dry\ mass}{1000}$ if AS is ([A,B,C],D) : sum[2] $\left(\frac{SS\ dry\ mass}{1000}\right)$	≤	Max Deck Cargo [t]
	Device (DEV) dry mass [kg] Device (DEV) Dimensions [m] Sub-system (SS) dry mass [kg] Sub-system (SS) dimensions [m] Assembly Strategy (AS)	if AS is ([A,B,C,D]) : $\frac{DEV\ dry\ mass}{1000\ \times\ DEV\ lenght \times width}$ if AS is ([A,B,C],D): *max* [3] $\left(\frac{SS\ dry\ mass}{1000\ \times\ SS\ lenght \times width}\right)$	≤	Max Deck Load [t/m²]
Lift Capabilities	Device (DEV) dry mass [kg] Sub-system (SS) dry mass [kg] Assembly Strategy (AS)	if AS is ([A,B,C,D]) : $\frac{DEV\ dry\ mass}{1000}$ if AS is ([A,B,C],D) : sum[2] $\left(\frac{SS\ dry\ mass}{1000}\right)$	≤	Crane weight capacity [t]
Positioning (non jack-up)	*none*	$DP > 0$	>	DP [-]
Positioning (jack-up)	*none*	$DP > 0$	>	DP [-]
	Device position [x,y,z] Bathymetry [m]	*max(bathymetry(device* position*))*	≤	Leg Operating Water Depth [m]

Table 2-11 Tow transportation vessel requirements

	AHV			
	Upstream inputs	**Function**	**Eval.**	**Logistic parameter**
Tow capabilities	Required towing bollard pull of the device [t]	*Required towing bollard pull of the device/component*	≤	Vessel bollard pull [t]

Table 2-12 ROV requirements

ROV system

[1] If the support structure is installed separately, the geometric disposition of the different sub-systems is not known, therefore it's assumed that the area required by the device corresponds to the largest dimension of one of the other 3 sub-systems A, B or C.

[2] If the support structure is installed separately, it's assumed that the weight of the device corresponds to the sum of the other 3 sub-systems A,B and C dry-mass.

[3] If the support structure is installed separately, the geometric disposition of the different sub-systems is not known, therefore it's assumed that the deck loading required by the device corresponds to the largest loading of one of the other 3 sub-systems A, B or C.

	Upstream inputs	Function	Eval.	Logistic parameter
ROV class	-	*Inspection Class*	==	ROV Class [-]
Performance capabilities	Device position [x,y,z]	*max(bathymetry(device position))*	≤	ROV depth rating [m]
	Bathymetry [m]			

2.2.5 PERFORMANCE FUNCTIONS

Table 2-13 outlines the underlying methods and input data relevant to the time assessment of each logistic operation. Values or source of the values for both the durations and the Operational Limit Conditions (OLC) are given. These are approximate values, which have been derived from literature review and industrial expertise (references included where possible). To obtain these values, there was the need to simplify complex and highly project specific tasks, as the actual times and limits require a much more complex assessment between a wide range of factors, from the vessel and equipment characteristics to the crew experience, which are outside the scope of this tool. Since the devices are not designed by the DTOcean tool, most input data required to estimate the time and cost associated with the installation of ocean energy devices originates from the end-user.

Table 2-13 Logistic operation details considered for the installation of devices

Operation sequence	Detail of the operation	Operation duration [h]	Operational Limit Conditions			
			Hs [m]	Tp [s]	Ws [m/s]	Cs [m/s]
Mobilization	-	Vessel database: Mob time [h]	-	-	-	-
Assembly at port	-	User input – device: Assembly duration [h]	-	-	-	-
Vessel preparation & loading	Option 1 - Lifted away	Default value: 48 [h]	-	-	-	-
	Option 2 - Skidded/Trailer					
	Option 3 - Floated away					
	Seafastening					
Transportation from port-site / site-port / site-site	Option 1 - On deck transportation	Distance × Vessel transit speed	Vessel database: OLC transit limits			
	Option 2 - Tow transportation	Distance × Vessel towing speed	Vessel database: OLC towing limits			
Vessel positioning at site	-	If Jack-up: Jacking speed X water depth Else: Default value: 1 [h]	Vessel database: OLC transit limits or OLC jacking limits for jack up vessels/barges			
Device positioning and connection	Device/ Sub-assembly positioning and connection to moorings / foundations	User input – device: connect duration	User input – device: OLC during device positioning and connect/disconnect			
Demobilization	-	Vessel database: Mob time [h]	-	-	-	-

2.3 INSTALLATION OF MOORING SYSTEMS

This logistic phase is related to the installation of mooring systems (Figure 2-4). In this section, the reader will find a description of how the mooring lines and anchors are transported and put in place at the desired location, using the logistic phase framework:

- Listing of the required inputs from the upstream modules (section 2.3.1),
- Description of the operation sequence during installation (section 2.3.2),
- Possible combinations of vessels and equipment (section 2.3.3),
- The minimum requirements associated with the maritime infrastructures (section 2.3.4).
- The time and met-ocean limit conditions associated to each operation (section 2.3.5).

Figure 2-4 Mooring and anchor installation vessels

A mooring system can consist of multiple lines made of different materials such as chain, wire and synthetic ropes. At the same time, different kinds of anchors can be used, depending on the type of mooring line and seabed soil conditions. Depending on the type of anchor, the installation of the two elements can be undertaken simultaneously (mooring lines attached to the anchors) or sequentially (anchors and moorings installed separately). For most anchors types the installation of moorings and anchors can be combined into one single operation. As this saves time and costs it will be the preferred choice, however, pile anchors require installation in advance of the mooring line hook up. As the procedures to install these anchors are almost identical to the installation of pile foundations, these will be installed using the procedures detailed in section 2.5, followed by the installation of the moorings with the procedures detailed in the current section. Also, the gravity anchors types and corresponding mooring lines will be installed using a separate logistic phase, detailed in section 2.4.

The base case assumption for this stage is that the mooring installation and hook-up of the Marine Renewable Energy (MRE) device will be completed in two phases. The first phase comprises the installation of the anchor along with any ground chains and mooring lines and the second phase will consist of the final hook up to the MRE device.

Depending on the type of vessels used for installation, consideration should be given as to whether the mooring line assembly including anchor, ground chains and synthetic mooring should be connected on shore during the load out. This could save considerable time, cost and be a safer solution.

Synthetic mooring lines will normally be supplied on wooden or steel transport reels depending on the size and length of the moorings, however these reels are generally only supplied for shipment purposes and as such mooring lines will need to be re-reeled onto either an installation reel or onto the integral winch of the installation vessel.

2.3.1 INPUTS

The list of inputs from the different WPs and their corresponding format and unit, for the installation of moorings is the following (Table 2-14):

Table 2-14 Inputs for the installation of moorings logistic phase

#	Module	Parameter	Python name (panda name: parameter name)	Unit	Format
1	Data base	Points of the grid coordinate system in the lease area	site: x coord	[m]	float
2			site: y coord	[m]	float
3			site: zone coord	[-]	string
4		Bathymetry	site:bathymetry	[m]	float
5		Seabed Conditions - Geophysics/Geotechnics	site:soilt type	[-]	string
6		Date and time of the measure met-ocean historical data	met-ocean:year	[-]	integer
7			met-ocean:month	[-]	integer
8			met-ocean:day	[-]	integer
9			met-ocean:hour	[-]	integer
10		Resource met-ocean data (wave): (Hs, Tp)	met-ocean:wave Hs	[m]	float
11			met-ocean:wave Tp	[s]	float
12		Resource met-ocean data (wind): wind speed	met-ocean:wind speed	[m/s]	float
13		Resource met-ocean data (tide): tidal speed	met-ocean:tide speed	[m/s]	float
14	Hydro dynamic	Device number	device:units	[-]	integer
15		Device ID number	device:device	[-]	string
16		Position of devices in the UTM grid coordinate system	device:x coord	[-]	float
17			device:y coord	[-]	float
18			device:zone	[-]	string
19	M&F	Device ID number	found:devices	[-]	string
20		Foundation ID number	found:foundations	[-]	string
21		Foundations/anchors type	found:foundation type	[-]	string
22		Foundations/anchors subtype	found:foundation subtype	[-]	string

23		Foundations/anchors quantity per device	found:quantity	[-]	integer
24		Foundations/anchors coordinates	found:location X coord foundation	[-]	float
25		Foundations/anchors coordinates	found:location Y coord foundation	[-]	float
26		Foundations/anchors dimensions	found:foundation width	[m]	float
27			found:foundation height	[m]	float
28			found:foundation depth	[m]	float
29		Foundation penetration depth	found:installation depth	[m]	float
30		Foundations/anchors dry mass	found:foundation dry mass	[t]	float
31		Foundation grout type	found:grout type	[-]	string
32		Foundation grout volume	found:grout volume	[m^3]	float
33		Device ID number	line:device	[-]	string
34		Mooring line ID number	line:lines	[-]	string
35		Component list of the mooring system - i.e. anything between the anchoring point and the device	line:component list	[-]	string
36		Type of mooring system	line:mooring system type	[-]	string
37		Mooring line length	line:line length	[m]	float
38		Mooring line dry mass	line:line dry mass	[t]	float
39	Logistics	Vessel database	vessels:	various	floats and strings
40		Equipment database	equipments:	various	floats and strings
41		Port database	ports:	various	floats and strings

2.3.2 LOGISTIC PHASE SEQUENCING

In Figure 7-2 in Appendix 7.1.2 the high level operation sequence required to conduct this specific logistic phase is presented.

The operation "vessel preparation and loading" includes any necessary sea-fastening work as well as any reeling work. Finally, any mid-layer buoys, surface buoys and/or clump weights are assumed to be installed in a single operation when lowering the anchors along with the mooring line.

After all this initial setup is complete, and the elements are transported to site, the operation will depend on the mooring type and installation procedure chosen.

If drag-embedment anchors have been chosen, it is necessary to perform the anchor dragging after the lowering of the anchors until it is positioned at the targeted seafloor window and proof loading procedure in order for the anchor to be properly installed.

If direct embedment anchors have been chosen, then different installation and embedment procedures exist: suction embedment, hydro-jetting and mechanical embedment; each with their own operation sequence. A test load should follow and be applied to ensure that the correct bearing capacity is achieved before buoying off the mooring line.

If suction anchor is the option, then the mooring lines are lowered together with the anchor, and the embedment process is carried out by creating or pushing negative relative pressure inside the bucket with respect to the outskirt pressure, leading to the penetration of the anchor in the seafloor. This is followed by proof loading to ensure the anchor is properly installed.

If pile anchors are used, then the piles should have been installed in a previous logistic phase. When the vessel is in position, the end of the mooring chain is lowered to the seafloor and attached to the eye at the top of the pile manually. This process will require subsea support (with ROV's preferably). As with other anchor systems once the buoy has been pre-tensioned it can be buoyed off.

2.3.3 VESSEL AND EQUIPMENT TYPE COMBINATIONS

Next, the different possible sets of equipment to be used are presented (Table 2-15). They reflect the different possible methods presented before and the necessary operation equipment to accomplish the logistic phase.

Depending on the type of anchor to be installed, different vessels and equipment combinations can be considered more appropriate. Being a specific vessel for the installation of moorings, an AHTS can be used and will in principle be able to satisfy the task for any kind of anchor used. Also Multicats can be used to support the installation of smaller mooring systems. The main differentiation however is in the subsea support, since for direct-embedment / suction caisson / pile anchors, there's the need to actively support the subsea tasks, therefore requiring work class ROV's.

Table 2-15 Vessel and Equipment combination for the Installation of mooring systems

#	Anchor Type	Vessel 1 - Installation		Equipment 1 - Support	
1	Drag-embedment	1x	AHTS	1x	Inspection Class ROV
2		1x	Multicat	1x	Inspection Class ROV
3	Direct-embedment / Suction caisson / Pile anchor	1x	AHTS	1x	Work Class ROV
4		1x	Multicat	1x	Work Class ROV

2.3.4 FEASIBILITY FUNCTIONS

The feasibility functions are used to translate the inputs into maritime infrastructure parameters. They reflect the minimum infrastructure requirements regarding the inputs for ports, vessels and equipment. All reeling equipment required to perform the loading of the mooring lines is assumed to be readily available at port.

Table 2-16 Port infrastructure requirements

	PORT			
	Upstream inputs	**Function**	**Eval**	**Logistic parameter**
Area / Load capabilities	Anchor (ANC) dimensions [m]	$\max\left(\frac{ANC\ dry\ mass}{1000\ \times\ [ANC\ lenght\ \times width]}\right)$	$\leq$	Max. load bearing capacity [t/m²]
	Anchor (ANC) dry mass [kg]			
	Anchor (ANC) dimensions [m]	$\max(ANC\ lenght\ \times\ width)$	$\leq$	Terminal dock size area [m²]

Table 2-17 Anchor handling tug supply vessel requirements

	ANCHOR HANDLING TUG SUPPLY VESSEL / MULTICAT			
	Upstream inputs	**Function**	**Eval**	**Logistic parameter**
Area / Load capabilities	Anchor (ANC) dimensions [m]	$\max(ANC\ lenght\ \times\ width)$	$\leq$	Free deck space [m²]
	Anchor (ANC) dry mass [kg]	$\max\left(\frac{ANC\ dry\ mass}{1000}\right)$	$\leq$	Max deck cargo [t]
	Anchor (ANC) dimensions [m]	$\max\left(\frac{ANC\ dry\ mass}{1000\ \times\ [ANC\ Lenght\ \times Width]}\right)$	$\leq$	Max Deck Load [t/m²]
	Anchor (ANC) dry mass [kg]			
Anchor handling capabilities	Anchor (ANC) dry mass [kg]	$\max\left(\frac{(ANC\ dry\ mass + MOO\ dry\ mass)}{1000}\right)$	$\leq$	Winch rated pull [t]
	Mooring (MOO) line dry mass [kg]			
	Mooring (MOO) line dimensions [m]	$\max(MOO\ lenght)$	$\leq$	Winch drum capacity [m]

Table 2-18 ROV requirements

	ROV			
	Upstream inputs	**Function**	**Eval**	**Logistic parameter**
Metrology	Anchor type	*if anchor type == "direct-embedment"->ROV tooling must include Hydro Jetting OR Suction Pump*		ROV parameters to verify suitability to carry Hydro Jetting or suction pump equipment - TBD
	Site bathymetry [m, x, y, z]	*max(bathymetry(Anchor position))*	$\leq$	Depth rating [m]

2.3.5 PERFORMANCE FUNCTIONS

Table 2-19 depicts the underlying assumptions for the time assessment of the installation of an anchor and its subsequent mooring pre-lay. These data feed the scheduling functions as described later in section 2.10. In particular, the OLC are relevant to the weather function estimating the waiting time. By overriding the proposed default values, a user in possession of more accurate data can refine the analysis. For instance, this can improve the estimation of the anchor penetration time to the expected seafloor window.

Table 2-19 Logistic operation details considered for the installation of gravity based structures

Operation sequence	Detail of the operation	Operation duration [h]	Operational Limit Conditions			
			Hs [m]	Tp [s]	Ws [m/s]	Cs [m/s]
Mobilization	-	Vessel database: Mob time [h]	-	-	-	-
Assembly at port	-	Default value: 0h	-	-	-	-
Vessel preparation & loading	-	Default value: 48 h	-	-	-	-
Transportation port / site	-	Distance × Vessel transit speed	Vessel database: OLC transit limits			
Vessel positioning at site	-	If Jack-up: Jacking speed X water depth Else: Default value: 1 [h]	Vessel database: OLC transit limits or OLC jacking limits for jack up vessels/barges			
Seafloor & equipment preparation	Lowering anchor/mooring lines and ROV deployment	Default value: 1h	Vessel database: OLC transit limits	10 - 20	10 - 15	1.5
Anchor and mooring lines installation	Option 1: Drag embedment	Dragging (0.5 h) + Tensioning (0.5 h)	Vessel database: OLC towing limits	10 - 20	N/A	1.5
	Option 2: Direct-embedment through hydro-jetting	Penetration depth × Vertical penetration rate of equipment (soil type)[4]	Vessel database: OLC transit limits. No limit for jack-ups	10 - 20	17.5 - 22.5	1.5
	Option 3: Direct-embedment through suction					
	Option 4: Direct-embedment through mechanical					
	Option 5: Suction caisson anchor					
	Option 6: Pile anchor	Connecting (0.5 h)	Vessel database: OLC transit limits	10 - 20	10 - 15	1.5
Pre-lay moorings or buoy off	Pre-lay mooring lines + Proof loading + Tensioning (if any)	Default value: 0.5h	Vessel database: OLC transit limits			
Demobilization	-	Vessel database: Mob time [h]	-	-	-	-

[4] For the vertical penetration rates see Table 2-66

2.4 INSTALLATION OF GRAVITY BASED STRUCTURES

This logistic phase is related to the installation of (GBS) gravity based structures (Figure 2-5). These are simple heavy structures that can sustain both horizontal and vertical loads and which can be used in any regular soil through lowering and seabed deposition. In this section, the reader will find a description of how the foundation/anchor is transported and put in place at the desired location using the logistic phase framework:

- Listing of the required inputs from the upstream modules (section 2.4.1),
- Description of the operation sequence during installation (section 2.4.2),
- Possible combinations of vessels and equipment (section 2.4.3),
- The minimum requirements associated with the maritime infrastructures (section 2.4.4).
- The time and met-ocean limit conditions associated to each operation (section 2.4.5).

Figure 2-5 Gravity based foundation installation

2.4.1 INPUTS

The list of inputs from the different WPs and their corresponding format and unit of measurement, for the installation of gravity based systems is the following (Table 2-20):

Table 2-20 Inputs for the installation of gravity based systems logistic phase

#	Module	Parameter	Python name (panda name: parameter name)	Unit	Format
1	Data base	Points of the grid coordinate system in the lease area	site: x coord	[m]	float
2			site: y coord	[m]	float
3			site: zone coord	[-]	string
4		Bathymetry	site:bathymetry	[m]	float
5		Seabed Conditions - Geophysics/Geotechnics	site:soilt type	[-]	string
6		Date and time of the measure met-ocean historical data	met-ocean:year	[-]	integer
7			met-ocean:month	[-]	integer

8			met-ocean:day	[-]	integer
9			met-ocean:hour	[-]	integer
10		Resource met-ocean data (wave): (Hs, Tp)	met-ocean:wave Hs	[m]	float
11			met-ocean:wave Tp	[s]	float
12		Resource met-ocean data (wind): wind speed	met-ocean:wind speed	[m/s]	float
13		Resource met-ocean data (tide): tidal speed	met-ocean:tide speed	[m/s]	float
14	Hydro dynamic	Device number	device:units	[-]	integer
15		Device ID number	device:device	[-]	string
16		Position of devices in the UTM grid coordinate system	device:x coord	[-]	float
17			device:y coord	[-]	float
18			device:zone	[-]	string
19	M&F	Device ID number	found:devices	[-]	string
20		Foundation ID number	found:foundations	[-]	string
21		Foundations/anchors type	found:foundation type	[-]	string
22		Foundations/anchors subtype	found:foundation subtype	[-]	string
23		Foundations/anchors quantity per device	found:quantity	[-]	integer
24		Foundations/anchors coordinates	found:location X coord foundation	[-]	float
25		Foundations/anchors coordinates	found:location Y coord foundation	[-]	float
26		Foundations/anchors dimensions	found:foundation width	[m]	float
27			found:foundation height	[m]	float
28			found:foundation depth	[m]	float
29		Foundation penetration depth	found:installation depth	[m]	float
30		Foundations/anchors dry mass	found:foundation dry mass	[t]	float
31		Foundation grout type	found:grout type	[-]	string
32		Foundation grout volume	found:grout volume	[m^3]	float
33		Device ID number	line:device	[-]	string
34	Logistics	Vessel database	vessels:	various	floats and strings
35		Equipment database	equipments:	various	floats and strings
36		Port database	ports:	various	floats and strings

2.4.2 LOGISTIC PHASE SEQUENCING

In Figure 7-3 found in Appendix 7.1.3, the high level operation sequence required to conduct this specific logistic phase is presented. After mobilization of the required gear, two main options exist: on deck transportation and towing transportation (e.g. foundations designed with ballast tanks). However there's no information from upstream modules regarding towing possibilities, therefore, it is assumed that gravity structures are always transported on-deck.

At site the operations are mainly related to the positioning of the installation vessel, hoisting the gravity structure and lowering it to the seabed. If the gravity structure is an anchor, this element is lowered to the seafloor together with the mooring line and fairlead chains attached, where after are secured to a surface pennant buoy to wait for the hook-up phase.

2.4.3 VESSEL AND EQUIPMENT TYPE COMBINATIONS

Next, the different possible sets of equipment to be used are presented (Table 2-21). They reflect the different possible methods presented before and the necessary operation equipment to accomplish the logistic phase. Depending on the transportation mode different vessels are considered suitable. For on deck transportation a Multicat is assumed to be required for support together with an inspection class ROV for the adequate installation of the gravity based structure. In the case of tow transportation a vessel capable of towing the structures is required.

Table 2-21 Vessel and Equipment combination for the Installation of gravity based structures

#	Transportation Mode	Vessel 1 - Installation		Vessel 2 - Support		Equipment 1 - Support	
1	On deck Transportation	1x	Crane vessel	1x	Multicat	1x	Inspection Class ROV
2		1x	Crane Barge + Tugboat	1x	Multicat	1x	Inspection Class ROV
3		1x	Jack-Up Vessel	1x	Multicat	1x	Inspection Class ROV
4		1x	Jack-Up Barge + Tugboat	1x	Multicat	1x	Inspection Class ROV
5		1x	Construction Support Vessel	1x	Multicat	1x	Inspection Class ROV

2.4.4 FEASIBILITY FUNCTIONS

The feasibility functions are used to translate the inputs into maritime infrastructure parameters. They reflect the minimum infrastructure requirements regarding the inputs for ports, vessels and equipment. These are calculated considering that <u>at least</u> one gravity based structure is required to be installed per trip. The actual number of elements installed per trip is obtained during the performance assessment, which varies depending on each suitable vessel characteristics. Therefore, the feasibility functions are designed to ensure the infrastructures are suitable for the largest element (weight/dimensions) on the list to be installed. Because of the expected heavy weight of gravity/shallow base structures, lifting capabilities become the most important requirement of the installation vessels, which is here reflected. For gravity/shallow base anchors, it's assumed the vessel is equipped with an installation reel with sufficient capacity to accommodate the mooring lines, since area/load, lifting and positioning capabilities are the base requirements within these feasibility functions.

Table 2-22 Port infrastructure requirements

	PORT			
	Upstream inputs	**Function**	**Eval.**	**Logistic parameter**
Area/Load capabilities	GBS Dimensions [m]	$max(GBS\ lenght\ \times\ width)$	$\leq$	Terminal dock size area [m²]
	GBS Dimensions [m] GBS dry mass [kg]	$max\left(\frac{GBS\ dry\ mass}{1000\ \times\ GBS\ lenght\ \times width}\right)$	$\leq$	Max. terminal load bearing [t/m²]

Table 2-23 Installation vessel requirements

	JACK-UP VESSEL / JACK-UP BARGE / CRANE VESSEL / CRANE BARGE / CONSTRUCTION SUPPORT VESSEL			
	Upstream inputs	**Function**	**Eval.**	**Logistic parameter**
Area/Load capabilities	GBS Dimensions [m]	$max(GBS\ lenght\ \times\ width)$	$\leq$	Free deck space [m²]
	GBS dry mass [kg]	$max\left(\frac{GBS\ dry\ mass}{1000}\right)$	$\leq$	Max Deck Cargo [t]
	GBS Dimensions [m] GBS dry mass [kg]	$max\left(\frac{GBS\ dry\ mass}{1000\ \times\ GBS\ lenght\ \times width}\right)$	$\leq$	Max Deck Load [t/m²]
Lift capabilities	GBS dry mass [kg]	$max\left(\frac{GBS\ dry\ mass}{1000}\right)$	$\leq$	Crane weight capacity [t]
Positioning (non jack-up)	-	$DP > 0$	$>$	DP class [-]
Positioning (jack-up)	Bathymetry [m] Foundation position [x,y,z]	*max(bathymetry(foundation* position) *)*	$\leq$	Leg Operating Water Depth (m)

Table 2-24 ROV requirements

	ROV			
	Upstream inputs	**Function**	**Eval.**	**Logistic parameter**
ROV class	-	*Inspection Class*	==	ROV Class [-]
Performance capabilities	Site bathymetry [m, x, y, z] Foundation positions [x,y,z]	*max(bathymetry(foundation position))*	$\leq$	ROV depth rating [m]

2.4.5 PERFORMANCE FUNCTIONS

Table 2-25 depicts the underlying assumptions for the time assessment of the installation of a GBS and its subsequent mooring pre-lay in the case of an anchor. These data feed the scheduling functions as described later in section 2.10. In particular, the OLC are relevant to the weather function estimating the waiting time. By overriding the proposed default values, a user in possession of more accurate data can refine the analysis. For instance, this can improve the estimation of the positioning and hoisting preparation time.

Table 2-25 Logistic operation details considered for the installation of gravity based structures

Operation sequence	Detail of the operation	Operation duration [h]	Operational Limit Conditions			
			Hs [m]	Tp [s]	Ws [m/s]	Cs [m/s]
Mobilization	-	Vessel database: Mob time [h]	-	-	-	-
Assembly at port	-	Default value: 0 [h]	-	-	-	-
Vessel preparation & loading	-	Default value: 48 [h]	-	-	-	-
Transportation port / site	-	Distance × Vessel transit speed	Vessel database: OLC transit limits			
Positioning & hoisting preparation	-	If Jack-up: Jacking speed × water depth Else: Default value: 1 [h]	Vessel database: OLC transit limits or OLC jacking limits for jack up vessels/barges			
Lowering	-	Lowering Rate[5] × Bathymetry	Vessel database: OLC transit limits. No limit for jack-ups	10 - 20	10 - 15	Lifting limited to slack tide (1.5 m/s) Limited to 2.5 m/s for DP Vessels
Pre-lay moorings or buoy off	Only if the GBS is an anchor	Default value: 0.5 [h]	Vessel database: OLC transit limits			
Demobilization	-	Vessel database: Mob time [h]	-	-	-	-

[5] The lowering rate is calculated based on the equation found in [78], $v_{max} = \frac{W_{bv}}{66A_v}$ where W_{bv} is equal to the submerged weight of installation in kilograms and A_v is equal to the vertical projected area of the package in square meters. In order not to achieve the maximum threshold, the lowering rate is assumed to be 60% of the v_{max} calculated.

2.5 INSTALLATION OF DRIVEN PILES

This logistic phase is related to the installation of driven piles and pile anchors (Figure 2-6). These are elements which can sustain both horizontal and vertical loads and which can be used in softer soils through different burial processes. In this section, the reader will find a description of how the foundation/anchor is transported and put in place at the desired location using the logistic phase framework:

- Listing of the required inputs from the upstream modules (section 2.5.1),
- Description of the operation sequence during installation (section 2.5.2),
- Possible combinations of vessels and equipment (section 2.5.3),
- The minimum requirements associated with the maritime infrastructures (section 2.5.4).
- The time and met-ocean limit conditions associated to each operation (section 2.5.5).

Figure 2-6 Installation of driven piles (towing transportation and crane lifting)

Monopiles may be transported to the offshore site by a jack-up vessel, a barge or floated-out. The monopiles can be loaded directly from the port to the transportation vessel by a self-propelled modular transporter (SPMT) or via crane lift. Once the loading stage is complete, the structure is seafastened to the vessel. To float-out, the ends of the pile are capped and the structure is towed to the site. Therefore, when a significant number of piles must be transported, large vessels (e.g. jack-up or barge) offer an advantage over towing individual monopiles.

Towing being a technique mostly employed with large monopiles expected to be more suitable for offshore wind than fixed ocean energy devices has been disregarded in DTOcean. On-deck transportation via lifting load-out and seafastening was considered as the default solution.

The standard method for installing piled structures is to lift or float the structure into position and then drive the piles into the seabed. The monopile maneuver may require the use of specialized equipment, such as upending and grip tools, while the driving process is achieved using either steam or hydraulic powered hammers, drilling rigs, vibro-driver or suction pump. The latter case is generally supported by the use of a workclass ROV featuring the appropriate pump which will allow the pressure difference. The handling of the pile and required piling equipment will require the use of a crane, and jack-ups are the most widely used vessels for the installation of large monopoles.

2.5.1 INPUTS

The list of inputs from the different modules and their corresponding format and unit, for the installation of suction piles is the following (Table 2-26):

Table 2-26 Inputs for the installation of driven piles logistic phase

#	Module	Parameter	Python name (panda name: parameter name)	Unit	Format
1	Data base	Points of the grid coordinate system in the lease area	site: x coord	[m]	float
2			site: y coord	[m]	float
3			site: zone coord	[-]	string
4		Bathymetry	site:bathymetry	[m]	float
5		Seabed Conditions - Geophysics/Geotechnics	site:soilt type	[-]	string
6		Date and time of the measure met-ocean historical data	met-ocean:year	[-]	integer
7			met-ocean:month	[-]	integer
8			met-ocean:day	[-]	integer
9			met-ocean:hour	[-]	integer
10		Resource met-ocean data (wave): (Hs, Tp)	met-ocean:wave Hs	[m]	float
11			met-ocean:wave Tp	[s]	float
12		Resource met-ocean data (wind): wind speed	met-ocean:wind speed	[m/s]	float
13		Resource met-ocean data (tide): tidal speed	met-ocean:tide speed	[m/s]	float
14	Hydro dynamic	Device number	device:units	[-]	integer
15		Device ID number	device:device	[-]	string
16		Position of devices in the UTM grid coordinate system	device:x coord	[-]	float
17			device:y coord	[-]	float
18			device:zone	[-]	string
19	M&F	Device ID number	found:devices	[-]	string
20		Foundation ID number	found:foundations	[-]	string
21		Foundations/anchors type	found:foundation type	[-]	string
22		Foundations/anchors subtype	found:foundation subtype	[-]	string
23		Foundations/anchors quantity per device	found:quantity	[-]	integer
24		Foundations/anchors coordinates	found:location X coord foundation	[-]	float
25		Foundations/anchors coordinates	found:location Y coord foundation	[-]	float
26		Foundations/anchors dimensions	found:foundation width	[m]	float

27			found:foundation height	[m]	float
28			found:foundation depth	[m]	float
29		Foundation penetration depth	found:installation depth	[m]	float
30		Foundations/anchors dry mass	found:foundation dry mass	[kg]	float
31		Foundation grout type	found:grout type	[-]	string
32		Foundation grout volume	found:grout volume	[m³]	float
33	Logistics	Vessel database	vessels:	various	floats and strings
34		Equipment database	equipments:	various	floats and strings
35		Port database	ports:	various	floats and strings

2.5.2 LOGISTIC PHASE SEQUENCING

In Figure 7-4 in Appendix 7.1.4 the high level operation sequence required to conduct this specific logistic phase is presented. After mobilization of the required gear, two main options exist: pre-piling or post-piling.

In the first scenario, a guiding template is lowered to the seabed and properly positioned. Afterwards, depending on soil conditions and other variables, different penetration methods are available, each with their one technical procedure: drilling, hammering, vibro-driving. It should be noted here that suction caisson are only solutions for mooring systems in the DTOcean tool and, hence, the suction-piling technique is reserved to floating structures which have been described in section 2.3. Finally if pre-piling has been initially applied, it is necessary to remove the respective guiding and support structure, before coming back to port.

2.5.3 VESSEL AND EQUIPMENT TYPE COMBINATIONS

Next, the different possible sets of equipment to be used are presented. They reflect the different possible methods presented before and the necessary operation equipment to accomplish the logistic phase. An inspection class ROV is used for the proper installation of the piles at the desired location. The different installation equipment associated to installation method of the pile will have to be transported and handled in a proper vessel: a Construction Support Vessel, a Jack-up barge or Jack-up vessel.

Table 2-27 Vessel and Equipment combination for the Installation of driven-piles

#	Vessel 1 - Installation	Equipment 1 - Installation		Equipment 2 - Support	
1	Construction Support Vessel (CSV)	1x	Hammer	1x	Inspection Class ROV
2		1x	Drilling rig	1x	Inspection Class ROV
3		1x	Vibro-driver	1x	Inspection Class ROV
6	Jack-up barge + Tugboat	1x	Hammer	1x	Inspection Class ROV
7		1x	Drilling rig	1x	Inspection Class ROV
8		1x	Vibro-driver	1x	Inspection Class ROV

10	Jack-up vessel	1x	Hammer	1x	Inspection Class ROV
11		1x	Drilling rig	1x	Inspection Class ROV
12		1x	Vibro-driver	1x	Inspection Class ROV

2.5.4 FEASIBILITY FUNCTIONS

The feasibility functions are used to translate the inputs into maritime infrastructure parameters. They reflect the minimum infrastructure requirements regarding the inputs for ports, vessels and equipment. These are calculated considering that at least one pile is required to be installed per trip. The actual number of elements installed per trip is obtained during the performance assessment, which varies depending on each suitable vessel characteristics. Therefore, the feasibility functions are designed to ensure the infrastructures are suitable for the largest element (weight/dimensions) on the list to be installed.

Table 2-28 Port requirements

	PORT			
	Upstream inputs	**Function**	**Eval.**	**Logistic parameter**
Dock capabilities	Foundation (FDT) dimensions [m] Foundation (FDT) dry mass [kg]	$\frac{FDT\ dry\ mass}{1000\ \times FDT\ lenght\ \times diam}$	≤	Max. load bearing capacity [t/m²]
	Foundation (FDT) dimensions [m]	$sum(FDT\ lenght \times diam)$	≤	Terminal dock size area [m²]

Table 2-29 Installation vessel requirements

	JACK-UP VESSEL / JACK-UP BARGE / CONSTRUCTION SUPPORT VESSEL			
	Upstream inputs	**Function**	**Eval.**	**Logistic parameter**
Dock capabilities	Foundation (FDT) dimensions [m]	$max(FDT\ lenght\ \times diam)$	≤	Free deck space [m²]
	Foundation (FDT) dry mass [kg]	$max\left(\frac{FDT\ dry\ mass}{1000}\right)$	≤	Max deck cargo [t]
	Foundation (FDT) dimensions [m] Foundation (FDT) dry mass [kg]	$max\left(\frac{FDT\ dry\ mass}{1000\ \times FDT\ lenght \times diam}\right)$	≤	Max Deck Load [t/m²]
Lifting capabilities	Foundation (FDT) dry mass [kg]	$max\left(\frac{FDT\ dry\ mass}{1000}\right)$	≤	Crane weight capacity [t]
Positioning capabilities (non jack-up)	-	$DP > 0$	>	DP class [-]
Positioning capabilities (jack-up)	Foundation (FDT) dry mass [kg]	$max\left(\frac{FDT\ dry\ mass}{1000}\right)$	≤	Maximum payload [t]
	Site bathymetry [m, x, y, z] Foundation (FDT) positions [x,y,z]	*max(bathymetry(FDT position))*	≤	Leg operating water depth [m]

Table 2-30 Hammer requirements

	HAMMER			
	Upstream inputs	**Function**	**Eval.**	**Logistic parameter**
Metrology	Foundation (FDT) dimensions [m]	$min(FDT\ diameter)$	≥	Min pile sleeve diameter [m]
	Foundation (FDT) dimensions [m]	$max(FDT\ diameter)$	≤	Max pile sleeve diameter [m]
	Site bathymetry [m, x, y, z] Foundation (FDT) positions [x, y, z]	max(bathymetry(FDT position))	≤	Depth rating [m]

Table 2-31 Drilling rig requirements

	DRILLING RIG			
	Upstream inputs	**Function**	**Eval.**	**Logistic parameter**
Metrology	Foundation (FDT) dimensions [m]	$max(FDT\ diameter)$	≤	Drilling diameter range [m]
	Site bathymetry [m, x, y, z] Foundation (FDT) positions [x, y, z]	*max(bathymetry(FDT position))*	≤	Max water depth [m]
	Foundation (FDT) penetration depth [m]	*FDT penetration depth*	≤	Max. Drilling depth [m]

Table 2-32 Vibro-driver requirements

	VIBRO-DRIVER			
	Upstream inputs	**Function**	**Eval.**	**Logistic parameter**
Metrology	Foundation (FDT) dimensions [m]	$min(FDT\ diameter)$	≥	Min pile diameter [mm]
	Foundation (FDT) dimensions [m]	$max(FDT\ diameter)$	≤	Max pile diameter [mm]
	Foundation (FDT) dry mass [kg]	$max\left(\frac{FDT\ dry\ mass}{1000}\right)$	≤	Max pile weight [t]
	Site bathymetry [m, x, y, z] Foundation (FDT) positions [x,y,z]	*max(bathymetry(FDT position))*	≤	Depth rating [m]

2.5.5 PERFORMANCE FUNCTIONS

Table 2-33 depicts the underlying assumptions for the time assessment of the installation of a driven pile. These data feed the scheduling functions as described later in section 2.10. In particular, the OLC are relevant to the weather function for estimating the waiting time. By overriding the proposed default values, a user in possession of more accurate data can refine the analysis. For instance, this can improve the estimation of the pile penetration time depending on the equipment employed and the soil type conditions specified at the pile location.

Table 2-33 Logistic operation details considered for the installation of driven piles and pile anchors

Operation sequence	Detail of the operation	Operation duration [h]	Operational Limit Conditions			
			Hs [m]	Tp [s]	Ws [m/s]	Cs [m/s]
Mobilisation	-	Vessel database: Mob time [h]	-	-	-	-
Assembly at port	-	Default value: 0 [h]	-	-	-	-
Vessel preparation & loading	-	Default value: 48 [h]	-	-	-	-
Transportation port/site	-	Distance × Vessel transit speed	Vessel database: OLC transit limits			
Positioning	-	If Jack-up: Jacking speed X water depth Else: Default value: 1 [h]	Vessel database: OLC transit limits or OLC jacking limits for jack up vessels/barges			
Seafloor & equipment preparation	Option 1 (pre-piling): Guiding template positioning + seafloor preparation equipment preparation	Default value: 2 [h]	Vessel database: OLC transit limits. No limit for jack-ups	10 - 20	10 - 15	Lifting limited to slack tide (1.5 m/s) Limited to 2.5 m/s for DP Vessels
	Option 2 (post-piling): seafloor preparation + support structure positioning and equipment preparation	Default value: 2 [h]				
Seafloor penetration & pile positioning[6]	Option 1: Drilling	Drilling penetration Rate (soil type) X Penetration depth	Vessel database: OLC transit limits. No limit for jack-ups	10 - 20	10 - 15	Lifting limited to slack tide (1.5 m/s) Drilling can continue under all current speeds from jack-up Limited to 2.5 m/s for DP Vessels
	Option 2: Hammering	Hammering penetration rate (soil type) X penetration depth				
	Option 3: Vibro-piling	Vibro-Pilling penetration rate(soil type) X penetration depth				
Equipment removal & grouting	Option 1 (pre-piling): guiding template removal + grouting	Default value: 0.5 [h] + grouting rate X grouting volume	Vessel database: OLC transit limits. No limit for jack-ups	10 - 20	10 - 15	1.5 - 2.5
	Option 2 (post-piling): grouting	grouting rate X grouting volume				
Demobilisation	-	Vessel database: Mob time [h]	-	-	-	-

6 For the vertical penetration rates see Table 2-66

2.6 INSTALLATION OF STATIC ARRAY CABLES AND STATIC EXPORT CABLES

The installation of submarine power cables are among the most complex logistic activities within the lifecycle of the MRE projects. The logistic operations required to complete this phase are a result of a complex interaction between the specific characteristics of the power cables, the design of the cable route and the availability of installation machinery.

The installation of the subsea power cables requires a highly customized plan, with each project being unique due to its specifics. The installation procedures are affected by a number of parameters:

- Cable mechanical properties, such as length, weight, maximum bending radius among others affect the choice of vessels and cable protection equipment.
- Seabed characteristics, affect the design of the cable route and the installation strategies both on buried and non-buried cables.
- Environmental restrictions may constrain the decisions on the cable route, feasible trenching techniques and shore landing methods.
- Even public policies can be responsible for enforcing certain cable protection requirements.

Defining the scope boundaries of the model outputs was a complex task, which required finding the right balance between data requirements from the user (e.g. geophysical, geotechnical, met-ocean…), marine infrastructure data, and the reliability of the output results. With this approach, the authors believe it was possible to create an inter-model (requiring a collaborative work between the electrical and logistical modules in DTOcean package) that is able to select a cable route, most suitable cable protection, feasible marine vessel/equipment spreads, and conduct a performance assessment with timeframe and costs. Mind that the accuracy of the solutions will be directly dependent of the detail level the input data (e.g. export cable corridor data).

As mentioned, part of the analysis is performed upstream in the electrical module. This module outputs all the mechanical properties of the power cable and a proposed geographic route plus the cable protection requirements (burial depth and external cable protection). From this point on, the logistic module computes the feasible logistic solutions to install the power cables with the logistic phase framework described in the following sections:

- Listing of the required inputs from the upstream modules (section 0),
- Description of the operation sequence during installation (section 2.6.2),
- Possible combinations of vessels and equipment (section 2.6.3),
- The minimum requirements associated with the maritime infrastructures (section 2.6.4).
- The time and met-ocean limit conditions associated to each operation (section 2.6.5).

Due to shared characteristics, the methodology described covers both export and array static cables, however these are treated as two individual logistic phases inside the python module. This is justified as in real case scenarios, it’s common to use different vessel/equipment spreads to perform the installation of these two types of cables, due to the variance in cable lengths and terminations.

2.6.1 INPUTS

The list of inputs from the different WPs and their corresponding format and unit of measurement, for the installation of static cables systems is the following (Table 2-34):

Table 2-34 Inputs for the installation of static cables logistic phase

#	Module	Parameter	Python name (panda name:parameter name)	Unit	Format
1	Data base	Points of the grid coordinate system in the lease area	site:x coord	[m]	float
2			site:y coord	[m]	float
3			site:zone	[-]	integer
4		Bathymetry	site:bathymetry	[m]	float
5		Seabed Conditions - Geophysics/Geotechnics	site:soilt type	[-]	string
6		Date and time of the measure met-ocean historical data	met-ocean:year	[-]	integer
7			met-ocean:month	[-]	integer
8			met-ocean:day	[-]	integer
9			met-ocean:hour	[-]	integer
10		Resource met-ocean data (wave): (Hs, Tp)	met-ocean:wave Hs	[m]	float
11			met-ocean:wave Tp	[s]	float
12		Resource met-ocean data (wind): wind speed	met-ocean:wind speed	[m/s]	float
13		Resource met-ocean data (tide): tidal speed	met-ocean:tide speed	[m/s]	float
14		User optional decision	landfall method	[-]	string
15		User optional decision	ground-out	[-]	bollean
16	Electrical	Static cable id number	static cable:id	[-]	string
17		Static cable type	static cable:type	[-]	string
18		Static cable dry mass	static cable:dry mass	kg/m	float
19		Static cable total dry mass	static cable:total dry mass	kg	float
20		Static cable length	static cable:length	m	float
21		Static cable diameter	static cable:diameter	mm	float
22		Static cable minimum bend radius (MBR)	static cable:MBR	m	float
23		Static cable minimum breaking load (MBL)	static cable:MBL	N	float
24		Static Cable termination parameters	static cable:upstream termination type	[-]	string
25			static cable:upstream termination id	[-]	integer
26			static cable:downstream termination type	[-]	string
27			static cable:downstream termination id	[-]	integer
28		Static Cable electrical interface parameters	static cable:upstream ei type	[-]	string
29			static cable:upstream ei id	[-]	integer
30			static cable:downstream ei type	[-]	string

31			static cable:downstream ei id	[-]	integer
32		Cable route UTM coordinates	cable route:x coord	[-]	float
33			cable route:y coord	[-]	float
34			cable route:zone	[-]	string
35		Soil type	cable route:soil type	[-]	string
36		Soil bathymetry	cable route:bathymetry	[m]	float
37		Burial depth	cable route:burial depth	[m]	float
38		Split pipe required	cable route:split pipe	[-]	boolean
39		Electrical connector id number	connector:id	[-]	string
40		Electrical Connector type	connector:type	[-]	string
41		Electrical Connector dry mass	connector:dry mass	[kg]	float
42		Electrical Connector dimensions	connector:length	[m]	float
43			connector:width	[m]	float
44			connector:height	[m]	float
45		Electrical connector required mating force	connector:mating force	[N]	float
46		Collection point dry mass	collection point:dry mass	[kg]	float
47		Collection point dimensions	collection point:width	[m]	float
48			collection point:length	[m]	float
49			collection point:height	[m]	float
50		Number of Pigtails	collection point:nr pigtails	[-]	integer
51		Pigtails total dry mass	collection point:pigtail total dry mass	[kg]	float
52	Logistics	Vessel database	vessels:	various	floats and strings
53		Equipment database	equipments:	various	floats and strings
54		Port database	ports:	various	floats and strings
55		Average fixed duration default values	durations:	various	floats and strings
56		Safety factors default values	safety:	various	floats and strings
57		Horizontal progress rates default values	vert_penetration:	various	floats and strings
58		Operational limit conditions default values	olc:	various	floats and strings

2.6.2 LOGISTIC PHASE SEQUENCING

Following the framework of logistic functions, the installation sequence is where export and inter-array cables mostly differ in terms of methodology (specifically the cable terminations). Therefore the first part of this section will explain the approach defined for the export static cable, with the following dedicated to the array static cable.

The installation sequence of an export cable can be split into 3 segments, presented in Figure 2-7:

- The **onshore termination**, commonly designated as landfall.
- The installation of the **export cable spread** throughout the cable route.
- The **offshore termination**, linking the export cable to the offshore grid.

A short description of the logistic options and corresponding assumptions derived for the DTOcean tool are described below.

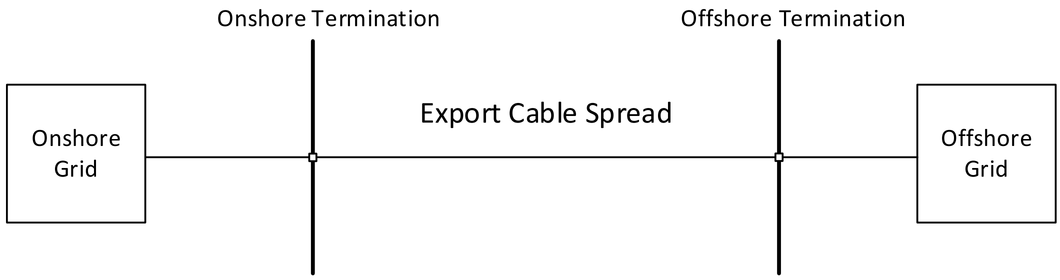


Figure 2-7 – Diagram with the 3 core steps required to install an export cable

The **onshore termination** usually named Landfall, corresponds to the transition section between the offshore low water mark and the onshore joint bay where the land-based cable and subsea cable are jointed. In order to protect the cable along this transition section, two main methodologies are used: Open-Cut Trenching (OCT) and Horizontal Directional Drilling (HDD). The OCT method requires the excavation of a trench (using conventional excavating equipment, e.g. excavator and trench wall stabilization techniques, e.g. cofferdams) which is then back-filled following the installation of the cable. The HDD method involves drilling of a pilot hole through the ground from an entry point (drilling rig site), to an exit point. The OCT method is usually the cheaper and preferred option, however, if there is no beach zone or obvious trenching route (e.g. due to cliffs, rocky outcrops, sensitive habitats), then HDD becomes the only feasible option. The decision for the most suitable method is based on the results of a detailed design study by the installation contractor. Based on these premises, the following assumptions were made:

- Since most of the landfall preparation works are related to onshore operations, which can be performed independently of other logistic works, these will not be assessed with the level of detail of a standard logistic phase. Furthermore, onshore work preparations are outside the DTOcean scope.
- The preparation works of both methods are accounted for based on a simplified cost assessment, explained in later section 0.
- The OCT method will be considered as the default option, but the user will have the possibility to choose HDD if this method is better suited to the characteristics of his project.
- The landfall preparation works are assumed to be executed and concluded before this logistic phase is initiated.

The **cable route** corresponds to the installation section where the cable is required to be laid and protected within a pre-defined route. Two main types of cable protection are used: cable burial (characterized by its burial depth) and external cable protection (characterized the by type: split pipes, concrete mattresses, rock filter bags, rock dumping). The routing and type of protection is computed in upstream modules, and will not be addressed here. Considering the routing and external protection as inputs, the logistic module selects the most suitable installation strategy. Four types have been identified[7]: Pre-Lay Trenching, Simultaneous Lay and Burial, Post-Lay Burial and Surface Laying. A short description and assumptions taken for each of these strategies are described below:

- Pre-Lay Trenching: This strategy involves decoupling the work-steps of opening the trench and laying the cable. First, a vessel and equipment spread opens a trench along the cable route, where after a cable laying vessel positions the cable into the trench while laying. This helps minimize the requirements of the vessels used for each step and the time to perform each operation, requiring shorter weather windows.
- Simultaneous Lay and Burial: With this strategy, the cable is laid and buried simultaneously, with the help of towed, bottom crawling or free-swimming burial tools. The speed of installation is governed by the burial speed; therefore, a large weather window is usually required.
- Post-Lay Burial: This strategy involves decoupling the work-steps of cable laying and burial. First the cables are surface laid by a cable-laying vessel, where after the burial is carried out in a post-lay mode using a separate vessel and burial tool spread.
- Surface Laying: This strategy represents non-burial protection, where the cable is surface laid on the seabed and externally protected. This external protection can be performed during the cable laying, using tubular products such as the cable split pipes considered in this tool, or by a separate logistic phase where the external protection elements (concrete mattresses, rock filter bags and rock dumping) are placed above the laid cable.

Since it's likely to see a combination of cable burial and surface laying protections for wave and tidal arrays, due to the hard seabed conditions expected, the operation sequence allows the combination of these two strategies. As previously mentioned, these decisions will be made within the cable routing algorithm inside the electrical module, based on a number of factors such as soil type or bathymetry.

The suitability of the different installation strategies considered is constrained by some decision factors. The first decision factor is the upstream input regarding cable burial. If no cable burial is considered, then only surface laying installation strategy is applied. If cable burial is required, 3 installation strategies are available (pre-lay trenching, simultaneous lay and burial, post-lay burial). For this tool, the only constraints applied to the selection of the burial installation strategies are the applicable trenching techniques (which will be assessed in the following section 2.6.4).

	Trenching Techniques			
Burial Strategy	**Dredging**	**Jetting**	**Ploughing**	**Cutting**
Pre-Lay Trenching	Suitable	Not suitable	Suitable	Suitable
Simultaneous Lay-Burial	Not suitable	Suitable	Suitable	Not suitable
Post-Lay Burial	Not suitable	Suitable	Not suitable	Suitable

(red)	Not suitable
(green)	Suitable

Figure 2-8 - Suitability of different installation strategies depending on the trenching technique applicable for the cable route

All suitable installation strategies will be assessed later in the performance functions.

According to the electrical infrastructure scope diagram (see Figure 3-10), the **offshore termination** of export static cables can be either a device, a dynamic cable or a collection point. Within the

[7] Surface laying and Simultaneous lay-and-burial were the only strategies implemented in the installation module.

electrical infrastructure installation sequence, the static cables are always installed before any other element in the network, with the following exceptions:

- If the termination is a device and the electrical interface is a J-tube.
- If the termination is a collection point and the electrical interface is a J-tube (meaning the collection point type is Surface Piercing).
- If the termination is a collection point and the electrical interface is a wet-mate connector.

Based on the descriptions and assumptions within this section, a flowchart containing the operation sequences modeled to install static export cables can be found section 7.1.5 of this report. Refer to more detailed descriptions of the individual operations in [2] sections:

- "3.1.1 - Static subsea cables" for the onshore termination and cable route sections, while for the offshore termination refer to section
- "3.1.3.2 - Subsea to surface umbilical" for the connection to surface piercing collection points and J-tube devices,
- "3.1.2.2 - Dry-mate connectors" for the procedures to connect dry-mate cables,
- "3.1.3.1 - Surface to subsea umbilical" for the connection to subsea elements using wet-mate connectors.

The decision symbols correspond to specific inputs from different data frames. See Input section 0 of this report for more information.

The installation sequence of an array static cable can also be split into 3 segments, namely:

- The **upstream termination**, defined as the entry point of the power flow through the cable.
- The installation of the **array cable spread** throughout the cable route.
- The **downstream termination**, defined as the exit point of the power flow through the cable.

The operation sequence for installing the downstream/upstream terminations depends not only on the termination type but also on the electrical interface. In order to reduce the logistic efforts of the overall installation of the array, the static cables are always installed before any other element in the network, with the following exceptions:

- If the termination is a device and the electrical interface is a J-tube, the device is required to be installed prior to the cable
- If the termination is a collection point and the electrical interface is a J-tube, meaning the collection point is of a surface piercing type installed prior to the cables.
- If the termination is a collection point and the electrical interface is a wet-mate connector, the collection point should already be installed on the seabed, so the connection is achieved when the cable laying platform arrives on-site.

The cable route section shares a similar approach to the one already described on the export static cable, thus it will not be repeated here.

Based on the descriptions and assumptions within this section, a flowchart containing the operation sequences modeled to install static array cables can be found section 7.1.6 of this report.

2.6.3 VESSEL AND EQUIPMENT TYPE COMBINATIONS

The main installation vessels used for both export and array cable logistic phases are the cable laying vessel/barge. These are assumed to be equipped with all the specialized equipment required to lay power cables: an integral turntable or reel for storage, equipment needed for proper tensioning of the cable and reliable positioning systems. Along with the installation vessel, one or more offshore support vessels (Multicats) are typically required as mentioned in [6] and [7]. These are used to carry out various light hoisting operations, storage of supplies, and serve as launch base for both diving teams and ROV systems. It is assumed that two support vessels are required to conduct this logistic phase. For the cable laying barge combination these are particularly important for handling and placing the anchors that will sustain the progress of the propulsionless installation barges.

Depending on the landfall method, the onshore spread required will range from: winches, bulldozers, backhoes, dredgers, drilling rigs, drill pipes, storage areas, workshop facilities, etc. As previously mentioned, the onshore operations will only be accounted as a simplified cost assessment and this equipment will not be considered in the V&E combinations.

For installation processes where cable burial is required, a diverse range of burial tools can be used, these are extensively described in the literature with [4], [6] and [7] being the main references used in this study. Based on this review, the types of burial equipment considered in DTOcean are the following:

- Cable Plough: a passive tool which requires a tow force to be exerted by the host vessel to ensure continuous progress through the seabed.
- Tracked Cable Burial Vehicles: self-propelled vehicles commonly on wide caterpillar tracks, controlled by an umbilical connected to the host vessel. These are typically equipped with Jetting tools and Mechanical cutting tools.
- Free swimming ROVs: negatively or neutrally buoyant vehicles, which use thrusters for propulsion and maneuverability. These are typically equipped with Jetting tools and Mechanical cutting tools.

It's commonly repeated in the literature and by industrial experts that diver operations should be avoided where practical (in particular in high current areas). Based on these premises, we've excluded diving teams from this logistic activity.

Regarding the connection procedures associated with wet-mate connectors, several manufacturers provide both ROVs and Diver mate-able connector types. However, as suggested in [10], the use of divers have negative HSE implications, with ROVs being the most common choice. We'll assume a Workclass ROV to be required whenever a wet-mate connection is needed. The technical requirements of these systems will be evaluated on the feasibility functions tab.

Depending on the installation strategy and burial technique, this logistic phase may require a decouple of the operation sequence (pre-cable laying, the cable lay and post cable laying as defined in section 2.6.2), with each of the steps requiring different vessel spreads.

Based on the premises defined in the previous paragraphs, Table 2-35, Table 2-36 and Table 2-37 present the vessel and equipment combinations considered for each one of the three operation steps considered in this logistic phase.

Table 2-35 Vessel and Equipment combination for the pre-cable laying operations

#	Trenching Technique	Vessel 1 - Installation	Equipment 1 - Installation	
1	Dredging	Dredger	-	-
2	Ploughing / Cutting	Anchor Handling Vessel (AHV)	1x	Cable Burial Tool
3		Construction Support Vessel (CSV)	1x	Cable Burial Tool

Table 2-36 Vessel and Equipment combination for the cable laying operations

#	Installation Strategy	Vessel 1 - Installation	Vessel 2 - Support		Equipment 1 - Installation		Equipment 2 - Installation		Equipment 3 - Support	
1	Simultaneous Lay and Burial	Cable Laying Vessel (CLV)	2x	Multicat	1x	Cable Burial Tool	1x	Split pipe	1x	ROV System
2		Cable Laying Barge (CLB) + Tugboat	2x	Multicat	1x	Cable Burial Tool	1x	Split pipe	1x	ROV System
3	Pre Lay Trenching + Post Lay Burial + Surface laying	Cable Laying Vessel (CLV)	2x	Multicat	-	-	1x	Split pipe	1x	ROV System
4		Cable Laying Barge (CLB) + Tugboat	2x	Multicat	-	-	1x	Split pipe	1x	ROV System

Table 2-37 Vessel and Equipment combination for the post-cable laying operations

#	Trenching Technique	Vessel 1 - Installation	Equipment 1 - Installation	
1	Jetting / Cutting	Anchor Handling Vessel (AHV)	1x	Cable Burial Tool
2		Construction Support Vessel (CSV)	1x	Cable Burial Tool

2.6.4 FEASIBILITY FUNCTIONS

The export cables are assumed to be loaded from the factory port, for this reason, no feasibility functions are required for the installation port.

The main factors here considered selecting the cable laying platform (vessel or barge) are: turntable/reel loading capability, positioning system and lifting and deck properties for handling the upstream termination of the static export cable. For calculating the turntable/reel minimum requirements, two main parameters are checked: the loading capacity must be higher than the total cable weight, and the inner radius of the turntable/reel must be higher than the cable minimum bending radius [4]. Every cable laying platform (vessel or barge) must be able to accurately position it-self on the cable corridor, either using anchoring systems (used by propulsionless barges) or dynamic position systems. We assume the minimum requirements to be: a 4 point mooring for anchoring systems and DP1 for dynamic position system.

If a cable is required to be lowered to the seabed, the lifting capabilities must be able to hold the connector plus a cable length of at least 3 times the bathymetry [10]. No particular feasibility functions are taken into account for the support vessels (Multicats).

Table 2-38 Installation vessel requirements

	Cable Laying Vessel (CLV) / Cable Laying Barge (CLB)			
	Upstream Input	**Function**	**Eval.**	**Logistic Parameter**
Area/Load capabilities	static cable: upstream termination [UT] type [-]	if (UT type == collection point && EI type == hard-wired) UT id (collection point:width) * UT id (collection point:lenght)	≤	Free deck space [m^2]
	static cable: upstream ei [EI] type [-]			
	static cable: upstream ei [EI] id [-]			
	collection point: width [m]			
	collection point: length [m]			
Lifting Capabilities	static cable:upstream termination [UT] type [-]	if (UT type == collection point && EI type == hard-wired): UT id (collection point:dry mass/1000) + UT id (collection point:nr pigtails) * UT id (collection point:pigtail total drymass/1000) elif (3*site:bathymetry)*static cable:dry mass/1000	≤	Max. onboard crane lifting capacity [ton]
	static cable:upstream termination [UT] id [-]			
	static cable:upstream ei [EI] type [-]			
	static cable:dry mass [kg/m]			
	site:bathymetry [m]			
	collection point:dry mass [kg]			
	collection point:nr pigtails [-]			
	collection point:pigtail total dry mass [kg]			
Positioning	-	if vessel DP ≥ 1 if barge DP ≥ 1 or Mooring system ≥ 4	-	DP class [-]
				Number of anchors [-]
Turntable / Reel capabilities	static cable:total dry mass [kg]	sum(static cable:total dry mass/1000)	≤	Turntable / reel - loading capacity [ton]
	static cable:MBR [m]	max(static cable:MBR) * 2	≤	Turntable / reel - Inner Diameter [m]

For the DTOcean tool, the equipment database includes a set of cable burial tools, which are selected based on: cable properties (cross-section and minimum bending radius), site conditions (bathymetry), burial depth requirements and trenching capabilities. Regarding the last assessment, soil types are governing the choice of the suitable trenching techniques. Using the soil categories defined for the DTOcean tool (further described in section 0), a trenching technique suitability table was compiled based on similar assessment tables existing on [8] and [11] plus industrial expertize analysis.

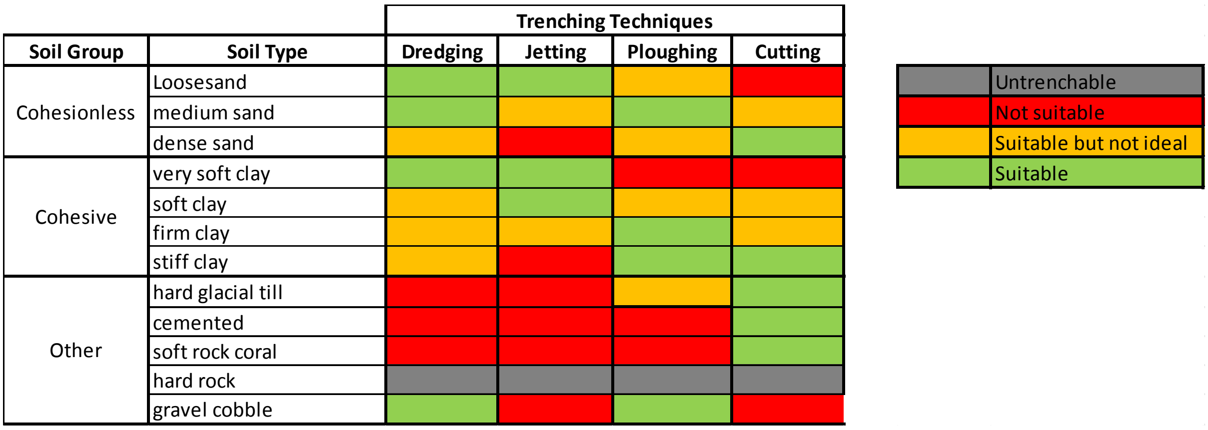


Figure 2-9 – Suitability of different trenching techniques depending on the soil type

The suitability evaluation (color code) is reflected on the performance of the burial tool, i.e. horizontal progress rate (further described in section 2.10.2). Each trenching technique can be succinctly described:

- Ploughing: This trenching technique works by lifting a wedge of soil while placing the cable at the base of the trench, before the soil backfills over the cable.
- Jetting: A jetting system works by fluidizing the sea-bottom sediments by combining different water pressures and flow rates, allowing the cable to sink down into the open trench which is almost simultaneously covered by the fluidized material that backfills over the cable.
- Cutting: The cutting technique consists of a rotating wheel disc, which cuts into hard bottom seabed opening a narrow slot into which the cable is lowered.
- Dredging: Dredging is the only trenching technique not performed by cable burial tools, although there are exceptions not covered in our tool. This technique is applied by a vessel with specialized tooling (which can range from, suction pipe, clamshell buckets, backhoe dippers) which gathers up bottom sediments and dispose them at a different location, leaving an open trench for the cable to be installed.

For ROV wet-mateable connectors, a minimum mating force from the manipulator is required to perform the connection.

Table 2-39 ROV requirements

	ROV Systems			
	Upstream Input	**Function**	**Eval.**	**Logistic Parameter**
ROV Metrology	cable route:bathymetry [m]	max(cable route:bathymetry)	≤	Depth Rating [m]
ROV Power	static cable:upstream termination [UT] type [-]	if (UT type == collection point && EI type == wet-mate) EI id(connector:mating force)	≤	Manipulator - max. grip force [N]
	static cable:upstream ei [EI] type [-]			
	static cable:upstream ei [EI] id [-]			

	connector:mating force [N]			

Table 2-40 Dredger requirements

	Dredger			
	Upstream Input	**Function**	**Eval.**	**Logistic Parameter**
Dredging capabilities	cable route:bathymetry [m]	max(cable route:bathymetry)	≤	Dredge Depth [m]

Table 2-41 Cable burial tool requirements

	Cable Burial Tool			
	Upstream Input	**Function**	**Eval.**	**Logistic Parameter**
Trenching capabilities	cable route:soil type [-]	TrenchingTechniques(cable route:soil type)	==	Trenching capability [-]
	cable route:burial depth [m]	max(cable route:burial depth)	≤	Max. Trench depth [m]
Power Cable Constrains	static cable:diameter [mm]	max(static cable:diameter)	≤	Max. Cable diameter [mm]
	static cable:MBR [m]	max(static cable:MBR)	≤	Min. Cable bending radius [m]
Burial Tool	cable route:bathymetry [m]	max(cable route:bathymetry)	≤	Max. Operating depth [m]

Table 2-42 Split pipe requirements

	Split Pipe			
	Upstream Input	**Function**	**Eval.**	**Logistic Parameter**
Cast-iron pipe characteristics	static cable:diameter [mm]	max(static cable:diameter)	≤	Maximum cable size [mm]
	static cable:MBR [m]	max(static cable:MBR)	≤	Minimum bending radius [m]

2.6.5 PERFORMANCE FUNCTIONS

Table 2-43 outlines the logistic operation details, such as duration and met-ocean limit conditions, necessary to conduct the performance assessment for the installation of static export cables. These are approximate values, which have been derived from literature review and industrial expertise (references included where possible). To obtain these values, there was the need to simplify complex and highly project specific tasks, since the actual times and limits require a much more complex assessment between a wide range of factors, from the vessel and equipment characteristics to the crew experience, which are outside of the scope of this tool.

Table 2-43 Logistic operation details considered for the installation of static export cables

Operation sequence	Detail of the operation			Operation duration [h]	Operational Limit Conditions			
					Hs [m]	Tp [s]	Ws [m/s]	Cs [m/s]
Mobilization				Vessel database: Mob time [h]	-	-	-	-
Assembly at port				Default value: 0 [h]	-	-	-	-
Vessel preparation & loading				Spooling speed [8] × Cable length	-	-	-	-
Transportation port / site				Distance × Vessel transit speed	Vessel database: OLC transit limits			
Onshore Termination: Landfall	OCT	Vessel Positioning		Default value: 3-8 [h]	0.75	10 - 20	17 - 23	2.5
		Winch wire connection to cable pull-head						
		Cable float-out onto the beach zone						
		Cable laid into the pre-excavated trench						
	HDD	Vessel Positioning		Default value: 3-8 [h]	0.75	10 - 20	17 - 23	2.5
		Winch wire connection to cable pull-head						
		Cable float-out onto the beach zone						
		Cable pull-in through HDD conduit to rigsite						
Cable route	Deploy cable burial tool			Default value: 2 [h]	1.5 - 2	10 - 20	17 - 23	1.5
	Cable lay through cable route			Surface laying rate [9] × Cable length				
	Cable lay through open trench							
	Cable lay and burial through cable route			Trenching rate [10] × Cable length				
	Cable lay with split pipes			Surface laying rate [11] × Cable length				
Offshore Termination	Device	Connector	Lower cable end to the seabed	Default value: 0.5 - 1 [h]	2	15	20	2.5
		J-tube	J-tube entrance inspection	Default value: 6 - 9 [h]	2	15	20	2
			Guide wire connection					
			Cable pull-in					
			Cable Connection					
	Dynmic Cable	Lower cable end to the seabed		Default value: 0.5 - 1 [h]	2	15	20	2.5
	Collection Point	Hard-wired	Lower collection point to the seabed	Default value: 1 - 3 [h]	2	15	20	1,5
		Dry-mate	Lower cable end to the seabed	Default value: 0.5 - 1[h]	2	15	20	2.5
		Wet-mate	Connect to guide wire	Default value: 0.5 [h]	2 - 2.5	10 - 20	17 - 23	1
			Lower cable and subsea connection equipment	Default value: 0.5 -1 [h]				
			Wet-mate connection	Default value:0.25 [h]				
			Recover subsea connection equip.	Default value: 0.5 [h]				

[8] The cable loading rate into the vessel turntable/reel is assumed to be within the range of 300-600m/h as suggested in [11]

[9] Surface laying speed depends whether it's a cable laying barge (200m/h) or a cable laying vessel (1000m/h)

[10] See Table 2-65 for more information related to trenching rates

[11] This will depend on type of split pipe. If using polyurethane sleeves one would not expect this to affect the laying rate. Use of cast iron split pipes will likely slow the layout from the vessel.

		J-tube	*Same operations as in device J-tube connection*	Default value: 6-9 [h]				
Demobilization				Vessel database: Mob time [h]	-	-	-	-

Table 2-44 outlines the logistic operation details, such as duration and met-ocean limit conditions, necessary to conduct the performance assessment for the installation of static array cables. The same conditions as for the export cables are applied.

Table 2-44 Logistic operation details considered for the installation of static array cables

Operation sequence			Detail of the operation	Operation duration [h]	Operational Limit Conditions: Hs [m]	Tp [s]	Ws [m/s]	Cs [m/s]
Mobilization				Vessel database: Mob time [h]	-	-	-	-
Assembly at port				Default value: 0 [h]	-	-	-	-
Vessel preparation & loading				Spooling speed [12] × Cable length	-	-	-	-
Transportation port / site				Distance × Vessel transit speed	Vessel database: OLC transit limits			
Downstream Termination	Device	Connector	Lower cable end to the seabed	Default value: 0.5 - 1 [h]	2	15	20	2.5
		J-tube	J-tube entrance inspection Guide wire connection Cable pull-in Cable Connection	Default value: 6-9 [h]				
	Dynamic Cable		Lower cable end to the seabed	Default value: 0.5 - 1 [h]	2	15	20	2.5
	Collection Point	Hard-wired	Lower collection point to the seabed	Default value: 1 - 3 [h]	2	15	20	1,5
		Dry-mate	Lower cable end to the seabed	Default value: 0.5 - 1 [h]	2	15	20	2.5
		Wet-mate	Connect to guide wire	Default value: 0.5 [h]	2 - 2.5	10 - 20	17 - 23	1
			Lower cable and subsea connection equipment	Default value: 0.5 -1 [h]				
			Wet-mate connection	Default value: 0.25[h]				
			Recover subsea connection equip.	Default value: 0.5 [h]				
		J-tube	J-tube entrance inspection Guide wire connection Cable pull-in Cable Connection	Default value: 6-9 [h]	2	15	20	2
Cable route	Deploy cable burial tool			Default value: 2 [h]	1.5 - 2	10 - 20	17 - 23	1.5
	Cable lay through cable route			Surface laying rate [13] × Cable length				
	Cable lay through open trench							

[12] The cable loading rate into the vessel turntable/reel, is assumed to be within the range of 300-600m/h as suggested in [11]

[13] Surface laying speed depends whether it's a cable laying barge (200m/h) or a cable laying vessel (1000m/h)

	Cable lay and burial through cable route			Trenching rate[14] × Cable length				
	Cable lay with split pipes							
Upstream Termination	Device	Connector	Lower cable end to the seabed	Default value: 0.5 - 1 [h]	2	15	20	2.5
		J-tube	J-tube entrance inspection	Default value: 6-9 [h]	2	15	20	2
			Guide wire connection					
			Cable pull-in					
			Cable Connection					
	Dynamic Cable	Lower cable end to the seabed		Default value: 0.5 - 1 [h]	2	15	20	2.5
	Collection Point	Hard-wired	Lower collection point to the seabed	Default value: 1 - 3 [h]	2	15	20	1,5
		Dry-mate	Lower cable end to the seabed	Default value: 0.5 - 1 [h]	2	15	20	2.5
		Wet-mate	Connect to guide wire	Default value: 0.5 [h]	2 - 2.5	10 - 20	17 - 23	1
			Lower cable and subsea connection equipment	Default value: 0.5 -1 [h]				
			Wet-mate connection	Default value: 0.25[h]				
			Recover subsea connection equip.	Default value: 0.5 [h]				
		J-tube	J-tube entrance inspection	Default value: 6-9 [h]	2	15	20	2
			Guide wire connection					
			Cable pull-in					
			Cable Connection					
Demobilization				Vessel database: Mob time [h]	-	-	-	-

[14] See Table 2-65 for more information related to trenching rates

2.7 INSTALLATION OF DYNAMIC CABLES

The purpose of umbilical cables in ocean energy arrays is to connect floating energy converters and/or surface piercing platforms to the static seabed electrical components. This process represents one of the most challenging installation phases and one where components are particularly susceptible to damage. It must, therefore, be carefully controlled. The cables are normally custom designs to withstand the dynamic loading conditions of a specific site, and this is also true for the installation process. Although some experience can be extracted from the Oil & Gas sector for the connection to surface piercing platforms, the connection of a large number of floating converters will require novel installation processes.

Figure 2-10 Installation of a dynamic bend stiffener

Figure 2-11 On-vessel installation of distributed buoyancy modules [12]

As such, it is hard to define a typical installation process. Additionally, the different types of terminations within the scope of electrical module (see section 3.1.2 for more information) have to be considered when designing this phase. The methodology described in this section attempt to model closely what has been described in previous works carried out in DTOcean project, especially in [2].

2.7.1 INPUTS

The list of inputs from the different WPs and their corresponding format and unit of measurement, for the installation of static cables systems is the following (Table 2-45):

Table 2-45 Inputs for the installation of dynamic cables logistic phase

#	Module	Parameter	Python name (panda name:parameter name)	Unit	Format
1	Data base	Points of the grid coordinate system in the lease area	site:x coord	[m]	float
2			site:y coord	[m]	float
3			site:zone	[-]	integer
4		Bathymetry	site:bathymetry	[m]	float
5		Seabed Conditions - Geophysics/Geotechnics	site:soilt type	[-]	string
6			met-ocean:year	[-]	integer

7		Date and time of the measure met-ocean historical data	met-ocean:month	[-]	integer
8			met-ocean:day	[-]	integer
9			met-ocean:hour	[-]	integer
10		Resource met-ocean data (wave): (Hs, Tp)	met-ocean:wave Hs	[m]	float
11			met-ocean:wave Tp	[s]	float
12		Resource met-ocean data (wind): wind speed	met-ocean:wind speed	[m/s]	float
13		Resource met-ocean data (tide): tidal speed	met-ocean:tide speed	[m/s]	float
14	Electrical	Umbilical id number	dynamic cable:id	[-]	string
15		Umbilical dry mass	dynamic cable:dry mass	kg/m	float
16		Umbilical total dry mass	dynamic cable:total dry mass	kg	float
17		Umbilical length	dynamic cable:length	m	float
18		Umbilical diameter	dynamic cable:diameter	mm	float
19		Umbilical minimum bend radius (MBR)	dynamic cable:MBR	m	float
20		Umbilical minimum breaking load (MBL)	dynamic cable:MBL	N	float
21		Umbilical termination parameters	upstream termination type	[-]	string
22			upstream termination id	[-]	integer
23			upstream termination x coord	[-]	float
24			upstream termination y coord	[-]	float
25			upstream termination zone	[-]	string
26			downstream termination type	[-]	string
27			downstream termination id	[-]	integer
28			downstream termination x coord	[-]	float
29			downstream termination y coord	[-]	float
30			downstream termination zone	[-]	string
31		Umbilical electrical interface parameter	upstream ei type	[-]	string
32			upstream ei id	[-]	integer
33			downstream ei type	[-]	string
34			downstream ei id	[-]	integer
35		Buoyancy modules number	dynamic cable:buoyancy number	[-]	integer
36		Buoyancy modules dimensions	dynamic cable:buoyancy diameter	m	float
37			dynamic cable:buoyancy length	m	float
38		Buoyancy modules weight	dynamic cable:buoyancy weigth	m	float
39		Electrical connector id number	connectors:id	[-]	string
40		Electrical Connector type	connectors:type	[-]	string
41		Electrical Connector dry mass	connectors:dry mass	kg	float

42		Electrical Connector dimensions	connectors:lenght	m	float
43			connectors:width	m	float
44			connectors:height	m	float
45		Electrical connector required mating force	connectors:mating force	N	float
46		Collection point type	collection point:type	[-]	string
47		Static cable id number	static cable:id	[-]	string
48		Static cable type	static cable:type	[-]	string
49		Static cable dry mass	static cable:dry mass	[kg/m]	float
50		Static cable total dry mass	static cable:total dry mass	[kg]	float
51	Logistics	Vessel database	vessels:	various	floats and strings
52		Equipment database	equipments:	various	floats and strings
53		Port database	ports:	various	floats and strings
54		Average fixed duration default values	durations:	various	floats and strings
55		Safety factors default values	safety:	various	floats and strings
56		Vertical penetration rates default values	vert_penetration:	various	floats and strings
57		Operational limit conditions default values	olc:	various	floats and strings

2.7.2 LOGISTIC PHASE SEQUENCING

The design of this logistic phase had to take into account the installation sequence of the other electrical components. In order to minimize the logistic efforts the following table summarizes the assumptions related to other logistics phases, based on the potential cable end terminations and electrical interfaces:

- Floating devices are installed after the dynamic cables, except in the case of hard-wired types, for these particular scenarios where a device comes "packed" with the dynamic cable, the installation occurs in a single operation, modeled on the device installation logistic phase.
- Static cables are always installed before the dynamic cables.
- Collection points installation sequence depends on their onboard connector type, if wet-mate the collection point is installed before the dynamic cables, if dry-mate these are installed after the dynamic cables.

From the onshore logistics point of view, regarding the vessel loading and preparation operations, the following is assumed:

- The dynamic cables are pre-cut and terminated onshore before being transported to the installation port;
- The dynamic cables are placed on individual drums before being transported to the installation port;

- At the installation port, the cables are loaded onto the cable laying ship turntable/reel (multiple lengths can be stored on a single turntable/reel).

The design of the logistic operation sequence was based on the electrical infrastructure scope (see section 3.1.2), and is highly dependent on the type of terminations and electrical interfaces of each cable end. In Figure 7-11 found in Appendix 7.1.7, the high level operation sequence required to conduct this specific logistic phase is presented. Refer to the descriptions of these individual steps in D5.2 sections:

- "3.1.3.2 - Subsea to surface umbilical" for the connection to surface piercing collection points,
- "3.1.2.2 - Dry-mate connectors" for the procedures to connect dry-mate cables,
- "3.1.3.1 - Surface to subsea umbilical" for the connection to subsea elements using wet-mate connectors.

The decision symbols correspond to specific inputs from different data frames. See Input tab for more information.

2.7.3 VESSEL AND EQUIPMENT TYPE COMBINATIONS

The cable laying vessel/barge is assumed to be equipped with all the specialized equipment required to lay dynamic cables: an integral turntable or reel for storage, equipment needed for proper tensioning of the cable, reliable positioning systems.

One or more offshore support vessels (Multicats) are typically required as mentioned in [6] and [7]. These are used to carry out various light hoisting operations, storage of supplies, and serve as a launch base for both diving teams and ROV systems. It is assumed that two support vessels are required to conduct this logistic phase. In the case of combinations using a cable laying barge as an installation vessel, these are particularly important for handling and placing the anchors that will sustain the progress of the propulsionless installation barges.

It is assumed that underwater support is required for such operations. Therefore one ROV system is always assumed to be required in the V&E spread.

Regarding the connection procedures associated with wet-mate connectors, several manufacturers provide both ROVs and Diver mate-able connector types. However, as suggested in [10], the use of divers has negative HSE implications, with ROVs being the most common choice. We'll assume a Work class ROV to be required whenever a wet-mate connection is needed. The technical requirements of these systems will be evaluated on the feasibility functions section.

Table 2-46 Vessel and Equipment combinations for installing Dynamic Cables

#	Vessel 1 - Installation	Vessel 2 - Support		Equipment 1 - Installation	
1	Cable Laying Vessel (CLV)	2x	Multicat	1x	ROV system
2	Cable Laying Barge (CLB) + Tugboat	2x	Multicat	1x	ROV system

2.7.4 *FEASIBILITY FUNCTIONS*

The main factors considered to select the cable laying platform (vessel or barge) are: turntable/reel loading capability, positioning system and lifting and deck properties for handling the dynamic cable terminations. For calculating the turntable/reel minimum requirements, two main parameters are checked: the loading capacity must be higher than the total cable weight, and the inner radius of the turntable/reel must be higher than the cable minimum bending radius [8]. If a cable is required to be lowered/raised from the seabed, the lifting capabilities must be able to hold a connector plus a cable length of at least 3 times the bathymetry [10].

For ROV wet-mateable connectors, a minimum mating force from the manipulator is required to perform the connection.

No minimum requirements are considered for the support vessels (Multicats).

Table 2-47 Installation vessel requirements

	Cable Laying Vessel (CLV) / Cable Laying Barge (CLB)			
	Upstream Input	**Function**	**Eval.**	**Logistic Parameter**
Area/Load capabilities	dynamic cable:downstream termination [DT] type [-]	Average deck-area required to install buoyancy modules on umbilical's + if (DT type == static cable && (EI type == dry-mate || EI type == splice): Average deck-area required to install buoyancy modules on umbilical's	≤	Free deck space (m2)
	dynamic cable:downstream ei [EI] type [-]			
	dynamic cable:buoyancy number [-]			
	dynamic cable:buoyancy length [m]			
	dynamic cable:buoyancy diameter [m]			
Lift capabilities	dynamic cable:downstream termination [DT] type [-]	if (DT type == static cable && (EI type == dry-mate || EI type == splice)): (3*bathymetry*static cable:dry mass + connectors:dry mass)/1000 elif: (3*bathymetry*dynamic cable:dry mass + connectors:dry mass)/1000	≤	Max. onboard crane lifting capacity (ton)
	dynamic cable:downstream ei [EI] type [-]			
	dynamic cable: downstream [UTM] coordinates [-]			
	static cable:dry mass [kg/m]			
	dynamic cable:dry mass [kg/m]			
	connectors:dry mass [kg]			
	site:bathymetry [m]			
Turntable / Reel capabilities	dynamic cable:total dry mass [kg]	sum(dynamic cable:total dry mass/1000)	≤	Turntable / reel - loading capacity [ton]
	dynamic cable:MBR [m]	max(dynamic cable:MBR) * 2	≤	Turntable / reel - Inner Diameter [m]

Table 2-48 ROV requirements

	ROV Systems			
	Upstream Input	**Function**	**Eval.**	**Logistic Parameter**
ROV Metrology	cable route:bathymetry [m]	max(cable route:bathymetry)	≤	Depth Rating [m]
ROV Power	static cable:upstream termination [UT] type [-]	if (UT type == collection point && EI type == wet-mate) EI id(connector:mating force)	≤	Manipulator - max. grip force [N]
	static cable:upstream ei [EI] type [-]			
	static cable:upstream ei [EI] id [-]			
	connector:mating force [N]			

2.7.5 PERFORMANCE FUNCTIONS

Table 2-49 outlines the logistic operation details, such as duration and met-ocean limit conditions, necessary to conduct the performance assessment for this logistic phase. These are approximate values, which have been derived from literature review and industrial expertise (references included where possible). To obtain these values, there was the need to simplify complex and highly project specific tasks, since the actual times and limits require a much more complex assessment between a wide range of factors, from the vessel and equipment characteristics to the crew experience, which are outside of the scope of this tool.

Table 2-49 Logistic operation details considered for the installation of static export cables

Operation sequence	Detail of the operation			Operation duration [h]	Operational Limit Conditions			
					Hs [m]	Tp [s]	Ws [m/s]	Cs [m/s]
Mobilization				Vessel database: Mob time [h]	-	-	-	-
Assembly at port				Default value: 0 [h]	-	-	-	-
Vessel preparation & loading				Spooling speed [15] × Cable length	-	-	-	-
Transportation port / site				Distance × Vessel transit speed	Vessel database: OLC transit limits			
Downstream Termination	Device	Lower cable end to the seabed		Default value: 0.5 - 1 [h]	2	15	20	2.5
	Static Cable	Wet-mate	Connect to guide wire	Default value: 0.5 [h]	2 - 2.5	10 - 20	17 - 23	1
			Lower cable and subsea connection equipment	Default value: 0.5 -1 [h]				

[15] The cable loading rate into the vessel turntable/reel, is assumed to be within the range of 300-600m/h as suggested in [11]

			Wet-mate connection	Default value: 0.25 [h]				
			Recover subsea connection equip.	Default value: 0.5 [h]				
		Dry-mate	Lift array/export cable-end from seabed	Default value: 1.5 - 2 [h]	1.5 - 2	10 - 20	17 - 23	1.5
			Dry-mate connection on deck	Default value: 0.5 [h]				
			Lower cable connection to the seabed	Default value: 0.5 - 1 [h]				
		Splice	Lift array/export cable-end from seabed	Default value: 1.5 - 2 [h]	1.5 - 2	10 - 20	17 - 23	1.5
			Splice connection on deck	Default value: 0.5 [h]				
			Lower cable connection to the seabed	Default value: 0.5 - 1 [h]				
	Collection Point	Seabed with Pigtails: Wet-mate / Dry-mate / Splice	Lower collection point to the seabed	Default value: 1 - 3 [h]	2	15	20	1,5
		Seabed: Dry-mate	Lower cable end to the seabed	Default value: 0.5 - 1 [h]	2	15	20	2.5
		Seabed: Wet-mate	Connect to guide wire	Default value: 0.5 [h]	2 - 2.5	10 - 20	17 - 23	1
			Lower cable and subsea connection equipment	Default value: 0.5 -1 [h]				
			Wet-mate connection	Default value: 0.25[h]				
			Recover subsea connection equip.	Default value: 0.5 [h]				
		Surface Piercing: J-tube	J-tube entrance inspection	Default value: 6-9 [h]	2	15	20	2
			Guide wire connection					
			Cable pull-in					
			Cable Connection					
Cable lay with buoyancy modules				Surface laying rate [16] × Cable length	1.5 - 2	10 - 20	17 - 23	1.5
Upstream Termination	Device	Lower cable end to the seabed		Default value: 0.5 - 1 [h]	2	15	20	2.5
	Collection Point	Seabed with Pigtails / Seabed: Dry-mate	Lower collection point to the seabed	Default value: 1 - 3 [h]	2	15	20	1,5
		Seabed with Pigtails / Seabed: Wet-mate	Connect to guide wire	Default value: 0.5 [h]	2 - 2.5	10 - 20	17 - 23	1
			Lower cable and subsea connection equipment	Default value: 0.5 -1 [h]				
			Wet-mate connection	Default value: 0.25[h]				
			Recover subsea connection equip.	Default value: 0.5 [h]				
Demobilization				Vessel database: Mob time [h]	-	-	-	-

[16] Surface laying speed depends whether it's a cable laying barge (200m/h) or a cable laying vessel (1000m/h)

2.8 INSTALLATION OF OFFSHORE COLLECTION POINTS

The primary logistic tasks required during the installation of offshore collection points, whether it's of seabed or surface piercing type (see Figure 2-12 and Figure 2-13), are to deliver: secure storage during transportation, suitable lifting capacity for a safe and controlled offload and reliable positioning capabilities to accurately place the collection point at the offshore site.

Figure 2-12 Deployment of SEM-REV seabed collection point

Figure 2-13 Installation of topside module

Considering the types of collection points and electrical interfaces considered in this model (see section 3.1.2 for more information), this particular logistic phase is designed to model the installation of non-hard-wired collection points. For the case of hard-wired collection points, the installation is performed using the static cables installation logistic phases.

In this section, the reader will find a description of how the collection points are transported and put in place at the desired location using the logistic phase framework:

- Listing of the required inputs from the upstream modules (section 2.8.1),
- Description of the operation sequence during installation (section 2.8.2),
- Possible combinations of vessels and equipment (section 2.8.3),
- The minimum requirements associated with the maritime infrastructures (section 2.8.4).
- The time and met-ocean limit conditions associated to each operation (section 2.8.5).

2.8.1 INPUTS

The list of inputs from the different WPs and their corresponding format and unit of measurement, for the installation of static cables systems is the following (Table 2-50):

Table 2-50 Inputs for the installation of offshore collection points logistic phase

#	Module	Parameter	Python name (panda name:parameter name)	Unit	Format
1	Data base	Bathymetry	site:bathymetry	[m]	float
2		Seabed Conditions - Geophysics/Geotechnics	site:soil type	[-]	string
3			met-ocean:year	[-]	integer
4			met-ocean:month	[-]	integer

5		Date and time of the measure met-ocean historical data	met-ocean:day	[-]	integer
6			met-ocean:hour	[-]	integer
7		Resource met-ocean data (wave): (Hs, Tp)	met-ocean:wave Hs	[m]	float
8			met-ocean:wave Tp	[s]	float
9		Resource met-ocean data (wind): wind speed	met-ocean:wind speed	[m/s]	float
10		Resource met-ocean data (tide): tidal speed	met-ocean:tide speed	[m/s]	float
11	Electrical	Collection point id number	collection point:id	[-]	string
12		Collection point type	collection point:type	[-]	string
13		Position of collection points	collection point:x coord	[-]	float
14			collection point:y coord	[-]	float
15			collection point:zone	[-]	string
16		Collection point dry mass	collection point:dry mass	kg	float
17		Collection point dimensions	collection point:width	m	float
18			collection point:length	m	float
19			collection point:height	m	float
20		Collection point electrical interfaces parameters	collection point:upstream ei type	[-]	string
21			collection point:upstream ei id	[-]	integer
22			collection point:downstream ei type	[-]	string
23			collection point:downstream ei id	[-]	integer
24		Number of Pigtails	collection point:nr pigtails	[-]	integer
25		Pigtails length	collection point:pigtail lenght	m	float
26		Pigtails diameter	collection point:pigtail diameter	mm	float
27		Pigtails cable dry mass	collection point:pigtail cable dry mass	kg/m	float
28		Pigtails total dry mass	collection point:pigtail total dry mass	kg	float
29		Electrical connector id number	connectors:id	[-]	string
30		Electrical connector type	connectors:type	[-]	string
31		Electrical connector dry mass	connectors:dry mass	kg	float
32		Electrical connector dimensions	connectors:lenght	m	float
33			connectors:width	m	float
34			connectors:height	m	float
35		Electrical connector required mating force	connectors:mating force	N	float
36	Logistics	Vessel database	vessels:	various	floats and strings
37		Equipment database	equipments:	various	floats and strings

38		Port database	ports:	various	floats and strings
39		Average fixed duration default values	durations:	various	floats and strings
40		Safety factors default values	safety:	various	floats and strings
41		Operational limit conditions default values	olc:	various	floats and strings

2.8.2 LOGISTIC PHASE SEQUENCING

The rationale behind the installation sequence of seabed collection points is directly related to its onboard connector type (not including pigtails):

- Dry-mate: always installed after the array/export cables.
- Wet-mate: always installed before the array/export cables.

Following this rule guarantees that the collection point is never required to be lifted from the seabed during the installation phase. For the dry-mate onboard electrical interfaces, this rule guarantees that when the installation vessel arrives to site, the array/export cables are already laid on the seabed, the installation procedure starts by raising the cable connectors onto the vessel deck where the dry-mate connections between these and the collection point are made, after which everything is lowered to the seabed (this approach was used during the installation of the SemRev collection point [13]). For wet-mate onboard electrical interfaces, the procedures to install the collection point require less logistic effort: when the installation vessel arrives to site, the collection point is directly lowered to the seabed. After this, the static/dynamic cable installation activities begin and the cables are wet-mate connected underwater without having the need to lift the collection point back to surface.

Based on these descriptions and assumptions, a flowchart containing the operation sequences modeled to install collection points can be found section 7.1.8 of this report. Refer to more detailed descriptions of the individual operations in [2] section:

- "3.1.4 - Offshore substations "for both seabed and surface piercing collection points installation and section
- "3.1.2.2 - Dry-mate connectors" for the procedures to connect dry-mate cables.

The decision symbols correspond to specific inputs from different dataframes, see section 2.8.1 for more information.

2.8.3 VESSEL AND EQUIPMENT TYPE COMBINATIONS

For this logistic phase, the installation vessel requires a deck space with sufficient area to accommodate the collection points, a crane with sufficient lifting capacity plus an accurate positioning system. These requirements can be found within different types of vessels included in the database, this is reflected in Table 2-51, where the main difference between combinations is the installation vessel. Along with the installation vessel, it’s assumed that one offshore support vessel (Multicats) is required to carry out various light hoisting operations, storage of supplies, and serve as launch base for the ROV systems.

It is assumed that underwater visual support is always required to install collection points, therefore an inspection class ROV is included in every combination.

Table 2-51 Vessel and Equipment combinations for installing offshore collection points

#	Vessel 1 - Installation	Vessel 2 - Support		Equipment 1 - Support	
1	Crane Vessel	1x	Multicat	1x	Inspection Class ROV
2	Crane Barge + Tugboat	1x	Multicat	1x	Inspection Class ROV
3	Jack-up Vessel	1x	Multicat	1x	Inspection Class ROV
4	Jack-up Barge + Tugboat	1x	Multicat	1x	Inspection Class ROV
5	Construction Support Vessel	1x	Multicat	1x	Inspection Class ROV

2.8.4 FEASIBILITY FUNCTIONS

The maximum size collection point must be able to sit on the port terminal before being transferred to the installation vessel. If the electrical array solution requires more than one collection point, these can sit on the hinterland area before being transferred to the port terminal. As for the weight of all the elements in the analysis, it is assumed to be uniformly distributed when computing the load bearing. Due to the considerable dimensions and weights of surface piercing collection points, these are usually fabricated by specialized heavy engineering contractors and loaded directly from the manufacturer base port and transported to site for installation. Therefore, surface piercing collection points will not be assessed in the installation port feasibility functions.

The installation vessels selected must be able to, at least, accommodate and lift the maximum size collection point. The feasibility functions will then evaluate if the deck, lifting and positioning capabilities are met for this requirement. Regarding the support vessels (Multicats), no minimum requirements were considered.

Table 2-52 Port infrastructure requirements

<table>
<tr><th></th><th colspan="4">PORT</th></tr>
<tr><th></th><th>Upstream Input</th><th>Function</th><th>Eval.</th><th>Port Parameter</th></tr>
<tr><td rowspan="7">Area/Load capabilities</td><td>collection point:width [m]</td><td rowspan="7">max(collection point:width*length)
+
collection point:nr pigtails*(pigtail length*diameter/1000)
+
collection point:nr pigtails*(connectors:lenght*width)</td><td rowspan="7">≤</td><td rowspan="7">Terminal dock size area (m2)</td></tr>
<tr><td>collection point:length [m]</td></tr>
<tr><td>collection point:nr pigtails [-]</td></tr>
<tr><td>collection point:pigtail diameter [mm]</td></tr>
<tr><td>collection point:pigtail length [m]</td></tr>
<tr><td>connectors:lenght [m]</td></tr>
<tr><td>connectors:width [m]</td></tr>
</table>

	collection point:width [m] collection point:length [m] collection point:dry mass [kg]	(1/1000)*max(collection point:dry mass/(width*length))	≤	Max. terminal load bearing (ton/m2)

Table 2-53 Installation vessel requirements

	Jack-up Vessel / Jack-up Barge / Crane Vessel / Crane Barge / Construction Support Vessel			
	Upstream Input	**Function**	**Eval**	**Logistic Parameter**
Area/Load capabilities	collection point:width [m] collection point:length [m] collection point:nr pigtails [-] collection point:pigtail diameter [mm] collection point:pigtail length [m] connectors:lenght [m] connectors:width [m]	max(collection point:width*length) + collection point:nr pigtails*(pigtail length*diameter/1000) + collection point:nr pigtails*(connectors:lenght*width)	≤	Free deck space (m2)
	collection point:width [m] collection point:length [m] collection point:dry mass [kg]	(1/1000)*max(collection point:dry mass/(width*length))	≤	Max Deck Load (ton/m2)
	collection point:dry mass [kg] collection point:nr pigtails [-] collection point:pigtail dry mass [kg] connectors:dry mass [kg]	max(collection point:dry mass/1000 + collection point:nr pigtail*pigtail total dry mass/1000 + collection point:nr pigtail*connectors: dry mass/1000)	≤	Max Deck Cargo (ton)
Lift capabilities	collection point:dry mass [kg] collection point:nr pigtails [-] collection point:pigtail dry mass [kg] connectors:dry mass [kg]	max(collection point:dry mass/1000 + collection point:nr pigtail*pigtail total dry mass/1000 + collection point:nr pigtail*connectors: dry mass/1000)	≤	Max. crane lifting capacity (ton)
Positioning (non Jack-up)	-	DP ≥ 1	-	DP class (-)
Positioning (Jack-up)	-	DP ≥ 1	-	DP class (-)
	collection point: (x coord, y coord, zone) site:bathymetry	max(site:bathymetry(collection point coordinates))	≤	Leg Operating Water Depth (m)

Table 2-54 ROV requirements

	ROV Systems - Inspection Class			
	Upstream Input	**Function**	**Eval.**	**Logistic Parameter**
ROV Metrology	collection point:x coord	max(site:bathymetry(collection point coordinates))	≤	Depth Rating [m]
	collection point:y coord			
	collection point:zone			
	site:bathymetry			

2.8.5 PERFORMANCE FUNCTIONS

The logistic operation details are shown Table 2-55, such as duration and met-ocean limit conditions, necessary to conduct the performance assessment for this logistic phase. These are approximate values, which have been derived from literature review and industrial expertise. To obtain these values, there was the need to simplify complex and highly project specific tasks, since the actual times and limits require a much more complex assessment between a wide range of factors, from the vessel and equipment characteristics to the crew experience, which are outside of the scope of this tool.

Table 2-55 Logistic operation details considered for the installation of offshore collection points

Operation sequence	**Detail of the operation**			**Operation duration [h]**	**Operational Limit Conditions**			
					Hs [m]	**Tp [s]**	**Ws [m/s]**	**Cs [m/s]**
Mobilization				Vessel database: Mob time	-	-	-	-
Assembly at port				Default value: 0 [h]	-	-	-	-
Vessel preparation & loading				Default value: 48 [h]	-	-	-	-
Transportation port / site				Distance × Vessel transit speed	Vessel database: OLC transit limits			
Positioning				If Jack-up: Jacking speed X water depth Else: Default value: 1 [h]	Vessel database: OLC transit limits or OLC jacking limits for jack up vessels/barges			
Collection point installation	Surface Piercing	Lift top-side platform		Default value: 15 [h]	2	15	15	-
		Connect top-side platform to the support structure						
	Seabed / Seabed with Pigtails	Dry mate	Lift array/export cable from seabed	Default value: 1.5 - 2 [h]	1.5 - 2	10 - 20	17 - 23	1.5
			Conduct dry-mate connections on deck	Default value: 0.5 [h]				
			Lower collection point to the seabed	Default value: 0.5 - 1 [h]				
		Wet mate	Lower collection point to the seabed	Default value: 1 - 3 [h]	2	15	20	1,5
Demobilization				Vessel database: Mob time [h]	-	-	-	-

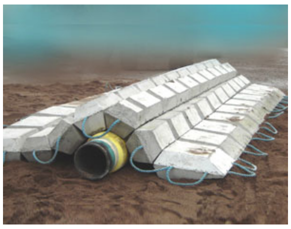
2.9 INSTALLATION OF EXTERNAL PROTECTION

Although cable burial is the primary choice for protecting subsea power cables, there are specific conditions where this method is not feasible/recommended to be used. For these, alternative protection is advised in order not to increase the risk of hazards. DNV recommended practices [8] advise external cable protection for the following conditions along the cable route and jointing areas:

- at the interface between cable and offshore units (transition areas);
- in the immediate vicinity of offshore units where burial is not practical;
- at infrastructure crossings, e.g. between power cable and pipeline;
- across boulder, cobble or gravel fields or in very hard (rocky) seabed, including areas with insufficient sediment thickness, where trenching may not be feasible or economic
- in areas with mobile sediments;
- where installation activities (e.g. ploughing) had been interrupted and cable was surface laid or minimum burial depth could not be reached;
- at cable repair (joint) locations;

For these specific conditions, several protection elements are available, with the main categories being tubular products, mattresses and rock placement. Table 2-55 summarizes the external protection elements considered in the model, including a short description of each element, the common rational behind the selection process plus a short description of the common installation practices. These were defined with the help of [8] and [9], plus industrial advice within the project consortium.

Table 2-56 Description of the external cable protection elements considered in the model

Protection Element		Description
Split pipe sleeves		These consist of cylindrical half-shells sections, usually made from polyurethane or ductile iron. Are commonly used for constraining cable bends, provide impact protection and stability due to the resistance and added mass of the split pipes, and provide abrasion resistance especially in hard seabed environments. The installation of such elements is usually achieved onboard of the cable laying vessel, by joining and bolting together the half-shells around the cable while laying.
Concrete Mattresses		These consist of pre-fabricated blocks of concrete connected by polypropylene ropes. Are commonly used as protection within cable crossings and transition areas (such as cable terminations or landfall areas). The installation method consists of lifting and deploying the mattresses using a vessel crane plus a dedicated installation frame.

Rock Filter Bags		These consist of pre-filled rock bags, which are commonly used to stabilize non-buried cables in high energetic environments (such as strong tidal current sites), while providing external impact protection. The installation method consists of using the vessel lifting capacity to deploy the filter bags accurately over the cable.
Rock dumping		These consist of the placement of crushed stones of varying size over the cable, creating a protective barrier against external aggression. The installation method consists of deploying the stones using a less accurate side stone dumping vessel, or a high accurate fall pipe vessel.

It's important to mention that due to the nature of split pipe installation procedures (explained in the previous table), these are typically conducted during the installation of the cables and not as a follow up phase, therefore these have been included in the installation of static cables logistic phase (see section 2.6). Having in consideration the previous descriptions and the limitations of the tool, a set of heuristic decisions are implemented in regarding the selection process and suitability of each protection element. This analysis is done together with the electrical module, and the set of rules will be part of later deliverables in the project.

2.9.1 INPUTS

The list of inputs from the different WPs and their corresponding format and unit of measurement, for the installation of static cables systems is the following (Table 2-57):

Table 2-57 Inputs for the installation of external cable protection systems

#	Module	Parameter	Python name (panda name:parameter name)	Unit	Format
1	Data base	Bathymetry	site:bathymetry	[m]	float
2		Seabed Conditions - Geophysics/Geotechnics	site:soilt type	[-]	string
3		Date and time of the measure met-ocean historical data	met-ocean:year	[-]	integer
4			met-ocean:month	[-]	integer
5			met-ocean:day	[-]	integer
6			met-ocean:hour	[-]	integer
7		Resource met-ocean data (wave): (Hs, Tp)	met-ocean:wave Hs	[m]	float
8			met-ocean:wave Tp	[s]	float
9		Resource met-ocean data (wind): wind speed	met-ocean:wind speed	[m/s]	float
10		Resource met-ocean data (tide): tidal speed	met-ocean:tide speed	[m/s]	float

11	Electrical	Type of protection element	external protection:type	[-]	string
12		Position of collection points	external protection:x coord	[-]	float
13			external protection:y coord	[-]	float
14			external protection:zone	[-]	string
15	Logistics	Vessel database	vessels:	various	floats and strings
16		Equipment database	equipments:	various	floats and strings
17		Port database	ports:	various	floats and strings
18		Average fixed duration default values	durations:	various	floats and strings
19		Safety factors default values	safety:	various	floats and strings
20		Operational limit conditions default values	olc:	various	floats and strings

2.9.2 LOGISTIC PHASE SEQUENCING

The flowchart containing the operation sequences to model the installation of external cable protections can be found section 7.1.9 of this report. These have mostly been derived from literature review, such as the IMCA guiding document on Concrete mattress handling deployment [14], or DNV recommendations for subsea power cables design and installation [8]. The decision symbols on the flow chart correspond to specific inputs from different data frames, see section 2.9.1 for more information.

2.9.3 VESSEL AND EQUIPMENT TYPE COMBINATIONS

The vessel and equipment types are mostly based on literature review, and have been selected based on the necessity of storage, lifting and positioning capabilities.

As recommended in [8], the deployment of mattresses and bags should be conducted with the help of underwater visual support. Also, it is mentioned that the use of divers should be avoided. Thus, it's assumed that all combinations require an inspection class ROV.

Table 2-58 Vessel and Equipment combinations for installing external cable protection systems

#	Protection Type	Vessel 1 - Installation		Equipment 1 - Installation		Equipment 2 - Support	
1	Concrete Mattresses & Rock Filter Bags	1x	Crane Vessel	1x	Concrete Mattresses / Rock Filter Bags	1x	Inspection Class ROV
2		1x	Crane Barge + Tugboat	1x	Concrete Mattresses / Rock Filter Bags	1x	Inspection Class ROV
3		1x	Construction Support Vessel	1x	Concrete Mattresses / Rock Filter Bags	1x	Inspection Class ROV
4		1x	Platform Supply Vessel	1x	Concrete Mattresses / Rock Filter Bags	1x	Inspection Class ROV
9	Rock dumping	1x	Fall Pipe Vessel	-	-	-	-

2.9.4 FEASIBILITY FUNCTIONS

The required density and thickness of a mattress depends on hydrodynamic loading and target impact resistance. For simplicity purposes, it is assumed that the thickness is required to be at least 0,3 meters. For the selection of rock filter bags, no specific minimum requirement was derived.

Table 2-59 Concrete Mattress requirements

	Concrete Mattresses			
	Upstream Input	**Function**	**Eval.**	**Logistic Parameter**
Mattress characteristics	-	0,3	≤	mattress unit - thickness [m]

Following the guidelines included in [14], it's recommended that mattresses should not be stacked higher than 2 meters. This number is relevant to compute the number of mattresses that can be transported in a single trip. The value was also assumed to be valid for rock-filter-bags units.

Table 2-60 Calculation of the number of units to be installed

Input Parameter	Function		
external protection:type	if (external protection:type == concrete mattress): count(external protection:type)	==	nr concrete mattress
	if (external protection:type == rock filter bags): count(external protection:type)	==	nr rock filter bags

Table 2-61 Calculation of the maximum number of stacked units

Equipment Parameter	Function		
mattress unit - thickness [m]	int(2/(mattress unit - thickness))	==	max nr stacked mattresses
rock filter bag unit – height [m]	int(2/(rock filter bag unit – height))	==	max nr stacked rock bags

Each vessel should be able to carry a minimum of one stack pile per trip. The feasibility functions were then designed according to this specification. Keep in mind that the orange variables included in Table 2-62 refer not to equipment parameters, but to calculated values depending on upstream inputs

Table 2-62 Installation vessels requirements

	Vessel/Equipment Compatibility All Vessels / Rock Filter Bags && Concrete Mattresses			
	Equipment Parameter	**Minimum Requirement**	**Eval.**	**Vessel Parameter**
Area/Load capabilities	nr concrete mattress nr rock filter bags mattress unit - length [m] mattress unit - width [m]	**if (nr concrete mattress > 0):** (mattress unit - length*width) + **if (nr rock filter bags > 0):** pi*(bag unit - diameter/2)^2	≤	Free deck space [m^2]

	bag unit - diameter [m]			
	nr concrete mattress nr rock filter bags mattress unit - length [m] mattress unit - width [m] mattress unit - weight in the air [ton]	**if (nr concrete mattress > 0):** nr stacked mattresses*(mattress unit - weight in the air)/(mattress unit - length * width)	≤	Max. Deck load [ton/m^2]
	nr concrete mattress nr rock filter bags bag unit - diameter [m] bag unit - weight [ton] bag unit - weight [ton]	**if (nr rock filter bags > 0):** nr stacked rock bags* (bag unit - weight)/(pi*(bag unit - diameter/2)^2)	≤	
	nr concrete mattress mattress unit - weight in the air [ton] nr rock filter bags bag unit - weight [ton]	nr concrete mattress*mattress unit - weight in the air + nr rock filter bags*bag unit - weight	≤	Max Deck Cargo [t]
Lift capabilities	nr concrete mattress mattress unit - weight in the air [ton]	**if (nr concrete mattress > 0):** mattress unit - weight in the air	≤	Max. crane lifting capacity (ton)
	nr rock filter bags bag unit - weight [ton]	**if (nr rock filter bags > 0):** bag unit - weight	≤	
Positioning (non jack-up)	-	$DP > 0$	>	DP class [-]

Table 2-63 Rock Dumping Installation vessel requirements

	Fall Pipe Vessel			
	Upstream Input	**Function**	**Eval.**	**Logistic Parameter**
Fallpipe Characteristics	cable route:bathymetry [m]	max(cable route:bathymetry)	≤	Max dumping depth [m]

2.9.5 *PERFORMANCE FUNCTIONS*

Table 2-64 outlines the logistic operation details, such as duration and met-ocean limit conditions, necessary to conduct the performance assessment for this logistic phase. These are approximate values, which have been derived from literature review and industrial expertise. To obtain these values, there was the need to simplify complex and highly project specific tasks, since the actual times and limits require a much more complex assessment between a wide range of factors, from the vessel and equipment characteristics to the crew experience, which are outside of the scope of this tool.

Table 2-64 Logistic operation details considered for the installation of gravity based structures

Operation sequence	Detail of the operation	Operation duration [h]	Operational Limit Conditions			
			Hs [m]	Tp [s]	Ws [m/s]	Cs [m/s]
Mobilization		Vessel database: Mob time	-	-	-	-
Assembly at port		Default value: 0 [h]	-	-	-	-
Vessel preparation & loading		Default value: 48 [h]	-	-	-	-
Transportation port / site		Distance × Vessel transit speed	Vessel database: OLC transit limits			
Positioning		Default value: 1 [h]	Vessel database: OLC transit limits			
Concrete Mattress Installation	Lift and overboard concrete mattress	Default value: 0.25 – 0.5 [h]	2 - 2.5	10 - 20	10 - 15	1.5
	Lower concrete mattress to the seabed					
	Position and release concrete mattress					
	Recover installation frame					
Rock dumping Installation	Fall pipe vessel end positioning					
	Rock dumping through route	Rock dumping progress rate[17] × Route length	2 - 3	-	-	-
Rock filter bag installation	Lift and overboard rock filter bag	Default value: 0.25 – 0.5 [h]	2 - 2.5	10 - 20	10 - 15	1.5
	Lower rock filter bag to the seabed					
	Position and release rock filter bag					
Demobilization		Vessel database: Mob time [h]	-	-	-	-

[17] A report from Energinet.dk [79] suggests an average progress rate of 100-1000m/day

2.10 THE SCHEDULING FUNCTIONS

In order to discriminate between feasible logistic solutions, one should estimate the performance of these solutions. As argued in Deliverable 7.1 [15], the Levelised Cost of Energy (LCOE) is the objective function metric chosen for the design optimization of an array of wave or tidal devices in the DTOcean tool. Three core components must be computed when deriving the LCOE:

- The Annual Energy Production (AEP),
- The capital expenditures (CAPEX),
- The operational expenditures (OPEX).

In this context, the installation module of the DTOcean global tool aims at considering all the key aspects potentially affecting the above three components. For what concerns the impact of the logistic activities on the AEP, the basic principle abides in collecting estimates of the duration of every single individual logistic operation forming the logistic phase. In turn, the forecast of the complete schedule of the installation phase will set the initial checkpoint to consider that the wave or tidal power plant is commissioned and electricity is being generated based on Met-ocean data. This directly impacts the AEP.

In section 2.1, the standard breakdown of a logistic phase into individual logistic operations was introduced. Sections 2.2 to 2.9 pursued this breakdown description by providing further details of the installation sequence.

Although not always going to the level of the individual blue boxes in the operation sequence flowcharts gathered in Appendix 7.1, the time assessment is performed for each major individual logistic operation. Two main underlying principles have been dictating the justification of finding the level of time evaluation for each logistic phase:

- The individual logistic operation will use a dedicated method for time assessment and therefore should be isolated,
- Having the flexibility to adjust default input values would bring significant added value and therefore the individual logistic operation should be isolated.

In terms of method for appraisal of the duration of these individual logistic operations, one can outline three categories:

- Fixed average duration,
- Vessel transit or towing speed multiplied by the distance to be covered,
- Average progress rate of use of an equipment multiplied by the corresponding physical characteristics of the element to be installed.

In the installation module, it is important to distinguish between the time spent at port and the time spent at sea. In fact, knowledge of the predicted total duration of the sea time is required to estimate the waiting time due to weather window. Hence, a convenient way to describe the total duration of a logistic phase can be given by equation (2-1):

$$T_{lp} = T_{port} + T_{wait} + T_{sea} \qquad (2\text{-}1)$$

$$T_{lp} = \sum_{lo_{port}=1}^{LO_{port}} t_{port}\left(lo_{port}\right) + T_{wait} + \sum_{lo_{sea}=1}^{LO_{sea}} t_{sea}\left(lo_{sea}\right)$$

Where:

- T_{lp} [hour]: Total duration of one logistic phase,
- T_{port}, T_{sea} [hour]: Total duration of operations before departure (T_{port}including mobilization and port operations) and sea operations, respectively,
- t_{port}, t_{sea} [hour]: Duration of one individual logistic operation at port and at sea, respectively,
- T_{wait} [hour]: Duration of the waiting time due to weather window (function of T_{sea}),
- LO_{port}, LO_{sea}: Total number of individual logistic operations for one logistic phase at port and at sea, respectively,
- lo_{port}, lo_{sea}: Index of a given individual logistic operation at port and at sea, respectively.

Note that the unit of measurement for the durations is expressed in hours to be consistent with the minimum resolution of the met-ocean time series resolution requested as input to the installation module. It should be relatively straightforward to refine this time increment in future versions of the tool.

2.10.1 PORT TIME

As previously mentioned the port operations for one logistic phase systematically consist of three tasks: mobilisation, assembly and vessel preparation & loading. Hence, one can write T_{port} as the sum of the durations of each of these operations, denoted respectively t_{mob}, t_{assemb} and t_{prep}.

$$T_{port} = t_{mob} + t_{assemb} + t_{prep} + t_{demob} \qquad (2\text{-}2)$$

The durations t_{mob}, t_{demob}, t_{assemb} and t_{prep} will all make use of default fixed average values which can be logistic phases specific, expressed in hours. For instance the assembly time at port for the devices will be an end-user input while for the other marine operations it will be retrieved from a default value table. Concerning the mobilization time, the values are directly extracted from the vessel database. All methods and default values assumed for $t_{mob}, t_{demob}, t_{assemb}$ and t_{prep} are depicted in the summary tables at the end of each logistic phase previously described in sections 2.2 to 2.9.

2.10.2 SEA TIME

Since the waiting time,T_{wait}, requires knowledge of the total sea operations time, T_{sea}, the latter item will be detailed first. Unlike the port operations the task to be performed at sea cannot be presented in a systematic form for all logistic phases due to the specificity of each marine operation to achieve a distinct goal.

However, one can align some individual logistic operations based on the methods used to estimate their duration:

- Transportation operations: including the classic transit operation (with or without deck cargo) and towing operation,
- Static power cables laying/trenching/burial operations: using a variety of cable burial tools,

- Foundations/anchors penetration operations: also using different techniques,
- Other operations: any other specific task to be performed at sea.

- ***Transportation time***

In the following paragraphs, the methods to assess these four categories of sea operations will be described. Regarding the transportation operations, there exist two alternatives to determine the transportation time, t_{transp}:

$$t_{transp} = \begin{cases} t_{transit} = D * V_{transit} \\ t_{towing} = D * V_{towing} \end{cases} \tag{2-3}$$

With:

- $t_{transit}$, t_{towing} [hour]: duration of the transit operation and towing operation, respectively,
- $V_{transit}$, V_{towing} [m/h]: vessel transit speed and vessel towing speed, respectively,

D [m]: shipping distance to be covered by the vessel.It should be noted here that the distance will be determined based on an algorithm developed by DTOcean WP3 partners. Details of the methodology governing the distance calculator algorithm can be found in Appendix 7.

While the vessel transit speed $V_{transit}$, is directly collected from the vessel database, the towing speed V_{towing}, has been the object of particular attention. The initial idea was to be able to determine the towing speed of a tugboat towing either an ocean energy device or a barge depending on the physical characteristics of the towed object. From this towing speed, the interval of time from port to the installation site could be evaluated. After a literature review presented in Appendix 0, it turned out to be difficult to establish a simple equation determining the towing speed depending on the geometry of the object and the environmental conditions at sea.

In addition, the towing speed is usually a parameter fixed in accordance with safe marine transportation. Therefore, the selection of an appropriate vessel capable of towing – in the framework of DTOcean WP5 – must be based on other criteria such as the required bollard pull while assuming a maximum towing speed. Appendix 0 reviews the standard approaches to evaluate the required bollard pull and concludes negatively with regards to the decision to implement such calculations in the first version of the installation module.

$$V_{towing} = F_{tow} * V_{transit} \tag{2-4}$$

- ***Cable laying/burial time***

Concerning the cable laying operations, a horizontal progress rate for the different cable burial/laying tools in the equipment database, was derived for each soil type conditions defined in DTOcean (see Table 2-65).

These indicative values were obtained mainly on specialized reports on cable laying and burial, references used were [9], [11], [16], [17], with the compiled values post-processed by industrial partners. Subjective interpolation and extrapolation across the DTOcean soil types was performed, taking into account the suitability of the trenching techniques.

Consider these values has rough estimates. The actual trenching progress rate will depend upon a highly complex combination between several factors, including:

- Seabed morphology (e.g slopes, bolders)
- Soil specific properties (e.g shear strength, particle size, permeability, compressibility, density)
- Environmental conditions and, in particular, tide
- Burial tool technical capabilities

This horizontal progress rate, denoted R_{prog}, is directly related to the cable route to determine the total duration of the cable laying operation, t_{lay}. One can therefore write equation (2-4):

$$t_{lay} = \sum_{soil=1}^{SOIL} R_{prog}(soil).D_{lay}(soil) \tag{2-4}$$

Where:

- $soil$ refers to one soil type among the list of DTOcean seabed soil types,
- $SOIL$ is the total number of soil types across the cable route,
- D_{lay} is the distance of static power cables in each soil condition.

Table 2-65 Default values for the horizontal progress rates of four cable laying/burial techniques across all DTOcean soil types

	Soil Type											
	Cohesionless			**Cohesive**				**Others**				
Technique	**loose sand**	**medium sand**	**dense sand**	**very soft clay**	**soft clay**	**firm clay**	**stiff clay**	**hard glacial till**	**cemented**	**soft rock coral**	**hard rock**	**gravel cobble**
Jetting [m/h]	100 - 400	100 - 300	0	350 - 600	350 - 600	150 - 350	0	0	0	0	0	0
Ploughing [m/h]	50 - 150	200 - 500	50 - 150	0	250 - 500	250 - 750	350 - 750	250 - 350	0	0	0	200 - 500
Cutting [m/h]	0	100 - 450	100 - 450	0	100 - 450	100 - 450	50 - 100	50 - 100	50 - 100	25 - 75	0	0
Dredging [m/h]	100 - 200	50 - 150	25 - 125	100 - 200	50 - 150	25 - 125	25 - 75	25 - 75	25 - 75	25 - 75	0	25 - 125

- ***Penetration time***

Similarly, a simple equation was established to assess the time of vertical penetration of a foundation into the seabed. In spite of making use of horizontal progress rates, default values for the vertical penetration rates of four driving techniques using four different equipment (present in the database) were derived for each soil type considered in DTOcean.

While it is clear that such penetration rates also depends on factors such as the size of the pile to installed or the capabilities of the equipment to be used, these approximate numbers serve as a basis for the time evaluation. Various sources have been consulted with the help of industrial partners to determine reasonable rough ranges as summarized in Table 2-66.

Table 2-66 Default values for the vertical penetration rates of four pile driving equipment across all DTOcean soil types

	Soil Type											
Equipment	Cohesionless			Cohesive				Others				
	loose sand	medium sand	dense sand	very soft clay	soft clay	firm clay	stiff clay	hard glacial till	cemented	soft rock coral	hard rock	gravel cobble
Drilling rig [m/h]	0	0	0	0	0	0.5 - 0.8	0.4 - 0.6	0.25	0.5	0.3 - 0.45	0.2 - 0.3	0
Hammer [m/h]	15 - 25	10 - 20	2.5 - 7.5	10 - 20	10 - 15	5 - 10	1.5 - 7.5	0	0	0	0	2.5 - 7.5
Vibro-driver [m/h]	300 - 450	200 - 300	50 - 100	150 - 200	50 - 100	0	0	0	0	0	0	50 - 100
Suction pump [m/h]	300 - 450	200 - 300	50 - 150	150 - 250	50 - 150	0	0	0	0	0	0	0

ROV with jetting [m/h]	100 - 400	100 - 300	0	350 - 600	350 - 600	150 - 350	0	0	0	0	0	0

Find in the following table a few specific comments and references for each equipment type.

	Comments/references
Drilling rig	1- Some material indicate a range from 0.2m up to 2.5m per hours of drilling rate depending on the soil conditions and the pile diameters (values specified here are interpolated from these indicative example values). 2- Appendix 7.3 evaluates the possibility to calculate the Rate of Penetration (ROP) but it appears too many parameters are necessary to implement such algorithm in DTOcean. It would at least require the determination of a drivability coefficient or a soil resistance to driving for each soil type (and possibly for a range of pile diameter).
	http://d3c6l3uum4x5po.cloudfront.net/wp-content/uploads/2014/06/SUT_140625_OSIG-SWI_FSC_SWGeoforum_Presentation.pdf
Hammer	1- IHC recommends 40 hammer blows / 25cm but the industrial standard procedure is 25 blows / 25cm (assuming stiff soil conditions). Assuming that the hammers specifications indicate that the blow rate ranges from 25 to 70 blow/min, one can conservatively assume a wider range of penetration rate for hammer varying from 1.5 up to 25 m/hours. Subjective extrapolation was done to estimate indicative ranges across all soil types with the help of industrial experts 2- Appendix 7.4 evaluates the possibility to calculate the Rate of Penetration (ROP) but too many parameters are necessary. It would at least require the determination of a drivability coefficient or a soil resistance to driving for each soil type.
	http://www.ihchydrohammer.com/fileadmin/IHC_Hydrohammer_-_ihchydrohammer.com/Home/IHC_Hydrohammer_Offshore_Brochure_IHC03-01-11.10.pdf
Vibro-driver	Indicative values were found for non-cohesive soils for different penetration depth and pile diameters. Subjective interpolation and extrapolation across the DTOcean soil types was performed with the help of industrial experts
	https://www.researchgate.net/publication/257774558_Prediction_of_penetration_rate_of_sheet_pile_installed_in_sand_by_vibratory_pile_driver
	http://www.diva-portal.org/smash/get/diva2:9149/FULLTEXT01.pdf
Suction pump	http://www.sptoffshore.com/en/equipment/suction-pumps
	http://www.eng.ox.ac.uk/geotech/publications/reports-offshore/OUEL_Report_2268_04.pdf
ROV with jetting	Assumed to be the same as for the horizontal progress rate in the absence of contradicting values in the literature.

Equation (2-5) gives the predicted time to position the foundation into the required penetration depth.

$$t_{pen} = \sum_{soil=1}^{SOIL} R_{pen}(soil).D_{pen}(soil) \tag{2-5}$$

Where:

- t_{pen} is the duration of the foundation penetration into the seabed,
- R_{pen} is the vertical penetration rate in a given soil type,
- $SOIL$ is the total number of soil types across the vertical layers of the seabed characterization at the location of the foundation,
- D_{pen} is the required penetration depth of the foundation.

In Appendices 0 and 7.6, a literature review on the drivability and penetration rate of both drilling rigs and hammer, respectively, is reported. This background research has motivated the endorsement of the above simplified and generic vertical penetration rate analysis in the installation module of DTOcean.

- ***Note on the default values***

The last method to get the time of a specific task at sea is to assume a default average duration value. At this stage, all default values (i. e. either the fixed average durations or the penetration and progress rates) are expected to be modified by the end-user of the DTOcean tool in case he/she has more accurate/contemporary information specific to the project conditions under consideration. In the absence of such extra information, the default values will be used.

2.10.3 WAITING TIME

The remaining item of equation (2-1) to quantify is the waiting time, T_{wait}. A time-domain approach, as recommended by DNV [18], was adopted. In offshore engineering, a weather window is a period of time where quantities such as H_s, T_p, wind speed, current speed, daylight and temperature remain at levels which permit a given set of marine operations to be performed safely. For planning management purposes, the durations and the starting time of the weather windows need to be specified [19].

Generally, the modelling of weather windows starts with the selection of the time slots where each individual criterion for marine operations is respected. Thus, one can keep only time slots where all criteria specified are simultaneously satisfied. Every satisfactory weather window is defined by a unique combination of starting time and duration. The procedure to obtain an average waiting time for a given set of Operational Limit Conditions (OLC) and a request for a marine operation (knowing its starting time T_{start} and total duration at sea T_{sea}) can be described in three steps:

- STEP 1 – Determination of all-weather windows respecting simultaneously all OLC criteria,
- STEP 2 – Identification of the first weather window satisfying the total duration of sea operations criterion and observed after requested starting time of the marine operation assuming the date is reported in the historical met-ocean data. This leads to the direct reading of the waiting time for every year of the met-ocean time series.
- STEP 3 – Statistical annual average of the waiting times.

To illustrate the first step, Figure 2-14 exposes the determination of the weather windows over a 10 days period of time using the following three accessibility criteria (hourly time series of wind speed, significant wave height and energy period were kindly supplied by the Irish Marine Institute):

- Significant wave height threshold: $H_s \leq 1.5$ meter, see Figure 2-14 (a),
- Energy period threshold: $T_e \leq 7$ seconds, see Figure 2-14 (b),
- Wind speed limit: $W_s \leq 30$ knots, see Figure 2-14 (c).

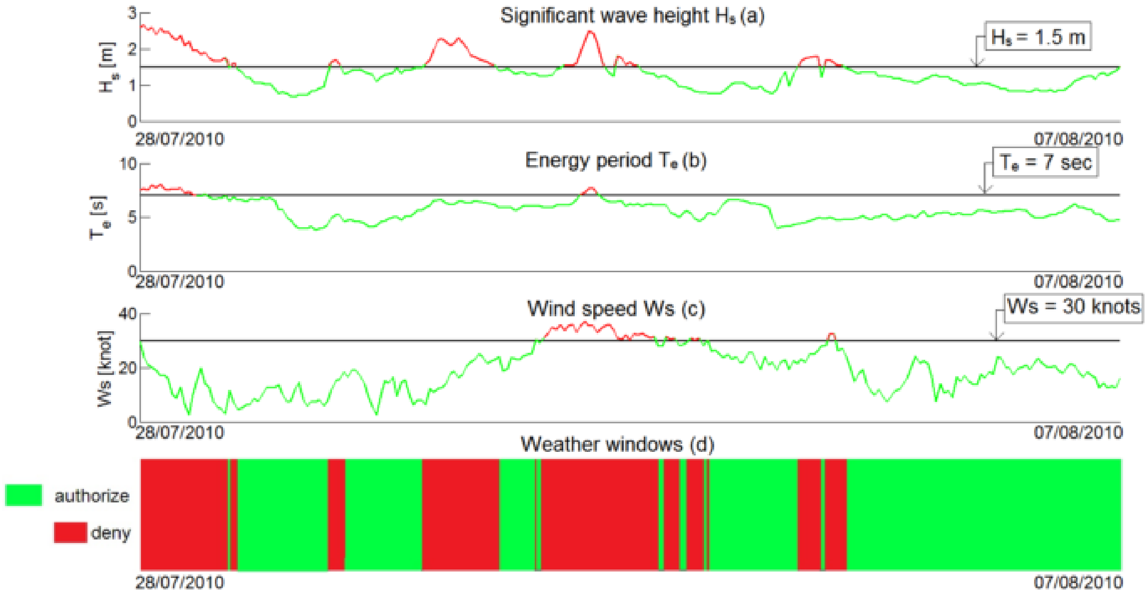


Figure 2-14 Example of the determination of weather windows with three accessibility criteria at AMETS in Summer 2010

Continuing with this example, one can reach the results of the first step of the weather window calculation, as depicted in Table 2-67. Over the 10 day period from the 28^{th} of July 2010 until the 07^{th} of August 2010 at AMETS, the starting times and durations of all weather windows satisfying the above criteria are listed chronologically in Table 2-67.

Table 2-67 Weather windows outcome for the period from the 28th of July 2010 to the 07th of August 2010 at AMETS

Weather window number	Starting time	Duration in hours
1	28/07/2010 at 2300	1
2	29/07/2010 at 0100	22
3	30/07/2010 at 0300	19
4	31/07/2010 at 1700	8
5	01/08/2010 at 0300	2
6	02/08/2010 at 0800	2
7	02/08/2010 at 1400	3
8	02/08/2010 at 2100	1
9	02/08/2010 at 2300	20
10	04/08/2010 at 0100	2

11	04/08/2010 at 0700	67

This example illustrates the first step leading to the estimation of a waiting time for a given marine operation. The influence of OLC is obviously of utmost importance. OLC for marine operations shall provide a realistic evaluation of the sensitivity of a marine operation to meteorological and oceanographic conditions. These limits are a major step to ensuring the safe execution of a marine operation. The OLC shall be obtained by establishing limiting criteria for the met-ocean parameters by which the meteorological and oceanographic conditions are characterized. The response characteristics of particular installation vessels to specific aspects of the met-ocean environment shall be considered when establishing these OLC [20].

In the DTOcean tool, four met-ocean parameters will be accounted for in the weather window predictions, namely: the significant wave height H_s, the peak wave period T_p, the wind speed and the current speed. While the wave and wind conditions are directly provided in a suitable time-series format (minimum one hour of resolution and one year of records), interpolation and extrapolation techniques may be required to arrange the input tidal current time-series into the same format. Directionality of waves, wind and currents will be ignored due to the complexity of accurately predicting the relative heading position of the vessels at any point of the grid coordinate system and at any time.

The second step of the weather window procedure progressively runs through all starting times and durations of the weather windows determined in the first step. The objective of this scanning is to find the first weather window with a duration superior to the total marine operation time requested which starts as early as possible after the requested starting time of the marine operation. In the previous example, if one considers a marine operation of 12 hours is requested from the 01st of August with the OLC aforementioned satisfied over the course of the marine operation, one can directly read Table 2-67 and identify the first satisfactory weather window, as being:

Weather window number 9; starting time = 02/08 at 23:00 and duration = 20 hours

The resulting waiting time is the difference of the requested starting time for the marine operation (i.e. 01st of August 00:00 in our example) and the starting time of the first satisfactory weather window identified (02nd of August at 23:00). In this example, the waiting time is 47 hours.

Finally, the third and last step iterates the previous two steps for every year available from the met-ocean time-series and post-processes statistical data. In other words, the waiting time for every year of the met-ocean data is derived and the mean value can be readily calculated. This average waiting time is used as final output of the weather window algorithm. It should be mentioned that, with little extra effort, additional statistical values can be measured including the standard deviation of the waiting time, the monthly/seasonal/inter-annual variability, the influence of the duration of the marine operation on the waiting time and more.

Transcribing the weather window algorithm in mathematical terms is not a plain elementary task as it involves multi-conditional statements and inequalities rather than more "conventional" equations. Concerning the first step, one can say that a weather window, denoted $W_{W,}$ should obey the following inequalities system (2-6):

STEP 1	$$W_W = W_W(w_{start}, w_{dur})$$ $$W_W = \begin{cases} H_S\big(t_{end}(lo_{sea}) - t_{start}(lo_{sea})\big) \leq H_{S\_max}(lo_{sea}) \\ T_p\big(t_{end}(lo_{sea}) - t_{start}(lo_{sea})\big) \leq T_{p\_max}(lo_{sea}) \\ W_{speed}\big(t_{end}(lo_{sea}) - t_{start}(lo_{sea})\big) \leq W_{speed\_max}(lo_{sea}) \\ C_{speed}\big(t_{end}(lo_{sea}) - t_{start}(lo_{sea})\big) \leq C_{speed\_max}(lo_{sea}) \end{cases}$$ With: $lo_{sea} = 1, \dots, LO_{sea}$	*(2-6)*

Where:

- w_{start}, w_{dur} [datetime, hour]: these are the starting times and durations of all weather windows satisfying the set of inequalities,
- $t_{start}(lo_{sea}), t_{end}(lo_{sea})$ [datetime]: these are the starting time and ending time of a given individual logistic operation at sea,
- $H_{S\_max}(lo_{sea}), T_{p\_max}(lo_{sea}), W_{speed\_max}(lo_{sea}), C_{speed\_max}(lo_{sea})$ [m, s, m/s, m/s]: these are the OLC for a given individual logistic operation at sea in terms of significant wave height, peak wave period, wind speed and current speed, respectively.

IMPORTANT NOTE: due to time constraints imposed by the DTOcean project, STEP 1 was simplified. Indeed, it was assumed that the most stringent OLC that will be required during the various tasks at sea shall be satisfied under the entire sea time. In other words, the most restrictive limits in H_{S_max}, T_{p_max}, $W_{speed_max}$and C_{speed_max} will be considered for the total duration at sea.

The second step isolates the nearest weather window which respects to the duration and starting time requirements of the marine operation. This can be represented by (2-7):

STEP 2	$$W_{W\_select} = \begin{cases} w_{start}(i) \geq t_{start}(1) \\ w_{dur}(i) \geq T_{sea} \end{cases}$$ Subject to: $\min(w_{start}(w))$ With: $i = 1, \dots, W$ $$T_{wait} = w_{start\_select} - t_{start}(1)$$	*(2-7)*

Where:

- i: this is an index referring to one of the weather window determined in step 1,
- W: this is the total number of weather windows found in step 1,
- W_{W_select}: this is the selected weather window which satisfies the requirements of the requested weather window,
- w_{start_select}[datetime]: this is the starting time of the first satisfactory weather window.

As explained before, iterating step 1 & 2 over the number of years of met-ocean data available lead to a statistical analysis which include the mean value of the waiting time as show below:

STEP 3		*(2-8)*

	$$< T_{wait} >= \frac{1}{Y}\sum_{y=1}^{Y} T_{wait}(y)$$

Where:

- y: this is an index referring to a year in the met-ocean time-series,
- Y: this is the total number of years in the met-ocean time series,
- $< T_{wait} >$ [hour]: this is the average waiting time of the requested marine operation.

2.10.4 DETERMINATION OF THE NUMBER OF VESSEL JOURNEYS

The port, sea and waiting time assessment previously described implicitly assumes that a logistic phase is composed of one single trip. In other words, it is assumed that all elements to be installed are transported at once and therefore there is no need to return to port to reload the vessel(s). In the context of a large array of ocean energy devices, one can anticipate a series of marine operations. Installation or replacement of a large number of components of the same type would potentially involve several returns to port for loading operations.

In order to reflect this possible organizational strategy, the logistic functions of DTOcean determine the maximum number of units/items/elements (i.e. any component from the bill of materials including the devices) which can be transported in a single journey. When towing transportation is employed, it is always assumed that only one unit can be transported at a time.

In the case of deck transportation, a three-step procedure is deployed:

- STEP 1: calculate the area of all units/items/elements by multiplying their two largest dimensions (e. g. length*width). This leads to the creation of a vector containing the successive areas of all elements. There are a few underlying assumptions behind this calculation;
    - It is considered that the element is always being laid on deck by its two largest dimensions except
    - When the shape of the element is more complex than simple 3D objects like cylinders, spheres, cubes etc.; the dimensions specified in the bill of material should represent the separation distances between the outermost points in each of the three dimensional directions
    - The elements are stacked next to each other but there is no consideration of piling them up. Optimal deck lay-out can be a complex engineering challenge very specific to each marine operation. This is why such simplified assumptions are implemented in the context of the DTOcean tool.
- STEP 2: determine the cumulative areas from the vector of areas previously calculated
- STEP 3: establish how many of the largest elements can fit in the deck area of the transporting vessel. This operation is done by finding the index of the cumulative vector of areas which exceed the vessel deck area available while applying the corresponding safety factor.

It should be noted that the coordinates of the elements as provided by upstream WPs should follow the order of the device numbers established by the hydrodynamic module. Under this condition, the list of anchors or foundations, for example, is given per device. Since it is expected that the list of device numbers is defined by the hydrodynamic module developers in such a way that the distances between device number X to device number X+1 is minimized, the transit distances from the installation of one element to the other should also be minimized accordingly.

Once this maximum number of units/items/elements which can fit on the deck is determined, the actual total time of a given logistic phase can be determine through the upgraded comprehensive version of Eq. (2-5)

$$T_{lp} = t_{mob} + t_{assemb} + \sum_{j=1}^{J} \left[t_{prep} + T_{wait}(T_{sea}) + T_{sea}(j) \right] + t_{demob} \qquad (2\text{-}9)$$

With: $T_{sea}(j) = U(j) * t_{transp} + \sum_{lo_{sea}=1}^{LO_{sea}-1} t_{sea}\,(lo_{sea})$

Where:

- J is the total number of journeys and j the index associated with one journey
- U(j) is the number of units/items/elements to be transported per journey

Equation (2-9) gives the overview summary of all ingredients composing the time assessment as it is implemented in the logistic functions.

2.10.5 CONCLUSION

This closes the methodological description of the scheduling functions, as implemented in the installation module. The overriding challenge when designing these scheduling functions lies in finding the adequate balance between accuracy, complexity, requirements to the end-user, compatibility with a computational tool and flexibility.

To achieve a satisfactory tradeoff, the proposed methodology intends to offer a reasonably well-conceived standalone and flexible application. Depending on the profile of the end-user of the DTOcean tool, optional features accessible through the insertion of own estimates in the default values can be of significant added-value. An advanced user should even be in the position to adapt the methods to its own needs or make use of external software to refine the installation planning assessment. Thanks to the open source nature of the underlying code, a user literate in Python will have the possibility to extend the scope of the installation module relying on the solid structure of the code.

Conversely, a user seeking to have a fair representation of the impact of the logistic activities on the installation planning of an ocean energy project without any other effort than respecting the end-user requirements (i. e. inserting all required user input data in the correct format requested) should receive pertinent information for design purposes. This standalone mode is suited to users without the need or the capabilities to investigate further the specifics of the project simulated by the DTOcean tool.

2.11 THE ECONOMIC FUNCTIONS

Lifecycle logistics costs represent a significant proportion of the overall capital costs (CAPEX) and operational cost (OPEX) of an offshore project. The Institute of Shipping Economics and Logistics (ISL) [21] estimates that the share of logistics expenses can reach up to 20% of the total cost of an offshore wind farm with an average value around 15%. While in the long term one can reasonably expect similar share for the lifecycle logistics of the wave and tidal sector, in the first small pre-commercial arrays the share of logistic costs may be even higher [22]. Figure 2-15 indicates a share of 14% for the transportation and installation costs alone in the life cycle of an offshore wind project.

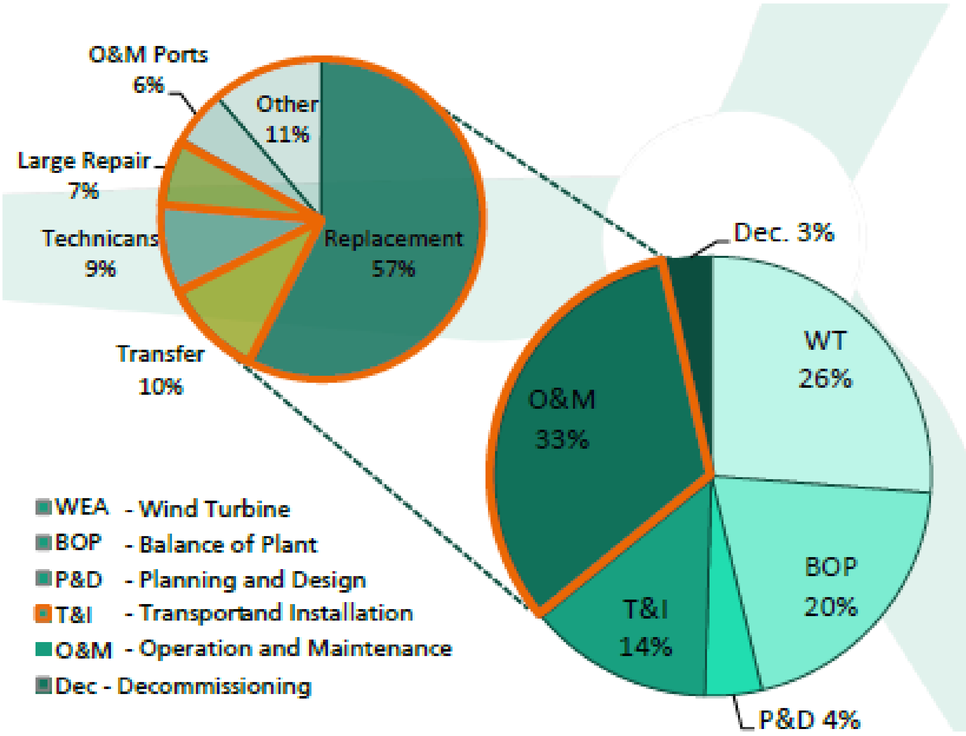


Figure 2-15 Life cycle cost in the offshore wind adapted from Scottish Enterprise [23]

To come out with a cost assessment methodology associated with the logistic activities, it is prerequisite to clarify the tight relationship existing between time and variable cost. In the electrical infrastructure and moorings & foundations module, the economic functions essentially correspond to the manufacturing expenses associated with components to be installed. The economic functions presented here are designed for having an estimate of the cost of a logistic activity. The lapse of time of the activity is firmly linked to the cost it will incur.

There are mostly two types of cost categories associated with the logistic activities:

- Port charges,
- Marine operations cost.

2.11.1 ASSESSMENT OF PORT CHARGES

The approach to account for the port charges was refined with the help of industrial partners and through the population of the DTOcean port databases. Port charges for a marine contractor are mainly linked to entering and exiting the harbor, e. g berth, pilotage and agency fees. This fluctuates largely for each port and depending on the size of the vessel, ranging between a few € 1000 to a few € 10,000

Transportation of components/devices from the manufacturing/assembly facility to the base installation port is typically the responsibility of the client of the marine contractor. The costs in relation to ports, e.g. rental of cranes and quays/terminals occupation charges, are typically also for the client of the maritime contractor. Based on the offshore wind experience, it should be observed that more and more Engineering, Procurement, Construction and Installation (EPCI) contracts are signed where some aspects of these procurement and port charges are the responsibility of the marine contractor.

Moreover, storage area is typically hired for a long term (number of months, depending on the size of the project), while cranes are typically hired for a shorter term although in some cases also long term. This means temporary cranes may be available in some ports in addition to those permanently present. Rental rates for quay walls and storage area depend on the load capacity t/m² and in big lines, range from 1 € to 10 € per m² and per month.

In the DTOcean port database, the following economic parameters are considered:

- Tonnage charges [€/GT[18]],
- Mooring/unmooring charges [€],
- Shifting/pilotage charges [€].

To-date, 77 ports have been characterized over 11 European countries (see map in Figure 2-16). During the population effort, most DTOcean partners have been involved to support this exercise for their corresponding countries. While technical specifications were obtained with a satisfying success rate, data for the aforementioned economic parameters was very delicate to retrieve. Beyond the confidentiality issue which can be very sensitive, three major obstacles in getting these port charges values can be highlighted:

- Port charges are highly project specific and negotiated accordingly. It is therefore not reasonable to disseminate average values or even ranges.
- It is not always the responsibility of the port authority to value some port charges. Satellite port companies are often in place to take care of the negotiation of the prices even when a base tariff brochure exists.
- The methods to calculate the port charges can vary from one port to another and, there is no standard or prevalent unit system recognized. For instance, pilotage charges are often also dependent on the vessel size likewise tonnage charges which may also differ depending on the goods/content that is transported by the vessel.

[18] GT= Gross Tonnage of a vessel in ton. Note that this parameter is available from the DTOcean vessel database

Figure 2-16 Map of the ports (blue points represent their UTM coordinates) currently available in the DTOcean database

Based on these conclusions, it was decided, in agreement with project partners having experience in offshore project management that the DTOcean port charges analysis should not attempt to sum-up the very uncertain economic parameters in the database but rather use an alternative approach. To this extent, the total port charges associated with one logistic phase, denoted C_{port}, relies on a percentage (p_{pc}) of the total costs for the marine operation, noted C_{sea}, summed up with the mobilisation cost (C_{mob}) per hour of the vessels weighted by the port time (T_{port} which equates the sum of the mobilization and the vessel preparation time but does not include the waiting time at port!) in hours. This can be expressed as follows:

$$C_{port} = p_{pc}.C_{sea} + C_{mob}.T_{port} \quad (2\text{-}9)$$

Where $C_{mob} = p_{mob} \times C_{vessel}$, where p_{mob} is factor to apply on the vessel day rate, in order to obtain the mobilization day rate, which is available on the vessel database, this should be expressed in €/hour to match with t_{mob}. This method for port charges evaluation is a fair trade-off between accuracy, flexibility and exploitation of the other features of the installation module. The percentage to apply to the marine operation cost is a default value which can be modified by the end-user of the tool.

2.11.2 ASSESSMENT OF MARINE OPERATION COSTS

The second major contributor to the costing assessment of the installation module is the vessel and equipment hire. Vessel day-rate is the widely accepted metric to assess the cost of hiring a vessel. They vary depending on many factors, such as:

- Vessel type and features,
- Market conditions,
- Chartering strategy (duration, crew included or not, etc.),
- Seasonal variations,
- Regulatory issues,
- Other special requests from the marine contractor’s client.

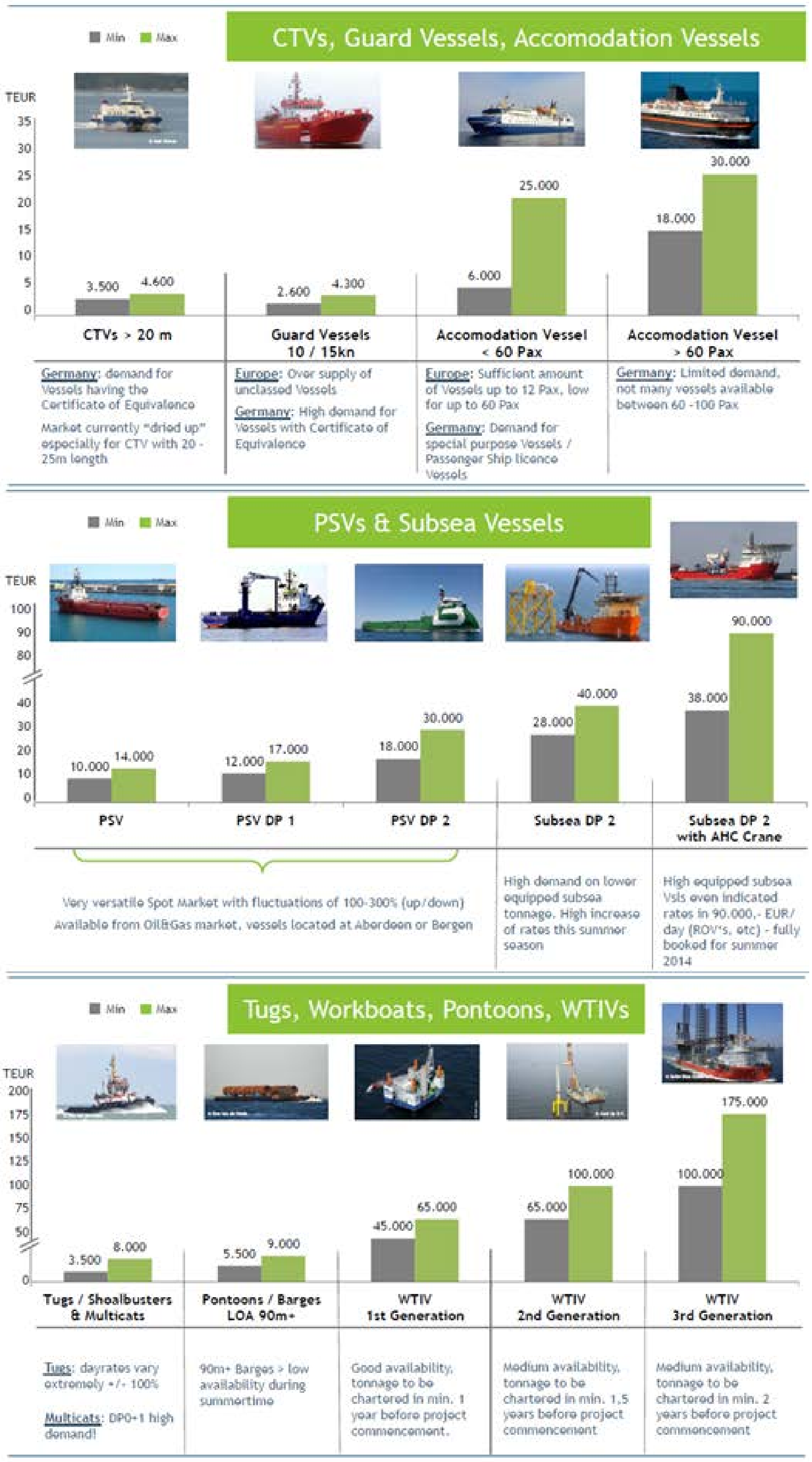
Looking at the offshore experience available from the oil & gas industry, and in particular the offshore wind industry, one can fairly envisage strong similarities in the contracting procedure. Generally, the client (such as a wave or tidal energy project developers) will either contact directly the marine contractor or will delegate part of the negotiation process to a shipbroker. The network and expertise of shipbrokers is often seen as an advantage which is why they work as intermediary between client and marine contractors. To epitomize this privilege position shipbrokers may have in terms of access to data, Figure 2-17 displays minimum and maximum vessel day-rates observed in 2014 by the Global Renewables Shipbrokers [24].

As pointed out by Dalgic *et al*. [25], three types of contractual arrangements can be signed between a marine contractor and its client:

- Voyage charter: ship owner contracts to carry a specific cargo with a specific ship for a negotiated price per ton, which covers capital charges, daily running, and voyage costs.
- Time charter: agreement between owner and charterer to hire the ship, complete with crew, for a fee per day, month or year. In this case, the ship owner pays the capital costs and operating expenses, whilst the charterer pays the voyage costs.
- Bareboat charter: the bareboat charterer hires out the ship without crew or any operational responsibilities, so in this case the charterer is responsible for daily running costs, voyage costs, and expenses related to cargo handling and claiming.

While the bareboat charter agreement may be attractive when very specialized operations have to be carried out with skilled and experienced technicians (such as many O&M activities), the time charter arrangement remains the preferred option in the case of more well-established operation (such as cable, moorings and foundations installation activities). This is the reason why the latter was adopted for the installation module.

Under a time or bareboat charter contract, it is expected that equipment that are not by default part of the vessel specifications should be hired separately. In DTOcean, equipment day-rates (in ranges) for the full scope of our current database have been amassed.



Vessel acronyms:
CTV = Crew Transfer Vessel
PSV = Platform Supply Vessel
WTIC = Wind Turbine Installation Vessel

Figure 2-17 Vessel charter day-rates ranges for a various vessel types [24]

Due to inherent volatility of charter day-rates, ranges of values have been included for each vessel and equipment type in the database. Cross-referencing of different sources was explored as far as possible. Some values come from shipbrokers, others from marine contractors and regression analysis models (using vessel CAPEX information available in more experienced offshore industries, as presented in [26]) have also been exploited.

According to Agnolucci *et al.* [27], in the time charter market the daily price for hiring a ship excludes the fuel costs which are additionally borne by charterers. To account for this extra-cost, the installation module will make use of the average fuel consumption parameter (U_{fuel}) in the vessel database. A default fuel cost value (C_{fuel}) will be assumed which can be overridden by the end-user.

As for the cost incurred while waiting for the weather window, it is usually the responsibility of the client of the marine contractor and charged at the same level as the charterer day-rates. In the end, the calculation of the marine operation cost directly multiplies the estimated total time including waiting time (i.e $T_{sea} + T_{wait}$) with the sum of the average vessel and equipment day-rates considered for a given logistic phase plus the fuel costs. This reads as in (2-10) below:

$$C_{sea} = (T_{wait} + T_{sea}).\left(C_{vessel} + C_{equip}\right) + T_{sea}.U_{fuel}.C_{fuel} \qquad \text{(2-10)}$$

Like mobilization cost (C_{mob}), demobilisation cost (C_{demob}) of the vessel and equipment (including setup and dismantling) to the base installation port is typically the responsibility of the marine contractor. Costs can be calculated using vessel speed, distance from base port, day rate (mostly different than when installing) and fuel consumption and a similar approach could be derived for equipment spread. However, since in fact it can be expected that a given vessel won't have to return to its own port after the installation but move on instead to the next operation it was been hired fore, currently demobilization costs are not accounted for.

Since the vessel and equipment databases do not contain information relative to the home base location, the above method is not suitable. Consequently, it was decided to assume that mob/demob day-rates would be a percentage (p_{mob}) of the hiring charter day-rates. These weighted day-rates are measured against the assumed fixed average duration for the mobilisation and demobilisation stages. The total cost associated with one logistic phase can eventually be formulated:

$$\begin{aligned} C_{lp} = \ & C_{port} + C_{sea} \\ & = p_{pc}.C_{sea} + C_{mob}.t_{mob} + (T_{wait} + T_{sea}).\left(C_{vessel} + C_{equip}\right) \\ & + T_{sea}.U_{fuel}.C_{fuel} \end{aligned} \qquad \text{(2-11)}$$

Where: $C_{mob} = p_{mob}.(C_{vessel} + C_{equip})$

Conclusively, one may recall that several assumptions underlie the economic functions of the installation module in DTOcean. In selecting the appropriate hypothesis, the main goal is to reflect the most faithfully possible how the cost of any logistic phase can be translated into a standalone numerical tool while maintaining a certain level of accuracy and flexibility for the end-user. It should also be emphasized that the use of default values increases the flexibility of this tool. Indeed, any default value can be optionally altered by the end-user.

2.11.3 OPTIMISATION ROUTINE IN THE LOGISTIC FUNCTIONS

All feasible logistic solutions can be discriminated in terms of time efficiency, cost and environmental impact score. Since the LCOE is the chosen objective metric for the global optimization of the DTOcean tool, the logistic functions adopt a straightforward and yet coherent approach in trying to reach the most LCOE attractive installation plan. To this extent, the optimization routine within the installation module consists of always opting for the least costly logistic phase among the feasible solutions.

In mathematical terms, this reads:

$$\min_{\text{solution}=1:\text{S}} C_{lp} \; with \; C_{lp} = C_{port} + C_{sea} \tag{2-12}$$

2.12 THE RISK FUNCTIONS IN THE INSTALLATION MODULE

The purpose of introducing risk functions into the code for the logistic cost calculation is to quantify the uncertainty related to the LCOE. Such risk functions should allow the end-user of the DTOcean global tool to have more hindsight in the decision making process when designing an array of ocean energy devices. As previously explained, several assumptions were made when developing the logistic functions for the installation and O&M modules of the DTOcean tool. Implementing risk functions for uncertainty analysis is a widely adopted practice in the MRE industry for decision-supporting tools.

Therefore, in discussion with the experienced industrial partners DEME Blue Energy and Scottish Power Renewables, the major risks of causing cost risks for the installation and O&M phases of a wave/tidal energy generation array has been identified. Examples from publications in this field of research have also been considered. The major risks identified to be in scope for a detailed analysis process are described in the following section 2.12.1.

To be able to quantify the risks in scope, an analysis has been performed using a common understanding approach of risk effects with respect to Health and Safety (H&S) implications, cost risk, delay of performance risk, environmental impact and conflict with regulatory issues. Furthermore, the probability of the occurrence a risk event has been considered by defining an individual "risk frequency". Section 2.12.2 gives the results of this analysis steps in form of a risk ranking.

In section 2.12.3, some approaches to consider the cost impacts of the risk analysis in the logistic functions are proposed. Section 2.12.4 concludes the findings with respect to the definition of risk functions.

2.12.1 RISK IDENTIFICATION FOR THE INSTALLATION AND O&M PHASES

As a result of the risk identification process, four major risks related to offshore logistic activities have to be defined as the scope for the following analysis process:

1. Organizational and logistic risks
2. Weather risk
3. Risk of failure of vessels and equipment
4. Risk related to seabed conditions

All risks described either directly generate additional installation /O&M cost (e. g. by higher rates for vessels and equipment) or indirectly contribute to higher costs by causing delays in the performance of the respective logistic operations. Since vessel/equipment rates continue in these cases, this leads to higher costs.

2.12.1.1 Organisational and logistics risk

The following questions require answering to quantify the organisational and logistic risk type:

- how many vessels of the required vessel type for a certain operation exist on the spot market:
  -> the less vessels of that type exist, the larger the risk of delays and/or higher rates (competitive situation, e. g. with oil and gas industry).
- how many specialized equipment for the scheduled job is available:
  -> the less equipment of that type exist, the larger the risk of delays and/or higher rates (competitive situation, e. g. with oil and gas industry).
- how many specialists for the scheduled job are available
  -> the less specialist with the required skills exist, the larger the risk of delays and/or higher rates (competitive situation, e. g. with oil and gas industry).

2.12.1.2 Weather risk

Weather uncertainty is of course key for transit and offshore operation planning purposes (both during the installation and O&M phases). Parameters/items to quantify this risk type:

- Site specific: sites with extreme exposure to bad weather conditions, (e. g. North Europe / Orkney Islands / EMEC test field) vs. sheltered sites (e. g. Strangford Lough /SEAGEN site) -> the more severe is the site, the larger the risk for delays is. Reversely, the more sheltered is the site, the smaller the delay risk is.
- Variability: periods with stable weather conditions (e. g. summer season in the North Sea area) vs. periods with unstable weather (North Sea: autumn and winter) -> the more met-ocean conditions variability there is at the site, the larger is the delay risk
- If, in addition to weather uncertainty, the tidal phase is essential for performing the offshore activity, i. e. if the preferable operating window is a neap tide (e. g. to meet a tidal current speed limitation for the scheduled operation at the site), then available operation windows are vastly reduced compared to only weather constraints. If this is the case, the largest risk is that a major operation is planned for a neap, and now we have to overlay an appropriate weather window to coincide perfectly. This can result in delays not only in relation to weather systems (days), but missed neaps and therefore operating windows can come in larger blocks (month at a time). -> the more strict are the constraints of the scheduled operation with respect to maximum allowed tidal currents, max. wave height and max. wind speed, the higher is the delay risk
- Quality of the forecast/hindcast met-ocean data: whether hindcast data is used for the weather window predictions or forecast data in the case of planning marine operations that will occur in a near future, the quality of the data used for the analysis will impact the accuracy

of the results. -> the least reliable is the accuracy of the input met-ocean data, the higher the risk is to wrongly estimate the weather window

2.12.1.3 Risk of failure of vessels and equipment

Working limits of vessels are pushed further than other sectors due to the combination of wind limitations, with wave operating limits for the vessel, and then also stability in highly dynamic currents (dynamic positioning, DP). Therefore risks associated with vessel selection can be managed, but not always by cost alone (simply paying more for a bigger vessel is not only a commercial, but also a technical risk often). So tidal array marine operation risks are key due to the consequences of failure – paying more for a better anticipated solution is always possible, but the consequences of a DP fault, mooring breakage represent the most prominent risk to safety, the technology and sector viability. Risk at this level goes beyond just cost / delay – this is potentially catastrophic for a device / vessel safety. Vessel and equipment failure risks can be reduced by increasing redundancy. For example, using DP/Anchors:

➔ the more redundancy (DP2 instead of DP1, more anchors, etc.), the lower are the risk of failures, i. e.:

- less potential safety issues
- less potential cost implications
- less potential time increase
- less potential environmental issues

2.12.1.4 Risk related to seabed conditions

Parameters / items to quantify this risk type:

- Lack of information about the seabed conditions (e. g. due to a too crude grid during seabed exploration) or seabed conditions have been changed due to a longer time period between seabed exploration and installation or during a 20ar O&M phase -> the less is known about the site or the more dynamic changes appear on the seabed in the explored area, the larger the risk with respect to safety, cost, delay time and environmental impact due to inappropriate seabed conditions
- Accuracy of the positioning system used -> the more accurate the positioning system work, the smaller the risk for time delays due to the necessity of subsequent positioning approaches.
- Sensitivity of the devices to be installed and maintained to spatial deviations, i. e. can the device placed with a certain tolerance (e. g. within a radius of about 50m around the designated installation position -> the smaller the tolerance is, the larger is the risk that the device cannot be installed as planned, resulting in delays of the installation process.

2.12.2 RISK ANALYSIS

As part of task 5.4.3 (Reliability Functions for Lifecycle Logistics), this section proposes a method of risk analysis suitable for implementation in DTOcean Work Package 5.

Full management of risk typically requires the use and maintenance of a risk register – a repository where identified risks are logged along with corresponding risk analysis results and risk management procedures. The process of operating a risk register is ongoing and can be summarized as in Figure 2-18 [28].

Figure 2-18: Risk Register Development Process [28]

The following sections focus on stage 2 of the above process – the method by which risks can be analysed in a quantitative manner.

2.12.2.1 Risk analysis approach

Only through quantification it is possible to effectively prioritise and manage identified risks. The risk R of a particular operation is defined as:

$$R = \frac{\text{expected consequence in case of accident}}{\text{occurrence}} \cdot \frac{\text{probability of accident}}{\text{occurrence}} \qquad (2\text{-}13)$$

Hence, upon identification, risks are typically characterised in terms of:

- Type and Severity of consequence = expected consequence in case of accident/occurrence
- Frequency of occurrence = probability of accident/occurrence

Risk Type and Severity

A suggested categorisation of risk type and severity can be found in a study from the NREL "Marine and Hydrokinetic Technology Development Risk Management Framework"[28] and is shown below in Table 2-68.

Table 2-68 Categorisation of Risk Type and Severity [28]

Consequence to persons, project, environment and regulatory compliance								
Severity	Severity Level	Risk Type						
		Safety (S)	Cost (C)	Time (T)	Scope (P)	Quality (Q)	Environment (E)	Regulation (R)
0	None	No injury	$0K	No delay	No scope impact	No quality impact	No pollution	Full compliance
1	Insignificant	Nuisance	$1K	Less than one week delay	Insignificant scope impact	Insignificant quality impact	Insignificant pollution	Insignificant regulatory infraction with no consequences
2	Marginal	Minor injuries	$10K	1 week to 1 month delay	Moderate scope impact	Moderate quality impact	Minor pollution	Moderate regulatory infraction with inconvenient but reversible consequences
3	Critical	Significant injuries and/or health effects	$100K	1 month to 6 months delay	Major scope impact (re-scoping required to some of the project)	Critical quality impact (possibly irreversible)	Limited levels of pollution, manageable	Major regulatory infraction causing system shutdown until compliance is reassured
4	Catastrophic	Life threatening injuries and/or health effects	$1M	6 months to 1 year delay	Serious scope impact (re-scope most of project)	Catastrophic quality impact (likely irreversible)	Moderate pollution, with some clean-up costs	Serious regulatory infraction likely causing irreversible system shutdown and substantial fines
5	Lethal	Fatality	$10M	1 year or more delay	Complete scope impact (re-scope entire project)	Devastating and irreversible quality impact	Major pollution event, with significant clean-up costs	Very serious regulatory infraction causing project shutdown, major fines and/or bankruptcy, lengthy legal

Risk Frequency

A risk frequency value can now be assigned based on the probability of an accident / risk event occurring during a given period of time. Such probabilities are typically computed using a combination of historical data, expert input and market mechanisms. Suitable risk frequency values and corresponding probabilities of occurrence are suggested in Table 2-69 & Table 2-70.

Table 2-69 Risk frequency values [28]

Risk Frequency Value	Estimated probability (p) of occurrence of risk event over one year (% per year)
0	$p < 0.01\%$
1	$0.01\% < p < 0.1\%$
2	$0.1\% < p < 1.0\%$
3	$1\% < p < 10\%$

4	10% < p < 50%
5	p > 50%

Table 2-70 Risk frequency values - verbal interpretation [28]

Risk Frequency Value	Estimate of frequency of occurrence
1	Very infrequent, e.g. once in a lifetime
2	Infrequent, several times in a lifetime
3	Typical occurrence once in 5 years
4	Occasional occurrences e.g. once per annum
5	Several occurrences per annum

Risk Priority

Having assigned a type, severity value and frequency value to an identified risk, it is now possible to assign a risk priority value (i. e. to "R" as defined in Equation 2-4 above). Using these values, it is possible to compare, prioritise and manage any number of risks together. These values should be used to inform the risk responses required under stage 3 in Figure 2-18.

A risk priority value is simply the product of a severity value and a frequency value for a given risk. These values are summarised in the matrix given in Table 2-71, along with suggested categorisations of risk priority values. Based on these categories, suitable risk management actions can be defined. For instance, risks categorised as "Low" may be acceptable and not require any further action, those categorised as "Medium" may require suitable mitigation measures, while those categorised as "High" must be avoided.

Table 2-71 Risk priority values and categories [28]

Frequency					
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5
0	**1**	**2**	**3**	**4**	**5**
Severity					

Low	**Medium**	**High**

This quantified risk value should be used to inform the methods by which the risk will be managed. Typical risk management strategies include:

- Mitigate (e.g. select vessels with higher safe working limits to reduce likelihood of these limits being exceeded)
- Accept (i.e. do nothing explicit to manage the risk, simply cover the cost incurred)
- Avoid (e.g. re-site devices in an area where safe working limits will not be exceeded)
- Transfer (e.g. take out insurance against costs incurred by this risk)

2.12.2.2 Application to the organisational and logistics risk

To quantify the organisational and logistics risk, three typical cases of logistic operations, which will occur during installation and operation of marine energy arrays, will be evaluated. After each of the cases, the short references to the logistic functions are given as they are defined in the DTOcean deliverables for the installation phase [4] and for the O&M phase [5],respectively:

1. Logistic operation using small CTV/MultiCat and regular technician crew (related to the O&M logistic functions Insp1, Insp2, MoS1, MoS2: see [5] page 19)
2. Logistic operation requiring special technicians / ROV operators / divers (related to the O&M logistic functions Insp3, Insp4, Insp5, MoS3, MoS4)
3. Large installation / repair / detachment of entire device using large crane ships, jack-up barges, etc. (related to the O&M logistic functions MoS5 to MoS6, RtP1 to RtP6 (see [5], page 19]) and to all installation logistic functions: see section 2.11 and [4])

The risk event considered in all three cases is: “non-availability of the required vessels/equipment”.

Definition of Severity level: The severity level, i.e. the expected consequence in case of non-availability of the required vessels/equipment, will be evaluated for each of the items in the first row of Table 2-72 below. The resulting severity level is the maximum of the individual levels. Risk type “safety”, which is related to safety of persons will always set to “0” value, since a delay in the operation in principle does not add risks to personnel safety. Analogously, risk types “Scope”, “Quality”, “Environment” and “Regulation” will not be considered here, i. e. set to “0” value. Since organisational /logistic risks, as mentioned in section 2.12.1, are mainly linked to cost and time, such simplifications are useful here.

Table 2-72 Case severity value estimation for organisational / logistic risk

Case #	Safety (S)	Cost (C)	Time (T)	Scope (P)	Quality (Q)	Environment (E)	Regulation (R)	Maximum
1	0	1	1	0	0	0	0	1
2	0	2	2	0	0	0	0	2
3	0	3	2	0	0	0	0	3

Definition of the Risk Frequency Value (RFV): The value will be defined using the probability zones as given in Table 2-73. The value given represents the probability related to a delay of a certain number of days in the designed life time of the ocean energy array. So, if a delay of 1 day is caused within the 22 year period (assuming an installation period of 2 years + an operational period of 20 years), the probability will be given by (2-14):

$$p = \frac{1\ day}{22\ y \cdot 365\ days/y} \cdot 100\% = 0.012\% \qquad (2\text{-}14)$$

Table 2-73 Case risk frequency value estimation

Case #	RFV	Comment

1	1	estimated 5 days delay during installation and operational phase I+OP ➔ p=0.06%
2	2	estimated 50 days delay during I+OP ➔p=0.6%
3	3	estimated 200 days delay duringI+ OP ➔p=2.5%

Resulting Risk Priority: the resulting risk priority with respect to Table 2-71 is given in Table 2-74.

Table 2-74 Case risk priority and category

Case #	Risk Priority Value	Category
1	1	low
2	4	low
3	9	medium

2.12.2.3 Application to the weather risk

In principle, for risk analysis it makes no difference if an operation (installation or O&M) is delayed due to non-availability of vessels/personnel/equipment or due to inadequate weather conditions and/or sea states. Therefore, the same approach as described in section 2.12.2.2 is used here. However, a spilt into several cases is not used, since the weather risk will be considered as not depending on the type of logistic operation. The potential risk event discussed below is: "operations will not be able to take place at planned time due to bad weather/too strong tidal currents".

Risk Type

With reference to Table 2-68, it could be argued that this risk may be of type Safety, Cost or Time. However, project safety will not actually be impacted as vessel safe working limits ensure that unsafe conditions are not encountered. Since the logistic operation itself will be delayed, we need to consider potential effects on time delays, causing extra cost.

Risk Severity

Having identified a risk to project cost, it is now necessary to assess the severity of the risk. Cost impacts are likely to arise from:

- Vessel, equipment and (specialized) crew charter payments: the cost risk depends strongly on the contractual arrangements as described in the section 2.11 of this report. The three types of charter (voyage, time, bareboat) are related to different types of operations and cost risks respectively. One could also consider a service boat owned by the MRE array owner/operator)
  - It can be assumed that the marine operations as characterized in "case 1" above are worked out with bareboat charter or with owned boats
  - Since most of the O&M operations are more or less good plannable with respect to date (condition & calendar based maintenance) or at least will have a certain pre warning / mobilisation time (corrective maintenance), a permissible assumption is to relate this kind of operation to a "voyage charter" arrangement. The mentioned operations are related to the cases 2 and 3 (see above)
  - During installation phase (related entirely to "case 3"), vessels and equipment are typically hired on a time charter basis. Even if there is a reduced rate for the

vessel/heavy equipment when not operation, significant cost will sum up during waiting periods due to the high daily rates of the vessels/equipment (see Figure 2-8)

- Loss of power output / energy revenue losses (operational phase only)
    - This may not be applicable if the cancelled maintenance mission was scheduled rather than corrective and the array can continue to output as normal
    - The level of lost output will vary according to the nature of the maintenance being required. That is to say, not all device faults imply a complete loss of output
    - The level of lost output will vary with wave conditions and resulting potential output

For the purposes of this document, the estimated risks severity values are shown in Table 2-75. The values are meant to be the daily cost rates. In the case of the revenue losses, a device rated power of 500kW and an average operation time of 12 h is assumed. With an LCOE of 10ct/kWh, this results in a cost risk of 500kW * 12h * 0.1Euro/kWh = 600 Euro per day per device. It is unlikely that more than 10% of the devices in an array are down, so the number of devices down at the same time shall be assumed with 10 at a maximum. This means a cost risk of 6000 Euro per day (worst case!)

Table 2-75 Risk severity estimation for weather constraints

Risk type	Safety (S)	Cost (C)	Time (T)	Scope (P)	Quality (Q)	Env. (E)	Reg. (R)	Maximum
charter bareboat	0	2	1	0	0	0	0	2
charter voyage	0	3	1	0	0	0	0	3
charter time	0	3	1	0	0	0	0	3
energy revenue loss	0	2	0	0	0	0	0	2

Risk Frequency

In the DTOcean logistics functions, a time series based approach to determine suitable weather windows for all logistic operations is used. The algorithm to implement this approach uses operational limit conditions (OLC) for vessels, transit operations, access to devices, etc. For instance, one can assume max Hs of 2m during transit, 1.5m during jacking and max. wind speed of 20m/s during drilling etc. The OLCs will be either user defined or default values will be retrieved from the database. The user must also provide the met-ocean data time series (required is at least one year of data with one hour resolution minimum, whereas The IEC standard stipulates a minimum of 10 years data).

In the DTOcean logistic functions, the OLCs are already considered during the determination process of the weather windows. Therefore, the weather risk is already account for through the weather window algorithm depicted in section 2.10.2. The remaining uncertainties with respect to the DTOcean tool are the accuracy associated with the met-ocean data time series and the OLC.

An initial attempt to reflect this additional risk could be to consider setting the risk frequency to a value of 2 with respect to Table 2-69. This value corresponds to a time delay of approximately 1 to 3 days within a year. Since the logistic operations in scope of this document normally do not last for more than a year, this assumption can be related to the operations itself. A frequency value of 2 is also high enough to consider possible weather forecast uncertainties as they appear in the real life of MRE array installation and O&M phase.

While this initial consideration will be further exemplified below, a more advanced risk analysis would relate the length and the resolution of the met-ocean time series to the quality of the data. Also, the longer the marine operation is expected last, the higher is the risk of wrong weather forecast in real-time operations since it is well-known that the quality of a weather forecast degrades as the time horizon for the prediction increases. More sophisticated risk frequency values could be derived from these considerations. Considering the uncertainty on the OLC, the weather window algorithm could do some sensitivity analysis around the specified OLC values to assess the waiting time variability. This method is likely to significantly increase the computational time.

Risk Priority

Calculation of a risk priority value is now possible by simply taking the product of the allocated severity and frequency values. The results of this multiplication and the related risk categories are shown in Table 2-76.

Table 2-76 Weather risk priority and category

Risk type	Risk Priority Value	Category
charter bareboat	2 * 2 =4	low
charter voyage	3 * 2 =6	medium
charter time	3 * 2 =6	medium
energy revenue loss	2 * 2 = 4	low

2.12.2.4 Application to the risk of failure of vessels and equipment

The severity of consequences of a failure of a vessel depends on its size. Again, as already introduced in section 2.12.1.1, the following three cases are considered for the risk analysis:

1. Logistic operation using small CTV/MultiCat and regular technician crew
2. Logistic operation requiring special technicians / ROV operators / divers
3. Large installation / repair / detachment of entire device using large crane ship / jackup barge

The risk event considered in this case is: “total failure of the vessel/equipment”.

Risk Severity

Definition of the Risk Severity level: The severity level will be evaluated for each of the items in the first row of the Table 2-77 below. The resulting severity level is the maximum of the individual levels. Deviant from the analysis given in section 2.12.1.1, the risk types “Safety”, which is related to safety of persons, and “Environment” (related to environmental pollution) cannot be neglected here. Looking at case 1, even a minor failure, which leads to the stop of the motor of a CTV, can cause H&S risks to the crew when the boat is disabled in harsh weather / sea state conditions.

The more complex the operation is (e. g. ROV operation in case 2 or heavy lifting in case 3) or the more dangerous the work is (diving in harsh conditions, case 2), the higher is the related severity level ranking. The severity levels are given in Table 2-77 below. The risk types “Scope”, “Quality” and “Regulation” will not be considered here, i. e. set to “0” value.

Table 2-77 Case severity value estimation for failure risks

Case #	Safety (S)	Cost (C)	Time (T)	Scope (P)	Quality (Q)	Environment (E)	Regulation (R)	Maximum
1	3	2	1	0	0	3	0	3
2	3	3	1	0	0	3	0	3
3	3	4	2	0	0	3	0	4

Definition of the Risk Frequency Value (RFV), i. e. answering the question “What is the probability of total failure of the vessel/equipment during the operation?”: Failure risk frequency estimation is a difficult business. For example, the BSCA has reported a number of 216 diving accidents in the UK in 2014 [29]. Related to an estimated number of 200,000 divers in the UK, this corresponds to a rate of 0.1% for the probability of having an accident for the individual diver per. But this contains mainly sport diving activities. Professional divers might face a significantly lower risk due to optimum equipment, regular exercise and more intensive training. Therefore, the risk frequency for a professional diver might be at 0.01% accidents per year (case 2). Locking at case 1, a technical failure of a small boat might occur twice a year. Assuming a number of 200 working days per year, this corresponds to a frequency of 2/200=0.01, i. e. 1%.

Working with large vessels, complex equipment and heavy loads will be done by professionally trained personnel. In addition, some vessels and equipment are made in such a way that redundancy is present. Think about the DP2 system on DP vessels and jack-up vessels. Another example is to have several mooring lines in place to hold a vessel/piece of equipment. The more redundancy is foreseen, the less chance of total failure. The duration of the operation also needs to be considered. The longer it takes for the operation to finish, the higher the chance a failure might occur.

Risk Frequency

Based on the above, following RFV’s are linked to each of the three cases:

Table 2-78 Case risk frequency value estimation

Case #	RFV	Comment
1	3	p=1.0%
2	1	one accident per diver every 100 years ➔ p=0.01% (low due to trained personnel)
3	1	low due to trained personnel

Risk Priority

Resulting Risk Priority: the resulting risk priority with respect to Table 2-71 is given in Table 2-79.

Table 2-79 Case risk priority and category

Case #	Risk Priority Value	Category
1	**9**	**medium**
2	**3**	**low**
3	**4**	**low**

2.12.2.5 Application to the risk related to seabed conditions

In this case, the risk event can be seen as: *"the seabed conditions do not agree with the provided site info/design"*.

An example is that during installation works of a tidal turbine, the rock appears to be much stronger than foreseen or the seabed is cohesionless (sand) rather than cohesive (clay). Looking at floating devices, in this case it may appear that mooring lines need to be extended to reach into a cohesive area when using drag embedded anchors or suction caisson anchors need to be used instead.

Risk Severity

The cost risk resulting from deviations of the actual soil type (see Table 2-65 for details), at the installation point from the expected soil type depends on the soil type itself. In addition, the deviation can not only happen in the upper surface soil layer but could also deviate in the underlying sub-surface layers if they have been specified.

In a first instance, to avoid an overly complex approach for considering risk related to soil type deviations in several soil layers, the risk shall be estimated for a "worst case scenario", applicable to several installation operations (embedding anchors, pilling, cable laying, etc.). Such a scenario shall be assumed as the finding of hard rock (e. g. huge erratic boulders from the ice age) where firm clay should appear.

This requires more complex/costly drilling techniques, causing additional safety or environmental issues. When an alternative drilling technique needs to be applied, this would lead to higher costs and a time delay. Hence, the severity value estimation for the example above is:

Table 2-80: Case severity value estimation for seabed condition risks

	Safety (S)	Cost (C)	Time (T)	Scope (P)	Quality (Q)	Environment (E)	Regulation (R)	Maximum
Severity	1	3	1	0	0	2	0	3

The maximum value is 3, originating from the Cost associated risks.

Risk Frequency

What is the probability that the seabed conditions do not match the design values? It might be that in some particular locations the seabed model is not well validated. Furthermore, it could be that there was simply not enough time/money to carry out a proper geotechnical survey.

For tidal sites, typically a number of drill holes are made during the geotechnical survey, enabling to characterize the build-up of the seabed and the strength of the rock. Typically for most tidal and wave sites, a thorough site investigation is carried out, both through geophysical and geotechnical investigations. This is quite obvious when thinking of investment volumes of up to a 100 M€, for which project shareholders will expect a maximum reliability of the estimated installation and O&M costs.

The risk of unknown seabed conditions is also determined by the size of the array. The more devices to be installed, the larger the area considered and the more chance seabed conditions might deviate from what came out of the limited number of obtained data. For the moment, let assume a good knowledge of the site is presented, hence the RFV value is 1. In a more sophisticated approach it would be possible to relate the RFV to the quality of the seabed conditions input data. The higher the resolution and the more vertical layers are characterized, the less is the risk associated with deviation and unsuitable foundation/cable/anchor design and installation techniques.

Risk Priority

Multiplying the maximum severity value with the RFV results in a risk priority R equal to 3, i.e. overall a low risk for the seabed condition risk to be considered for the DTOcean tool development.

2.12.3 CONSIDERATIONS FOR IMPLEMENTATION IN THE LOGISTIC FUNCTIONS

The implementation of the above four risk analysis is not going to be completed in the DTOcean tool due to project scheduling. In order to proceed with the development of the computational modules and the integration effort, it was necessary to freeze the structure of the database shortly after the release of a Beta version of the computational modules. As a result, the insertion of the risk tables related to severity, frequency and priority was not possible before this freeze.

However, the methodology and examples provided in section 2.12.2 serve as a basis which can be readily implemented in future version of the tool. From a practical point of view, the step to follow in order to add the risk functions feature to the logistic functions would be as follows:

- Create all risk tables in the database with pre-filled default values
- Develop the instances to pass the information from the risk tables to the logistic functions. For this step, one
- Format the output from the risk tables to give a risk priority

In an early stage of the tool development process in the DTOcean project, it was decided to follow a time based approach rather than a statistical approach for the planning of any logistic offshore operation with respect to installation and operation and maintenance. Looking at risk consideration, this leads to the following consequences:

1. Some of the typical risks mentioned above are considered intrinsically in the logistic functions. For example, the weather risk is mainly covered by considering the operational limit conditions (OLCs) of different vessels and equipment during the selection process. This means that the OLC will be used to select suitable weather windows and only suitable vessels/equipment will be scheduled for the requested logistic operation

2. For consideration of risks, which are not intrinsically covered by the logistic functions, a rather simple approach of adding additional portions of time to the overall duration of certain logistic operations can be used (the "simplicity" of the approach is meant with respect to calculation, not with respect to the definition of the time portions to be added!)
3. More advanced risk evaluation relating the quality of the input data (e.g met-ocean data and seabed conditions) and the complexity of each logistic phase to compute more customized risk frequency, severity and priority values. Some examples of these advanced risk analysis have been mentioned in the previous section.

The consideration of risks and the potential time delays of offshore operations to be caused by inacceptable operational conditions is a very complex issue. In principle, the impact of the risk to the offshore operation depends on (as described in [30]):

- The type of operation: A drilling operation, which needs to be performed below a maximum current speed (on seabed level), might require slag water conditions with very limited time windows (probably down to 30 minutes or less). In contrast, the installation of a device on a fixed foundation can be performed at much higher current speeds, resulting in longer working windows
- The type of vessel/equipment: vessels and equipment will have OLC restrictions. The wider the range with respect to maximum wave height, current speed, wind speed etc. are, the less is the sensitivity to duration extension of the logistic operation in scope
- The rates for vessels and equipment can differ quite a lot (e. g. between 30 000 Euro for a special offshore renewable device installation HF4 "fit for purpose" vessel up to 125 000 Euro for a state of the art offshore construction vessel as used for example in the oil and gas industry [30]).

With respect to the above described complexity, the separation of the major risks with respect to its consideration in the DTOcean tool seems to be quite ineffective. This is mainly related to the fact, that independently from the nature of the risk, the consequence with respect to the logistic operation will in the majority of the cases cause an extension of its duration. Therefore, a common approach to consider this extension of the period of performance will be described in the following.

In [31], DNV proposes an approach with a "contingency time T_C to be added to the "planned operation period T_{POP} as calculated in the DTOcean logistic functions. This result then in the "operation reference period" T_R:

$$T_R = T_{POP} + T_C \tag{2-14}$$

The parameter T_C needs to be defined by consideration of the following assumptions [31]:

- The knowledge about T_{POP} for is based on a detailed operation planning and/or is well established from experiences with similar operations ➔ T_C = 50% of T_{POP}
- If there is less established knowledge about TPOP, TC should be increased ➔ $T_C = T_{POP}$
- A minimum contingency time of 6 h should not be undershoot in principle. An exception could be the performance of very short and simple operations based on robust equipment. In the case of DTOcean, this can be applied to the O&M inspection operations.

To consider the contingency time within the logistic functions of the DTOcean tool, T_C should be implemented as a user defined parameter. This parameter could be implemented as a contingency factor f_{CONT} to be multiplied with T_{POP} for calculation of T_C:

$$T_C = T_{POP} * f_{CONT} \tag{2-15}$$

The contingency factor f_{CONT} should be initialised with a value of 0.75 as a compromise between a well-established and defined logistic operation and a “weak” defined one. The contingency factor can be assigned to each of the defined logistic functions and can be stored (with its above proposed initial value) in the respective data base tables. If required / desired, it can be then modified to consider special demands from the user of the DTOcean tool. This method may be implemented in future release of the DTOcean logistic functions upon the creation of the two extra input variables T_C and f_{CONT} are included in the database.

The above described approach of adding a contingency time covers the risks of vessel/equipment failures and the remaining risk of inaccurate short term weather forecasts. As stated before, the “main” weather risk” i. e. the infeasibility of performance of offshore operation over longer periods (several days) is already covered by the design of the DTOcean logistic functions. The organisational /logistic risk can be covered with a similar approach to be applied to the port waiting time (when a vessel/equipment is on permanent hire) or by defining a delay with respect to the earliest possible starting time of the requested logistic operation.

A special case is the risk related to unexpected seabed conditions. In the real world planning of an offshore renewable energy array as well as in the DTOcean tool, there should be a mandatory evaluation of the seabed conditions. This will add additional CAPEX to the entire project, since costly site inspections are required. In chapter 6 of [32], a large variety of possible solutions for all kinds of soil types, water depth, sizes of inspection areas, etc. are proposed to perform an accurate seabed condition evaluation. This evaluation must also include the corridor for the export cable.

The consideration of the seabed risk within the DTOcean tool should be made by adding a given absolute budget to the CAPEX to cover the costs for an accurate seabed condition assessment. The budget should be implemented as a user defined parameter.

2.12.4 CONCLUSION

The approach for consideration of risks to the logistic operations as in scope within the DTOcean logistic functions has been executed by identifying relevant risks (literature, expert discussion). The identified four relevant risks (organisational/logistics, weather, vessel/equipment failure and seabed conditions) have been analysed with respect to their severity and frequency and, derived from that, with their priority. This has been done under consideration of the purpose in scope, namely the estimation of logistic costs under the DTOcean optimisation tool.

Parts of the identified risks are already considered by the logistic functions intrinsically. This has been reflected in giving such risks a smaller “frequency” ranking than it would have been assigned in “state of the art” risk estimations (e. g. for the weather risk). In the release candidate version, no risk functions will be implemented but the risk tables depicted above for the four risk categories may be added to the database in future release of the tool.The proposed approaches to "generate" the resulting additional risk analysis to those inherently captured by the current logistic functions are kept simple at this stage. Some suggestions have been made on the path that could be followed to more advanced risk functions. The initial simple functions would facilitate initial testing and validation. In turn, all key ingredients necessary to perform the DTOcean tool.

2.13 THE ENVIRONMENTAL FUNCTIONS IN THE INSTALLATION MODULE

2.13.1 INTRODUCTION

Logistics activities are essential operations for the development Marine Renewable Energies (MRE) as they organize the flow of resources required to perform the various activities during the development, construction, operation and decommissioning stages of future arrays. Such logistic activities drive inevitably various environmental issues. The presence of vessels and equipment during a given period causes certain pressures on the marine environment. These pressures can be physical, chemical and biological. The large variety of vessel types used creates impacts of different levels within the area of the farm of ocean energy devices. For instance, during the installation of foundations and cables comes a clogging, a loss of habitat. The pile driving or any seabed soil drilling activity is a source of noise which can disrupt the fauna living in the area. Within the framework of DTOcean, all these pressures are considered in order to ultimately determine an environmental impact score associated with each major logistic phase. In the context of these logistic activities, five main environmental impacts have been identified as major:

- the risk of chemical pollution,
- the collision risk,
- the footprint,
- the underwater noise and
- the potential raise of turbidity.

To quantify the environmental impact during the installation phase, the DTOcean databases of vessels and tools have been used. Each category of vessels and equipment is ascertained, and the relevant environmental pressure score has been derived. A background of environmental pressures identified during the logistic activities is presented in this section.

2.13.2 ENVIRONMENTAL ISSUES ASSOCIATED WITH THE INSTALLATION PHASE

2.13.2.1 Footprint

Disturbance of the benthic habitats by vessels anchors and other special equipment will mostly occur during marine operations. This disturbance is related to a direct physical effect on the substrata (e.g. sediment penetration, removal, abrasion, disturbance or recovery with concrete mattresses installations, etc.) leading to an alteration of seabed habitats. Habitat removal affects infauna (organism living within the sediment) for mobile sediment (usually sands) and 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 two 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 as well as ophiuroids, sponges, bryozoans or hydroids within subtidal coarse (gravels) and mixed sediments (gravels, sands and muds). 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.

During logistic operations, footprint issues can be generated by either vessel anchorages, subsea cable installation/removal or preparation for foundations. The level of seabed disturbance depends on the nature of sediments as well as the nature of the operations. These levels of sediment disturbance have been evaluated and reviewed for the offshore wind sector regarding cable installation [33]. This report shows a ranking from 1 to 10 (with 1 indicating a low level of disturbance and 10 a high level of disturbance) for the different installation methods and the different sediment types. This ranking is summarized in Table 2-81 [33].

Table 2-81 Level of sediment disturbance arising from use of cable installation tools for different sediment types [33]*(Level of disturbance 1 = Low, 10 = High, n/a = Not applicable)*

Plough Type		**Cohesion less**	**Cohesive**		**Other**			
		Sand	**Silts**	**Clay**	**Gravels**	**Unstructured Rock**	**Chalk**	**Structure d Rock**
PLOUG H TYPE	Conventional Narrow Blade	1	1	1	1	n/a	n/a	n/a
	Advanced with Jetting	2	3	2	2	2	n/a	n/a
	Deep Burial	1	1	1	1	1	n/a	n/a
	Rock Ripping	1	1	1	1	1	4	
	Vibrating	1	2	1	1	2	6	
OTHER BURIAL TOOLS	Jetting	2 - 3	2 - 4	3	3	n/a	n/a	n/a
	Dredging	4	6	n/a	4	n/a	n/a	n/a
	Rock wheel	3	4	3	3	3	8	4
	Mechanical chain excavators	3	4	3	3	3	n/a	n/a

The most significant disturbance is generated by rock wheeling and dredging in chalk and silts sediment using respectively rock wheel and dredging. These different levels of disturbance reflect the pressure on the seabed itself, but once the sediment particles have been lifted into suspension they will also disperse under the action of the tidal flows. Sands and gravels disturbed during the cable burial operations will settle back to the seabed very rapidly and the footprint is unlikely to extend any great distance from the cable route. Silt, clay and chalk particles will remain in suspension for a greater period of time and will be dispersed over a much greater distance, depending upon the strength of the tidal currents. Cable burial operations can then locally cause severe damage to habitats.

Footprint issues associated with anchorages, moorings and foundations are also related to sediment disturbance and therefore habitat alteration. The environmental impact of foundations and anchors is directly related to the area of seabed contact under the footprint of the foundation structure. But it is furthermore acknowledged that the area covered by the over shallowing foundation structure itself can also alter the seabed. Despite no direct contact (e. g. seabed located beneath the lattice of a steel jacket but not under one of the footings), the presence of an artificial structure modifies surrounding water and sediment flows, which in turn may alter the sediment granulometry and therefore alter seabed communities. This shallowing effect is presented on Figure 2-19.

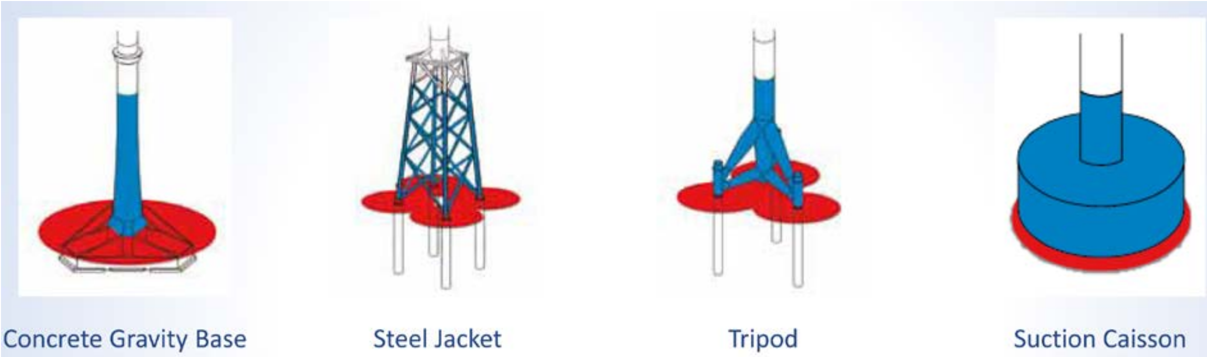


Figure 2-19 Shallowing effect of different type of foundations [34]

Besides, mooring lines can also increase the footprint issues around the foundations. In term of environment, taut leg mooring is often preferred over catenary moorings as the footprint of taut leg moorings is smaller than the footprint of catenary moorings. Indeed catenary moorings require a relatively large paid-out length of chains horizontally laid on the seabed while the taut leg mooring reaches the seabed with an angle. The mooring radius of the taut leg mooring will be smaller than the mooring radius of a catenary mooring for a similar application.

2.13.2.2 Collision risk

Under 'collision risk' and within the framework of DTOcean and the development of the lifecycle and logistic tool, only the interactions between marine wildlife (mammals and birds) and vessels that may a result in a physical injury to the organism are considered. Indeed, logistic operations imply an unusual number of vessels within the project development area. As such, this may increase the risk of collision between vessels and marine wildlife. Chemical pollution resulting from vessels interactions themselves is treated in a separate environmental impact function.

Marine mammals

Although not very well documented, the risk of collision between ships and marine mammals exists (Figure 2-20). The collision risks between MRE devices and reference therein [35], ship strikes are a known cause of mortality for both whales and dolphins worldwide and strikes are far from infrequent as the majority go unnoticed.

Figure 2-20 Bryde's whale, Balaenoptera edeni, draped over the bow of a ship © Fernando Felix [36]

The main drivers identified to influence the number and severity of ship strikes are:

- Vessel type: even though all vessel sizes and vessel classes are involved in collision with marine mammals, most fatal casualties are due to large vessels (more than 80 m length),
- Underwater noise as high levels of ambient noise can result in difficulty in detection of approaching vessels,
- Weather conditions and time of navigation that can directly affect the ability of crew to detect or avoid marine mammals,
- Mammals specific behaviour during specific feeding, preying or resting time,
- Mammal's conditions as juvenile and sick individuals appear to be more vulnerable.

Birds

Among several factors affecting some aspects of species' behavior, ship and helicopter traffic have been recognized as important for offshore wind. Furness et al. [37] showed that marine bird species vary in their reactions to the ship (and helicopter) traffic that occurs during maintenance operations. Even if no significant operational experience is available yet, the same type of disturbance is also expected for wave and tidal developments during the installation and maintenance phases.

In particular, in the context of the installation phase, sea birds can be vulnerable to the presence of ships, especially because of vessel noise or enhanced light conditions during night operations [38]. Indeed, birds are attracted to lights and bird strikes occur during darkness and heavy fog. High intensity lights used during navigation aids during the fall can attract birds, often resulting in birds colliding into ship structures [39].

2.13.2.3 Underwater noise

Underwater noise is inherent to marine operations and will unavoidably be generated during the development of wave and tidal energy arrays. Noise sources include of course specific operations such as pile driving, dredging activities or other activities dedicated to foundations installation, but noise results also from enhanced general vessel traffic. Temporary increase in noise levels resulting in a change in the characteristics of ambient background noise is therefore expected affecting transitory and resident marine fauna within the vicinity of these activities. As pile driving generally generates the loudest sound, it is often discussed in this section rather than the others activities such as installation of static power cables, installation of gravity based structures or drag embedment anchoring.

The amplitude (loudness), frequency (pitch) and duration are key characteristics for sound waves. To describe sound waves quantitatively, the sound intensity level or pressure level is described relatively to a fixed reference intensity of pressure (Figure 2-21). The sound level unit of measurement is the decibel (dB) and the intensity is typically expressed as dB re 1 µPa at 1 m. There are no widely accepted international standards for reporting sound pressure levels (SPL, unit of measurement in dB re 1 µPa) and depending on how the pressure or energy is calculated or measured, the numerical value associated with a sound can vary significantly (by 20 dB or more). Peak amplitudes, peak-to-peak amplitudes and root mean square (RMS) may all be used. Sound exposure levels (SEL) measure the total energy of a signal over time (unit in dB re 1 µPa). They can be used to compare sounds that are continuous, single, or multiple pulses, and can also be used to describe the cumulative exposure of a sound over the duration of a specified time period.

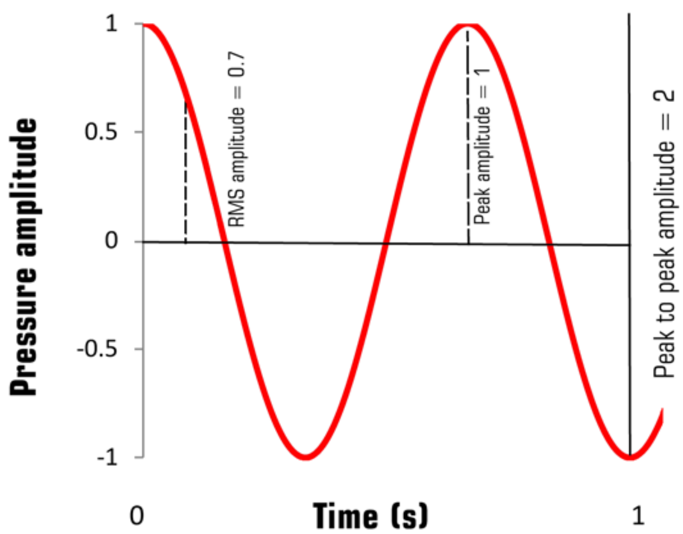


Figure 2-21 Continuous sound waveform illustrating several typical ways of characterization of sounds

Table 2-82 gives an example of generated underwater noise for different types of vessels. The noise produced by the vessels depends on parameters such as the propulsion unit, the size and shape of the vessel, the machinery and the cavitation due to the bubble collapse [40]. Individual ships produce unique acoustic signature which can change with the vessel speed [40], [41]. The frequency range encompassed by the vessel noise is generally within 50 and 300 Hz.

Table 2-82 typical underwater noise produced by vessels [41]–[43]

Vessels	Type of vessels	Underwater noise measurement
small	vessel and machinery	152-192 dB re 1µPa (1m)
medium	boat medium size	130-160 dB re 1µPa (1 m)
	tug	144 dB re 1µPa (60m)
	cabin cruiser workboats ~20m	182 dB re 1µPa rms (1m)
large	tug an empty barge	170 dB re 1µPa (1m)
	dive support vessel >100m	178 dB re 1µPa (1m)
	supply vessels	174 dB re 1µPa (1m)
	bulk cargo> 150m	190 dB re 1µPa (1m)
	large container ship	192 dB re 1µPa (1m)
	large tanker	177 dB re 1µPa (1m)

Noises emitted by offshore logistic activities (mainly based on oil and gas activities) have been received increased attention in recent years. Several reviews have been carried out [41]. Genesis [44] reported on noise production related to operations of construction (pilling), dredging or drilling. A summary of the various measurements or estimations range is presented in Table 2-83. More details can be found in [41].

Table 2-83: underwater noise produced during installation phase [41]

Activity	Extrapolated peak to peak (dB re 1 µPa)
Impact pile driving	136-262
Vibration pile driving	161-182
Trenching	160
Dredging activities (pumping, loading, dumping digging...)	108-200
Drilling activities	140-197

Amongst the various activities related to construction are piling of structures, dredging, trenching and rock placement. One widespread method for piling involves the repetitive striking of metal piles by a hammer to drive them into the seabed. As such, piling noise is characterized by a waterborne impulse which has a rapid rise time. Different types of pile diameter, driven in by different techniques into variable seabed conditions have been found to give rise to a wide range of sound levels. Sound pressure levels in impact pile driving are dependent on the length and diameter of the pile and impact energy [42]. The diameter of the pile installed is one of the key variables in terms of determining the levels of underwater sound that will be generated [44]. The noise generated by impact pile driving usually extends in frequency from 10 Hz to 120 kHz with rms values constant with depth. However, peak values vary with depth and pulse duration is related to, and increases with distance from the pile.

Dredging operations are also necessary when the seabed conditions are not optimal for installation. These activities generate noise and in particular using common types of dredger like cutter suction dredger, bucket ladder dredger, grab dredger and trailing section hopper dredger. Dredging related noises are generally continuous, but some events can also generate impulsive noise (e.g. dropping events). Overall, the noise emitted during dredging operations is mainly influenced by the sediment type being removed. Despite a wide range of potential noise emitted by produced by different types of dredgers, noise is predominantly characterized as having a low frequency < 500 Hz with peak to peak values typically below 200 dB re 1 µPa. More details can be found in Genesis [44].

Drilling activities are mainly carried out from platforms, ships or semi-submersible vessels. They generally emit continuous type noise, and are therefore characterized by root mean squared units (RMS). The noise originates from the transmission of the vibrations of the machinery and drilling equipment such as pumps, compressors and generators that are operating on the platform. Drill ships produce higher sound levels than those produced from a drilling platform, as all the machinery is contained within the hull that radiates out into the water. The utilization of dynamic positioning (DP) implemented through powerful engines also contributes to the noise in the vicinity of the operations. Drill ships have been also reported to produce higher sound levels than semi-submersible drilling rigs, with maximum sound pressure levels of 195 dB (RMS) re 1µPa@1m having been reported. Overall drilling activities are relatively low levels and are predominantly low frequency.

Many marine organisms have developed and use a range of complex mechanisms both for emitting and detecting sound signals. Hearing systems of animals are not equally sensitive to all frequencies. There is also considerable variability between the frequency ranges that marine fauna can emit. Therefore, sounds effectively ‘heard’ by the animal are likely to differ considerably from the actual sounds emitted from the source. Birds are not considered here as noise is considered as an indirect effect. Indeed it may cause a reduction in fish abundance and consequently the reduction of food resources.

Fishes are characterized with a wide range of hearing structures, resulting in different capacities and sensitivities to noise. They use biological noise to gain information about their surrounding environment in order to locate their prey and predators or even communicate. Excessive noise may generate physical injury, hearing loss and behavioral changes as mentioned before. Fish receiving high intensity sound pressures (i.e. in close proximity to the MRE installation site) may be physically impacted to some degree [45], [46], whereas those at distances of hundreds of meters to few kilometers may exhibit only behavior responses. However, the impact remains unknown and will be highly dependent on the nature of the received sound. During the exploitation phase of a MRE project there may be more subtle behavioral effects.

Marine mammals can adapt to a wide variety of natural sounds. The frequencies that can be heard from marine mammals range from less than 100 Hz up to 180 kHz. However, exposure to anthropogenic sounds can potentially impact them, especially when anthropogenic sounds are excessive in level, frequency or even duration. Sounds might then exceed the mammals’ adaptive capacities and then cause the following effects (more details in: Marine Mammals and noise, A Report to Congress from the Marine Mammal Commission, 2007 and reference therein) [47]:

- 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 [45],
- 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 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.

Typical sound levels for pile driving were related to noise exposure criteria for marine mammals to assess possible effects. The pile-driving noise is measured at distances of 0.1 km (maximum broadband peak to peak sound level 205 dB re 1 µPa) to 80 km (no longer distinguishable above background noise) [46]. This study shows that for bottlenose dolphins auditory injury would only occur within 100 m of the pile-driving and behavioral disturbance would occur up to 50 km away. Harbour porpoises and seals are also likely to be able to hear pile driving blows at ranges of more than 80 km and severe injuries in the immediate vicinity of piling activities cannot be ruled out [43]. This latter study also suggests that behavioral responses are possible over many kilometers, perhaps up to ranges of 20 km and that masking might occur in harbor seals at least up to 80 km.

Most of the studies emphasize that there is a lack of standardization of survey and analytical methodologies to aid in future comparison and assessment [46]. An interesting initiative in that way is the one developed by Nedwell [48] with the validation of a frequency weighted scale, the dBht (Species), as a metric for the assessment of the behavioral and audiological effects on underwater animals of man-made underwater noise. The dBht scale incorporates the concept of “loudness” for a species. The metric incorporates hearing ability by referencing the sound to the species’ hearing threshold, and hence evaluates the level of sound a species can perceive. For instance, the same installation event might have a level of 70 dBht (Salmo salar) for a salmon, and 110 dBht (Tursiops truncatus) for a bottlenose dolphin. Table 2-84 below summarizes the assessment criteria when using the dBht (Species) process [48] [49]:

Table 2-84: the assessment criteria when using the dBht (Species) process

Level in dB_{ht}(*Species*)	**Effect**
90 and above	Strong avoidance reaction by virtually all individuals.
Above 110	Tolerance limit of sound; unbearably loud.
Above 130	Possibility of traumatic hearing damage from single event.

In addition, a lower level of 75 dBht has sometimes been used for analysis as a level of “significant avoidance”. At this level, about 85% of individual organisms will react to the noise, although the effect will probably be limited by habituation [49].

Regarding other measurements, as mentioned before, sound may be expressed in Sound Exposure Levels (SEL). SEL sum up the acoustic energy over a measurement period, and takes effectively account of both the SPL (Sound Pressure Levels) of the sound source and the duration the sound is present in the acoustic environment [49]. SPL (expressed as dB re 1 µPa @ 1 m) is normally used to characterize noise and vibration of a continuous nature such as drilling, boring, continuous wave sonar, or background sea and river noise levels. To calculate the SPL, the variation in sound pressure is measured over a specific time period to determine the RM) level of the time varying sound. The SPL can therefore be considered to be a measure of the average unweighted level of the sound over the measurement period.

At the same reference pressure P_{ref} of 1µPa, the SEL and SPL can be compared using the expression:

$SEL = SPL + 10\log_{10}T$, where T is the duration of the sound in s.

Therefore, for continuous sounds of duration less than one second, the SEL will be lower than the SPL. For periods of greater than one second the SEL will be numerically greater than the SPL (i.e. for a sound of ten seconds duration the SEL will be 10 dB higher than the SPL)

Based on the evidence of auditory damage, Bailey et al. [46] propose a set of auditory injury criteria based on peak pressure levels and M-weighted Sound Exposure Levels (see Table 2-85).

Table 2-85: auditory injury criteria based on peak pressure levels and M-weighted Sound Exposure Levels [50][49]

Species	**Sound type**
Marine mammal group	**Single pulses**
Low Frequency Cetaceans	
Sound Pressure Level	230 dB re 1 µPa (peak)
Sound Exposure Level	198 dB re 1 µPa2/s (M_{lf})
Mid Frequency Cetaceans	
Sound Pressure Level	230 dB re 1 µPa (peak)
Sound Exposure Level	198 dB re 1 µPa2/s (M_{mf})
High Frequency Cetaceans	
Sound Pressure Level	230 dB re 1 µPa (peak)
Sound Exposure Level	198 dB re 1 µPa2/s (M_{hf})
Pinnipeds (in water)	
Sound Pressure Level	218 dB re 1 µPa (peak)
Sound Exposure Level	186 dB re 1 µPa2/s (M_{pw})
Sound Exposure Level	198 dB re 1 µPa2/s (M_{pw}) Proposed by Thompson and Hastie (in prep.)

2.13.2.4 Turbidity

Turbidity is the cloudiness or haziness of a fluid caused by large numbers of individuals particles. It usually gives an indication of the concentration of suspended particles in water. MRE developments can modify the turbidity of ecosystems and especially during the installation phase, while activities necessitate interacting with the sediment. Marine operations such as dredging generally generate high turbidity waters through local resuspension of sediment particles in the water column (Figure 2-22). Jack up vessels or barges can also locally increase the concentration of suspended particulate matter due to the disturbance caused by their legs/studs (SPM).

Figure 2-22 Example of enhanced turbidity due to dredging activities

The modification of the turbidity related to the electrical components mostly occurs during the installation phase and, especially, during the cable burial operations. The intensity of the pressure depends on several parameters: burial methods, nature of the sediment and local hydrodynamics. Impacts remain limited in space around the cable route and in time during the cable burial operations period [51].

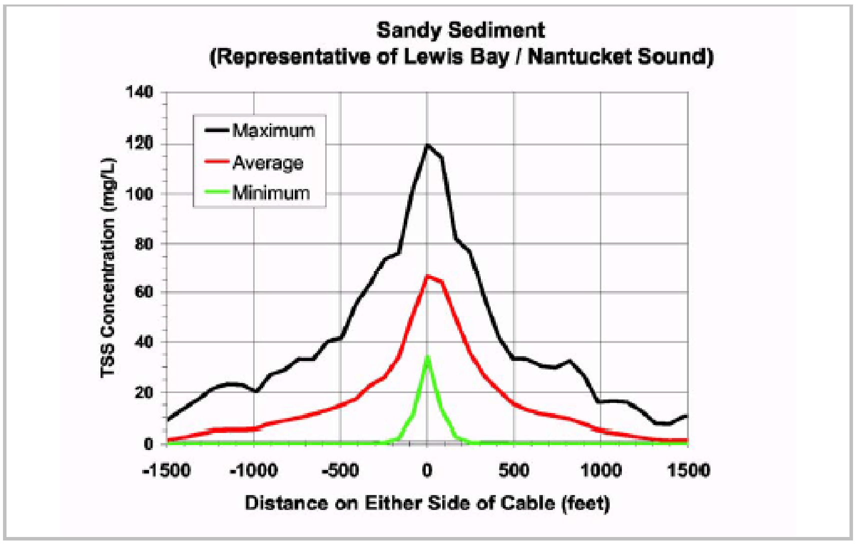


Figure 2-23 Suspended sediment concentration as a function of distance from the cable route in sand-sized sediment in Lewis Bay during the cable installation of the Cape Wind Energy Project [52]

The difficulty to quantify this kind of impact is related to the high variability of turbidity in coastal waters [33] [53]. Typical concentration values range from few mg/l to hundreds mg/l during storm event or near estuarine areas. Monitoring turbidity has been carried out in several cable burial for offshore wind farm [33]. Results and main findings are described below.

Sheringham Shoal Offshore Wind Farm

For ploughing chalk during a neap tide, the dispersion footprint extends for around 9 km in each direction, with concentrations dropping to levels of less than 1 mg/l (above background) within a single flood or ebb excursion. For the spring tide simulation the higher turbulence causes the chalk concentrations to drop below 1 mg/l (above background) within 4 km of the cable route.

London Array Offshore Wind Farm (prediction)

The work assumed that jetting techniques would be adopted and burial depths would be between 1 m and 3 m. The assessment concluded that the fine sand disturbed during the cabling could typically be carried a distance of about 1,170 m. Re-suspended sediment would remain in suspension for about 30 min (based on peak flows).

Nysted Offshore Wind Farm

Cable laying operations were undertaken using jetting where the substrata permitted and using pre-trenching and backfilling where hard substrata were encountered. The trenching operations were undertaken using a back hoe dredger rather than the more specialist systems described earlier in this section. Turbidity measurements were continuously carried out during the cabling operations and daily mean as well as maximum values determined. The jetting operations resulted in significantly less turbidity than the pre-trenching and backfilling operations with mean and maximum values at 200 m from the various operations of:

- Trenching Mean = 14 mg/l
- Trenching Max = 75 mg/l
- Backfilling Mean = 5mg/l
- Backfilling Max = 35mg/l
- Jetting Mean = 2mg/l
- Jetting Max = 18mg/l

These values compare with the restrictions set by the Danish Energy Agency of 15 mg/l as a mean value and 45 mg/l as a maximum value.

Kentish Flats Offshore Wind Farm

During the cable burial operations site measurements were taken 500 m down-tide of the three export cables which were laid using ploughs. The results of the monitoring showed:

- Marginal, short-term increases in background levels (approximately a 9 % increase to the modal concentrations); and
- Peak concentrations occasionally reaching 140 mg/l (equivalent to peaks in the natural concentrations driven by the tidal cycle).

First feedbacks show that the turbidity modification seems to remain limited in intensity, time and space.

2.13.2.5 Chemical pollution

Marine operations enhance the number of vessels and marine infrastructures that usually contains oil, lubricants and other chemical substances in the same area. For MRE developments, most wave and tidal energy converters also contains oil and lubricants. Therefore, there are potentially enhanced risks of leakages and collisions between the different entities due to vessel traffic during installation, operation & maintenance and decommissioning phases.

The main impacts related to chemical pollution will be the degradation of water quality altering the ecosystem in the vicinity of the accident. Hydrocarbon pollution in marine ecosystems is a well-known and growing global problem [54]. Associated harmful effects are killing of organisms, stress for benthic communities [55] and major disturbance of food chains [56]. Polmear et al. [55] have also recently shown evidence of toxicity of lubricants on phytoplanctonic community.

Anti-fouling paints also represent a potential source of chemical pollution. Such paints are very likely to be applied to most sub-systems of ocean energy devices arrays. These products contain a wide range of chemicals which have very different physicochemical properties and therefore differing environmental fates, behaviour and effects. Despite being a natural element, copper has been used as an antifoulant for centuries as at high concentration it is lethal for most marine species. Biocides like Irgarol 1051 and Diuron have been also widely used over the last decades. There are also new or candidate biocides such as Triphenylborane pyridine, Econea, Capsaicin and Medetomidine for which there is very little information in the public domain. The use of antifouling paints can introduce high levels of contamination into the environment, raising some concerns about toxic effects on marine communities. Marine organisms can directly accumulate antifouling contaminants and transfer contaminants to higher trophic levels. If the uptake of the contaminant exceeds the organism's ability for excretion and detoxification, this can reduce normal metabolic functioning [57][58].

The toxicity is directly related to the properties of the contaminant and especially to its bioavailability. Toxicity will increase if a contaminant is more bioavailable. This bioavailability is also driven by the environmental chemical conditions (e.g., temperature and pH) as well as the contaminant affinity for particles (sediment binding). Sediments tend to usually act as a contaminant sink when settle down. However, the remobilisation of sediments by natural (storms) or anthropogenic events such various marine operations can then be a major source of pollution through the release of contaminant in the water column.

Studies on antifouling paints have shown that phytoplancton communities were really sensitive to antifouling substances. The embryo/larval stages of the mussel, oyster and sea urchin were also found to be sensitive, with total dissolved copper EC50 concentrations of 6.8, 12.1 and 14.3 µg L^{-1}, respectively. Fishes are more tolerant to copper exposure with EC/LC50 concentrations ranging between 0.12 and 1.5 mg L^{-1} total dissolved copper. Organic biocides appear to be much more toxic to phytoplankton species than other aquatic animals. Irgarol 1051 appears to be especially toxic to the freshwater diatom (Navicula pelliculosa; (5 day EC50 0.136 µg L^{-1}) [59]and the freshwater macrophytes Chara vulgaris (14 day EC50 0.017 ng L^{-1}) [60]. Table 2-86 gives example of toxicity effects and levels for different biocides.

Table 2-86: toxicity of biocides (benthos and fishes)

Biocide	Toxic effects
Irgarol 1051	blocks the electron transport at photosystem II (inhibiting photosynthesis)
Diuron	blocks the electron transport at photosystem II (inhibiting photosynthesis)
Dichlorofluanid	Fungicide, inhibitor photosystem II electron transport
DCOIT Sean Nine 211	toxic effect: 2,7-32 µg.L-1
CuPT	toxic effect: 2,7-32 µg.L-1
ZnPT	toxic effect: 2,7-32 µg.L-1
Medetomidine	toxic effect: reduce pheromone of amphipod (Corophium volutator) at 10µg.L-1

Overall, issues related to water quality may also indirectly generate temporary displacement from surrounding areas and affect mammals via their influence on preys or habitats [61]. However tidal and wave devices will be located in energetic environments and impacts linked to water quality generated by point source pollution will be largely diluted due to the high hydrodynamic dispersive capacity of the area [62].

2.13.3 ENVIRONMENTAL IMPACT ASSESSMENT MODULE (EIAM) PRINCIPLE

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 functions' 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 2-24:

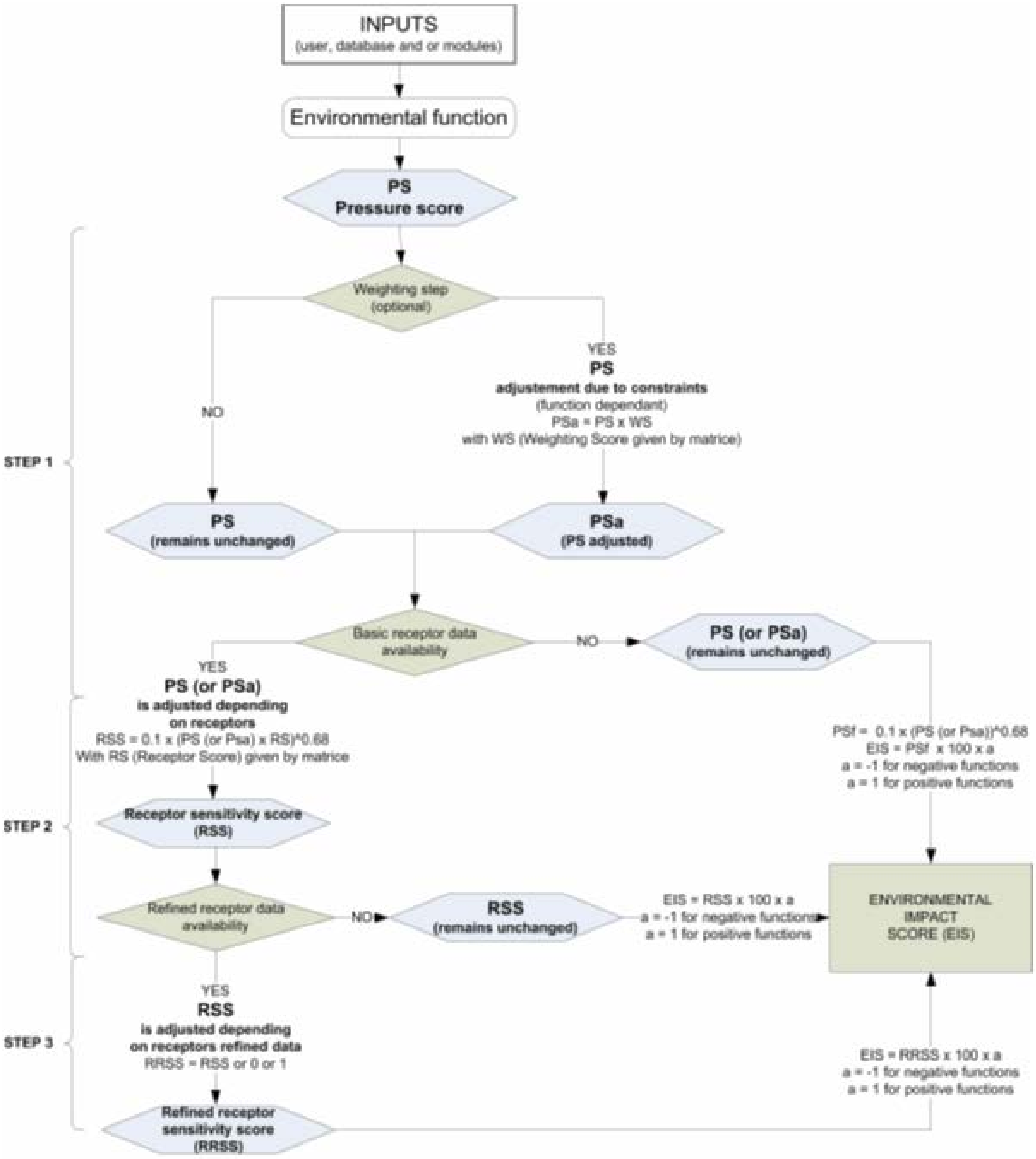


Figure 2-24 Architecture of decisional flowchart for the DTOcean Environmental Impact Assessment Module (EIAM)

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, etc.).

2.13.4 EIAM FUNCTIONS ASSOCIATED WITH THE INSTALLATION PHASE

All parameters involved in the environmental processes are presented in this section. Stressors create the pressure and receptors are the sensitive animal and vegetal species impacted by the stressors. The environmental function uses inputs to produce a result. The environmental function uses inputs to produce a results. As shown in the previous figure, a weighting factor can also occur in the first step of the evaluation process to better qualify the pressure:

- Stressors: the physical anthropogenic elements that generate the 'footprint' pressure.
- Receptors: all biological components (animal and vegetal species, habitats) potentially impacted by the stressors.
- Weighting step: ranging from 0 to 1; if there is no data for the constraints, the precautionary principle lead to the worst weighting case, i.e 1.
- Inputs: to quantify the pressure and the impact, some parameters or inputs are required. They are provided by the DTOcean database, the other modules or the user.

For clarity purposes, the identification of the vessel and equipment types for each of the five environmental functions has been summarized in Table 7-10 and Table 7-11.

Objective

The footprint function aims at evaluating the pressure on the seabed occupied by equipment and anchors of vessels on the benthos and some other species of this ecosystem living on the sea bed.

Stressors

Stressors are the physical anthropogenic elements that generate the 'footprint' pressure. In the logistic process, the footprint is induced by vessels and equipment which can generate significant interaction with the sediment and lead to habitat degradations during marine installation. The footprint is here considered as the total surface area occupied by anchors, ROV tracks, etc.

Receptors

Receptors are all the biological (fauna and flora) species which can be 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).

Inputs

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

- Substrata surface area covered by equipment and other anchoring systems (size of the tools or anchors) [m²] obtained through a formula based on ship size,
- Total surface of the lease area [m²].

Function's formula

The 'footprint' function is calculated as written in equation (2. 1):

$$footprint = \frac{Total\ substrata\ surface\ area\ covered\ by\ equipment}{Totla\ surface\ lease\ area} \qquad (2\text{-}1)$$

Note: The total substrata surface area covered by equipment is the sum of footprints from anchors, cable burial ploughs, cable burial ROVs, concrete mattresses, subsea excavating and tracked cable vehicles.

Rule

If the function's formula's result is near to 0 then the impact is minor. It becomes major if the ratio 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 2-87).

Table 2-87 Footprint Pressure Scores

Function result	Pressure Score - PS
<0.1	0.25
[0.1-0.3]	0.5
[0.3-0.5]	0.8
>0.5	1

Step2

The ecosystem in hard substrata is potentiality more vulnerable because the number and the variability of species are richer than in a soft substrate and that these species are less mobile. The types of benthic species are more diversified in hard substrate. This is the reason why a score of 3 is applied to species living in hard substrata and a score of 1 is applied to species in soft substrata. The receptor scores (Table 2-88) are based on the nature of the ecosystem.

Table 2-88: 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 equation (2. 1):

$$RSS = 0.1 \times (PS \times RS)^{0.68} \quad (2.1.)$$

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 receptor. 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's 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, for Steps 1, 2 or 3, the final Environmental Impact Score is ultimately calculated as follow (2. 2).

$$EIS - Environmental\ impact\ score = A \times 100 \times a \quad (2.2.)$$

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.

Special recommendations

- Reduce the number of vessels in the area,
- Avoid burial of the cable where possible or reduce burial depth,
- Try to limit gravity anchors or gravity foundation,
- Have a good knowledge of the sensitive species (such as benthos and other sensitive ecosystem) in the project area.

2.13.4.1 Collision risk

Objective

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

Stressors

Stressors are the physical anthropogenic elements which cause collision risk. In WP5, only collision is considered and not the entanglement. Vessels used during the installation can generate a risk during the transport for marine mammals and birds.

Receptors

Receptors are all the sensitive species that can by impacted by the stressor. Regarding the collision risks, the major species that can be impacted are mainly marine mammals. Birds can be also affected by interactions with vessels.

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 number of vessels used during the installation phase,
- Total of the surface lease area [m²].

Function’s formula

The 'collision risk' function is calculated as a ratio of occupied by vessels and equipment during the installation phase by the total lease volume area (2. 3)

$$Collision\ risk = {}^{number\ of\ vessels}/_{total\ surface\ lease\ area} \qquad (2.3.)$$

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 no weighting step.

Calibration

Step 1

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, four ranges have been defined as presented in Table 2-89.

Table 2-89: Collision Risk Pressure Scores

Function result	Pressure score - PS
[0-0.01]	1
[0.01-0.1]	2
[0.1-0.2]	3
>0.2	5

Step 2

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

According to GUYDRO project [62], 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 (CITES) [63], Berne convention[64], Convention on migratory species (CMS) [65], OSPAR, etc. They are also directly protected by international agreements such as ASCOBANS [66], ACCOBAMS [67] or the International Whaling Commission [68].

At the European level, the Habitats Directive (Natura 2000) [69] also mentions many species of marine mammals in Annexes IV (species protection) and II (protection of species and their habitats). Finally, the Marine Strategy Framework Directive (MSFD) [70] also shows a close interest in marine mammals and the human activities that threaten them.

An example of RS for marine mammals and birds values are presented in the table below (Table 2-90).

Table 2-90: Some examples of Collision Risk Birds Receptor Scores

Birds Diving depth	Example of species for user	Score
shallow diving	Up to 5m - Fulmar	4
medium diving	5 to30 m - Shag/Cormorant/Gannet	3
deep diving	> 30 m - Common Guillemot/Puffin/Razorbill	2
Number of Regulations concerned	**Groups Marine Mammals**	**Score**
[1-3]	Seal	3
[4-5]	Large odontocete, Mysticete or Dolphinids	4
> 6	Odontoncete	5

After selecting the appropriate Receptor Score (RS), the Receptor Sensitive Score (RSS) can be obtained using the formula (2. 4):

$$\mathrm{RSS} = 0.1 \times (\mathrm{PS} \times \mathrm{RS})^{0.68} \qquad (2.4.)$$

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 STEP 3 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 2-24 Architecture of decisional flowchart for the DTOcean Environmental Impact Assessment Module (EIAM), the final Environmental Impact Score is ultimately calculated as follow (2. 6):

$$EIS - Environmental\ impact\ score = A \times 100 \times a \qquad (2.5.)$$

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

Special recommendations

- Vessel speed limitation with special care in the sensible areas. The speed limitation should be applied before reaching the site.
- Limit night vessel traffic or during bad weather.
- Limit the vessel light which attracts some species (especially birds).
- Reduce the number of vessels in the area.
- Have a good knowledge of the sensitive species (mostly marine mammals) at the ocean energy site.
- Avoid circulating in migrator corridor.
- Avoid presence at the site during the reproduction period.

2.13.4.2 Underwater noise

Objective

The goal of this function is to evaluate the impact of underwater noise produced by the vessels and equipment during the installation phase.

Stressors

Stressors are the physical anthropogenic elements that generate the environmental pressure. The noise created during the installation phase of foundations and anchors is evaluated for the lifecycle logistics. The speed and power of vessels and equipment influence the level of the noise.

Receptors

Receptors are all the species (fauna and flora) that can by impacted by the stressors. Underwater noise impacted only the fauna species. The noise produced by vessels and equipment is a physical pressure that can affect marine mammals and fishes.

Inputs

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

- Threshold sensitivity of species underwater noise [unit of measurement: dB re 1µPa] (DTOcean database)
- Noise produced by the vessels and equipment (source/intensity/speed of vessel/size of vessels) [unit of measurement: dB re 1µPa (1m)] (user, or database by default).

Function's formula

The 'underwater noise' function (2. 5) consists of a comparison between the threshold sensitivity of species and the underwater noise level produced by the vessels and equipment (specified above).

$$Underwater\ noise = \quad (2.6.)$$

$$comparison\ between\ threshold\ sensitive\ species$$

$underwater\ produced\ by\ vessels\ and\ equipment$

Rule

The noise induced by the mooring lines is compared to the sensitivity threshold of species to identify if there is concordance (or not). If yes, 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

The underwater noise varies mostly depending on the type of vessels (speed, tonnage, etc.), the power of equipment as well as the vibration of equipment. In the DTOcean tool, a formula to deduce the underwater noise induced by a vessel adapted from Ross [71] is employed. The noise levels of vessels used in the DTOcean tool are presented in Table 2-91Table 2-91.

According to Ross [71]

Inputs:

l = vessel size (m)

v = % speed (knots)

For frequencies higher than 500 Hz

$$ls0 = 173.2 - 18 \times \log_{10} f$$

For frequencies lower than 500 Hz

$$Is0 = -10 \times \log_{10}\left(10^{(-1.06\times\log_{10} f - 14.34)} + 10^{(3.32\times\log_{10} f - 21.25)}\right)$$

Power spectral density of radiated noise RPL

$$\text{RPL} = ls0 + 60 \times \log_{10}\left({}^{v}/_{12}\right) + 20 \times \log_{10}\left({}^{l}/_{300}\right)$$

Table 2-91: Noise of vessels calculated from Ross's formula (1976) for the DTOcean tool

Vessels type	Noise Broadband level [0-500Hz] [dB re 1uPa]	PS-Pressure Score
crane barge	214.192871	5
crane barge	207.365022	5
crane vessel	229.384262	5
crane barge	203.605601	5

crane vessel	239.507994	5
crane vessel	216.047267	5
crane vessel	216.026662	5
tug	211.32886	5
tug	202.63936	5
WFSV	233.122665	5

This formula allows obtaining the underwater noise of vessels but not of the equipment tools. It is difficult to calibrate the score of the vessels' noise because the choice of vessels can change and the transit speed can accelerate or slow down. That is why underwater noise calibration is based on available data for different existing types of devices. Tree ranges of underwater levels of noise are presented (Table 2-92):

Table 2-92: Underwater 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 terms of sensibility, Step 2 involves three expected types of effects:

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

The behavior effect is considered as a moderate effect, unlike TTS and PTS which 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 2-93 and Table 2-93.

Table 2-93: Example of underwater noise Receptor Scores assigned to different marine species

Sensitivity threshold	Species	Effect	RS
< 143 dB re 1µPa	Large Odontoncete, odontoncetes, Delphinids, Mysticetes	behavioural	3
[143-224] dB re 1µPa		TTS	5
>224 dB re 1µPa		PTS	5
<160dB re 1µPa	Seals	behavioural	3
[160-200] dB re 1µPa		TTS	5
>200 dB re 1µPa		PTS	5

After selecting the appropriate Receptor Score (RS), the Receptor Sensitive Score (RSS) can be obtained using the formula (2.7):

$$\mathrm{RSS} = 0.1 \times (\mathrm{PS} \times \mathrm{RS})^{0.68} \qquad (2.7.)$$

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.

The final Environmental Impact Score is ultimately calculated as follow (2. 8):

$$EIS - Environmental\ impact\ score = A \times 100 \times a \qquad (2.8.)$$

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

<u>**Special recommendations**</u>

- Avoid the use of powerful hammers for pile driving.
- Reduce the underwater noise during the installation of foundation by pile driving by using bubble curtains which can reduce the sound level transmitted through the water column.

- Choose carefully the period of installation of the foundation and subsea power cables to reduce the impact on marine mammals.
- Choose the least noisy cable burial method.
- Use an inflatable bladder which reduces the underwater noise during the pile driving.
- Use scaring sound system for marine mammals during any very noisy activities.
- Increase gradually the level of underwater noise during activities such as the pile driving.
- Have a good knowledge of the sensitive species in the ocean energy site.
- Reduce the transit speed of vessels on-site.
- Reduce the number of vessels on-site.

2.13.4.3 Turbidity

Objective

The goal of this function is to evaluate the impact of a raise of turbidity during the installation phase in the area.

Stressors

Stressors are the physical anthropogenic elements that generate the environmental pressure. The turbidity created during the installation phase of foundations and anchors, devices and electrical components is evaluated for the lifecycle logistics.

Receptors

Receptors are all the species (fauna and flora) that can by impacted by the stressors. The turbidity pollutants created during the installation phase is a physical pressure that can affect benthos and the ecosystem living on cohesionless soils, cohesive soils or cemented and rocky soils, but also fishes, marine mammals and sea birds.

Inputs

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

- initial turbidity,
- turbidity measured during the installation activity.

Function's formula

The 'turbidity' function consists of a comparison between the data of the initial turbidity measured and the turbidity measured during the installation phase (2. 6).

$$Risk\ of\ turbidity = \text{comparison between initial turbidity and turbidity during the installation phase} \tag{2.9.}$$

Rule

The rule of this function is to estimate the concordance or disagreement between the initial data and data during the installation phase. If there is concordance, 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

The difficulty to quantify this environmental impact is related to the high variability of turbidity in coastal waters [53]. Typical concentrations range from few mg/l to hundreds of mg/l during storm events or near estuarine areas. To quantify the turbidity risk a binary method is utilized which consists of comparing the initial turbidity and turbidity during the installation phase (Table 2-94).

Table 2-94: Pressure Score for the risk of turbidity

Result of the function	Pressure Score - PS
no concordance of data (turbidity stressor < Sensibility receptor)	0
concordance of data (turbidity stressor ≥ Sensibility receptor)	5

Step 2

The ecosystem in hard substrata is potentiality more vulnerable by an increase of turbidity because the number and the variability of species are richer than in soft substrata. That is the reason why the score of 3 was applied to species living in hard substrata and 1 to species in soft substrata. Marine mammals and birds can also be impacted by the increase of the turbidity but the lack of data and the low potential risk has led to a score of 1 (Table 2-95).

Table 2-95: Receptor Scores assigned to different marine species for the turbidity

Benthic ecosystem and habitats		Receptor Score - RS
Ecosystem living in hard substrate (Cemented to hard rock soil types)		3
Ecosystem living in soft substrate (Cohesion less soil group)		1
Particular habitats (other)		4
Deep sea birds	**Example of species for user**	**Receptor Score - RS**
0-5m	Fulmar	1
5-30m	Shag/Cormorant/Gannet	2

>30m	Common Guillemot/Puffin/Razorbill	3
Fishes and Marine Mammals		**Receptor Score - RS**
Elasmobranch		3
Bony fish		3
Marine mammals		3

After selecting the appropriate Receptor Score (RS), the Receptor Sensitive Score (RSS) can be obtained using the formula (2.10):

$$\mathrm{RSS} = 0.1 \times (\mathrm{PS} \times \mathrm{RS})^{0.68} \qquad (2.10.)$$

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

Step 3

The final step (STEP 3) considers 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 2-24 Architecture of decisional flowchart for the DTOcean Environmental Impact Assessment Module (EIAM), the final Environmental Impact Score is ultimately calculated as follow (2.11):

$$EIS - Environmental\ impact\ score = A \times 100 \times a \qquad (2.11.)$$

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.

<u>Special recommendations</u>

- Avoid any embedment activity.
- Prefer gravity based foundations/anchors over other foundation/anchor types.

- Have a good knowledge of the sensitive species in the project area.

2.13.4.4 Chemical pollution

Objective

The goal of this function is to evaluate the impact of the chemical pollution during the installation phase due to the presence of vessels in the area.

Stressors

Stressors are the physical anthropogenic elements that generate the environmental pressure. The risk of pollution created during the installation phase of foundations and anchors, devices and electrical components is evaluated for the lifecycle logistics. The stressor appears in the transport of chemical pollutant during the installation phase.

Receptors

Receptors are all the species (fauna and flora) that can by impacted by the stressors. The chemical pollutants transported by vessels and equipment are a chemical pressure that can affect benthos and the ecosystem living on cohesionless soils, cohesive soils or cemented and rocky soils.

Inputs

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

- List of potentially toxic chemical components (fuel, antifouling, etc.) transported by vessels and equipment,
- List of sensitive species.

Function's formula

The 'chemical pollution risk' function consists of a comparison between the threshold sensitivity of species and a list of chemical components (2. 12)

$$\begin{gathered} Chemical\ pollution\ risk = \\ comparison\ between\ chemical\ components\ which\ are\ used \\ at\ the\ farm\ site\ and\ the\ corresponding\ threshold\ sensitivity \\ of\ species \end{gathered} \quad (2.12.)$$

Note: The list of potentially toxic chemical pollutants and the list of sensitive species are stocked in the data base. The user just needs to tick the elements in the list.

Rule

The presence of chemical components induced by the vessels is compared to the sensitivity threshold of species to identify if there is concordance (or not). If yes, 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

Biocides are sometimes used in the offshore environment and most of them are highly toxic. To give a score for chemical pollutants, the toxic effect of biocides and oil on different organisms. This score is the Pressure Score PS (Table 2-96).

A score of 5 is given for the most toxic biocides which affect over six species of the given list, a score of 4 for bunker oil and biocides which impact more than two species of the list, and a score of 3 for garbage, crude oil and biocides which impact only one single species.

Table 2-96: Pressure Score for the risk of chemical pollution

Result of the function		PS
concordance of data (chemical pollution stressor ≥ Sensibility receptor)	Irgarol 1051	5
	ZnPT	4
	CuPT	4
	Pyrizine sulfonic acid	4
	Seanine 211	4
	Chlorothalonil	4
	TBT	4
	copper oxide	4
	TPBT	3
	medetomidine	3
	Bunker oil	4
	Garbage of vessel	3
no concordance of data (chemical pollution stressor < Sensibility receptor)		0

Step 2

During the second step, the sensitivity of species to chemical pollution is analyzed, resulting in the Receptor Sensitivity Score (Table 2-97). Five different groups have been considered and an arbitrary RS was attributed to each of these groups:

- Ecosystem living on cemented and rocky soils (the diversity of species is higher than in the soft substrata (cohesionless soils) so we consider the risk higher for these species),
- Ecosystem living in cohesionless soils (the diversity of species is less than a rocky substrate, but the risk is present because the pollutant particles can be accumulate in the sediment,

- Fishes, marine mammals and birds which can be impacted by the presence of oil or garbage in the sea. Toxic particles can be lethal for these species.

Table 2-97: Receptor Scores assigned to different marine species for the chemical risk

Benthic ecosystem and habitats		**Receptor Score - RS**
Ecosystem living in hard substrate (Cemented to hard rock soil types)		3
Ecosystem living in soft substrate (Cohesion less soil group)		1
Particular habitats (other)		4
Deep sea birds	**Example of species for user**	**Receptor Score - RS**
0-5m	Fulmar	3
5-30m	Shag/Cormorant/Gannet	3
>30m	Common Guillemot/Puffin/Razorbill	3
Fishes and Marine Mammals		**Receptor Score - RS**
Elasmobranch		3
Bony fish		3
Marine mammals		3

After selecting the appropriate Receptor Score (RS), the Receptor Sensitive Score (RSS) can be obtained using the formula (2. 13):

$$\mathrm{RSS} = 0.1 \times (\mathrm{PS} \times \mathrm{RS})^{0.68} \qquad (2.13.)$$

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

As shown in Figure 2-24 Architecture of decisional flowchart for the DTOcean Environmental Impact Assessment Module (EIAM), the final Environmental Impact Score is ultimately calculated as follow (2.14):

$$EIS - Environmental\ impact\ score = A \times 100 \times a \qquad (2.14.)$$

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.

Special recommendations

- Prohibit discharge of wastewater, ballast water and any garbage.
- Limit the number of vessels in the area.
- Limit the utilization of antifouling paints.

2.13.5 CONCLUSION

The Environmental Impact Assessment Module (EIAM) 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. The above section of thereport describes the environmental effects related to logistic activities. Only the installation / decommissioning / O&M phases are considered here, as environmental issues related to regular operational phase are treated separately and linked to a different DTOcean module. As such, considered adverse environmental effects are therefore chemical pollution, collision risks, footprint issues, underwater noise production and potential raise of high turbidities. 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 a (more or less accurate) 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 with the relevant logistic activities covered in the installation module of the DTOcean tool. This work is mostly based on bibliographic data when available which is often empirical. Best guesses have also been assumed when no reliable source of data was found. This set of functions feeds the EIAM to ultimately provide environmental impact scores (EIS).

3 LOGISTIC MODEL FOR OCEAN ENERGY ARRAYS – THE INSTALLATION MODULE

3.1 THE INSTALLATION MODULE WITHIN THE GLOBAL DTOCEAN TOOL

In order to situate the installation module within the global DTOcean tool, the architecture of the overall software package is presented first. DTOcean core outcome is a suite of shared-access design tools developed in the Python programming language. One module (or design tool) should be a standalone application suited to continuous edition.

The global tool embraces a modular architecture in which coupling with other software may be done given the specifications of the replaced module are respected. Additional data or information should be readily absorbed by a module to grant significant flexibility for the end-user. The first official release of the DTOcean final software shall also feature a Graphical User Interface (GUI).

Figure 3-1 depicts the modular architecture of the global DTOcean tool. Five computational modules (on top) communicate through the core global design tool (blue box in the center). Input-Output (I/O) connections are handled in the core through external functions. The global database (bottom) is also linked to the core. The left side of Figure 3-1 designates the end-user inputs and selections required to run the tool. Results are shown at the end right side of the figure.

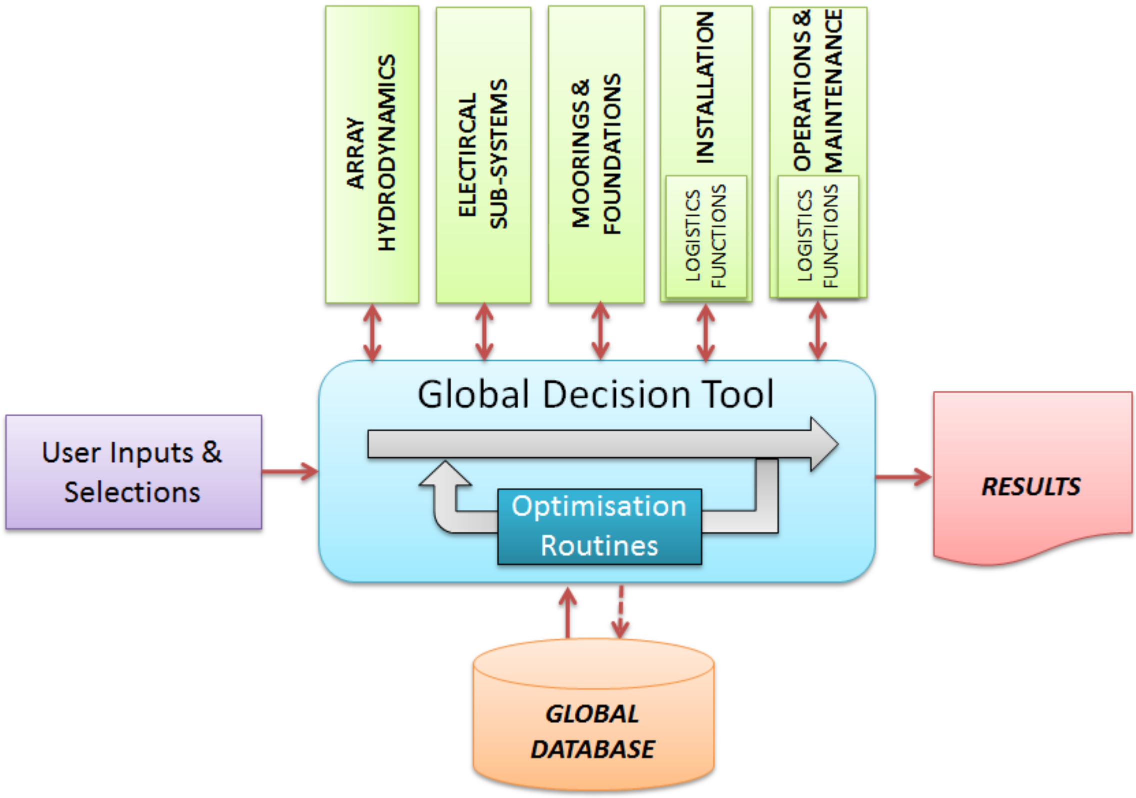


Figure 3-1 Functional structure of the DTOcean tool

In this software architecture, the installation module appears on the fourth position of the computational modules when reading them from left to right. This somewhat reflects the background incremental logic path governing the design of ocean energy arrays in DTOcean. In fact, the installation module is seeking to minimize the cost of installation of all components/sub-systems chosen by the upstream modules.

In other words, the installation module covers the following elements:

- Installation of wave or tidal devices as positioned by the array hydrodynamics module,
- Installation of the electrical infrastructure components as designed by the electrical sub-systems module,
- Installation of the moorings & foundations as arranged by the module.

As any other computational module, the logistics installation module aims to solve a given physical problem and returning new outputs. However, the nature of the logistic module slightly differs from that the hydrodynamic, electrical sub-systems and moorings & foundations modules in the sense that no physical array sub-component is selected nor designed as part of the bill of material. In contrast, the logistic module provides optimal logistic solutions by selecting feasible vessels, ports and equipment to accomplish the installation phase. These logistic solutions only intervene on a limited period of time of the project life cycle and do not directly affect the efficiency of the conversion chain transforming wave or tidal energy resource into useful electricity.

It should be noted that if the user wishes to use the installation module to assess the installation of only a restricted part of the entire bill of material (comprising devices, moorings & foundations and the electrical infrastructure), then the quantity of the item to be ignored (specified by the user through the GUI of the core module) by the installation module should be set to “zero” by the core. This allows the user to evaluate only the installation of the devices while disregarding the installation of the other components, for example. In these types of scenarios, the starting time to be assumed for the commissioning will still be the latest ending time of all components analysed by the installation module.

In addition to the simulation (logistic functions) of logistic phases as described in Chapter 2, the installation module comprises complementary features:

- A pre-defined logistic phase sub-module: this is where the operation sequences and vessels & equipment combinations are defined for all logistic phases.
- An installation procedure definition sub-module: it is divided into two functions; one defining the scheduling rules to determine the sequence of the logistic phases (see details in section 3.3) and another function selecting the base installation port (see details in 3.4).
- An optimization routine: the most inexpensive feasible logistic solutions are chosen.

Figure 3-2 gives a high level schematic of the structure of the installation module. From left to right one progresses through the analysis undertaken in the installation module. After loading all required inputs, the pre-defined logistic phase and the installation procedure definition sub-modules run sequentially.

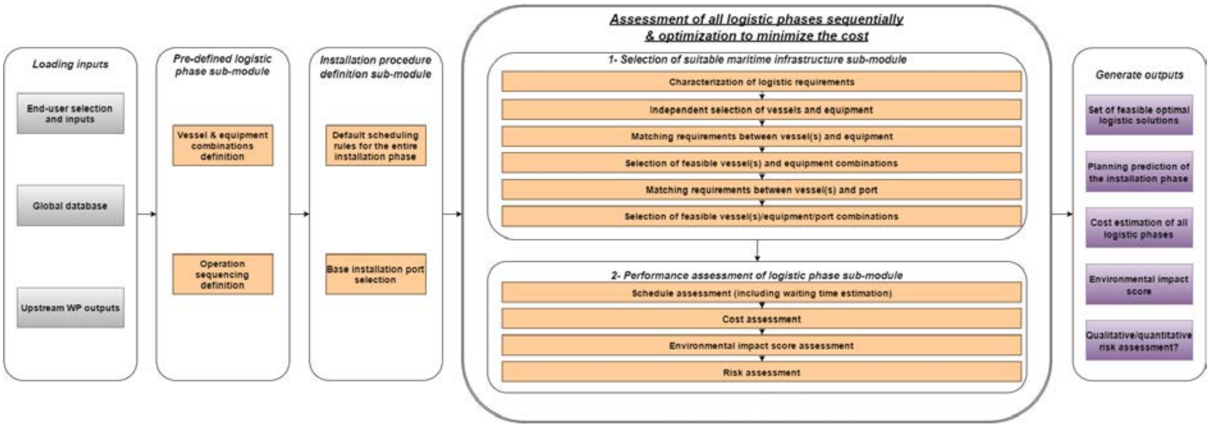


Figure 3-2 High level flow chart of the installation module

Having the information of the Gantt chart planning of all logistic phases, the assessment of these is performed in three steps:

- STEP 1 "selection of suitable maritime infrastructure sub-module": characterization of the logistic requirements relating the array physical parameters to the characteristics of the maritime infrastructure (ports, vessels and equipment). This step is followed with the matching of the logistic requirements previously determined with the database of vessels, ports and equipment purposely built-in for the DTOcean tool. To avoid unnecessary verification, the selection of the individual vessel(s), port and equipment is constrained by the pre-defined type of vessels and equipment. Ultimately, the end-user shall have the opportunity to specify its own set of type of vessel(s) and equipment he would like to assess. This feature would add significant flexibility to the WP5 module.
- STEP 2 "performance assessment of logistic phase sub-module": this assessment is four fold:
  - Firstly, an estimation of the schedule of the marine operation is conducted. The mobilization time associated with the availability of the maritime infrastructure (vessels and equipment) is straightforwardly evaluated, based on average values in the database. Similarly, the transportation times are readily computed through the average speed values along with an assessment of the distance from port to site. By combining various methods for time assessment presented in section 2.3, the expected waiting time associated with the marine operation can be predicted. In essence, the weather window function requires the requested starting time and the duration of the marine operation to return an estimate of the waiting time.
  - Secondly, the cost functions produce estimates of the costs incurred by the utilization of the maritime infrastructure. Both fixed and variable costs are accounted for by making use of relevant economic parameters available in the database of ports, vessels and equipment. Details of this assessment were given in section 2.11.
  - Thirdly, a qualitative assessment of the environmental impact associated with the use of the vessel and equipment returns an environmental score for five potential impacts. The implementation of these functions is done in collaboration with France

Energies Marines. Section 2.12 addresses the development of the environmental functions associated with the installation phase.

  - A risk assessment which will attempt to quantify the uncertainty of four core categories of logistic liabilities as described in section 2.12. Note that this feature will not be available in the first release of the DTOcean tool.

- STEP 3 "optimization routine": in the logistic module, the objective function is to find the feasible logistic solutions which minimize the total cost (C_{lp}) for a given logistic phase.

At the end of this process, the outputs of the installation module are sorted and formatted in the most convenient way for future results presentations. The outputs include a set of optimal feasible logistic solutions along with their schedule, cost, risk and environmental impact assessment.

To-date, a total of nine logistic functions Excel sheets have been developed in response to the scope of the DTOcean tool. Details of these functions can be accessed in both Deliverable 5.4 [4] and in Chapter 2. In turn, any array configuration that can possibly be proposed to the installation module should fit the nine logistic phases characterized. In other words, the installation of all array sub-components can be appraised from a time, cost and environmental perspective. Below is the list of the nine logistic phases, split within the 3 main groups:

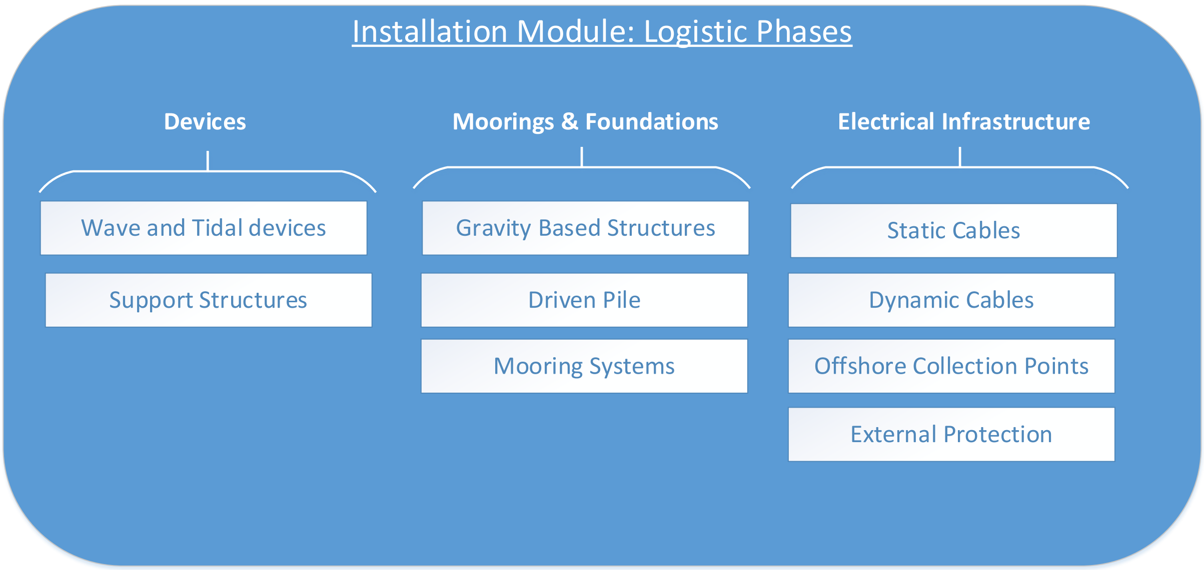


Figure 3-3 Scope of the logistic phases considered for the installation module

3.1.1 MOORINGS AND FOUNDATIONS SCOPE

Figure 3-5 to Figure 3-9 capture the options outlined in Figure 3-3 and illustrate the combinations of components that may be used to provide foundations or moorings for a marine energy device.

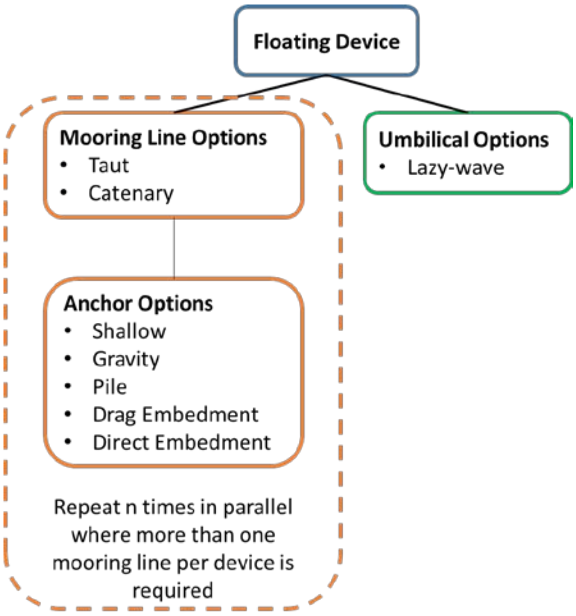


Figure 3-4 Mooring options for a floating marine energy device

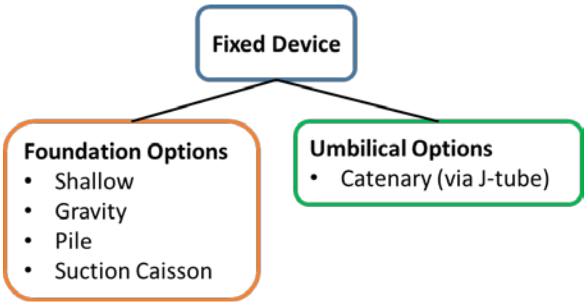


Figure 3-5 Foundation options for a fixed marine energy device

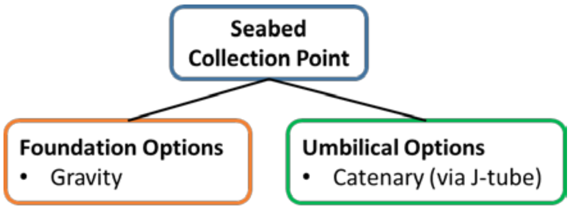


Figure 3-6 Foundation options for a seabed collection point

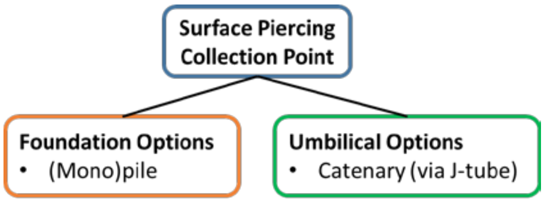


Figure 3-7 Foundation options for a surface piercing collection point

Mooring lines, whether taut or catenary, will be formed by one of the two patterns of components outlined in Figure 3-8and Figure 3-9.

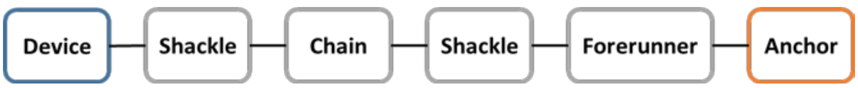


Figure 3-8 Components of a chain based mooring line

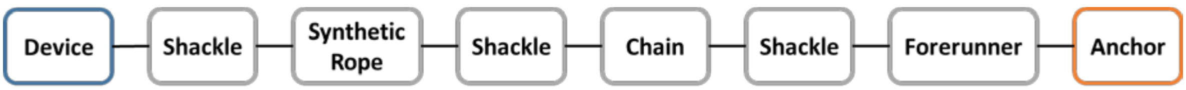


Figure 3-9 Components of a chain and synthetic rope based mooring line

3.1.2 ELECTRICAL INFRASTRUCTURE SCOPE

Figure 3-10 captures the options outlined in Figure 3-3 and illustrates the patterns of these components that may be used to form a marine energy array. Options for a given component are given as bullet points (e.g. a device can be of type floating or fixed). Branches in the diagram represent decisions to be made regarding routing of power from device to export.

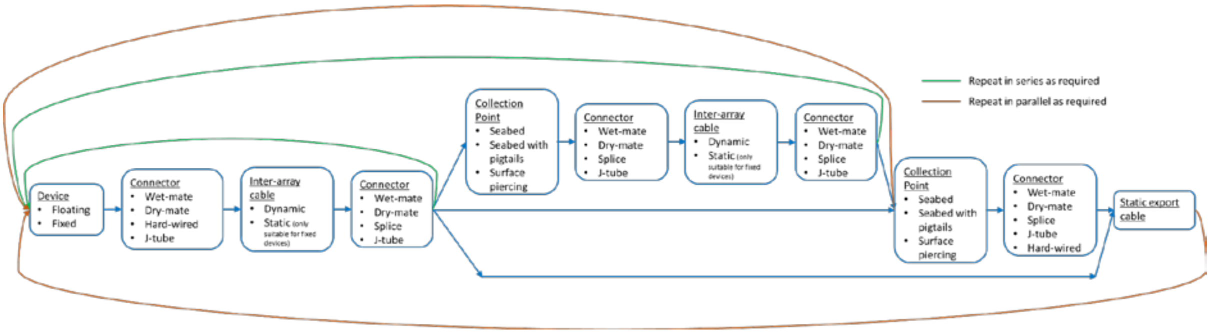


Figure 3-10 Allowable patterns of electrical components forming an array

Note that static inter-array cables are only suitable for use with fixed marine energy devices.

Figure 3-10 presents a number of ways in which arrays of devices may be connected, allowing output from numerous devices to be collected and exported.

1. A single device may be installed using the pattern device -> connector -> inter-array cable -> connector -> static export cable.
2. A number of devices may be installed in series by repeating the pattern device -> connector -> inter-array cable -> connector, before feeding down to a collection point or export cable.
3. Collection points may be inserted into a string as described in point 2 using the pattern collection point -> connector -> inter-array cable -> connector.
4. A number of strings as described in points 2 or 3 may be installed in parallel, all connecting down to a common collection point prior to a static export cable.
5. Any of the options described in points 1-4 may be repeated in parallel if more than one static export cable is to be used.

Three types of terminal can be highlighted in Figure 3-10, namely: device, collection point and static export cable. Allowable patterns of connection between two terminals are:

2. Device to device
3. Device to static export cable
4. Device to collection point
5. Collection point to collection point
6. Collection Point to static export cable

3.2 INPUTS TO THE INSTALLATION MODULE

In Chapter 2, the list of inputs for each logistic phase was individually presented. For this reason, rather than recapitulating the full list of inputs, this section will provide insight on the origin and nature of these inputs. Nevertheless, for the sake of comprehensiveness, the full list of inputs classified by their origin is included in Appendix 7.8. Although always passing through the core global decision tool of the DTOcean software, the input data to the installation module has three original providers that will be portrayed below.

3.2.1 REQUIREMENTS FOR THE END-USER

Any data that the user is required to enter into the system for the functionality of the installation module. In short the type of inputs falling into this category can be enumerated as follows (see details in Appendix 7.8.1):

- Site data: information about the bathymetry, the soil conditions at each grid point of the lease area characterized,
- Met-ocean data: time-series values of significant wave height, peak wave period, wind speed and current speed,
- Device data: device and device sub-systems specifications such as dimensions, weight, assembly strategy, load out strategy, transportation method.

Each category of inputs will be treated as panda DataFrame tables within the installation module. Although not compulsory requirements, the end-user is strongly advised to override the default values (e.g average fixed duration of logistic operations, vertical and horizontal progress rates, OLC, safety factor, day-rates and other cost input values) if more accurate data is available. Common default values pertaining to logistic phases associated with both the installation and O&M modules include:

- *Average fixed duration values and OLC values of individual logistic operations*. Table 7-16 summarizes how the installation module handles these default values or method for a restricted (and yet representative) list of the entire set of logistic operations covered by the installation module. While the first three columns refer to the short name, id and description of the logistic operation considered, the following three columns (starting with header 'Time:') indicate the method or default value assumed to estimate the duration of the operation. Only one of this column should be filled. The column 'Time: value [h]' only accept positive float numbers which will directly taken to estimate the time duration of the operation. The column 'Time: function [-]' currently supports only five strings options (namely 'transit algorithm', 'distance', 'grouting' and 'penetration time' & 'laying time') which uses simple calculation based on other user input or default values to get a time estimate of an operation. The column 'Time: other [-]' extracts the time duration value from either the vessel database or other user-specified input (device or O&M). Note that only the exact string characters messages shown in Table 7 8 are currently supported.
- *Vertical penetration rates in all DTOcean soil types for all piling equipment*: Table 7-17 depicts the default average values for each technique and soil type currently covered by the DTOcean global tool. These values are the result of literature survey as well as discussion with experts. It is, however, highly recommended for the user to override these values if more accurate data is available for the specific scenario to be simulated.

- *Horizontal progress rates in all DTOcean soil types for all cable trenching/laying equipment*: Table 7-18 depicts the default average values for each technique and soil type currently covered by the DTOcean global tool. These values are the result of literature survey as well as discussion with experts. It is, however, highly recommended for the user to override these values if more accurate data is available for the specific scenario to be simulated.
- *Other generic and diverse costing and time default value assumptions:* Table 7-19 indicates the nature, the unit and the values considered for these default parameters.
- *Safety factors to apply on selected feasibility functions*: Table 2-4, Table 2-5 and Table 2-6 summarize the core aspects scrutinized during the feasibility functions and their associated safety factors for the port, vessels and equipment respectively.

3.2.2 INTERACTIONS WITH THE GLOBAL DATABASE

The global database is the amalgamation of all data that is required for the operation of the computational packages that can be provided without direct input from the user. Figure 3-1 shows that the database information is fed into the global design tool and not into the computational packages directly. This allows the user to override the results from the global database and also removes some ambiguities and inefficiencies that can occur when several modules require the same data or where some data that has originated from the database has been modified by one of the computational packages.

Among the large set of data available in this global database, the installation module essentially extracts the following parameters:

- Port database: detailed information about European ports with the following parameter categories:
    - General Information *(13 parameters),*
    - Port Terminal Specification *(17 parameters),*
    - Port Cranes, Support, Accessibilities and Certifications *(16 parameters),*
    - Manufacturing capabilities *(8 parameters),*
    - Economic Assessment *(8 parameters),*
    - Contact details *(4 parameters),*
- Vessel database: detailed information about each vessel types considered in DTOcean (see Table 2-2) with the following parameter categories:
    - General Information *(9 parameters),*
    - Main Dimensions and Technical Capabilities *(18 parameters),*
    - Maximum Operational Working Conditions *(8 parameters),*
    - On-board Equipment Specifications *(~34 parameters),*
    - Economic Assessment *(4 parameters),*
- Equipment database: detailed information about each equipment types considered in DTOcean (see
- Table 2-3) with the following parameter categories (the number of parameters varies from one equipment type to another):
    - Metrology *(min. 4 parameters),*
    - Performance *(min. 2 parameters),*
    - Support systems *(min. 2 parameters),*

- Economic Assessment *(min. 2 parameters),*

Strictly, the global database is to provide inputs to the installation module as well as other computational module, not to store outputs. However, it is important to facilitate a means for the user to update the database with contemporary information or site and technology specific data, prior to the operation of the tools.

In addition to updating the default values, the end-user has the opportunity to manipulate the maritime infrastructure database (port/vessel/equipment) so that, for example, new vessel(s) or equipment are incorporated or negotiated chartered day-rates values are applied instead of the pre-defined values. This feature is particularly pertinent for an end-user which would already know which port(s) should be considered for the installation and O&M phases.

3.2.3 INTERACTIONS WITH UPSTREAM MODULES

The last interaction of the installation module copes with the results of upstream computational module. In other words, these inputs to WP5 correspond to outputs from other modules (details of the parameters can be found in Appendix 7.8.2), as listed below:

- Array hydrodynamic: number and position of the devices in the UTM grid coordinate system formatted in one panda DataFrame table.
- Electrical sub-system: specifications of six sub-systems, namely: the collection points, the dynamic cables, the static cables together with the cable routing information (one panda DataFrame for each), the external protection and the connectors. This gives six panda DataFrames tables.
- Moorings & foundations: specifications of two sub-systems, namely the foundations (which can be anchors in the case of mooring systems) and the mooring lines. This gives two panda DataFrame tables.

3.3 INTER-LOGISTC PHASES SCHEDULING

Among the nine logistic phases considered for the complete installation phase of an ocean energy array as introduced in section 2.1, it is clear that there exist scheduling relationships to plan them sequentially from a project developer standpoint. Therefore, "Gantt chart" rules to determine the sequence of the logistic phases forming the installation module have been created. For this purpose, it is necessary to first identify all possible scenarios that can reach the installation module. The definition of a scenario here is an array layout configuration which leads to a singular Gantt chart ruling system.

For instance, a Gantt chart rule can be the requirement to install the inter-array static power cables after the installation of the offshore collection point. Clearly, such rules are deeply project specific. Still, based on the literature review previously engaged in the early development of the logistic functions, some trends have been identified which are reported below:

- STEP 1 “Moorings & foundations”: any installation of moorings and/or foundations is likely to be completed before any other installation.

- STEP 2 “Electrical infrastructure”: all logistic phases associated with the installation of electrical infrastructure can be done simultaneously and should be conducted after the moorings and/or foundations and before the device installation.
- STEP 3 “Wave or tidal devices”: devices should be installed at last after completion of the installation of all electrical sub-systems.

These trends will be refined in the future through the construction of summary "Gantt chart rules tables" covering any possible array configuration scenario. DTOcean tool end-users should have the opportunity to override these default rules.

Table 3-1 exemplifies the use of user-specified integer values in the column ‘default order’ for the entire scope covering all possible logistic phase available in the installation module. It is in this column where the user should indicate integers which refer to the chronological order of one logistic phase with respect to others. The counting starts with ‘0’ (zero). The python file ‘planning.py’ selects which logistic phases are considered based on the presence of components to install (e.g if the panda table export cable is empty, the installation of logistic phase will not be simulated). A logistic phase with a default order set to ‘1’ means that it will look for the first weather window suitable after all logistic phases with default order ‘0’ have been completed. When no values are specified in the column ‘default order’, the installation module will enforce a default ordering based on generic Gantt chart rules. In other words, if a user does not wish to set the default order values, the installation module will take care of this task.

Table 3-1 Example of user specified order for each logistic phase in the corresponding default value table

id	logistic phases group	Default Order
E_export	Installation of electrical infrastructure	1
E_array	Installation of electrical infrastructure	3
E_external	Installation of static cable external protection	4
E_cp_seabed	Installation of electrical infrastructure	0
E_cp_surface	Installation of electrical infrastructure	2
E_dynamic	Installation of electrical infrastructure	4
Driven	Installation of moorings & foundations	0
Gravity	Installation of moorings & foundations	0
M_pile	Installation of moorings & foundations	0
M_drag	Installation of moorings & foundations	0
M_direct	Installation of moorings & foundations	0
M_suction	Installation of moorings & foundations	0

S_structure	Installation of devices	4
Device	Installation of devices	5

3.4 INSTALLATION BASE PORT SELECTION

The experience of offshore wind shows that one unique installation base port is mutualizing all logistic activities during the assembly, transportation and installation phase. There are obvious benefits in concentrating such complex organizational issues into one place, such as:

- Mutualisation of resources; in particular personnel and tools,
- Simplification of administrative/legal/regulatory issues; lesser authorities to confront,
- Cost reductions potential; minimization of transportation for procurement and mobilization, stronger negotiation process, etc.

For large offshore projects, the management team usually sets up a site office in/near the port area (or rent some offices nearby). From this office the daily operations are managed, operating from several ports would require additional offices and complicate coordination and logistics.

For all the above reasons, the installation module will select one unique base installation port in a two steps procedure:

- STEP 1 “minimum requirements”: verify that the port capabilities satisfy a set of minimum requirements that are:
    - o the availability of a suitable dry-dock for device assembly and loadout depending on the loadout strategy indicated by the end-user
    - o the presence of at least one terminal suitable to accommodate (in terms of quay area and quay bearing) one of the largest elements to be installed (the device or one of the elements of the electrical sub-systems or moorings/foundations)
- STEP 2 “nearest port selection”: the nearest port to the installation site, which meets the minimum requirements, is selected. For this step, the distance algorithm previously described determines the distances between all ports satisfying the minimum requirements and the first device appearing in the “layout” panda table generated by the hydrodynamic module (see Table 7-20). This would reduce the distances, and in turn, the voyage costs.

Alternatively, the end-user may opt for the option to prescribe the base installation base port himself/herself. In this case, either one of the ports available in the database is selected or a new one is fully characterized.

3.5 OUTPUTS OF THE INSTALLATION MODULE

In section 3.1, the outputs generated by the installation module were introduced. This section extends this description by providing an exhaustive list of the outputs. At the end of the installation module, the outputs generated by the logistic functions of all logistic phases that were under consideration are aggregated into a dictionary.

Assuming all upstream computational modules have successfully generated the outputs required to feed the installation module, no intervention from the user is required other than inputting the aforementioned four tables. The installation module terminates with the formatting of the outputs. Results obtained through the feasibility, scheduling, economic and environmental functions for all considered logistic phases convene in a predicted installation plan which contains

- The starting and ending dates & times of all sub-array components installation phases together with the estimated waiting time,
- The list of all logistic requirements associated with the logistic phase,
- The selected suitable combinations of port/vessel(s)/equipment associated with the logistic phase (list filtered and extracted from the maritime infrastructure database)
- The schedule assessment (including the total time T_{lp}) of each feasible logistic solution associated with the logistic phase. This comprises the duration of all elements forming T_{lp},
- The cost assessment (including the total cost C_{lp}) of each feasible logistic solution associated with the logistic phase. This comprises the cost of all elements forming C_{lp},
- The environmental impact assessment (including the final score of the five environmental functions concerned with the logistic functions) of each feasible logistic solution associated with the logistic phase

The parameters name, description, unit, format and some additional comments produced by each run of the logistic functions for a given logistic phase are compiled in Table 3-2.

Table 3-2 Dictionary output generated by the logistic functions for a given logistic phase

<table>
<tr><th>Logistic phase name</th><th>Output Field</th><th>Parameter</th><th>Unit</th><th>Format</th><th>Description</th></tr>
<tr><td rowspan="14"><u>LOGISTIC PHASE</u> (the different logistic phases names)</td><td rowspan="5">COST</td><td>Vessel Cost</td><td>[EUR]</td><td>float</td><td>Cost associated to the vessels (including fuel cost)</td></tr>
<tr><td>Equipment Cost</td><td>[EUR]</td><td>float</td><td>Cost associated to the equipments used</td></tr>
<tr><td>Port Cost</td><td>[EUR]</td><td>float</td><td>Estimation of the cost associated to port use</td></tr>
<tr><td>Fuel Cost</td><td>[EUR]</td><td>float</td><td>Fuel cost associated to the use of vessels</td></tr>
<tr><td>Total Cost</td><td>[EUR]</td><td>float</td><td>Total cost of the operation</td></tr>
<tr><td rowspan="5">TIME</td><td>Preparation Time</td><td>[h]</td><td>float</td><td>Time associated to the preparation</td></tr>
<tr><td>Waiting Ttime</td><td>[h]</td><td>float</td><td>Waiting time due to weather windows restrictions</td></tr>
<tr><td>Sea Transit Time</td><td>[h]</td><td>float</td><td>Time spent in transit at sea</td></tr>
<tr><td>Sea Operation Time</td><td>[h]</td><td>float</td><td>Time spent in operations at sea</td></tr>
<tr><td>Total Installation Time</td><td>[h]</td><td>float</td><td>Total time for accomplishment of the operation</td></tr>
<tr><td rowspan="3">DATE</td><td>Start Date</td><td>[dd-mm-yy]</td><td>date</td><td>Expected start time of operation</td></tr>
<tr><td>Depart Date</td><td>[dd-mm-yy]</td><td>date</td><td>Departing date from port to perform operation</td></tr>
<tr><td>End Date</td><td>[dd-mm-yy]</td><td>date</td><td>Final end date of the operation</td></tr>
<tr><td>VESSELS & EQUIPMENTS</td><td>Vessels number/type/ids</td><td>[-, -]</td><td>several</td><td>Listing of number and type of vessels and DB associated id</td></tr>
</table>

		Equipment number/type/ids	[-, -]	several	Listing of number and type of equipments and DB associated id
	LOGISTICS	Strategy Name	[-]	string	Description of the different strategies
		Number of Journeys	[-]	integer	Number of vessel journey to accomplish operation
		Elements per Journey	[-]	List integer	Number of elements carried in each journey
		Sea operations	[-, h, [m, s, m/s, m/s]]	Panda series dataframe	Description of operation at sea with duration and OLC
	SELECTION	Number Initial Solutions	[-]	integer	Number of initial solutions before selection stage
		Number Solutions after Feasibility & Requirements	[-]	Panda series dataframe	Number solutions after selection process + cargo/load/area requirements applied
		Number Solutions after Matching & Requirements	[-]	Panda series dataframe	Number solutions after selection process + cargo/load/area requirements applied

Ultimately, the installation module outputs consist of a dictionary containing as many dictionaries presented in Table 3-2 as they are logistic phases to be considered together with final dictionary dedicated to the Installation overall characteristics as presented next:

Table 3-3 Dictionary output generated by Installation module.

Output Field	Parameter	Unit	Format	Description
OPERATION	Logistic Phase Dictionary	[-]	several	Dictionary with the solutions of each logistic phase
COST	Total Vessel Cost	[EUR]	float	Total cost associated to vessels (includes fuel cost)
	Total Equipment Cost	[EUR]	float	Total cost associated to the equipments used
	Total Port Cost	[EUR]	float	Estimation of the total cost associated to port use
	Total Installation Cost	[EUR]	float	Total cost for the installation sequence
	Total Cost with Contingency	[EUR]	float	Total cost with for the installation sequence with contingency
	Yearly Cost	[yy, EUR]	several	Listing of the cost per year for LCOE calculation
TIME	Total Preparation time	[h]	float	Time associated to the preparation
	Total Waiting time	[h]	float	Waiting time due to weather windows restrictions
	Total Sea Transit time	[h]	float	Transit spent in transit at sea
	Total Sea Operation time	[h]	float	Total time spent at sea
	Total Installation time	[h]	float	Total time for accomplishment of installation sequence
DATE	Start Date	[dd-mm-yy]	date	Expected start time of installation sequence
	End Date	[dd-mm-yy]	date	Final end date of the installation sequence
	Comissioning Date	[dd-mm-yy]	date	Commissioning date for the array

PORT	Port Name & ID	[-, -]	several	Name and DB id of the port used in installation
	Port to Site Transit Distance	[km]	float	Distance between port and the site area
	Terminal Load Area Requirement	[m^2]	float	Port terminal load area requirement
	Terminal Load Bearing Requirement	[t/m^2]	float	Port terminal load bearing requirement
ENVIRONMENTAL	Number of Installation Vessels Used	[-]	integer	Number of vessels used in all operations
	Average Length of Installation Vessels	[m]	float	Mean length of the vessels used
PLANNING	List of Operations	[-]	List string	Listing of the operations sequence
WARNING	List of Warnings	[-]	List string	Listing of all the warning during simulation

3.6 NOTES ON THE O&M MODULE

While chapter 2 extensively described all logistic phases within the scope of the installation module, this section aims to highlight the role of the logistic functions within the O&M module and the similarities in the design process to characterize O&M operations. To-date, eight logistic functions Excel sheets have been developed in response to the scope of the DTOcean O&M module which can be found in [5].

In turn, all maintenance actions envisaged in the O&M module should fit the eight logistic phases characterized. Table 3-4 depicts the maintenance actions scope defined by the O&M module developers whilst Table 3-5 indicates the mapping of these maintenance actions to O&M logistic phases. This mapping was applied to limit the total number of O&M logistic functions. Each O&M logistic phase should differ sufficiently in terms of logistic requirements to justify the design of a dedicated logistic function.

Table 3-4 Failure mode type and maintenance action defining the scope of WP6 O&M DTOcean module

Failure mode type	Maintenance action ID	Maintenance action description
Failure mode type related to inspection	Insp1	Topside inspection of a floating item
	Insp2	Topside inspection of a surface piercing bottom fixed item
	Insp3	Underwater inspection near the water surface
	Insp4	Underwater inspection in deep water > 30m
	Insp5	Underwater inspection near the water surface (cleaning)
Failure mode type related to maintenance on site	MoS1	Topside maintenance of a floating item
	MoS2	Topside maintenance of a surface piercing bottom fixed item
	MoS3	Underwater maintenance near the water surface
	MoS4	Underwater maintenance in deep water > 30m
	MoS5	Replacement of mooring lines / chains
	MoS6	Maintenance of anchors
	MoS7	Maintenance of non-buried power cables
	MoS8	Maintenance of buried power cables

Failure mode type related to maintenance on port	RtP1	Retrieval from surface including lifting
	RtP2	Retrieval from bottom including lifting and subsea operations
	RtP3	Retrieval including towing
	RtP4	Retrieval from bottom including lifting, subsea operations and towing
	RtP5	Retrieval of mooring line
	RtP6	Retrieval of umbilical

Table 3-5 Mapping of maintenance actions defined by WP6 with O&M logistic phases designed by WP5.

O&M Logistic phase description	O&M logistic phase ID	Maintenance action ID
Use of rather small vessels to carry personnel, technicians and tools pertaining to the inspection or maintenance of topside elements (either floating or surface-piercing bottom fixed)	LpM1	Insp1
		Insp2
		MoS1
		MoS2
Underwater inspection or maintenance onsite at water depth<30 meter by means of divers	LpM2	Insp3
		MoS3
Underwater inspection or maintenance onsite by means of ROVs	LpM3	Insp4
		Insp5
		MoS4
Onsite maintenance on the mooring system	LpM4	MoS5
		MoS6
On-site maintenance on static power cables (export and inter-array cables)	LpM5	MoS7
		MoS8
Retrieval of devices or array sub-component from site to shore for repair at port with on-deck transportation	LpM6	RtP1
		RtP2
Retrieval of devices or array sub-component from site to shore for repair at port with towing transportation	LpM7	RtP3
		RtP4
Retrieval of mooring line or umbilical	LpM8	RtP5
		RtP6

As for the installation module logistic phase in [4], equivalent spreadsheets were developed in [5] where details on the following aspects are provided:

- List of inputs to the logistic functions
- Operation sequencing
- Vessel & equipment combinations
- Feasibility functions
- Compatibility check
- Performance functions

The standard list of inputs required from WP6 to run the O&M logistic functions is provided in Table 3-6. These 25 input parameters should feed the logistic functions in the form of a panda DataFrame table entitled “om”. The content of this table will vary depending on the nature of the maintenance intervention requested.

Table 3-6 List of inputs to the logistic functions for use in the DTOcean O&M module

Input number	Parameter description	Python name	Unit	Format	Additional comment

0	Maintenance action or Failure Mode Type as defined per WP6	ID	[-]	string	Maintenance action types list: Insp1; Insp2; Insp3; Insp4; MoS1; MoS2; MoS3; MoS4; MoS5; MoS6; MoS7; MoS8; RtP1; RtP2; RtP3; RtP4;
1	Element type	element_type	[-]	string	Element type list includes all array sub-component: device; mooring line; foundation; static power cable; umbilical; collection point
2	Element subtype	element_subtype	[-]	string	Element sub-type. For the device, it corresponds to one of the four sub-systems of the device, i.e: hydrodynamic; pto; control; support structure. For the other element types, it should follow WP3 & WP4 BoM and naming conventions for their types in their respective modules.
3	Element ID number	element_ID	[-]	string	ID number of the element under consideration should match with those defined in WP1, WP2, WP3 & WP4
4	Water depth at the O&M intervention location	depth	[m]	float	Diving operations are limited to 30 meters water depth. Zero should be indicated for surface/topside element O&M interventions
5	Element position	Element x coord	[m]	float	Position of the element to be replaced, repaired or inspected in the UTM grid coordinate system
6		Element y coord	[m]	float	
7		Element zone	[-]	integer	
8	Requested starting time for the O&M action	t_start	[DD/MM/YYYY at HH:MM:SS]	date	Corresponds to the exact date and time at which the O&M intervention is requested
9	Predicted duration of the accessibility to the element to be maintained	d_acc	[h]	float	Corresponds to the time necessary to access the component or sub-system to be repaired, replaced, inspected
10	Predicted duration of the maintenance action	d_om	[h]	float	Corresponds to the time necessary to perform the maintenance action (repair, replacement or inspection)
11	Presence of a helideck for helicopter landing operations	helideck	[-]	boolean	To check the suitability of using a helicopter to carry out the O&M action
12	Operational limit conditions during the accessibility operation	Hs_acc	[m]	float	These parameters are used for the weather window calculation
13		Tp_acc	[s]	float	
14		Ws_acc	[m/s]	float	
15		Cs_Acc	[m/s]	float	
16	Operational limit conditions during the maintenance action	Hs_om	[m]	float	These parameters are used for the weather window calculation
17		Tp_om	[s]	float	
18		Ws_om	[m/s]	float	
19		Cs_om	[m/s]	float	
20	Number of technicians	technician	[-]	integer	Total number of persons to be transported in addition to the crew members
21	Dry mass of the spare parts	sp_dry_mass	[m]	float	Cumulated dry mass of all required spare parts
22		sp_length	[m]	float	

23	Dimensions of the spare parts	sp_width	[m]	float	Cumulated dimensions of all required spare parts (with optimized packing density)
24		sp_height	[kg]	float	

The working mechanism of the logistic functions is perfectly identical for both the installation and O&M computational modules. The only difference on how simulations of logistic activities are treated between the installation and O&M modules resides in the port selection. As it was explained in section 3.4, only one single installation base port is chosen in a two-stage selection process.

Regarding the continuous O&M activities over the lifetime of an ocean energy project, a similar procedure will be carried out while trying to reflect that the proximity of the port becomes a prevalent factor. In fact, if the nearest large port infrastructure is located relatively far away from the site, it seems strategically better to find a nearby capable of managing at least most minor repairs and inspections. In such a scenario, major repair campaigns requiring larger specialized vessels may be considered as small stand-alone projects by themselves which can use the same base port as during the installation phase.

Consequently, the O&M ports selection procedure proposed is:

- STEP 1 “minimum requirements”: verify that the port has at least one terminal suitable to accommodate (in terms of quay area and quay bearing) one of the largest parts to be used for on-site maintenance operations.
- STEP 2 “nearest port selection”: the nearest port to the installation site conforming with the minimum requirements is selected.
- STEP 3 “overall nearest port”: the overall nearest port to the installation site is also selected from the database. If it differs from the nearest port satisfying the minimum requirement of STEP 1, this port will be considered for all on-site maintenance interventions which do not require the transportation of any port, i.e the first three logistic phases for maintenance corresponding to the first three rows in Table 3-5.

4 PRELIMINARY TESTING AND VERIFICATION OF THE LOGISTIC MODEL FOR OCEAN ENERGY ARRAYS

4.1 SCOPE OF THE VALIDATION EXERCISE

As part of the verification and validation process in the development of the installation module of the DTOcean suite of design tools, it was vital to undertake a comparison exercise of the outputs of the installation module against current assumptions of an experienced marine contractor.

For this section, the installation module is validated separately from the upstream modules of the DTOcean tool. Hence, Deme Blue Energy NV's (DBE) high level assumptions for a Fair Head project scenario, have been simplified to inputs to the installation module, which cover both user expected inputs (e.g. site, met-ocean and device data), and inputs typically generated by upstream modules of the installation module (e.g. number and position of the devices, electrical infrastructure and foundation design).

The generation outputs of the installation module are compared to the current high level estimations of DBE for a development scenario of the Fair Head site, since it is part of their development portfolio. Furthermore, comparisons were made with the general experience of GeoSea and Tideway in offshore wind installation as well as the current assumptions for tidal array installation and commissioning. It should be noted in the DBE assessment, risk contingencies have not been included because the installation module does not consider contingencies in this first release version.

Although still in its infancy, the tidal energy sector is considered more mature than wave energy sector which is still in earlier development stages. However, due to the strong synergies between the offshore wind industry and the MRE sector, this section will focus on offshore wind experience transferrable to tidal devices and sites. It should be borne in mind, however, that enabling technologies for fixed TECs are comparable to tidal stream floating devices, which are in turn comparable to those for WECs, and therefore may be also transferrable. Therefore, with a high level feasibility assessment in mind the assumptions in the validation of TEC devices can be applicable for WEC. Detailed engineering would be required a later stage for more accurate costs.

Bearing in mind MeyGen Phase 1A (6MW) will be the first tidal array (4 devices) installed in the world and, ambitiously, foreseen in one campaign (planned to be completed by end 2016), there are still many uncertainties and scope for optimization. High level feasibility assessments of a MRE project need to consider a large degree of contingency. As the tidal energy, and later wave energy, sectors progress to a commercial scale, deployment and O&M issues will be greater understood and these uncertainties are foreseen to be reduced significantly (e.g. increased weather windows, quicker installation, etc.). The DTOcean global tool (and the installation module) essentially aims to provide valuable support in the first feasibility gate decision with the view for more detailed engineering to be undertaken as a development project moves forward toward the final investment decision.

Considering the early stage design of both tidal and wave sectors, which reflects on the number of high level assumptions required to design such a tool, an "acceptable" level of uncertainty (variation in time and cost estimates) is to be in the same order of magnitude (less than a factor 10).

4.2 PROJECT SCENARIO CONSIDERED FOR FAIRHEAD

One option considered for the 10MW Fair Head tidal development is as follows:

- 10 x fixed seabed mounted turbines - AHH HS1000, with monopile foundation.
- 10 x pile foundations – 3m diameter x 10 metres depth
- 1 x marshalling tower (surface piercing), also monopile.
- 10 x 500m inter-array cables (11kv), with steel case cable protection system (CPS).
- 1 x 2000m export cable (33kv), also with steel case cable protection system (CPS).
- Sea bed type: hard rock.
- Installation scenario starting date: 01/06/2020

Note that this is an validation exercise of the installation module (not the DTOcean tool), hence, the above project description does not correspond to results of upstream DTOcean modules but to the current high level assumptions of DBE for the Fair Head site.

Figure 4-1 – Fair Head site location.

In the context of the global DTOcean tool, the upstream hydrodynamic module would position the ocean energy converters in the Agreement for Lease (AfL) area, and all downstream modules, including the installation module shall consider the coordinates determined. Since this validation scenario considers the installation module separately, the position was defined such that each device is distanced 500m from each other, matching the assumed length of the inter-array cables.

Table 4-2 - Indication of the different logistic phases specifically covered in the Fair Head validation scenario:

Logistic Phase	**Validation Fair Head Scenario**
Installation of wave energy devices	*no*
Installation of tidal energy devices	***Yes***
Installation of gravity based structures	*no*
Installation of pile foundation (driven/drilled)	***Yes***
Installation of mooring systems)	*no*
Installation of static export power cables	***Yes***
Installation of static inter-array power cables	***Yes***

Installation of dynamic power cables	*no*
Installation of offshore collection points	***Yes***
Installation of external cable protection	***Yes***
Installation of support structure	***Yes***

4.3 ANALYSIS AND RESULTS

This chapter includes the main output results from the installation module against DBE high level estimations for the installation activities. These mostly include time and cost comparisons together with an analysis of possible deviations between results.

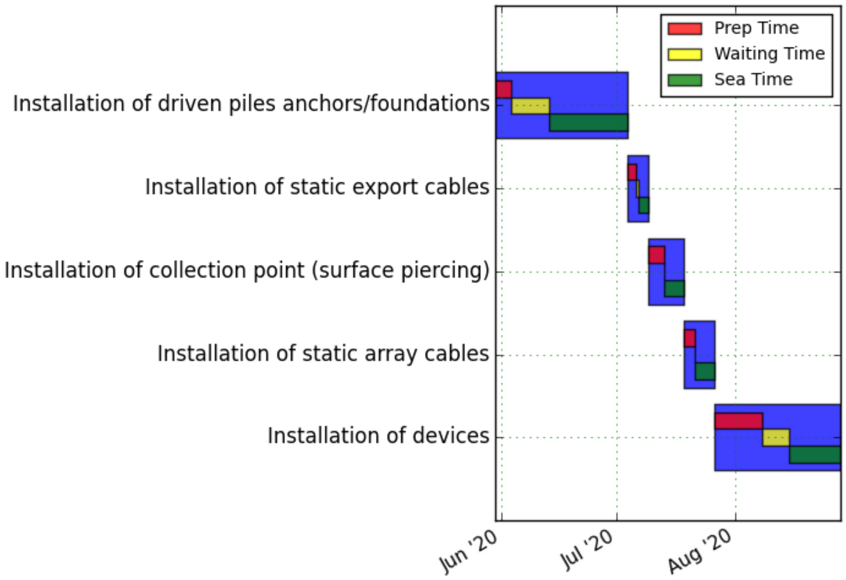


Figure 4-3 – Installation module output: GANTT Chart considering all installation logistic phases

Figure 4-3 shows a GANTT chart of the logistic phases, as computed by the installation module. The installation activities are conducted during a period close to 3 months, with the installation of driven piles together with the installation devices being the most time consuming. The following sub-chapters include detail results and analysis of each of these phases.

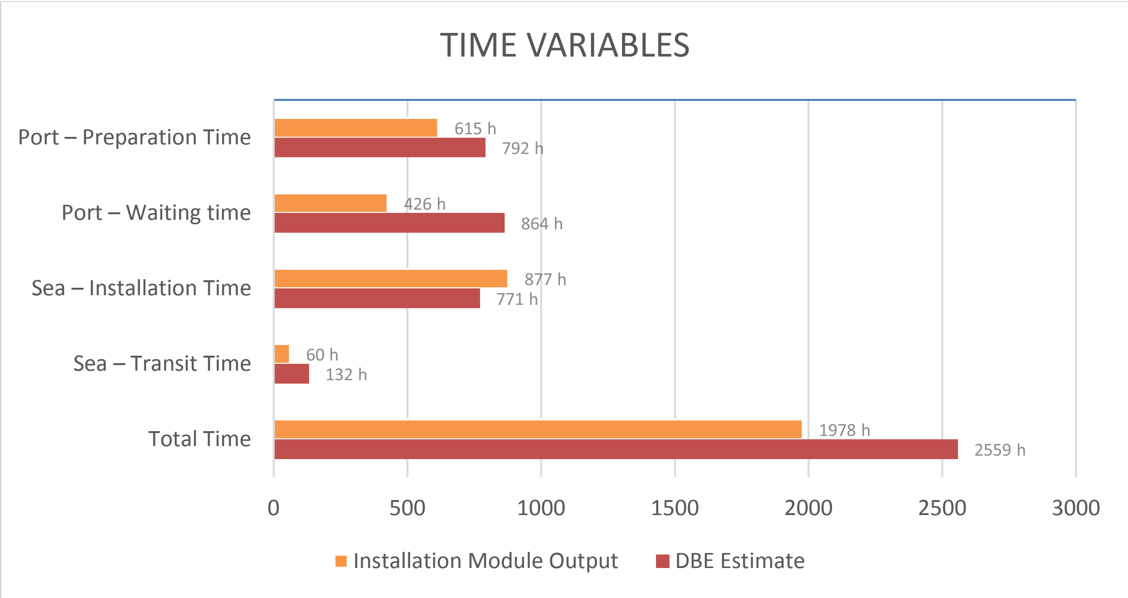


Figure 4-4- Installation time comparison between the module and DBE high level estimates

Figure 4-4 shows the overall time consumed of the main activities throughout all logistic phases:

- Port – Preparation Time include all preparation activities conducted at port such as loading elements onto the vessel, sea fastening and survey checks;
- Port – Waiting Time is the hold interval between preparation time and a suitable weather window to conduct the installation activities. Depends on the met-ocean conditions of the site.
- Sea – Installation Time include all sea operations dedicated to the installation of the project elements, such as cable laying, pile drilling or device connection.
- Sea – Transit time is the time spent in transit between port and installation sites, plus the intra-site travels between the different elements positions.

As it is possible to observe, the time results of the installation module closely match DBE estimations. The major absolute deviation is on the waiting time, which is mostly due to the different approaches employed by the installation module and DBE has it is further explained.

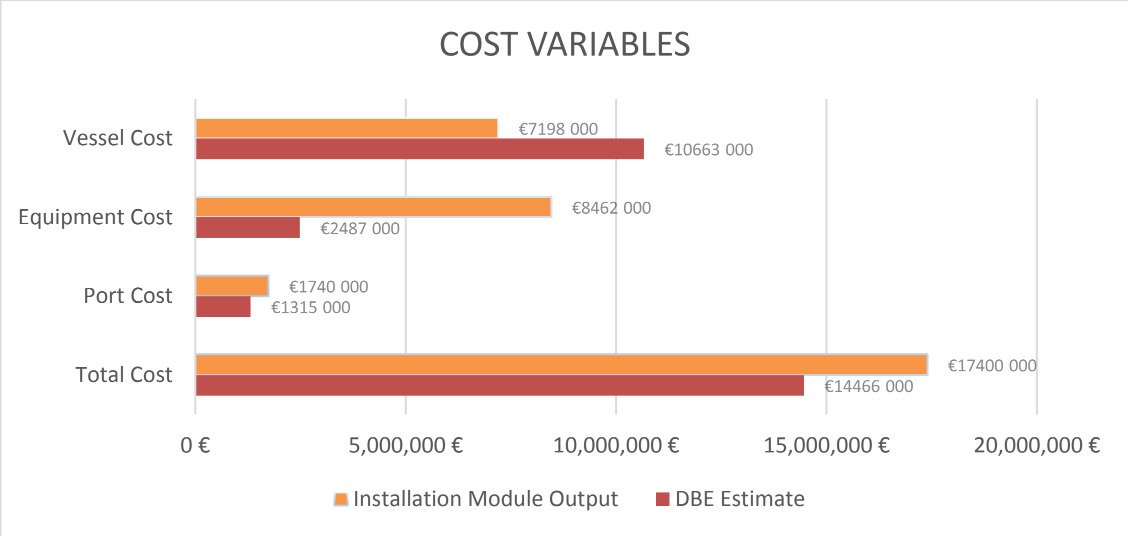


Figure 4-5 – Installation cost comparison between the module and DBE high level estimates

It should be noted in the DBE assessment, risk contingencies have not been included since this was not considered for the validation exercise by the installation module. For example, bearing in mind the infancy the tidal sector and the challenging environment it would be realistic to include multiple attempts to install turbines (depending on sites, TEC/TSS specifications and required accuracies) or missed weather windows (e.g. a delay in provision of equipment). Furthermore, these costs do not include mobilisation/demobilisation, engineering, project investments (e.g. seafastening, installation frame, etc.) and consumables. Furthermore, P&M costs for the foundations are not included. All such considerations need to be included overall for the project.

4.3.1 INSTALLATION OF PILE FOUNDATIONS

The pile foundations specified for this scenario consider a diameter of 3 m and a total installation depth of 10 m in the seabed (assumed to be homogenously hard rock). The assumption is a total of 10 piles to be installed, plus one more for the surface piercing substation. These inputs would be generated by the moorings and foundations' module in the full suite of DTOcean. The following tables summarise the outputs of the tool and the DBE assumptions for a like for like comparison.

Table 4-1 - Vessel and Equipment solution for conducting the installation the pile foundations

Optimal V&E Solution	**Installation Module Output**		**DBE Estimate**	
	Quantity x Type [DB id]	**Cost**	**Quantity x Type**	**Cost**
Installation Vessel	1 x Jack-Up Barge [38]	75.000€/day	1 x Jack-Up Vessel	100.000€/day
Support Vessel	1 x Tugboat [29]	1.500€/day	-	-

Installation Equipment	1 x Drilling Rig [2]	10.000€/day	1 x Drilling Rig 1 x Grouting Equipment	10.000€/day 13.000€/day
Support Equipment	1 x Inspection ROV [2]	5.700€/day	-	-

The selection process of the optimal V&E solution is based on a combination of feasibility functions involving specific vessel characteristics (e.g. deck area, deck cargo or crane capacity), matching the requirements of the elements to be installed, followed by a performance assessment of all feasible solutions. As shown in Table 4-1, the installation vessel selected by the module closely matches DBE's estimation, with both considering Jack-up types with similar day-rates. In regard to the Installation equipment side, drill rigs were the option for both the installation module and DBE, having exactly the same day-rate. Currently, grouting equipment is not included as part of the equipment database of the installation, although grouting operation is considered when computing the installation time. The DBE vessel day rate is based on the maximum cost of the supporting vessel database in order to provide sufficient contingency for a high level project feasibility assessment.

Table 4-2 - Other relevant outputs

Other	**Installation Module Output**	**DBE Estimate**
Number of Journeys (port-site-port)	1	1
Soil Penetration Technique	Drilling	Drilling
Soil Penetration Rate	0,25 m/hr	0,5 m/hr

Other relevant outputs are shown in Table 4-2. The expected number of journeys to install the full set of piles is the same for the module and DBE estimations. The same soil penetration technique is also selected. For making this decision, the installation module first identifies all suitable techniques based on the soil types to be experienced at site. From this shortlist of feasible pile driving techniques, the optimal technique is selected through a performance assessment of time and cost. The only deviation shown in Table 4-2 is with the soil penetration rate, with the DBE estimate 100% greater than the module estimation. This was because DBE included a conservative estimate (after a detailed engineering, precise location and tolerance, geotechnical data for micro site including vertical layering, and pile dimensioning would be known allowing the determination of a significantly more accurate figure). This deviation in drill rate will have a significant impact on the time variables since it largely impacts the installation time. However, it should be borne in mind that this is a default value, which should be available for the user to update through the GUI of the global DTOcean tool, as specified in the user manual.

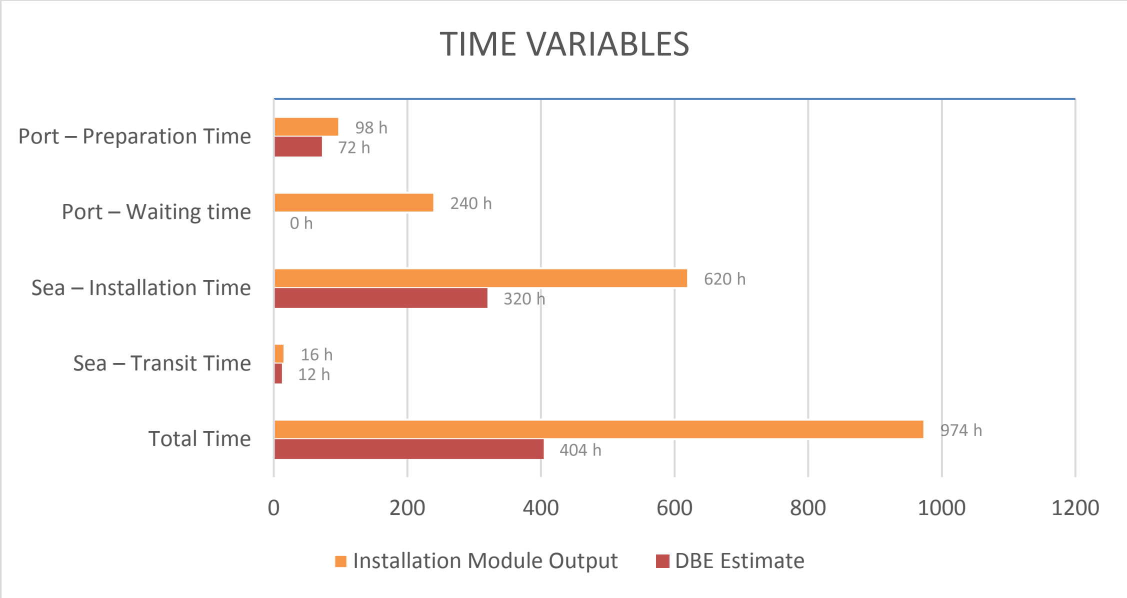


Figure 4-6- Installation of Piles time comparison between the module against DBE high level estimates

It should be noted that the assessment does not consider contingencies (in addition to Weather DownTime).

Regarding time variables shown in Figure 4-6, as expected, the larger absolute deviation is observed on the installation time, however waiting time shows a greater relative deviation. Comments on each variable results are found below:

- To compute the <u>port - preparation time</u>, the installation module sums the mobilization time (defined in the Vessel DB = 48h), with the loading time per pile onto the vessel (default value inside the module = 4h per pile). DBE did not assume a mobilization time since this will entirely depend on installation solution, site location, availability and ultimately is not deemed by them to be required for an initial high level feasibility assessment. Considering that DBE estimations don't include mobilization time, the module output is in-line with the estimations.
- To compute the <u>port - waiting time</u>, the installation module uses a weather windows function that has substantial differences from the approach used by DBE for this exercise since their high level estimation included indicative WDT per component since exact timings would need to be determined following detailed engineering, planning and time of year.
- To compute the <u>sea - installation time</u>, the installation module sums the following operation sequence, per pile: vessel and equipment positioning (default value = 6h), drive through seabed using drilling rig on hard-rock (10m x default rate = 0,25m/h), grouting time (default value = 1h, to updated by user when more information known). The primary driver of the deviation between the installation module and DBE estimates is the penetration rate.
- To compute the <u>sea - transit time</u>, the installation module depends on the vessel transit speed and overall port-site distance, and distance between devices. The transit speed is extracted from the vessel DB and the distances are computed with an algorithm inside the module. The

fact that the value from the installation module matches closely the estimation means that both the selected port and transit speed are adequate.

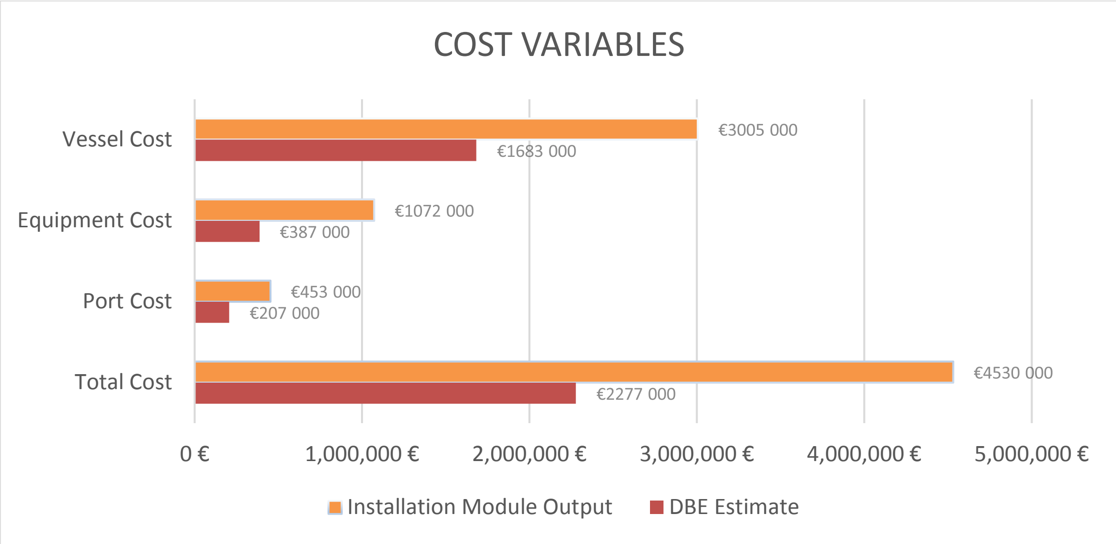


Figure 4-7 – Installation of Piles cost comparison between the module and DBE high level estimates

The overall costs are shown in Figure 4-7, considering that the day-rates of the vessels and equipment's closely matched (see Table 4-), the deviation in costs is justified by the time differences observed in Figure 4-9.

4.3.2 *INSTALLATION OF DEVICES*

The device specified for this scenario is a fixed seabed mounted tidal turbine (AHH HS1000). The device characteristics are direct user inputs to the installation module, however these cannot be disclosed on this report due to data confidentiality (these inputs include: device dimensions, total mass, installation time and operation limit conditions during installation). Apart from the user inputs required, the position of the devices would be generated by the hydrodynamic module in the full suite of DTOcean. For this scenario, the position was defined such that each device is distanced 500m from each other. The following tables show the tool results against DBE high level estimations.

Table 4-3- - Vessel and Equipment solution for conducting the installation of the devices

Optimal V&E Solution	Installation Module Output		DBE Estimate	
	Quantity x Type [DB id]	Cost	Quantity x Type	Cost
Installation Vessel	1 x Crane Vessel [41]	50.000€/day	1 x Jack-Up Vessel	100.000€/day
Support Vessel	2 x Multicat [55]	3.400€/day	-	-
Installation Equipment	-	-	-	-
Support Equipment	1 x Inspection ROV [2]	5.700€/day	-	-

Looking to Table 4-3, the optimal solution found by the module uses a DP Crane Vessel as against the Jack-Up type included by DBE in their current assumptions. It was confirmed with DBE that DP Vessels are suitable for these operations as long as they match the requirements with regards to sufficient DP capability, which is the case of the selected vessel. A cost-benefit analysis exercise would need to be undertaken. Regarding costs, the DP crane vessel's day rate is half of the one considered by DBE high level assessment which, although significant, is acceptable considering the uncertainty of such values, and that ultimately depends on user inputs. The DBE vessel day rate is based on the maximum cost of the supporting vessel database in order to provide sufficient contingency for a high level project feasibility assessment. Regarding the support vessels and equipment, DBE's high level estimations didn't specify requirement on logistic phases since the view was taken that due to the relatively lower costs of support vessels this would be covered by the stance of selecting the maximum rate from the database providing sufficient contingency. Research conducted during the development of the installation module, indicated that certain support vessels and equipment's were commonly used on these operations, and were therefore included. It is foreseen that the exact requirements would be identified during the detailed engineering phase.

Table 4-4- - Other relevant outputs

Other	**Installation Module Output**	**DBE Estimate**
Number of Journeys (port-site-port)	2	7

The number of site to load-out port journeys is shown in Table 4-4. The installation module solution suggests 2 journeys, against DBE's high level estimation of 7. The way the installation module computes this value is explained in detail before, but to justify the deviation, a succinct description of the process is done in this paragraph:

1. Initially, the installation module computes a range of feasible solutions (one feasible solution includes an installation vessel capable to carry, at least, one element);
2. Each solution is then associated with a specific number of journeys, depending on the number of elements that fit on each vessel with regards to area and cargo (note that this applies only in the case of deck transportation. For towing, only one device at a time is installed per vessel journey by default);
3. Finally, all solutions go through a performance assessment process, which computes the time and cost of the operations. After the performance assessment, an optimization routine selects the least costly solution.

For the installation vessel selected by the module (with database ID = 42, as shown in Table 4-3,), one can find the deck area available to be of 2.900 m^2, meaning that 2 journeys have a total of 5.800 m^2 of space available for the 10 devices to be installed. Considering the device characteristics, this seems realistic. The deviation between the module output and DBE estimate can be explained by different deck characteristics and conservative approach usually taken by the project developer at this early stage of development. Detailed engineering would determine the exact methodology, planning and number of vessel journeys based on a deck arrangement optimization according to safety standards.

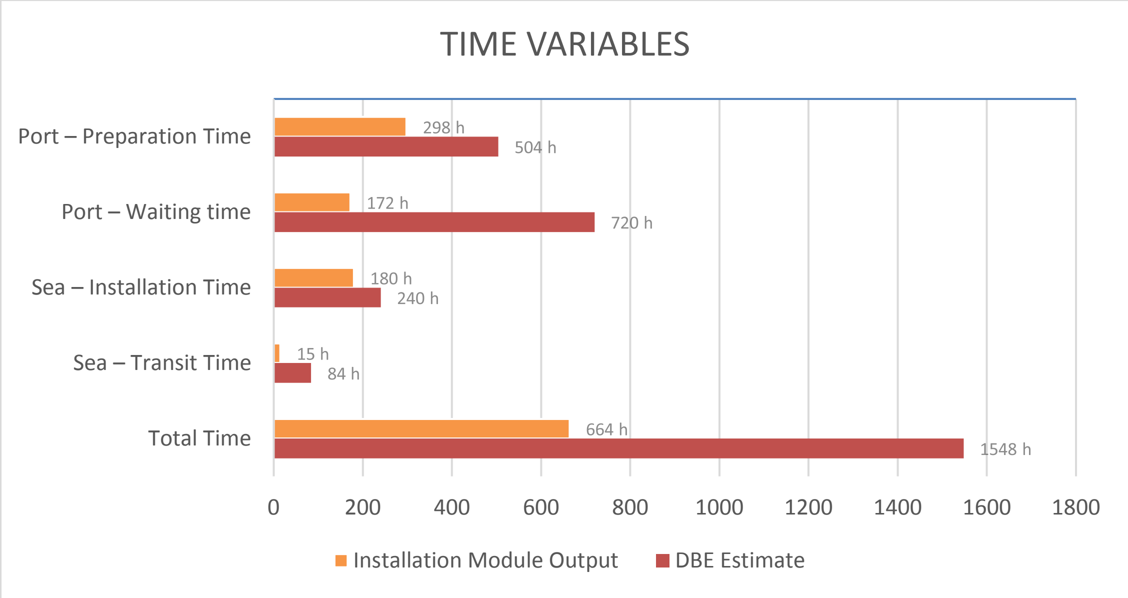


Figure 4-8 - Installation of devices time comparison between the module against DBE high level estimates

Regarding time variables shown in Figure 4-8Figure , one major deviation is observed on the waiting time, the remaining variables are within the same order of magnitude of the estimations. Comments on each variable are found below:

- To compute the port - preparation time, the installation module sums the mobilization time (defined in the Vessel DB), with the loading time per device onto the vessel (defined directly by the user). The module output is comparative to the DBE high level assessment since the difference is purely attributable to the view of DBE to include a 3 day period for loading to provide sufficient time for seafastening, survey checks, etc. at this stage of feasibility assessment.
- To compute the port - waiting time, the installation module uses a weather windows function that has substantial differences from the approach used by DBE for the scenario estimation. More insights on these differences can be found before, which helps to justify the deviation in the results. These, although significant (close to 100%), are within the accepted level of uncertainty defined in the scope, bearing in mind this is intended to be a high level estimation tool.
- To compute the sea - installation time, the installation module sums the following operation sequence per device: vessel positioning time (default value) plus lowering and connecting the device and support structure (specified by the user). These are found to be within the range expected by the estimations. However, it should be noted this assessment does not include contingencies for multiple attempts since this tool facility is not available, at present. At this stage of MRE development DBE advised this should be a consideration to attempt to quantify all risks.
- To compute the sea - transit time, the installation module depends on the vessel transit speed and overall port-site distance, and distance between devices. The transit speed is extracted from the vessel DB and the distances are computed with an algorithm inside the module. The

main reason explaining the deviation between the output and estimation result, is the number of journeys. The values are significantly different (see Table 4-4), this increases the number of travels between port and site from 4 on the module to 14 on the estimate, consequently increasing the total transit time.

The total time deviation is mostly due to the waiting time deviation previously explained.

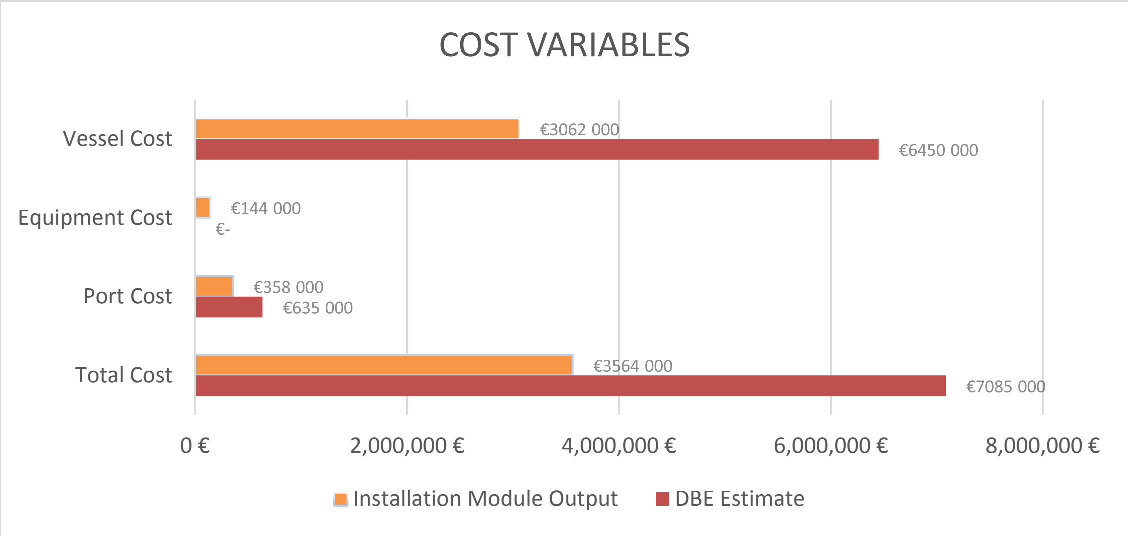


Figure 4-9 - Installation of devices cost comparison between the module against DBE high level estimates

Despite some significant deviations in V&E solution and time of operations, the overall cost comparison in Figure 4-9 show very close numbers. The lower day-rates of the solution found by the module (see Table 4-3), resulted in increased time of operations, mainly due to waiting time (seeFigure 4-8). This combination resulted in a deviation of only 24% in the total cost, which is not only within the same order of magnitude, but considering the uncertainties is deemed acceptable.

4.3.3 INSTALLATION OF EXPORT CABLES

The export cable specified for this scenario has a total length of 2.000 metres, and due to the hard rock seabed type, the inherent energetic nature of a tidal site and overall reliability, it was defined to be entirely protected using external casing shells. For the remaining inputs required by the tool (e.g. dry mass, cable diameter, minimum bending radius, etc.), common values were extracted from DTOcean database. Bearing in mind all these inputs would be generated by the electrical module, if the full suite of DTOcean modules was called. The following tables show the tool results against DBE high level estimations.

Table 4-5 - Vessel and Equipment solution for conducting the installation the export cable

Optimal V&E Solution	Installation Module Output		DBE Estimate	
	Quantity x Type [DB id]	Cost	Quantity x Type	Cost

Installation Vessel	1 x Cable Laying Vessel [9]	75.000€/day	1 x Cable Laying Vessel	80.000€/day
Support Vessel	2 x Multicat [55]	3.400€/day	-	-
Installation Equipment	3713 x Split Pipes [1]	445€/unit	2000 x Iron Casing	300€/unit
Support Equipment	1 x Inspection ROV [2]	5.700€/day	-	-

As shown in Table 4-5, the vessel solution computed by the tool is closely matching DBE's estimation, both on vessel types and overall day-rates. On the Equipment side, the number of cable protection units has a significant deviation. This is mainly due to the unit section length. On the equipment database, the tool finds split pipes with a unit length of 0.4 metres, while DBE assumed each unit to have 1 metre. It should be noted the tool offers the possibility to add user specified equipment and costs to the database.

There's also a significant deviation of 48.3% on the unit cost which can be explained by the nature of the source of information:

- The installation module cost assumptions are based on unitary values obtained through direct contact with a manufacturer and;
- While DBE has assumed special rates through the volume orders via DEME.

However, ultimately such equipment unit rates will need to be determined by the user since it will depend on site location. These can be after included in the Equipment database through the GUI.

Table 4-6 - Other relevant outputs

Other	**Installation Module Output**	**DBE Estimate**
Number of Journeys (port-site-port)	1	1
Cable Loading Rate (onto vessel turntable)	450 m/hr	-
Cable Laying Rate (with split pipes)	300 m/hr	300 m/hr

Other relevant outputs are shown in Table 4-6. As expected the installation module outputs one journey to install the export cable, which is the common procedure for single export cables and particular when such a relatively small distance. Also the cable laying rate is similar to DBE's high level estimations. Bear in mind that default values such as loading and laying rates are indicative and are available for the user to update through the GUI, as specified in the user manuals.

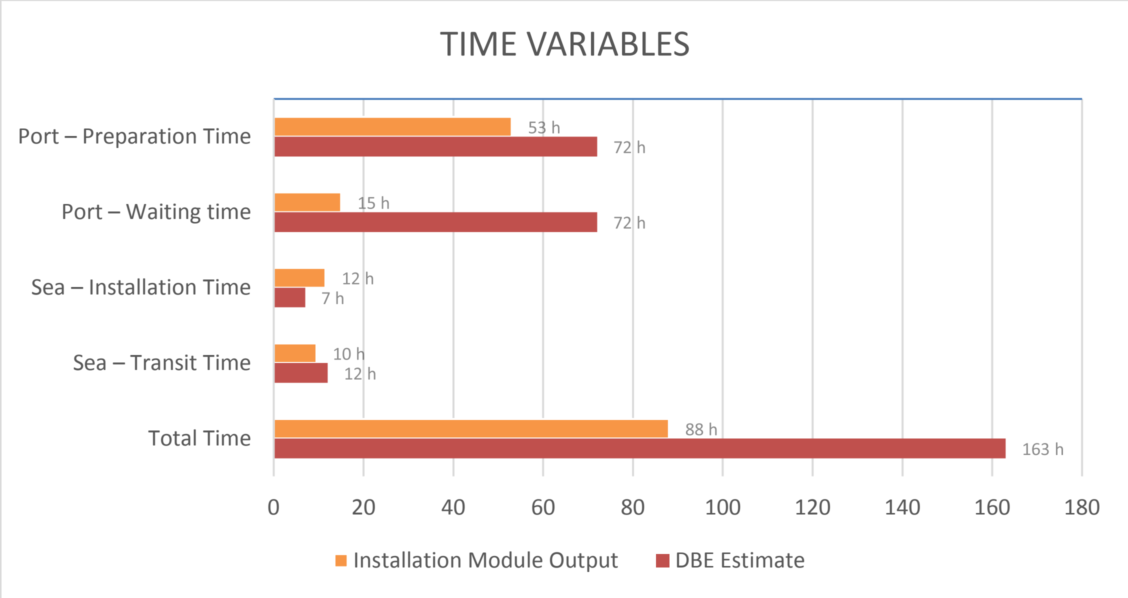


Figure 4-10 - Installation of static cables: time comparison between the module and DBE high level estimates

Regarding time variables shown in Figure 4-10, one major deviation is observed on the waiting time. The remaining variables are within the same order of magnitude of the estimations. Comments on each variable are found below:

- To compute the port - preparation time, the installation module sums the mobilization time defined in the Vessel DB with the loading time of the cable onto the vessel (default value inside the module). The assumptions are comparable with the high level estimations from DBE. DBE did not assume a mobilization time since this will entirely depend on site location, availability and ultimately is not deemed by them to be required for an initial high level feasibility assessment.
- To compute the port - waiting time, the installation module uses a weather windows function that has substantial differences from the approach used by DBE for the estimation. DBE's high level estimation included indicative WDT per component since exact timings would need to be determined following detailed engineering, planning and time of year.
- To compute the sea - installation time, the installation module sums the following operation sequence: landing time, laying time and connection time the offshore substation/marshalling tower (default values inside the module). These are within the range expected by the estimations.
- The sea - transit time depends on the vessel transit speed and overall distance between port and site. The installation module extracts the first from the vessel DB and the second from the distance to the selected port. The fact that the value from the installation module matches closely the estimation means that both the selected port and transit speed are adequate.

The total time deviation is primarily due to the waiting time deviation previously explained.

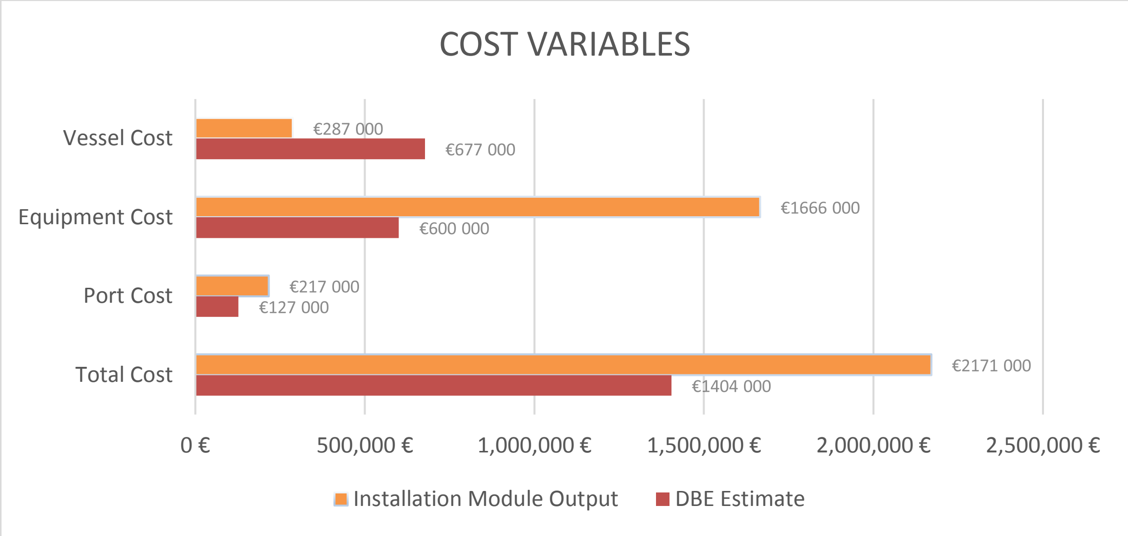


Figure 4-11 - Installation of static cables: cost comparison between the module and DBE high level estimates

The overall costs shown in Figure 4-11 are within the range expected. Considering that the day-rates of the vessels matched (see Table 4-5), the deviation in vessel costs is justified by the time differences observed in Figure 4-10. The equipment costs however, present the most significant deviation. This can be explained by the difference in number of units and unitary cost of the cable protection elements.

4.3.4 INSTALLATION OF INTER-ARRAY CABLES

The inter-array cable specified for this scenario has a total length of 5000 metres, and due to the hard rock seabed type, it was defined to be entirely protected using external casings as a high level assumption at this feasibility stage for an inherently dynamic site- detailed engineering including cable management and laying assessment would determine the exact requirements. Similarly, to the Export Cable logistic phase, for the remaining inputs required by the installation module (e.g. dry mass, cable diameter, minimum bending radius, etc.), common values were extracted from the DTOcean database. The following tables show the tool results against DBE estimations.

Table 4-7 - Vessel and Equipment solution for conducting the installation the interarray cable

V&E Solution	Installation Module Output		DBE Estimate	
	Quantity x Type [DB id]	**Cost**	**Quantity x Type**	**Cost**
Installation Vessel	1 x Cable Laying Vessel [9]	75.000€/day	1 x Cable Laying Vessel	80.000€/day
Support Vessel	2 x Multicat [55]	3.400€/day	-	-
Installation Equipment	12460 x Split Pipes [1]	445€/unit	5000 x Iron Casing	300€/unit
Support Equipment	1 x Inspection ROV [2]	5.700€/day	-	-

As shown in Figure 4-7, the vessel solution computed by the tool closely matches the DBE estimation, both on vessel types and overall day-rates. On the Equipment side, similarly to the export cable logistic phase, the number of cable protection units has a significant deviation. As previously discussed in section 4.3.4, this is mainly due to the section unit 'length'. On the equipment database, the tool finds split pipes with a unit length of 0.4 metres, while DBE assumed each unit to be 1 metre.

There's also a significant deviation of 48.3% on the unit cost. Which can be justified, since our costs are unitary values obtained through direct contact with a manufacturer, while DBE has assumed special rates through the volume of orders via DEME. However, ultimately such equipment unit rates will need to be determined by the user since it will depend on site location and availability. These can be after included in the Equipment database through the GUI.

Table 4-8 - Other relevant outputs

Other	Model Output	DBE Estimate
Number of Journeys (port-site-port)	1	1
Cable Loading Rate (onto vessel turntable)	450 m/hr	-
Cable Laying Rate (with split pipes)	300 m/hr	300 m/hr

Other relevant outputs are shown in Figure 4-8. The installation module outputs one journey to install all array cables, which matches DBE estimation. Also the cable laying rate is similar to DBE's high level estimations. Bear in mind that these default values are indicative and are available for the user to update through the GUI, as specified in the user manuals.

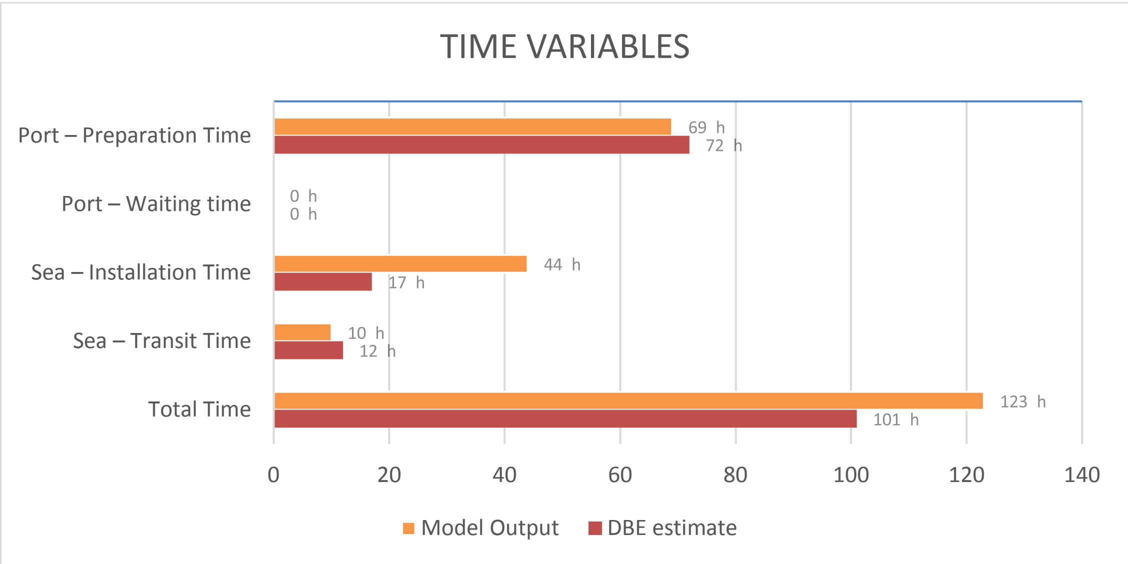


Figure 4-12- - Installation of array cables: time comparison between the module and DBE high level estimates

Regarding time variables shown in Figure 4-12, overall the values from the module are comparable to DBE estimations. The major deviation is observed on the installation time. Comments on each variable are found below:

- To compute the port - preparation time, the installation module sums the mobilization time defined in the Vessel DB with the loading time of the cable onto the vessel (default value inside the module). The assumptions are comparable with the high level estimations from DBE. DBE did not assume a mobilization time since this will entirely depend on site location, availability and ultimately is not deemed by them to be required for an initial high level feasibility assessment.
- To compute the port - waiting time, the installation module uses a weather windows function that has substantial differences from the approach used by DBE for the estimation. DBE's high level estimation included indicative WDT per component since exact timings would need to be determined following detailed engineering, planning and time of year.
- To compute the sea - installation time, the installation module sums the following operation sequence: cable upstream connection, cable laying and cable downstream connection (default values inside the module). The deviation observed is due to the module high level considerations of cable connection times, which was not included in DBE estimations. Detailed engineering would determine the exact methodology and time required to perform these connections.
- The sea - transit time depends on the vessel transit speed and overall distance between port and site. The installation module extracts the first from the vessel DB and the second from the distance to the selected port. The fact that the value from the installation module matches closely the estimation means that both the selected port and transit speed are adequate.

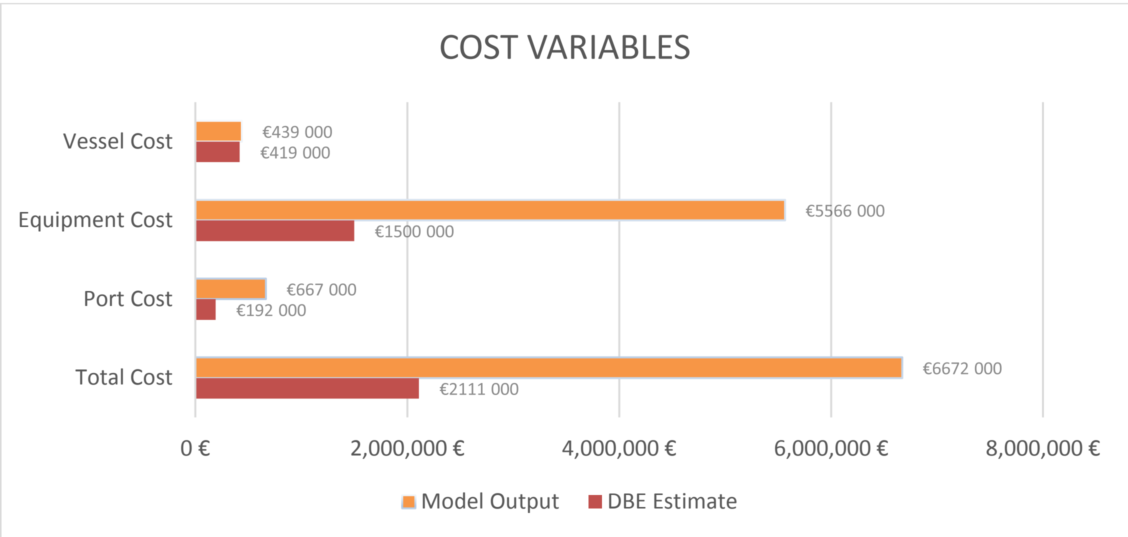


Figure 4-13 - - Installation of array cables: time comparison between the module and DBE high level estimates

The vessel costs shown in Figure 4-13 are closely matching DBE estimations. On the other side, the equipment costs show a very significant deviation between results. As already discussed for the export cable case, this deviation is explained through of the difference in number of units and unitary cost of the cable protection elements as shown in Table . The absolute deviation between results is amplified as the casing length increases.

This example shows the importance of the user knowledge over the values assumed in the installation module. The default values were compiled as part of the requirements of the DTOcean project, too aid the development of a module capable to deliver high level estimates of the logistic costs, however, these default values are not able cover the specificities of each project. As shown in this example, there's an intrinsic high level of uncertainty on the of the values computed by the tool, the only way to reduce this uncertainty, is with the help of the user, by providing project specific data over the assumptions included.

4.3.5 INSTALLATION OF SURFACE PIERCING SUBSTATION

A surface piercing substation was defined for this scenario to centralize power output of the 10 turbines, having 10 upstream array cables inputs and 1 downstream export cable output. For simulation purposes, the substation was specified 10 x 10m, weighting 250 tonnes (indicative) The following tables show the tool results against DBE estimations.

Table 4-9- Vessel and Equipment solution for conducting the installation of the surface piercing substation/marshalling tower

V&E Solution	Installation Module Output		DBE Estimate	
	Quantity x Type [DB id]	Cost	Quantity x Type	Cost
Installation Vessel	1 x Jack-up Vessel [30]	70.000€/day	1 x Jack-up Vessel	100.000€/day
Support Vessel	1 x Multicat [55]	3.400€/day	-	-
Installation Equipment	-	-	-	-
Support Equipment	1 x Inspection ROV [1]	5.700€/day	-	-

As shown in Table 4-9, the installation vessel selected by the module is matching DBE's estimation, with both considering Jack-up types with a small deviation on the day-rate. The DBE vessel day rate is based on the maximum cost of the supporting vessel database in order to provide sufficient contingency for a high level project feasibility assessment.

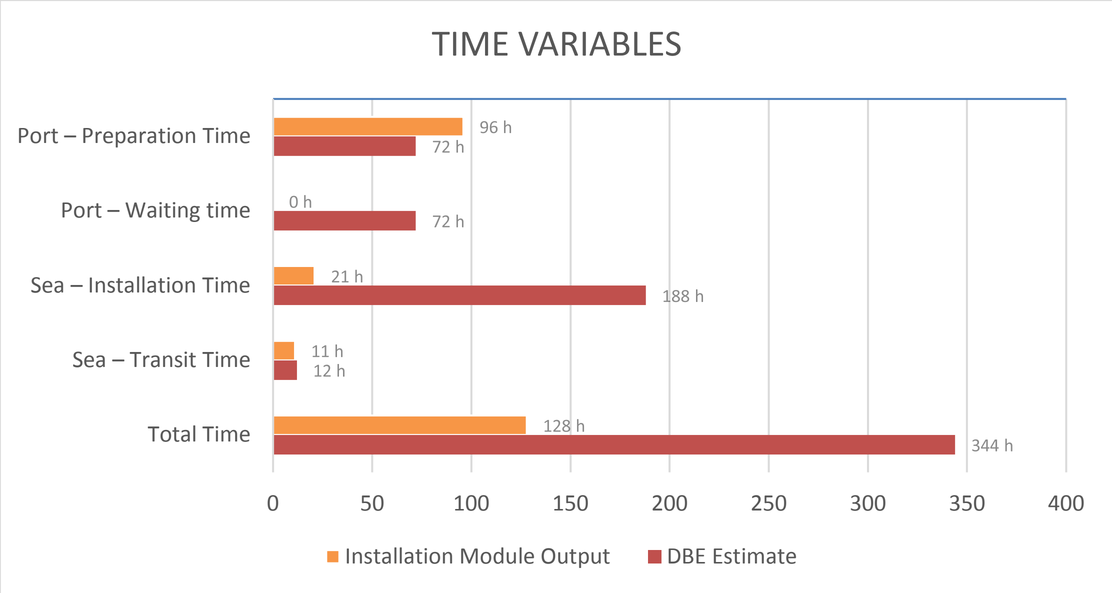


Figure 4-14 - - Installation of surface piercing substation: time comparison between the module and DBE high level estimates

The time variables in Figure 4-14 show a significant deviation between the module output values and DBE estimations, in particular the installation time. Comments on each variable are found below:

- To compute the <u>port - preparation time</u>, the installation module sums the mobilization time defined by default in the Vessel DB, with preparation and loading time of the substation platform onto the vessel (default value inside the module). The assumptions are comparable with the high level estimations from DBE. DBE did not assume a mobilization time since this will entirely depend on site location, availability and ultimately is not deemed by them to be required for an initial high level feasibility assessment.
- To compute the <u>port - waiting time</u>, the installation module uses a weather windows function that has substantial differences from the approach used by DBE for the estimation. DBE's high level estimation included indicative WDT per component since exact timings would need to be determined following detailed engineering, planning and time of year.
- To compute the <u>sea - installation time</u>, the installation module sums the following operation sequence: vessel positioning (default value: 6h), lifting top side platform (default value: 5h), topside positioning and connection (default value: 10h). Although still within the same order of magnitude, this variable show a significant deviation from DBE estimates. This can be justified by the type of operations considered by each approach. While the installation module considers only installation activities, DBE estimates include installation and commissioning, which include others such as electrical commissioning and testing that add up a significant amount of time. Although not included in this logistic phase, the installation module has a default value of 6 weeks for commissioning, after the last installation activity occurs.
- The <u>sea - transit time</u> depends on the vessel transit speed and overall distance between port and site. The installation module extracts the first from the vessel DB and the second from the distance to the selected port. The fact that the value from the installation module matches closely the estimation means that both the selected port and transit speed are adequate.

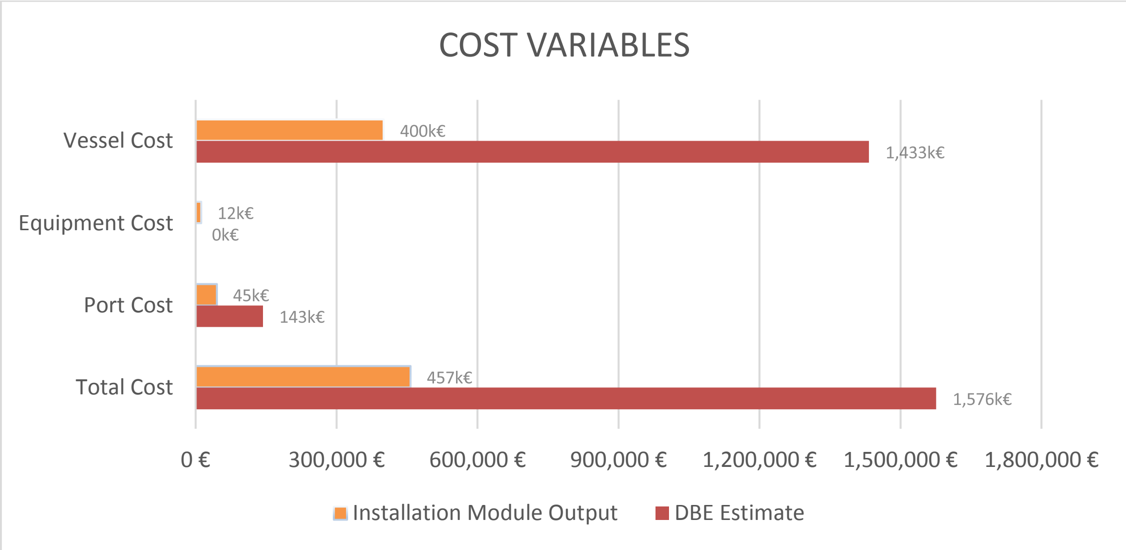


Figure 4-15 - - Installation of surface piercing substation: time comparison between the module and DBE high level estimates

The costs variables are presented in Figure 4-15. Considering the time variable analysis presented above, the costs show an expected deviation.

4.4 VALIDATION OF SPECIFIC FEATURES OF THE INSTALLATION MODULE

4.4.1 WEATHER WINDOWS

The installation module uses the weather windows function described before to compute the waiting time based on the met-ocean data available for the site, the operational limit conditions (OLC) of vessels, the requested starting time of the marine operation and the estimated total sea duration. The detailed analytical formulation and methodology of the waiting time calculation has been presented. This calculation is based on the historical time-series met-ocean data provided by the user. For each year of met-ocean data, the waiting time for a satisfactory weather window is determined from the requested starting date (day/month and hour) at the given recorded year. The final waiting time is the average of all those calculated for each year. Therefore, having as many years of historical time-series met-ocean data is crucial to have a good estimate (standards recommend a minimum of 10 years of met-ocean data). Similar methods have been implemented in other state-of-the-art marine operations planning tool (e.g. Mermaid from Mojo Maritime [2]).

A significant deviation between the installation module and DBE's estimation for the waiting time can be observed on several logistic phases commented on in the previous section. To attempt an explanation of this divergence, it seems logical to give some insight on DBE's approach. The waiting time estimation from DBE for this high level indicative assessment considered a judgement based on a sample counting of the weather downtime (where the OLC of the selected vessels were exceeded) of a given period of time. This method is used only at very early stage of planning since it does not attempt to reflect the seasonal variability, inter-dependence of weather parameters, duration of the sea operations among other factors. For more accurate estimates, DBE employs a more sophisticated model which can only be used after a more detailed engineering study of the marine operations, whereby exact planning is determined. The latter model often returns lower waiting time predictions. The weather window function implemented in the installation module of the DTOcean tool can be seen as an "intermediate" between the two models of DBE in terms of complexity. It may be considered overly complex when compared to the current stage of maturity of the tidal and wave energy sector. Further examination of this weather window function against other numerical planning tool for marine operations would certainly provide valuable feedback.

Despite the apparent large difference between the two waiting time estimations, one should keep in mind that there is currently a very large number of unknowns and assumptions that have to be made with regards to the deployment of arrays of tidal turbines (even more with wave energy converters). For instance, uncertainties related to the vessel and equipment capabilities in highly energetic tidal and wave site remain very large. Therefore, the workability conditions, the required time per operation at sea and many other factors are yet to be verified and refined like it is still happening with the offshore wind sector. Reflecting on these considerations, it is believed that the difference of waiting time estimations falls within an acceptable and reasonable margin of error at this current stage of knowledge.

4.4.2 PORT SELECTION

Port selection is based on either user inputting the site entry point and/or lease area UTM coordinates and zone ID. This was considered to make sense. The port selection output of Belfast Harbour is appropriate for the Fair Head scenario. In order to test the port selection component of the module, several real sites were tested, by changing the user input data, to determine the applicability of the output port gave by the module. As a result, Belfast Harbour is provided for West Islay Tidal Energy Park and Sound of Islay, while Kishorn harbour is provided for MeyGen. These results are considered appropriate for the high level exercise performed here. It is noted that, in fact, an alternative is planned to be used for installation and O&M – Scrabster Harbour, Thurso, which is in close proximity for final turbine fabrication and testing, whilst Nigg Energy Park, Scotland is foreseen for the main port.

4.4.3 CONCLUSION

As a conclusion, DBE considers the overall approach of the module to be extensive and executed well bearing in mind the complexities of an MRE project and the high level assessment approach. It is mentioned that the tool is a large step forward for ease of project feasibility assessment, although it can be over-ambitious for this stage of MREs development. At this point it is considered that a developer needs to have considered sufficient contingency for a first gate check on whether to proceed. With this in mind, since the outputs are generally reasonable, it was suggested that the added feature for the User to manually add contingency on the installation procedure costs depending on how confident they are with inputs.

4.5 SENSITIVITY ANALYSIS

As part of the validation of the tool, a sensitivity analysis is performed to assess the variation of the outputs as function of the main outputs and to verify the adequate behaviour of the tool.

Different parameters are varied from a nominal case in a given percentage range of:

[±10%, ±20%, ±30%, ±40%, ±50%, +75%, +150%, +200%, +500%, +1000%],

for the case of numerical values.

The initial values in the range, ±10%, ±20%, ±30%, ±40%, ±50%, where meant to test the sensitivity of the tool to variations in the inputs values. The higher values in the range, namely +75%, +150%, +200%, +500%, +1000%, were introduced to test the behaviour of the tool in extreme cases, to the point, that in some cases, no solution is found, which also goes towards validating the tool.

The parameters were varied within each different group of inputs:

- Installation of Devices
- Installation of Electrical Components
- Installation of Moorings and Foundations Components

Same of the operations default time values and rates of the module were also varied, namely:

- Operations Default Values
- Default Rate Values

Each of the parameters varied in each group of inputs or operations is indicated next.

The input parameters which variation resulted in variation of the outputs are represented in plots.

For each case, to reflect the impact of the specific inputs in the logistic phase considered, only the corresponding elements are considered. For example, for the installation of devices, no electrical and mooring and foundations elements are considered to be installed.

4.5.1 INSTALLATION OF DEVICES

For the case of the installation of devices the following parameters were varied:

Name	Example value	Meaning	Range	Remarks
sub-device[‘length [m]’]	22	Largest device sub-system length [m]	2,2 to 220	-
sub-device[‘width [m] ’]	22	Largest device sub-system width [m]	2,2 to 220	No significant variation observed (similar to length)
sub-device[‘dry mass [kg] ’]	160000	Largest device sub-system dry mass [kg]	16000 to 1600000	-

device['load out [-]']	lift away	Device load out method (float away, lift away, skidded)	float away, lift away, skidded	-
sub-device['assembly duration [h] ']	12	Largest device sub-system assembly duration [h]	0,6 to 60	-
device['transportation method [-]']	deck	Device transportation method (deck, tow)	deck, tow	-

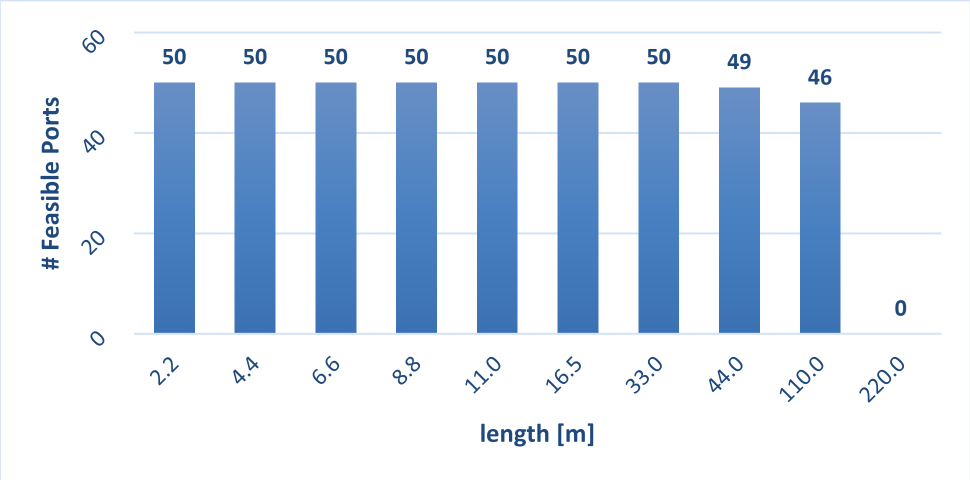


Figure 4-16 – Number of feasible port as function of the biggest of the sub-device length.

Figure 4-16 indicates the variation on the number of feasible ports depending on the length dimensions of the device to be installed. It is seen that after some length the number of feasible ports decreases and for a more extreme case value, the situation of no feasible ports can occur.

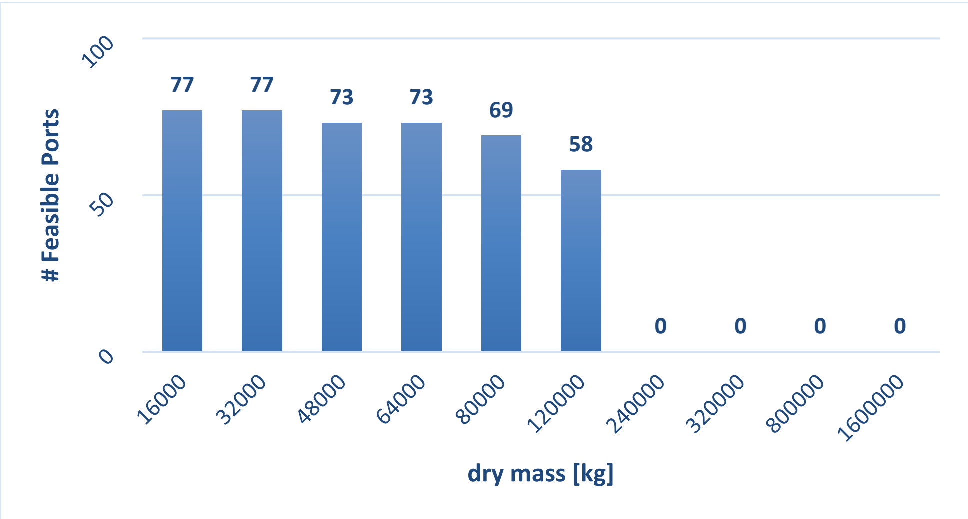


Figure 4-17 - Number of feasible port as function of the biggest of the sub-device dry mass.

Similarly, Figure 4-17 indicates the variation on the number of feasible ports depending on the dry mass of the heavies of the sub devices to be installed. It is seen that after some weight the number of feasible ports decreases and for a higher value, the situation of no feasible ports begins to occur, indicating that the dry mass can be a restringing parameter.

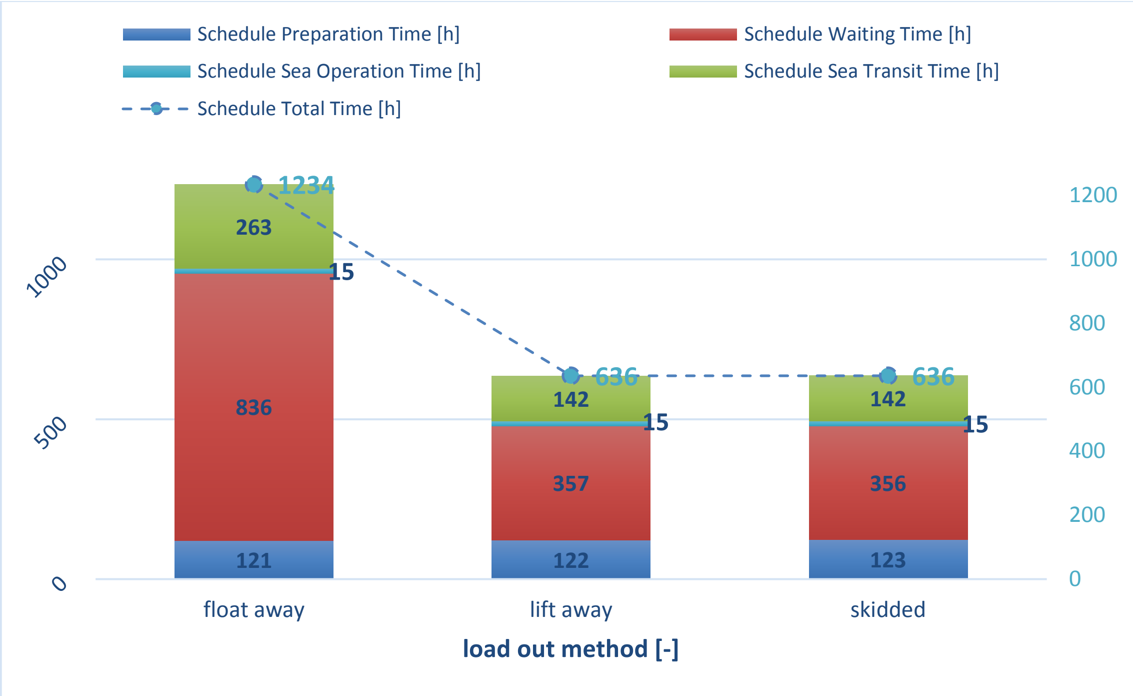


Figure 4-18 – Schedule time as function of the device load out method.

Figure 4-18 shows how the load out method can impact the different operational times. The float away scenario seems, for this scenario, to be the one that results in higher total time, namely because of higher waiting time, given the ore restrictive OLC.

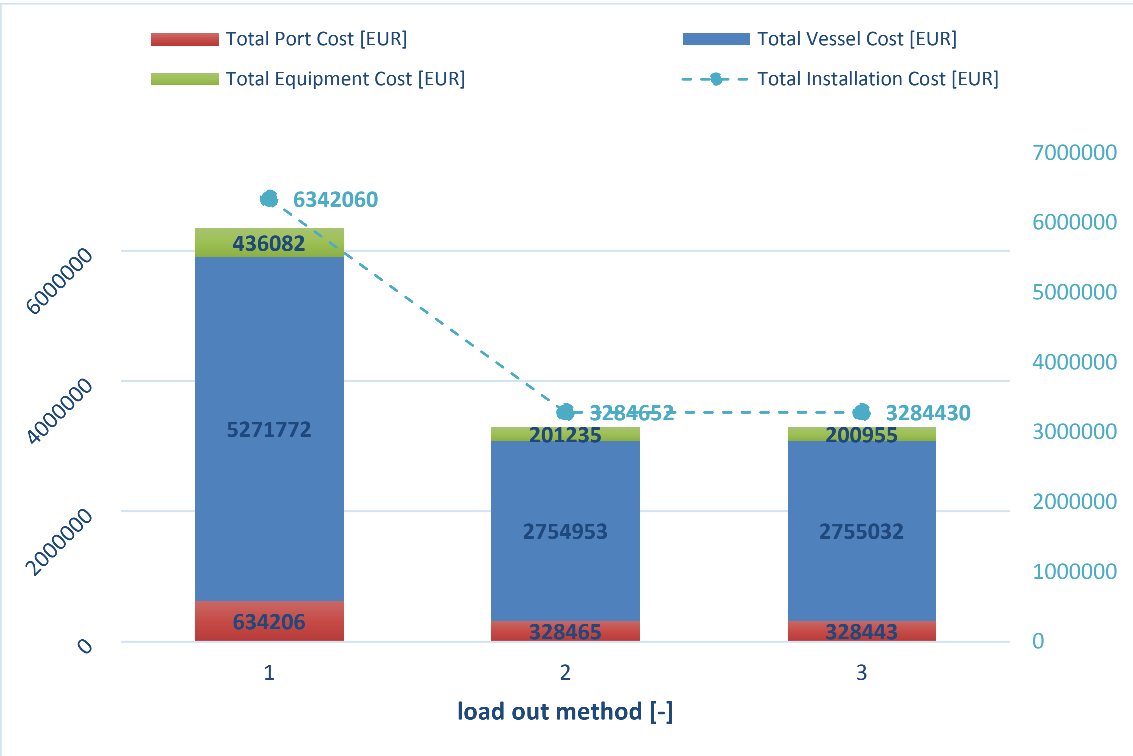


Figure 4-19 – Cost as function of the device load out method.

Consequently, Figure 4-19 shows that, as could be expected, a higher total time, results in higher total costs, namely with ta higher cost associated to the vessels and equipment used, since even if they are at port waiting for the operation to occur, there is an associated cost to that. Port cost is also higher, but only because the port cost is associated to a percentage of the total cost.

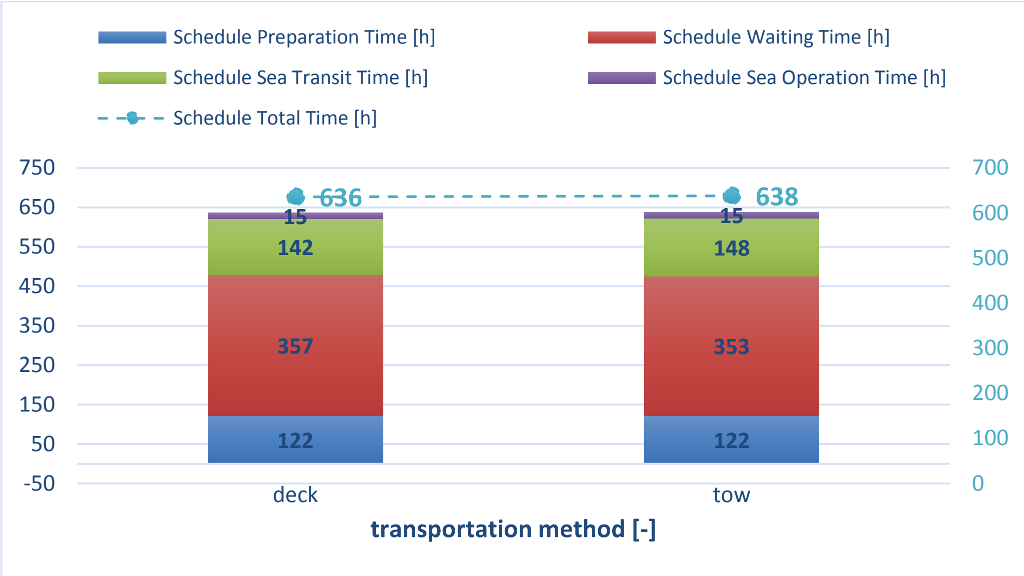


Figure 4-20 – Schedule time as function of the device transportation method.

Similarly to as before, Figure 4-20 shows the impact the transportation method can have in the schedule times. It can be seen that there are no significant differences between the two, albeit the difference in vessel speed and OLC.

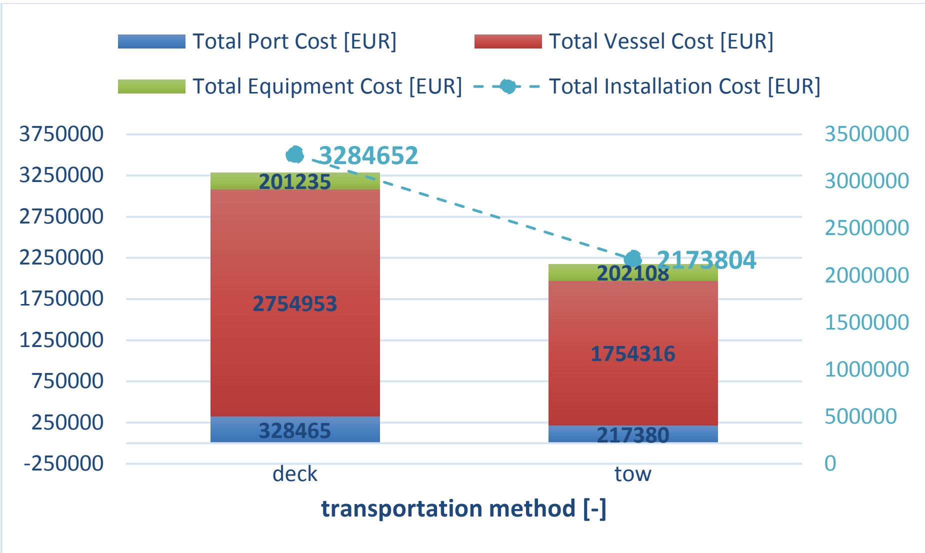


Figure 4-21 - Cost as function of the device transportation method.

Although no significant differences can be found in terms of schedule, since bigger vessels might be required for the case of on-deck transportation, this scenario results in a higher total cost, as can be seen in Figure 4-21.

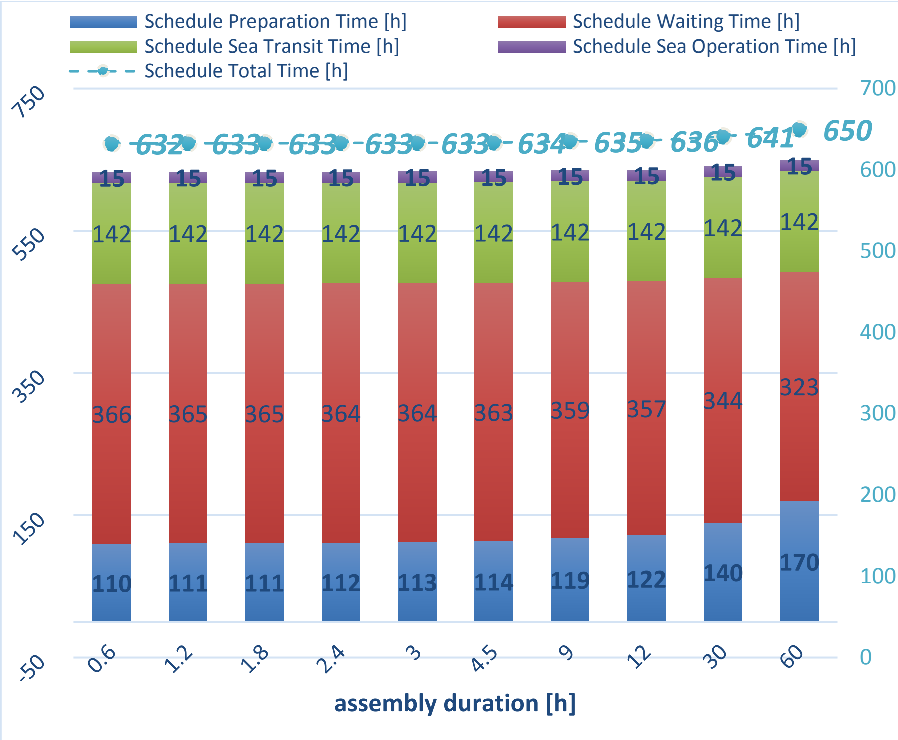


Figure 4-22 – Schedule time as function of the assembly duration.

Finally, Figure 4-22 demonstration the impact of the device assembly duration in the schedule time and Figure 4-23 the impact in the total cost. It can be seen from the figures that this parameter does not have a high impact in the final output results.

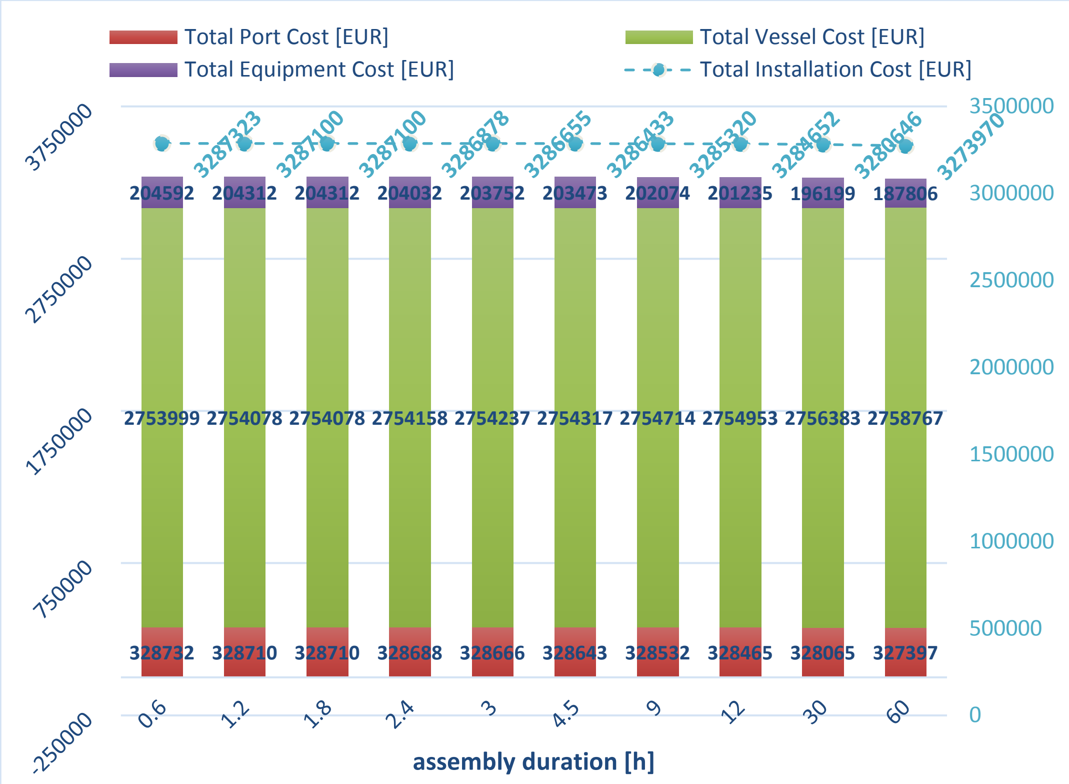


Figure 4-23 - Cost as function of the assembly duration.

4.5.2 INSTALLATION OF ELECTRICAL COMPONENTS

For the case of the installation of electrical components the following parameters were varied:

Name	Example value	Meaning	Range	Remarks
collection point['length [m]']	10	Collection point length [m]	1 to 100	No significant variation observed
collection point['width [m] ']	5	Collection point width [m]	0,5 to 50	-
collection point['dry mass [m] ']	2000	Collection point dry mass [m]	200 to 20000	No significant variation observed
dynamic cable['length [m] ']	500	Dynamic cable length [m]	50 to 5000	-
dynamic cable['dry mass [kg/m] ']	50	Dynamic cable dry mass [kg/m]	5 to 500	No significant variation observed
static cable['length [m] ']	20000	Static cable length [m]	2000 to 200000	No significant variation observed
static cable['dry mass [kg/m] ']	70	Static cable dry mass [kg/m]	7 to 700	No significant variation observed

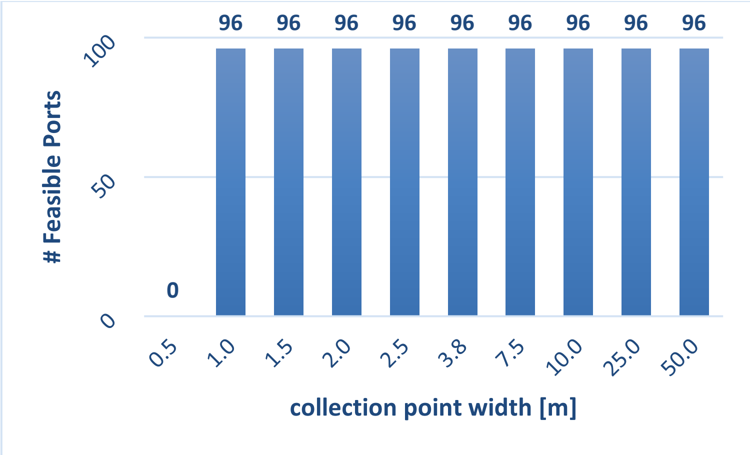


Figure 4-24 - Number of feasible port as function of the collection width.

Figure 4-24 shows that if the width of the device being too small, for the same dry mass, resulted in an overly high loading bearing requirement resulting in no feasible port being found.

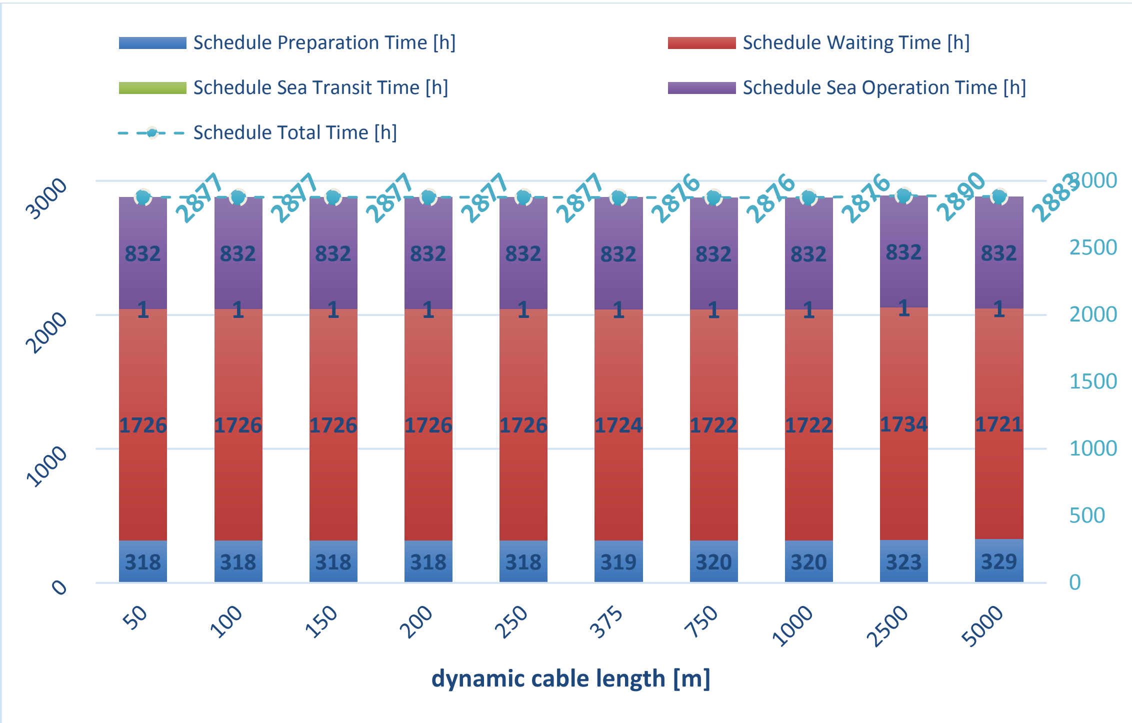


Figure 4-25– Schedule time as function of the dynamic cable length.

Figure 4-25 shows that varying the dynamic cable length only has a very residual impact in the overall schedule time associated to the installation of the dynamic cable.

4.5.3 INSTALLATION OF MOORINGS AND FOUNDATIONS COMPONENTS

For the case of the installation of mooring and foundation components the following parameters were varied:

Name	Example value	Meaning	Range	Remarks
line['length [m]']	92,38	Mooring Line length [m]	9,238 to 923,8	-
line['dry mass [kg]']	839,5	Line dry mass [kg]	83,95 to 8395	No significant variation observed
foundation['length [m]']	1,75	Foundation length [m]	0,175 to 17,5	-
foundation['width [m] ']	1	Foundation width [m]	0,1 to 10	No significant variation observed
foundation['dry mass [kg]']	678,125	Foundation dry mass [kg]	67,8125 to 6781,25	-
foundation['ins depth [m]']	10	Foundation installation depth [m]	1 to 100	
foundation['soil type']	70	Foundation soil type	ls, ms ds, vsc, sc, fc, stc, hgt, cm, src, hr, gc	

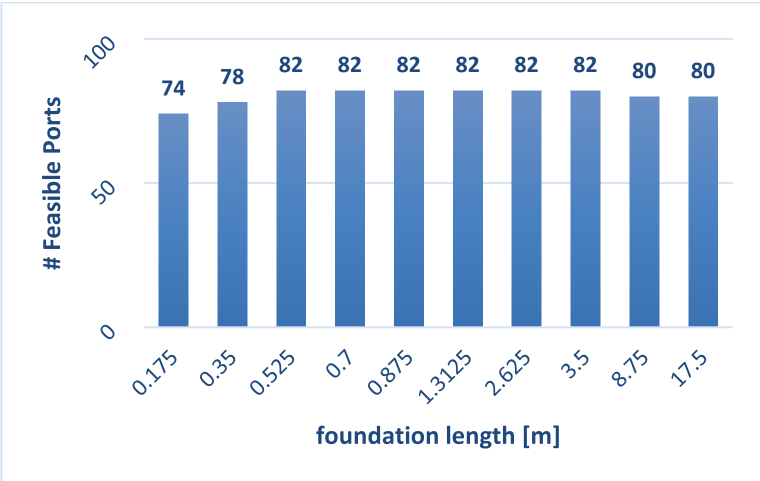


Figure 4-26- Number of feasible port as function of the foundation length.

Figure 4-26 shows the influence of the foundation length on the number of feasible ports. If it is too small, for the same dry mass, the loading bearing requirement will increase and as such, decrease the number of feasible ports that can handle that load bearing. On the other hand, if it increases too much, the total terminal area requirement will become also too big, and some ports, will be unable to handle such requirement.

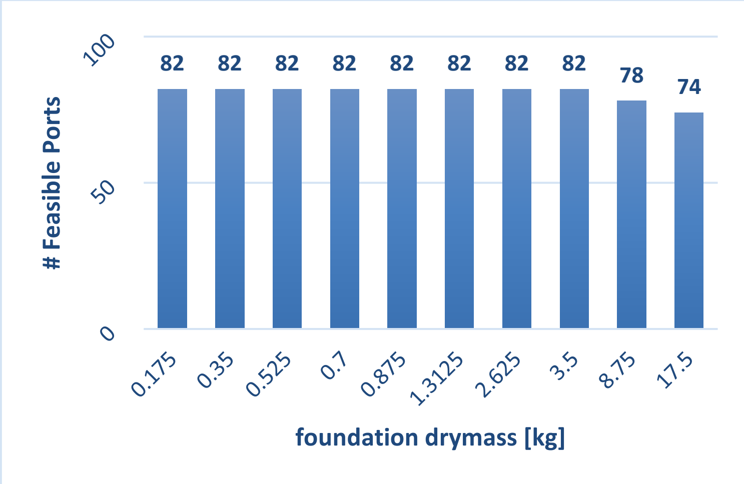


Figure 4-27 - Number of feasible port as function of the foundation dry mass.

Similarly to as before, if the dry mass increases the terminal cargo requirement can become too high for some ports to handle, and the number of feasible ports will decrease, as can be seen in Figure 4-27.

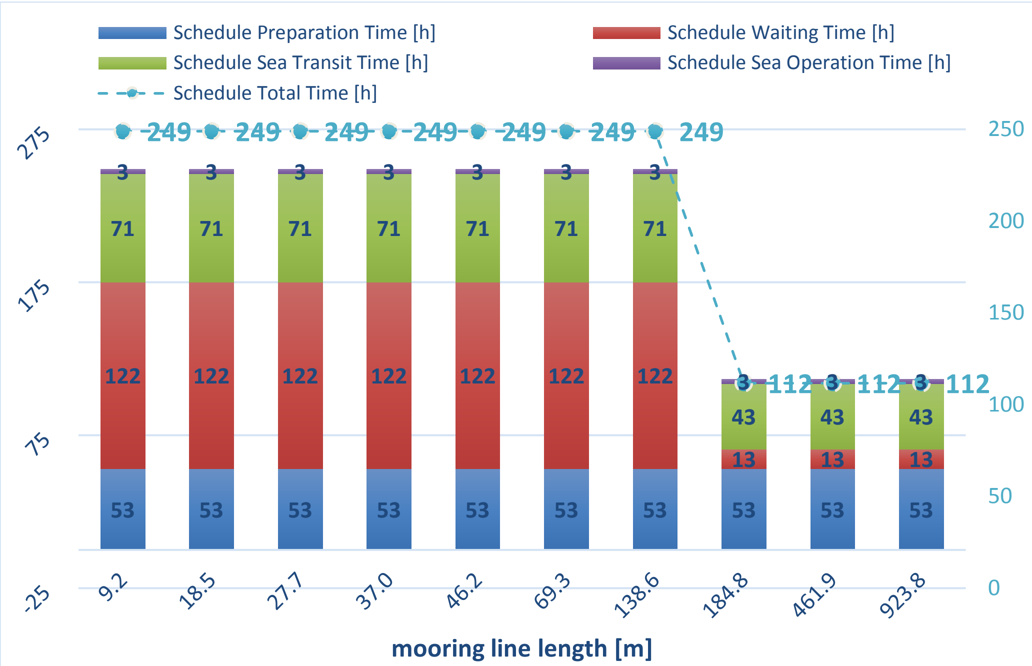


Figure 4-28– Schedule time as function of the mooring line length.

In terms of the mooring line length, if the length is too high, bigger vessels will be required, which allow for the operation to be performed in less time (see Figure 4-28), although of course, at the cost of an increase in the cost of the vessels, and therefore, of the total operation cost (see Figure 4-29).

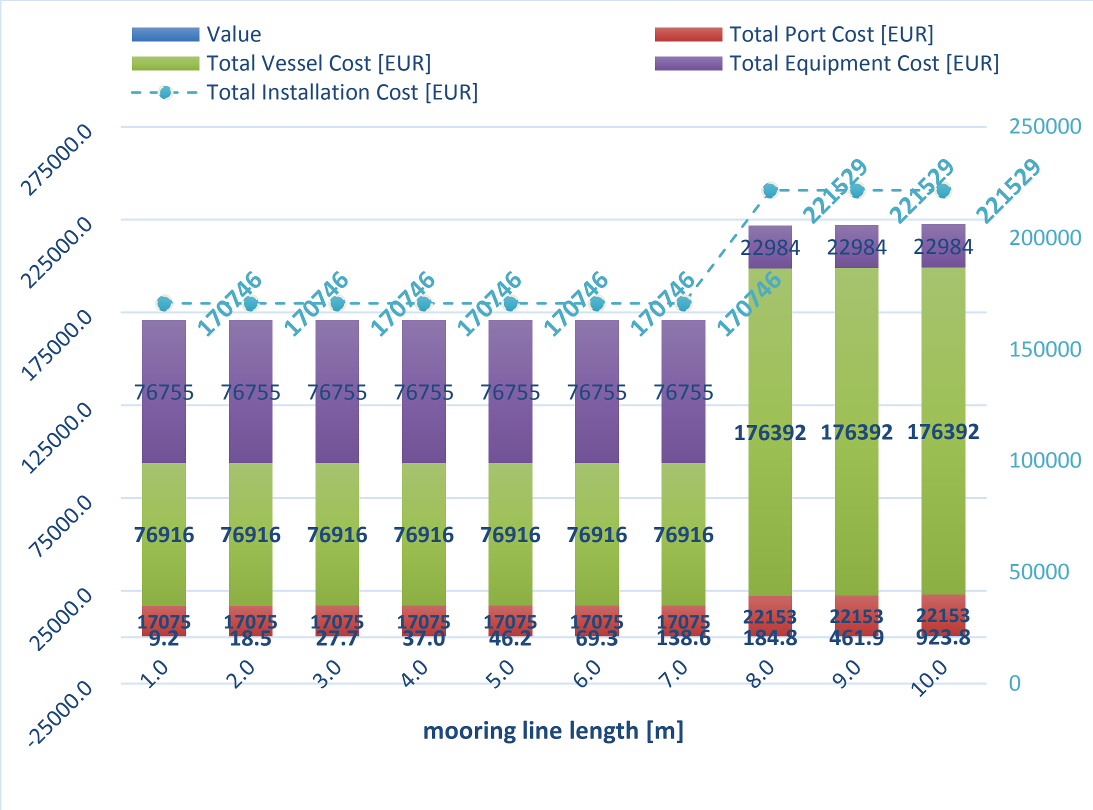


Figure 4-29- Cost as function of the mooring line length.

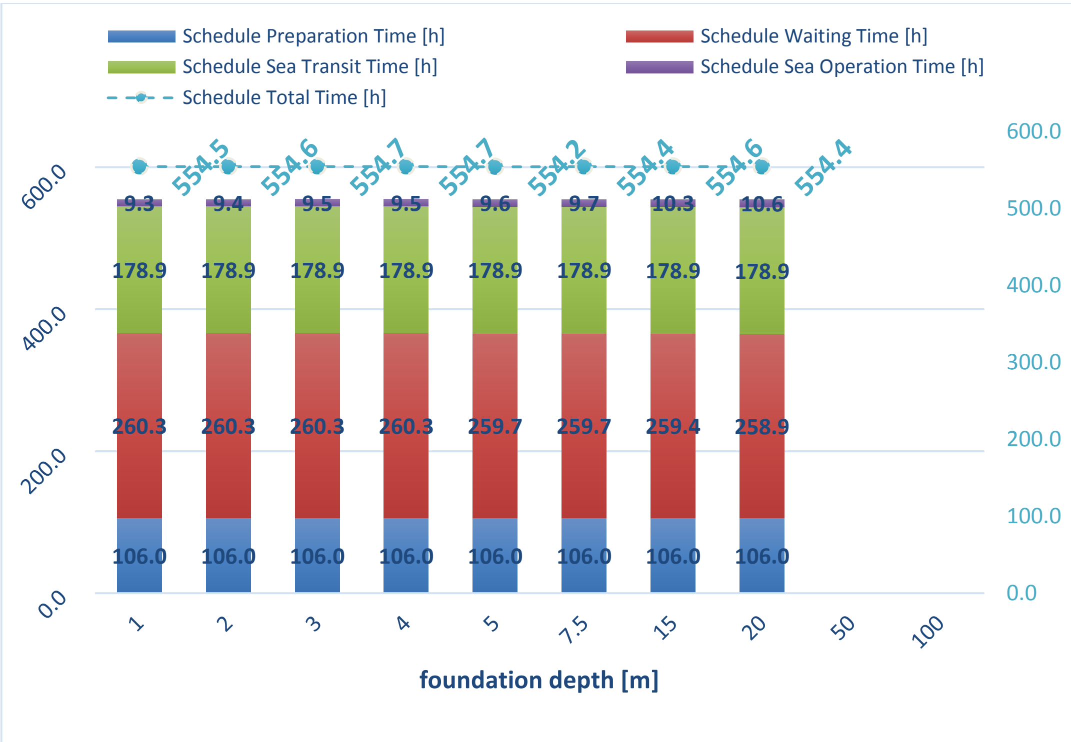


Figure 4-30 – Schedule time as function of the foundation depth.

The foundation installation depth will also influence if a certain operation is feasible or not. For the case of a driven pile, if the installation depth is required to be too high, a no solution scenario can occur, as seen in Figure 4-30.

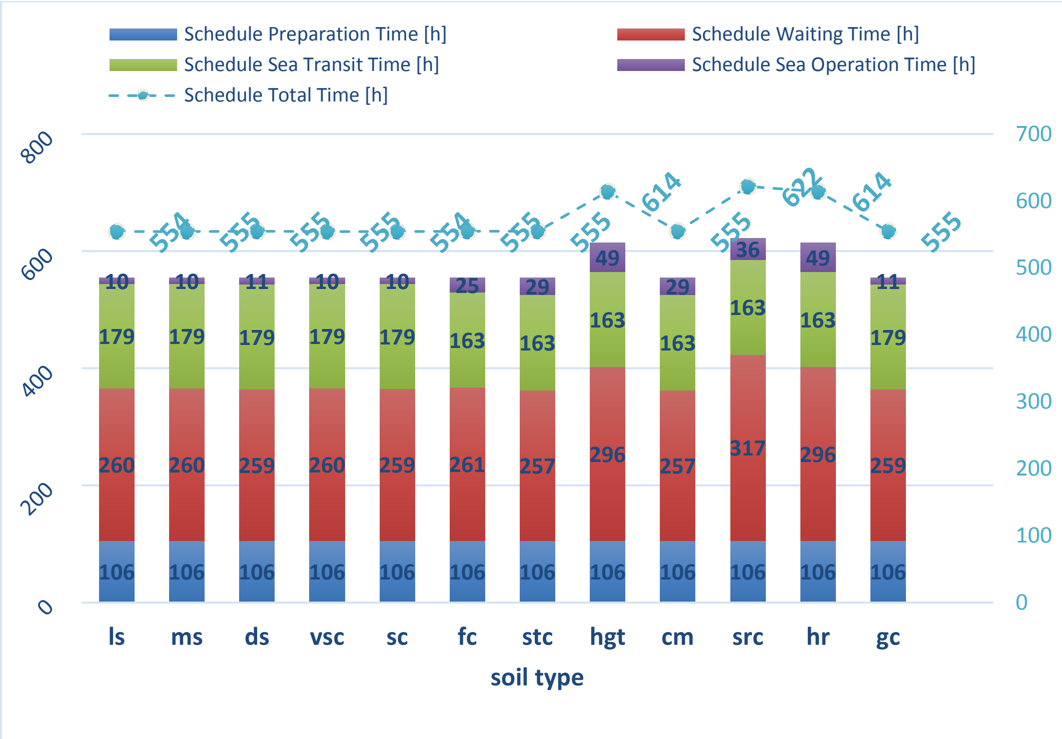


Figure 4-31 - Schedule time as function of the soil type.

Another interesting thing to observe, is the influence of the soil type in the installation of foundation. For the case of pile anchors, which burial procedure depends highly on the soil type, the influence in the schedule time can be seen in Figure 4-31. As can be seen, this can influence mainly the waiting time, because of the different OLC and the sea operation time, because different procedures will have different burial times, depending on soil penetration rate.

4.5.4 OPERATIONS DEFAULT TIME VALUES

For the case of the operation default time values the following parameters were varied:

Name	Example value	Meaning	Range	Remarks
Assembly at port Time [h]	1	Assembly at port Time [h]	0,1 to 10	-
Seafloor & equipment preparation Time [h]	1	Seafloor & equipment preparation Time [h]	0,1 to 10	No significant variation observed
Vessel Positioning Time [h]	6	Vessel Positioning Time [h]	0,6 to 60	-
Seafastening Time [h]	0,5	Seafastening Time [h]	0,05 to 5	No significant variation observed

Seafloor & equipment preparation Time OLC: Tp [s]	15	Seafloor & equipment preparation Time OLC: Tp [s]	1,5 to 150	No significant variation observed

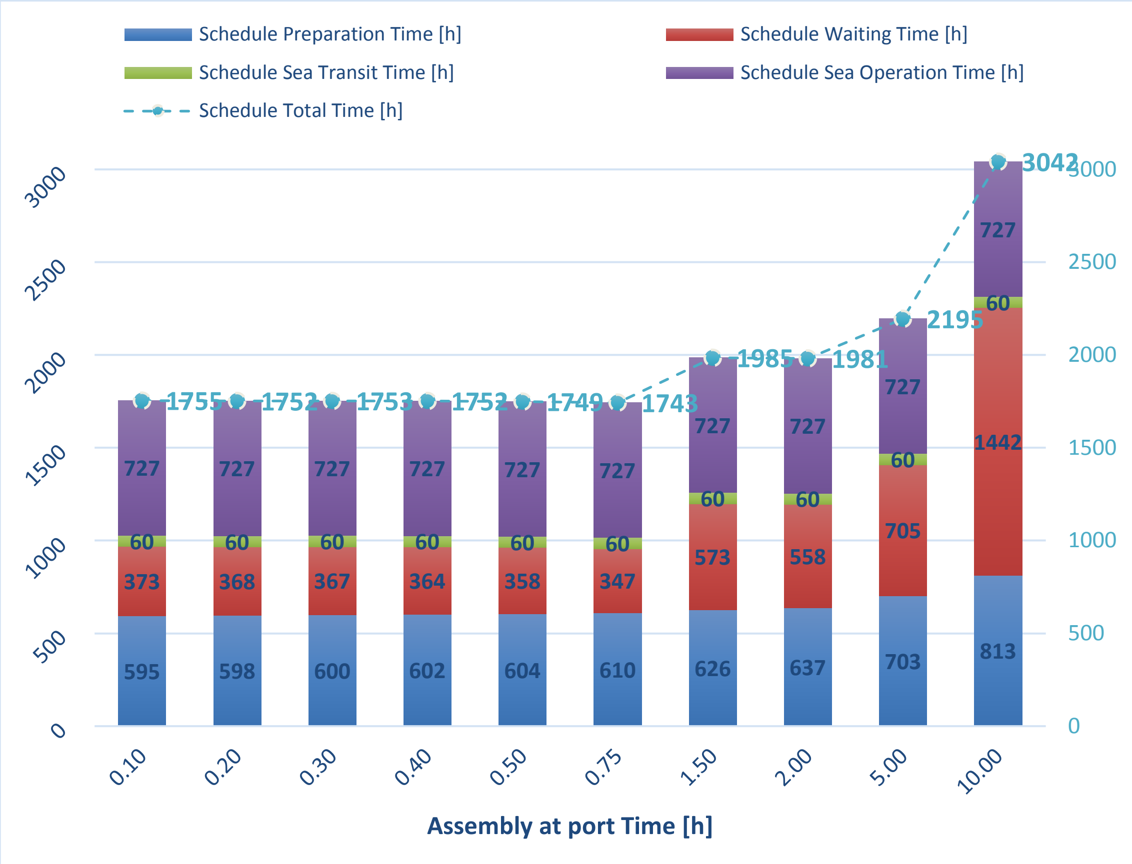


Figure 4-32- Schedule time as function of the assembly at port time.

As can be seen in Figure 4-32 and Figure 4-33, the influence of the assembly at port duration time can have an impact in both the schedule time and the costs. An increase in the assembly duration, besides increased preparation time, can result in increased waiting time, as the weather windows conditions can get worse.

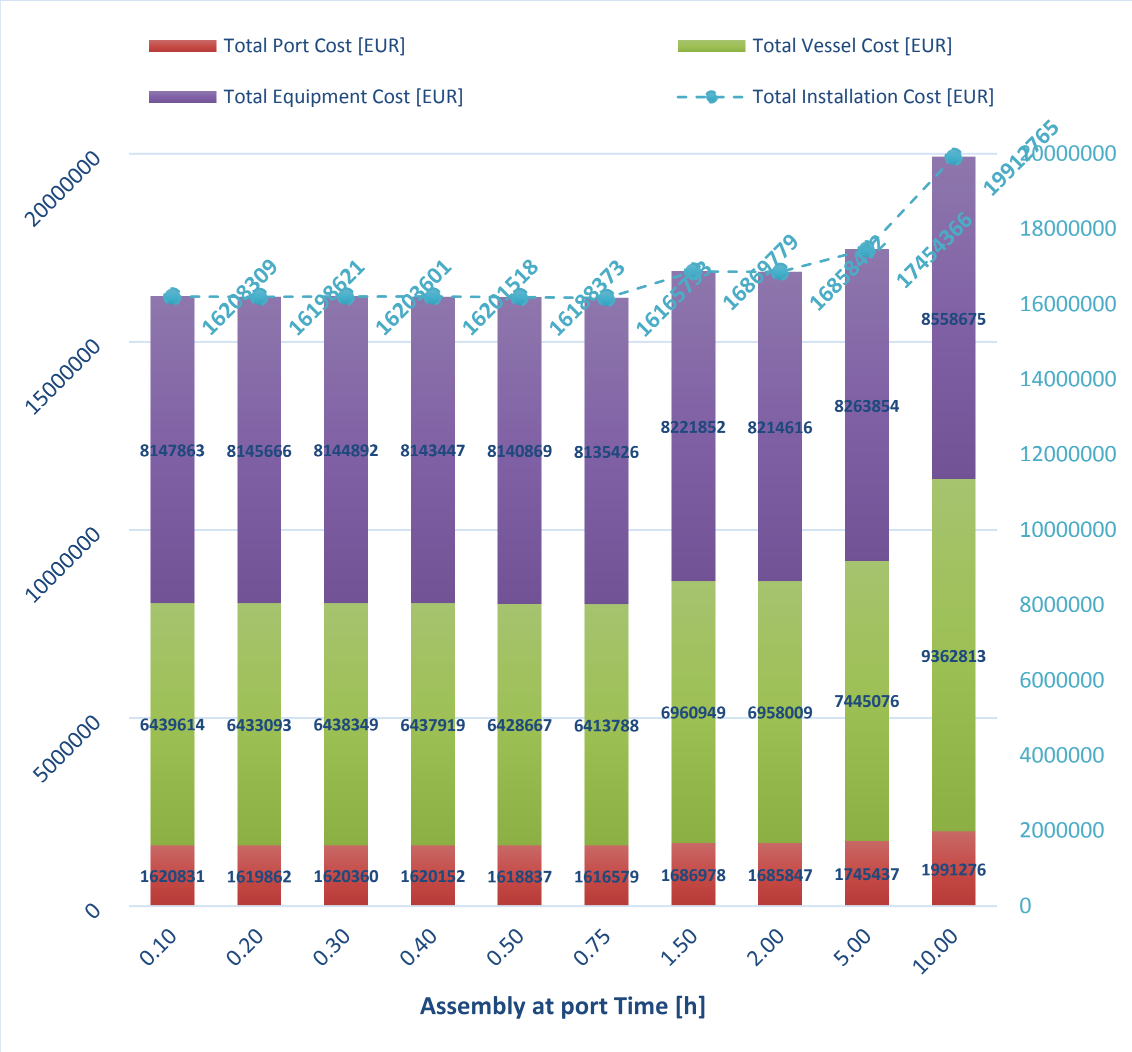


Figure 4-33 - Cost as function of the assembly at port time.

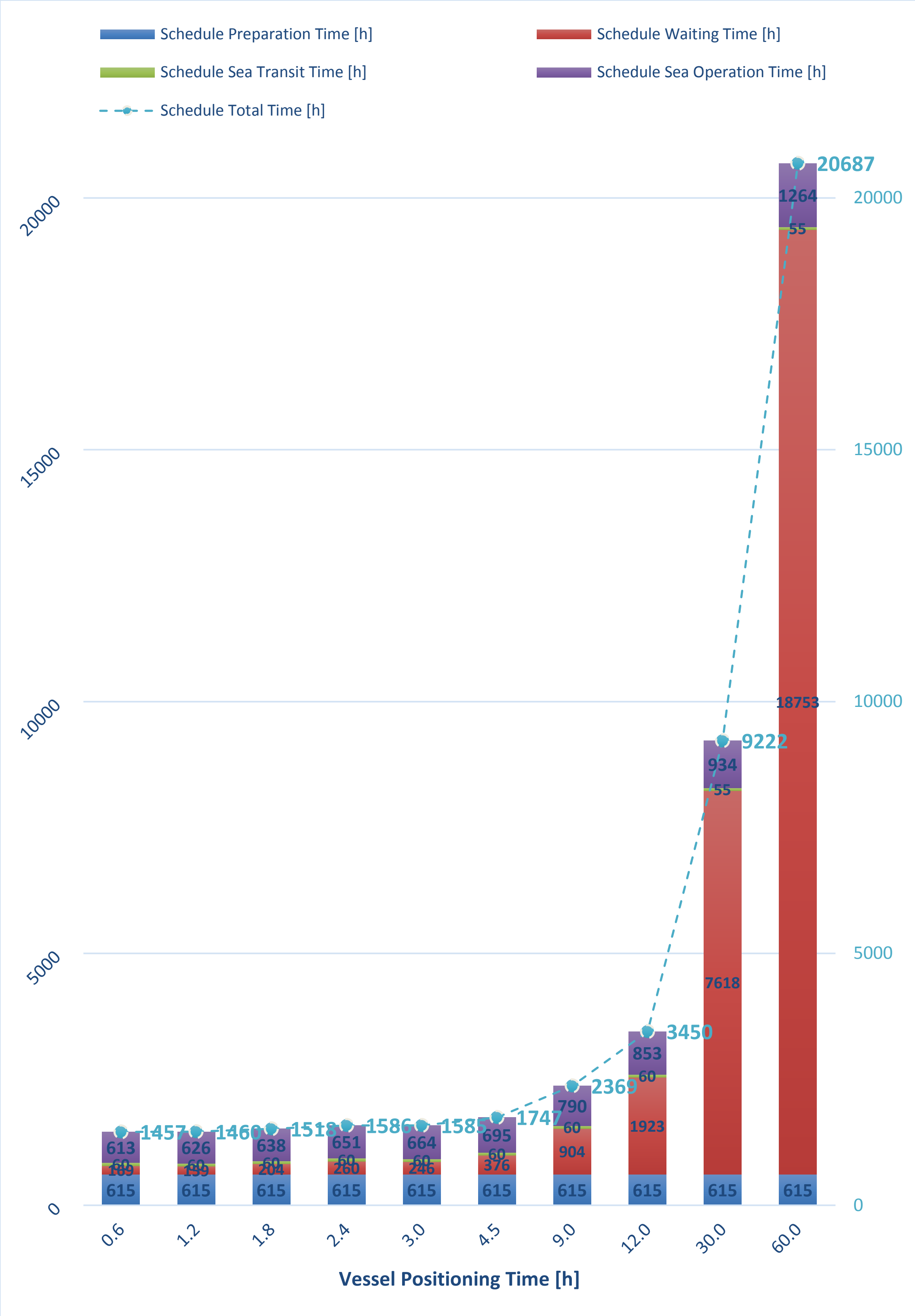


Figure 4-34- Schedule time as function of the vessel positioning time.

Doing the exercise of increasing, to even unrealistic values, the vessel positioning time allows also to test and validate the tool. It can be seen from Figure 4-34 and Figure 4-35 that a big increase in the vessel positioning time can result in quite high waiting times as a result of the imposed OLC conditions. This in turn, will result obviously in more expensive costs, as the cost of the vessels increases dramatically.

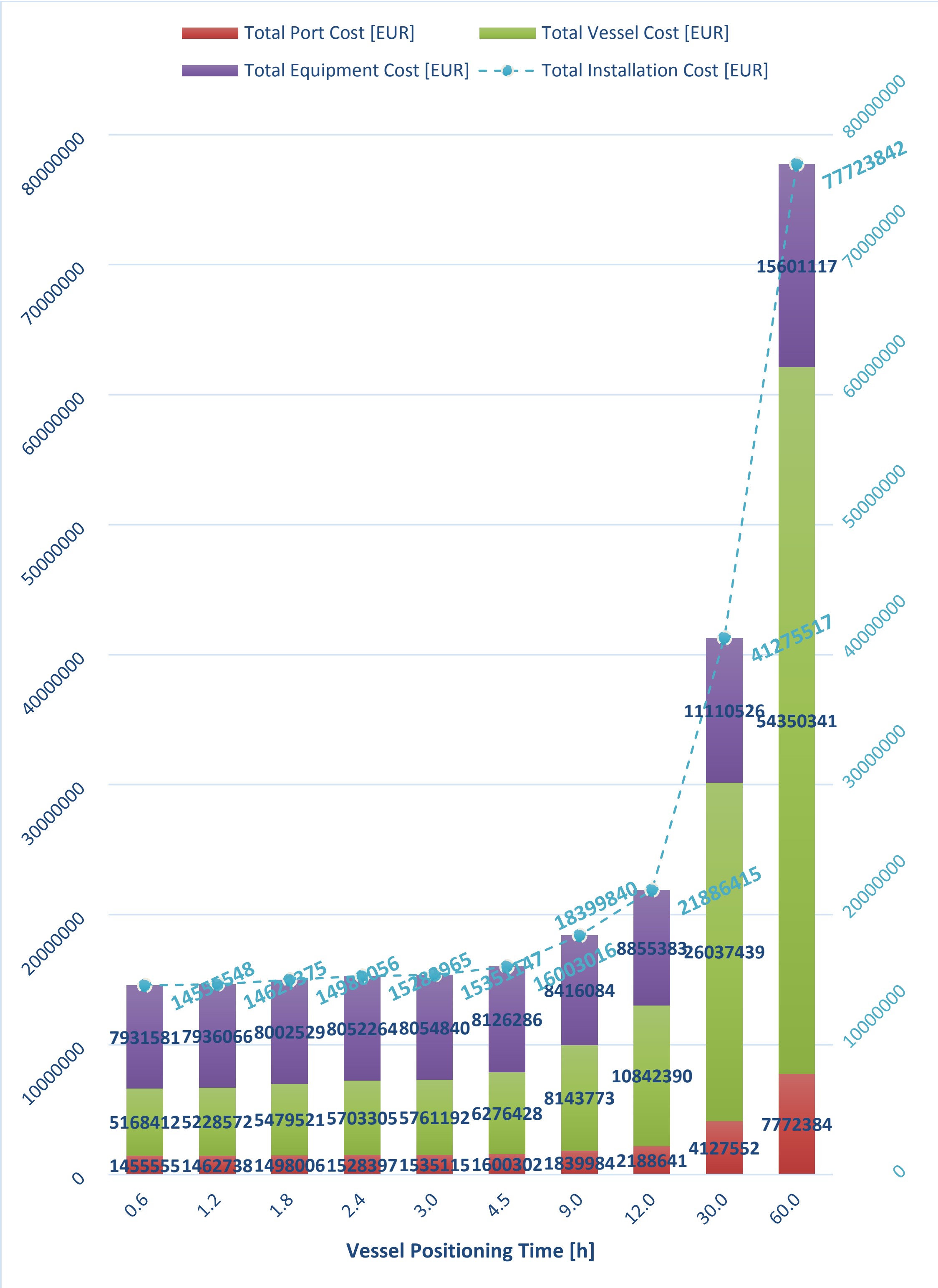


Figure 4-35 – Cost as function of the vessel positioning time.

4.5.5 DEFAULT RATE VALUES

For the case of the default operational and cost rates the following parameters were varied:

Name	Example value	Meaning	Range	Remarks
Surface laying [m/h]	1000	Surface laying [m/h]	100 to 100000	No significant variation observed
Installation of iron cast split pipes [m/h]	300	Installation of iron cast split pipes [m/h]	30 to 3000	No significant variation observed
Loading rate [m/h]	450	Loading rate [m/h]	45 to 4500	-
Grout rate [m3/h]	20	Grout rate [m3/h]	2 to 200	No significant variation observed
Fuel cost rate [EUR/l]	1,5	Fuel cost rate [EUR/l]	0,15 to 15	-
Port percentual cost [%]	10	Port percentual cost [%]	1 to 100	No significant variation observed

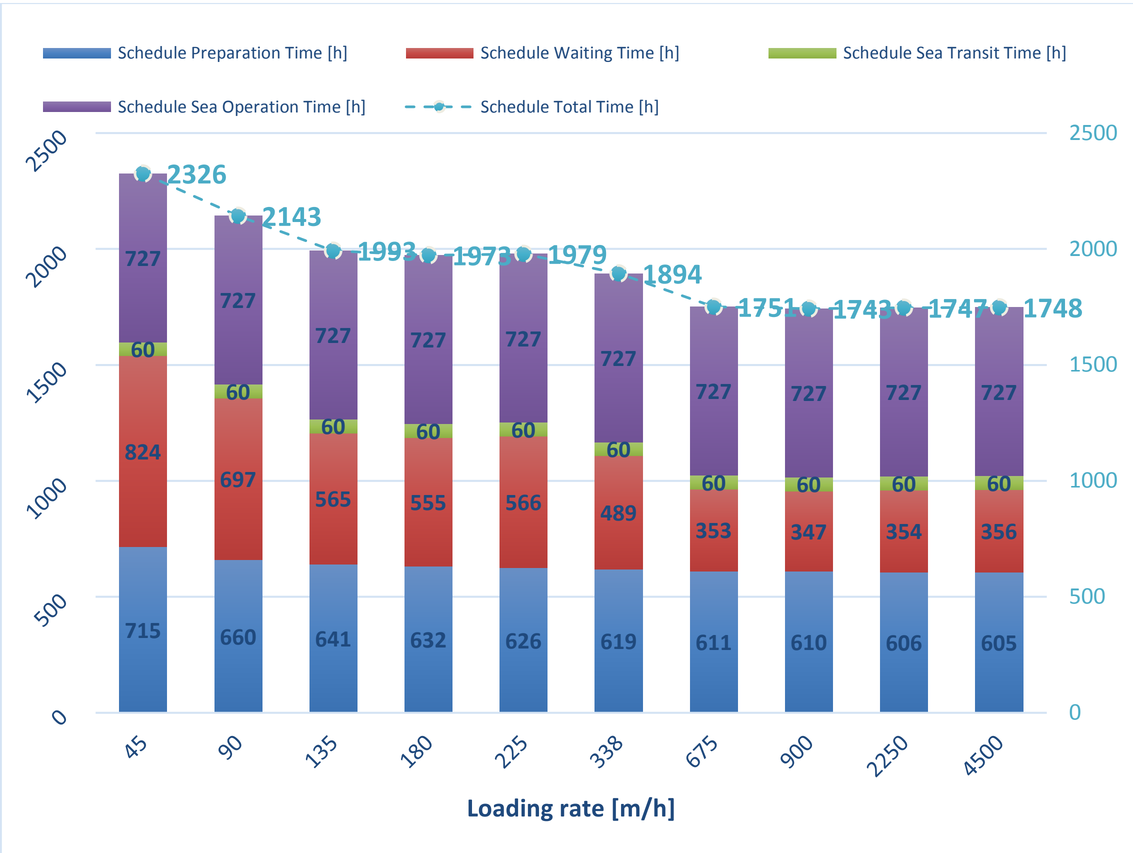


Figure 4-36 - Schedule time as function of the loading rate.

For the case of export and array cables, an increase in the default loading rate, will allow to perform the operation quicker and therefore reduce both the preparation time and the waiting time, as seen in Figure 4-36.

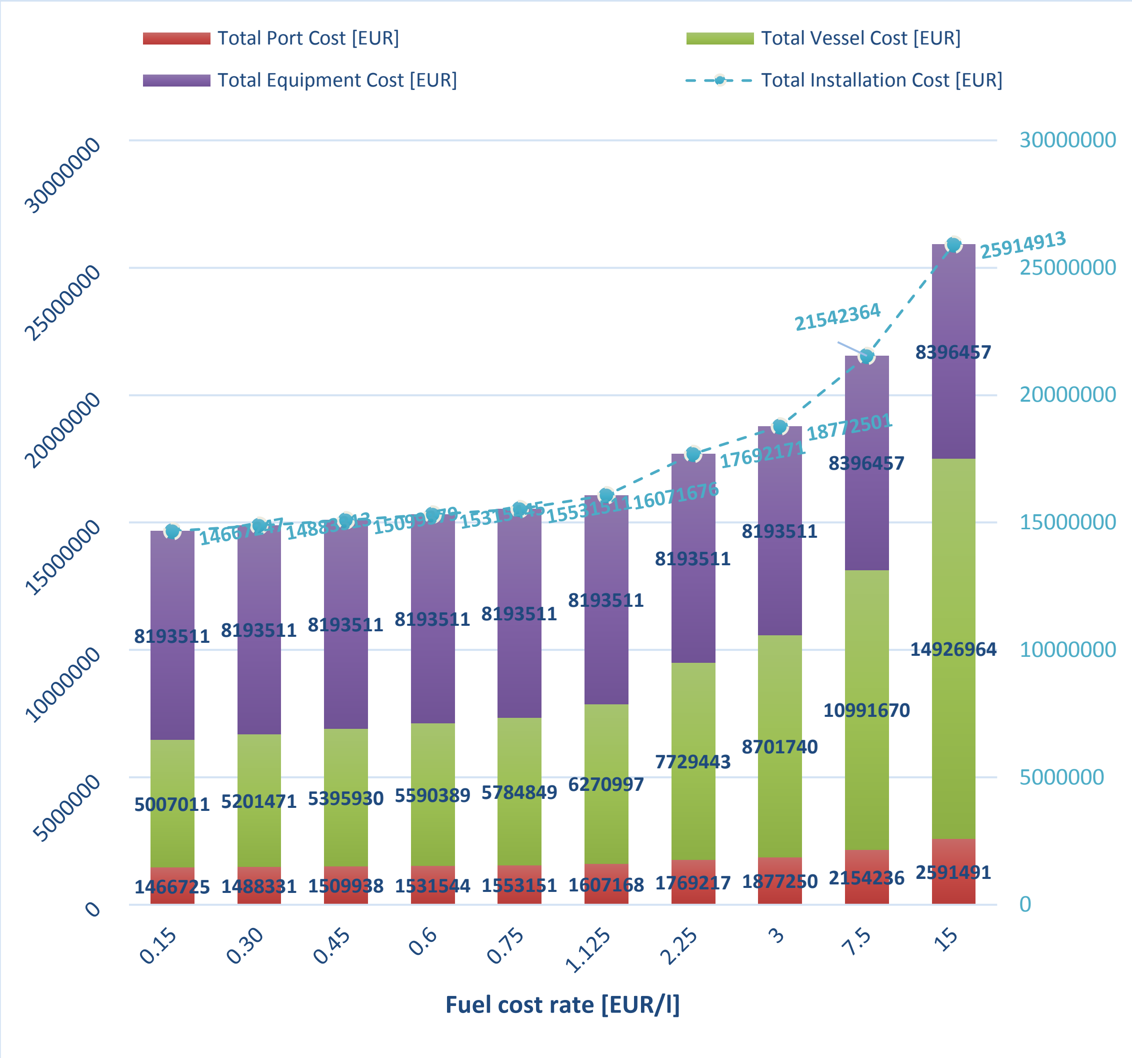


Figure 4-37– Cost as function of the fuel cost rate.

Finally, as seen in Figure 4-37 and as can be expected, an increase in fuel rate cost will result in higher vessel cost and therefore higher total cost.

4.5.6 LOCATION AND METOCEAN DATA

The exact same scenario as the FairHead, that is, 10 tidal turbines with the same electrical grid and mooring foundations, are used in a different location, the Sound of Islay, to assess the influence of a different location and of different metocean data. A comparison in installation costs and installation times is presented for the different logistics phases and the total installation.

Installation of Pile Foundations:

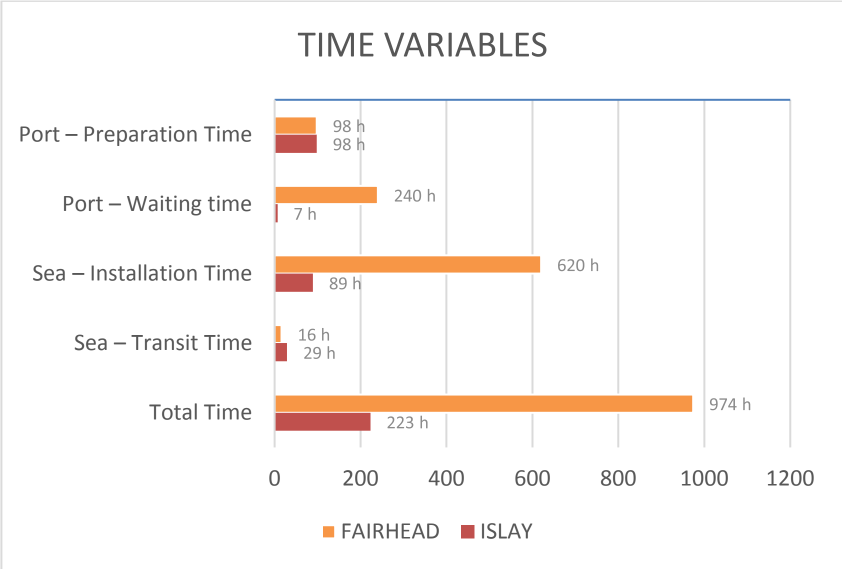


Figure 4-38 - Installation time comparison between the different location scenarios for pile foundations installation.

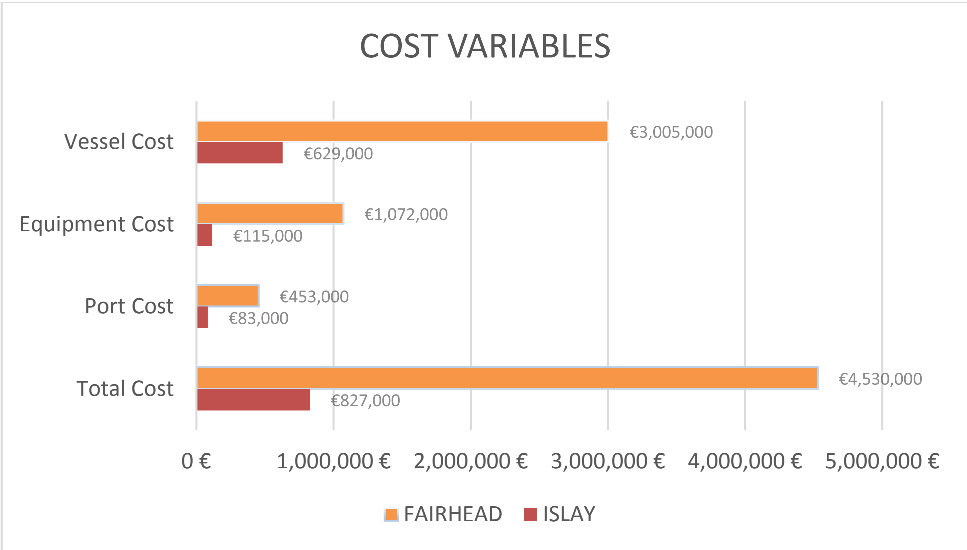


Figure 4-39 - Installation cost comparison between the location scenarios for pile foundations installation.

For the installation of the pile foundations it can be seen that the same preparation time is required, since this is not influenced by the location, but a big decrease in the waiting and installation times can be observed. This is given to the fact that the soil type for the Sound of Islay location permits hammering to be applied, in place of drilling as used in the FairHead scenario. For this scenario, a hammering technique with a 5 m/h penetration rate in GC soil type is considered, opposed to the FairHead scenario with a drilling technique with a 0,25 m/h penetration rate in HR soil type. This allows to considerably decrease the installation time from 620 h to 89 h. There is also a slight increase in the transit time due to the fact that there is a bigger port-site distance (130 km in this scenario as opposed to the Fairhead scenario with 79km distance) and the use of a slower vessel (JUP BARGE [38] with 2,5 m/s in this scenario, while a JUP VESSEL [30] with 3,6 m/s is considered for the FairHead scenario).

Even with a slight higher transit time, expectedly, the decrease in installation time reflects itself in a reduction in cost, mainly, as explained before, for the possibility to use a quicker penetration technique.

Installation of Devices:

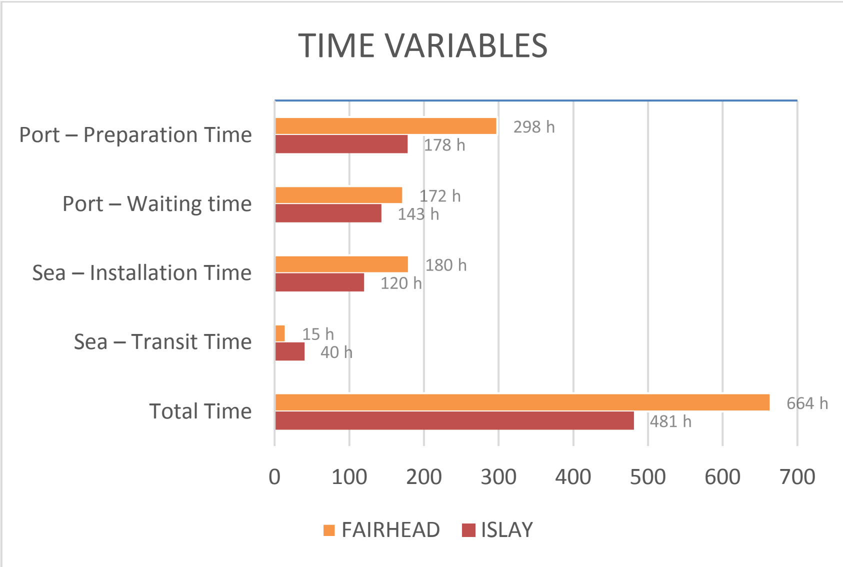


Figure 4-40- Installation time comparison between the different location scenarios for installation of devices.

For the case of the device installation, similarly to as before, a reduction in time in terms of waiting and installation time can be seen as consequence of less severe weather conditions with an increase in the transit time as result of a higher port-site distant and the use of a slower vessel (in this case a JUP VESSEL [30] with 3,6 m/s as apposed with a CRANE VESSEL [41] with 8,745 m/s for the FairHead scenario).

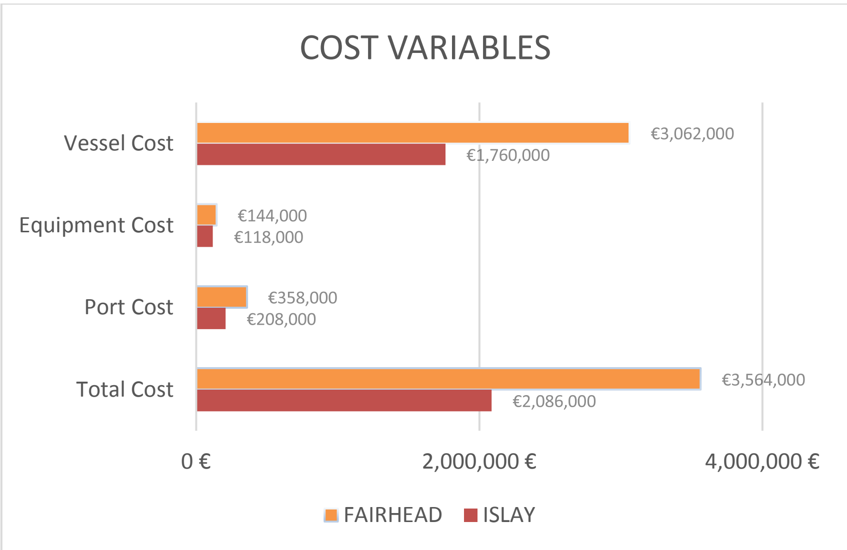


Figure 4-41- Installation cost comparison between the different location scenarios for installation of devices.

As before, a reduction in time permits to reduce the overall cost of the operation.

Installation of Electrical Components:

<u>Installation of Export Cables:</u>

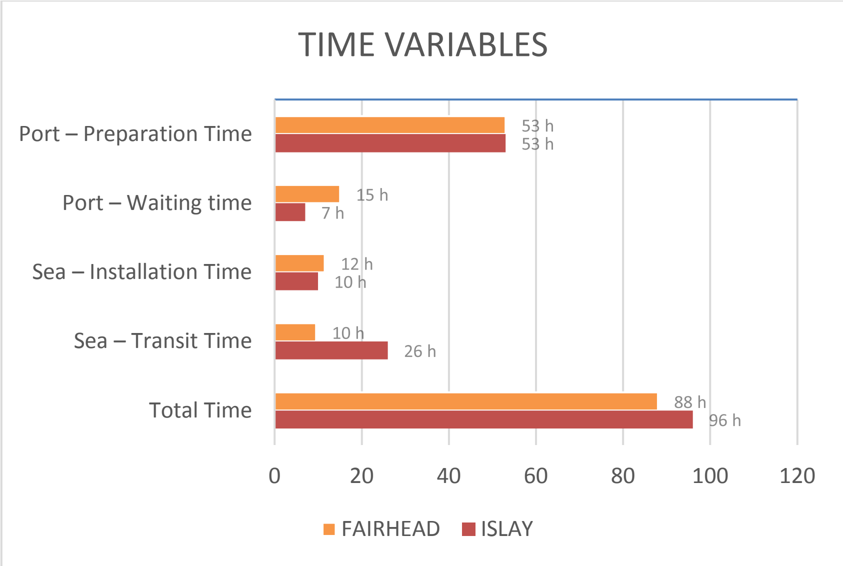


Figure 4-42- Installation time comparison between the different location scenarios for installation of export cable.

In this case the same vessel (CLV [9]) and equipment (Split Pipe [1]) are used therefore the different in times are solely due to difference in the distance to the port and to the different soil type, resulting in a small total time difference between the two scenarios.

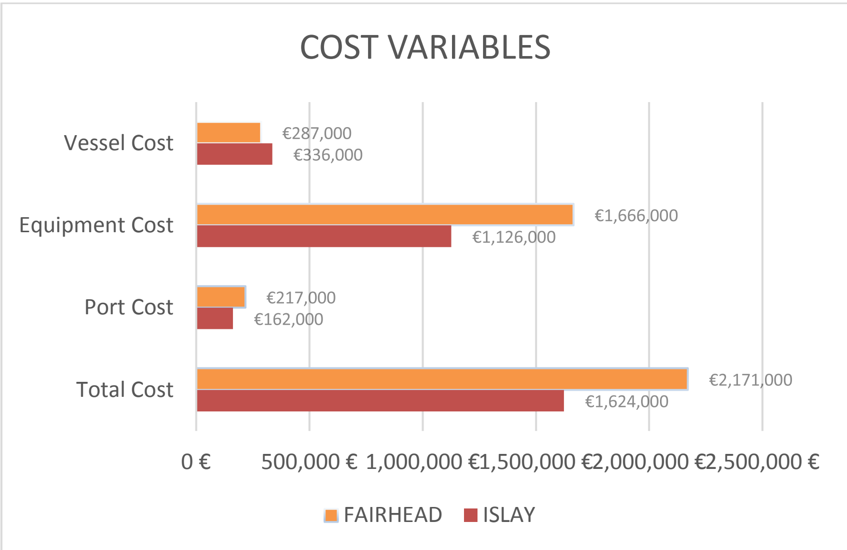


Figure 4-43- Installation cost comparison between the different location scenarios for installation of export cable.

Although the increase in the vessel cost due to bigger transit time, the reduction in operation time reflects in a reduction in the equipment cost and in the end, in a reduction in the total cost.

Installation of Inter-Array Cables:

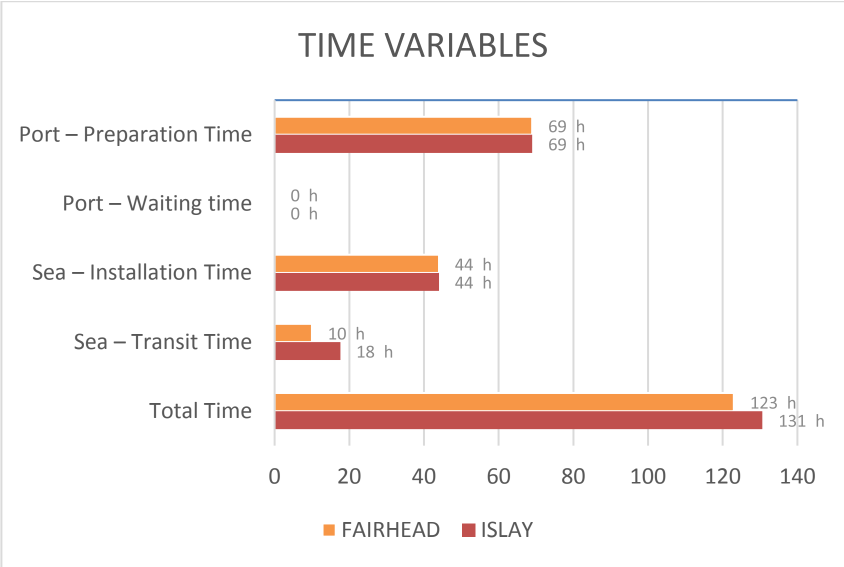


Figure 4-44- Installation time comparison between the different location scenarios for installation of inter-array cables.

As before, the same vessel and equipment (CLV [9] and Split Pipe [1]) and the only difference seen is in the transit time due to the bigger distance between port and installation sites.

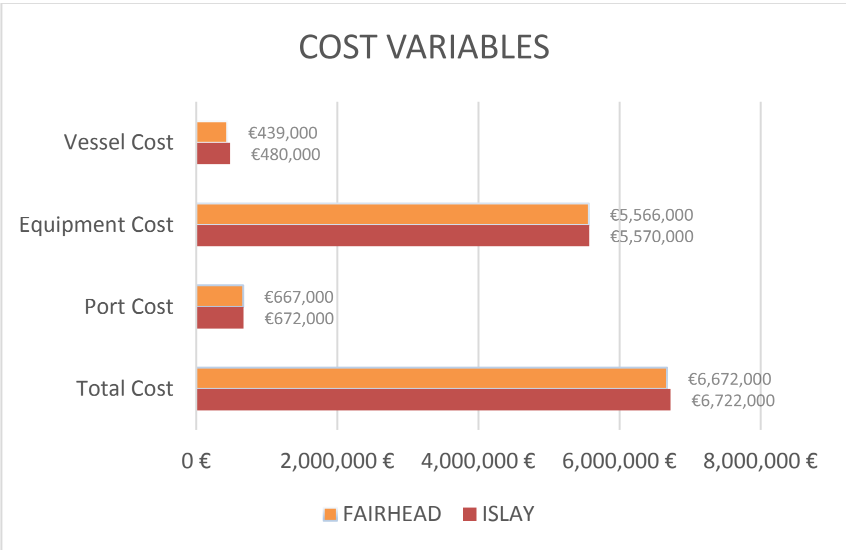


Figure 4-45- Installation cost comparison between the different location scenarios for installation of inter-array cables.

The bigger difference in cost is due to the vessel cost related to the bigger transit time.

Installation of Surface Piercing Substation:

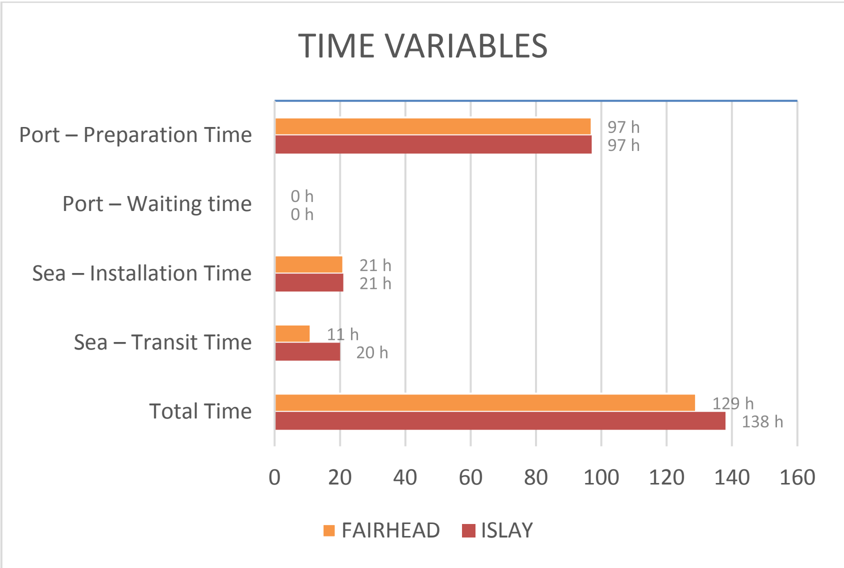


Figure 4-46 - Installation time comparison between the different location scenarios for installation of surface piercing substation.

For this case the only difference is in the transit time due to the different distance port-site, since the same vessel is used (JUP vessel [30]).

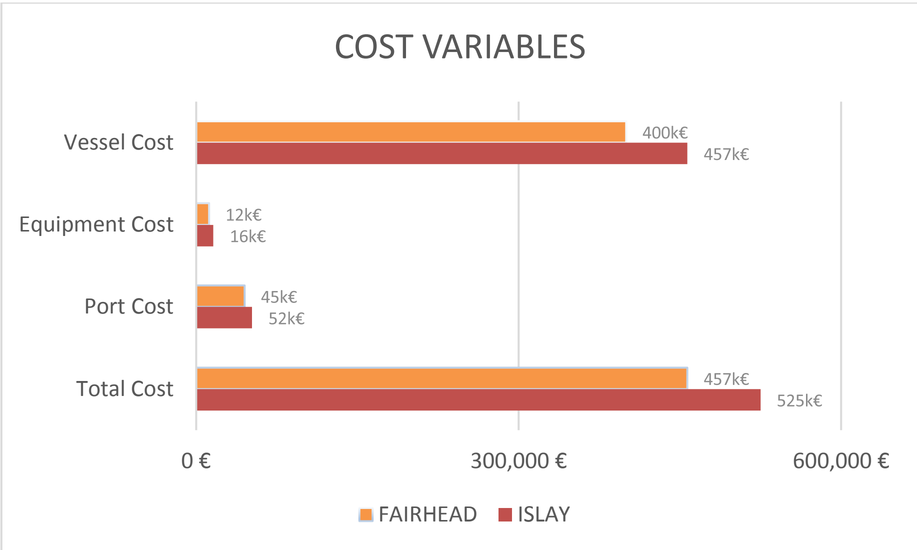


Figure 4-47- Installation cost comparison between the different location scenarios for installation of surface piercing substation.

The increase in transit time mentioned before explains the difference in the total cost. The increase in transit time leads to an increase in vessel cost, and in the end, of the total cost.

Overall Installation:

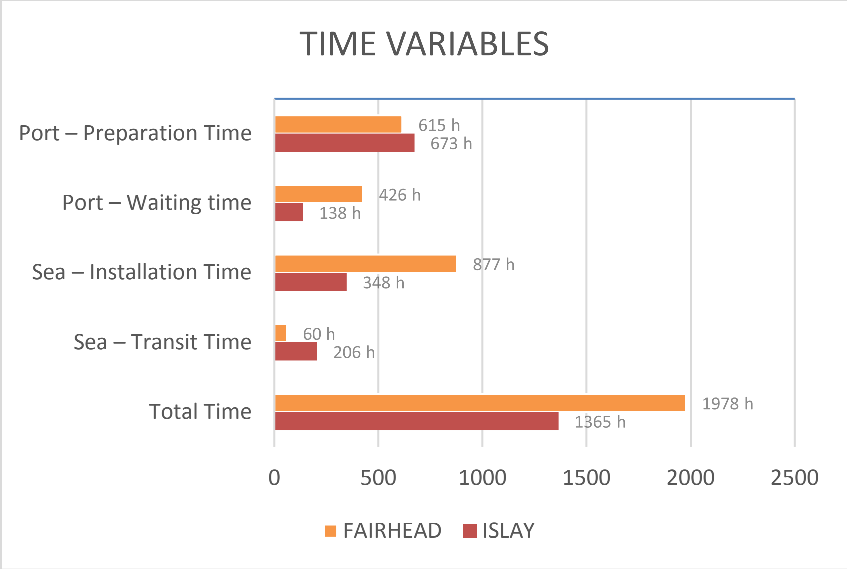


Figure 4-48- Installation time comparison between the different location scenarios for the overall installation Sound of Islay scenario.

Finally, in terms of the overall installation times I can be seen that there is an overall reduction in the time, mainly due to a decrease in the waiting and the installation times. This can be explained by less severe weather conditions and the use of faster installation techniques depending on soil type. On the opposite site, an increase in the total transit time can be seen as a result of the increase in the transit times associated to each logistic phase, given the bigger distance between the port and the site.

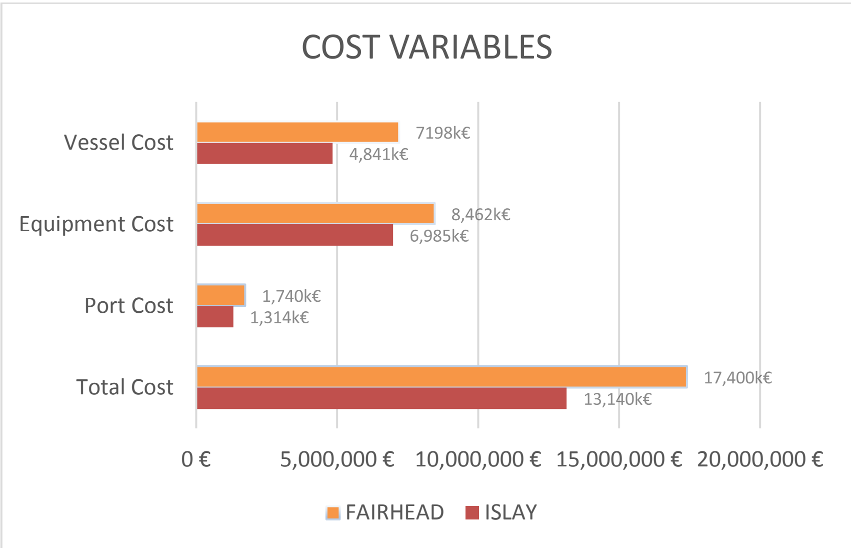


Figure 4-49 - Installation cost comparison between the different location scenarios for the overall installation Sound of Islay scenario.

As can be expected a reduction in the total installation time will ultimately represent a decrease in the total cost, which can be seen in Figure 4-49, is mainly due to the reduction in the total equipment but also vessel cost.

4.5.7 DEVICE TYPE

The two previous scenarios, FairHead and Sound of Islay, were for the installation case of fixed tidal turbines. Next, a scenario of ten floating devices in the Shetland location was performed, to assess the different logistic phases not covered in the previous scenarios.

Table 4-50- Indication of the different logistic phases specifically covered in the Shetland validation scenario:

Logistic Phase	**Validation Shetland Scenario**
Installation of wave energy devices	***Yes***
Installation of tidal energy devices	*no*
Installation of gravity based structures	***Yes***
Installation of pile foundation (driven/drilled)	*no*
Installation of mooring systems)	*no*
Installation of static export power cables	~~***Yes***~~ *no*
Installation of static inter-array power cables	~~***Yes***~~ *no*
Installation of dynamic power cables	*no*
Installation of offshore collection points	~~***Yes***~~ *no*
Installation of external cable protection	~~***Yes***~~ *no*
Installation of support structure	*no*

An interesting result of this scenario is that for the case of array cables, a no solution output is obtained since the port selected by the module (port of Ågotnes, Norway with a distance of 363 km) is not capable to handle any of the feasible vessels required for this operation (CLV or CLB with DP>1). This occur since the port is selected considering only the characteristics of the elements to be installed, since the vessel to used is not known. It happens, that in this case, the vessels length is always bigger than the chosen port terminal length.

In this scenario, the user is advised to enforce that a different port is selected by manipulating the port database. This way it can be ensured that a solution is found. The user can either remove this port to see if another port that gives a solution is chosen, or can just remove all other ports than the port it wants to use, which will then necessarily by the selected port for installation.

The following figures summarize the remaining results for this scenario, without the installation of electrical components.

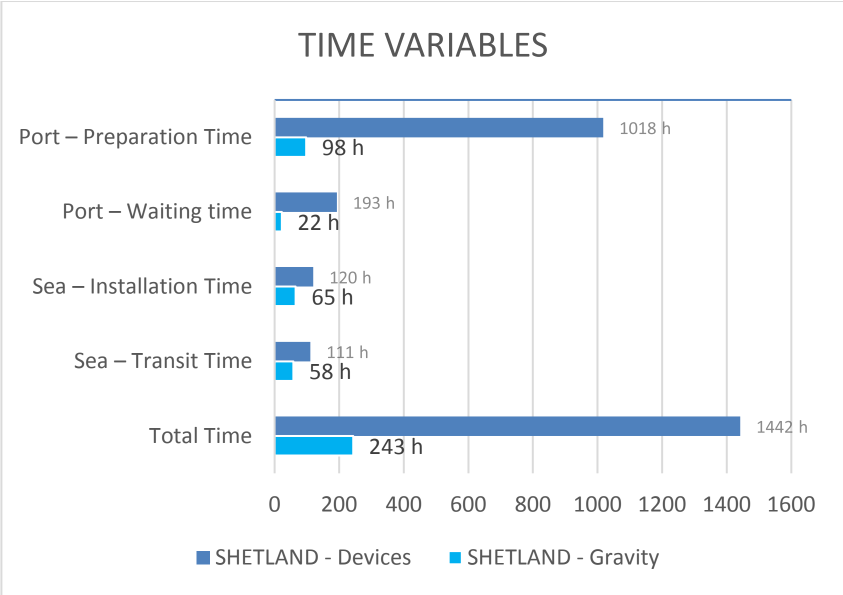


Figure 4-51- Installation time for the Shetland scenario.

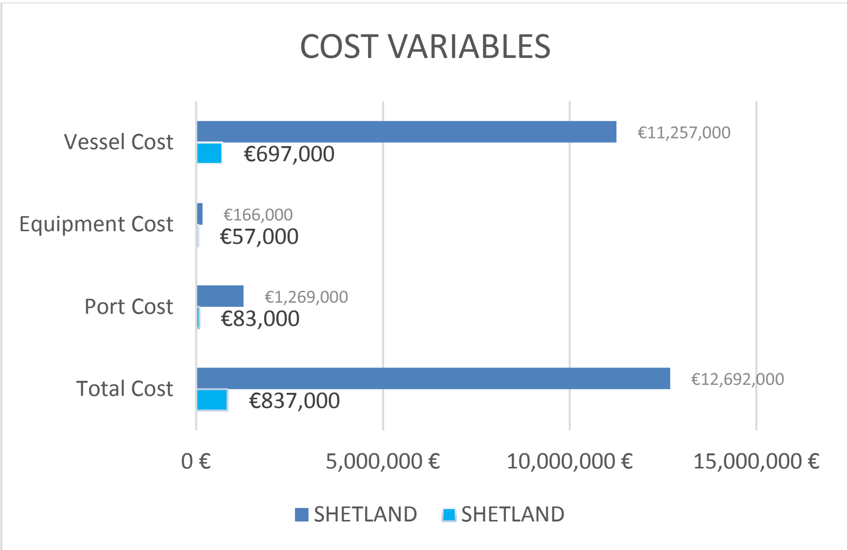


Figure 4-52- - Installation cost for the Shetland scenario

Although the testing performed strengthens the maturity of the logistic functions by reducing the likelihood of unexpected bugs, it does not pretend to cover all scenarios possible by any means. It also shows that the user may require to manipulate the database and other of the inputs to ensure that solutions will be found. The sensitivity also proves the possibility to benchmark alternative scenarios and logistic solutions.

5 CONCLUSIONS

In this document, the path toward the construction of the logistic functions and the installation module forming part of the DTOcean global tool is detailed. Both the workflow and the underlying assumptions considered when developing the code have been presented. Analytical and schematic description supports the understanding of the methodology which has been developed.

The use of the logistic functions through the installation module has also been illustrated. A comparative exercise with a high-level assessment of a maritime contractor involved in the tidal energy sector demonstrates the validity of the approach implemented as an early-stage decision-supporting planning numerical tool.

The installation module together with the O&M module which encompasses the logistic functions can serve as a useful tool to have a perception on the impact of novel components, processes or infrastructure. In particular, the following aspects could be investigated:

- Impact of using tailored components designed for the ocean energy sector such as novel wet-mate connectors or simple plug-in mechanical hook-up systems for attaching a floating device to its pre-laid mooring system.
- Impact of employing alternative equipment and on-board tools such as vibro-drivers and upending tools for installation of driven piles or underwater robotic arms for manipulation of mooring lines or umbilicals
- Impact of introducing fit-for-purpose vessels by looking at aspects such as the weather risk (workability), transit speed versus fuel consumption and multi-tasking capabilities (especially if one vessel can be used for several logistic phases instead of having the need to have a specialized vessel for each marine operation)
- Impact of various solutions for the process of a given marine operation. Alternative task sequencing of operations at sea can be tested or alternative number of vessel journeys among other variations
- Impact of various O&M strategies by looking at the shared-use of maritime infrastructure or at the possibility to acquire service vessels instead of hiring or using a mothership etc…

To carry out the suggested studies above, one should not only collect the required data but also, in some cases, develop new or adapt existing logistic phases which have been coded in the first release of the DTOcean suite of design tools (i.e those described under Chapter 2). For this reason, a sound understanding of the underlying program is almost indispensable.

Given the wide scope of potentially valuable feedback the suggested studies may offer, learning how to become an advanced user of the installation and O&M module can, in turn, benefit various profiles, including:

- Enabling-technology developers and OEM; in setting minimum performance targets or in promoting the benefit of their technology
- Maritime contractor; in discriminating between alternative logistic solutions (preliminary competitors' study) or in understanding the influence of different logistical and contractual strategies on their customers
- Shipbuilding companies; in identifying the needs of the ocean energy sector in terms of maritime infrastructure

- Insurance companies; in evaluating the risk associated with the logistic operations at early-stage of planning
- Project developer and O&M service providers; in de-risking and planning their projects/services

In the first release of the DTOcean global tool, the module developers have identified areas of improvements which could enhance the capabilities or the accuracy of their own module. Regarding the installation module (and concurrently the logistic functions too), several upgrades or new features can be proposed:

- On the "user flexibility": the programming structure of the logistic functions has been made in an effort to be versatile for adaptation and creation of new logistic phases. Therefore, an advanced user could, with the help of the supporting documentation such as Deliverables 5.6 and the technical manual adapt existing or create new logistic phase responding to the specific requirements he/she intends to simulate. An effort to give easy access of such features by direct manipulation of the GUI would also add flexibility. In particular, giving the opportunity to the user to provide his/her own prescribed logistic solutions (with personal daily-rate quotations for instance) would also significantly enhance the ease of
- On the "feasibility" functions: the scope of the feasibility functions has been purposely restricted to basic physical check requirements (e.g lifting capacity, deck space etc…) in order to avoid eliminating too many vessels, ports or equipment's for reasons that could easily be circumvented with proper planning and engineering. In case, the logistic functions are intended to be used after a more detailed engineering study, refined logistic functions could be developed. For instance, pile driving equipment selection could be the result of a geotechnical analysis of the pile specifications and geotechnical properties at site. Other enhanced feasibility functions could be developed for the bollard pull requirement and for the consideration of more complex vessel's deck arrangements of components/equipment, for example.
- On the "port selection" and "vessel transit distance" functions: among the feasible ports, the base port for installation is selected as the nearest to the entry point of the lease area. However, the no-go zones between these feasible ports and the entry point have not been considered. This could be implemented with the view to obtain a more realistic path for the vessel route from port to site. In the long-term, one may even envisage to feed live vessel traffic (through AIS system) information to simulate the vessel routes and predict more accurately the transit time.
- On the "time assessment per operation" functions: many logistic operation assumes a default value which can be provided by the user. However, more sophisticated scheduling functions could be developed in a similar fashion than the proposed enhanced feasibility functions above. For instance, pile driving and cable laying time could make use of more site and tool equipment data to refine the estimated speed rate of accomplishing the work.
- On the "weather window" function: although the first release version of the installation module already features a relatively advanced weather window algorithm, complementary factors could be taken into account. First of all, instead of assuming that the most stringent Operational Limit Conditions (OLC) must be satisfied for the entire time spent at sea, the weather window function could consider that the OLC should only be satisfied during their corresponding tasks while allowing a marine operation being interrupted (for example the vessel could "secured" a safer position permitting less restrictive OLC to wait for the wind or wave conditions to become favourable) for a chosen period of time if need be. It should be

noted that this “dynamic” interpretation of the OLC with possible interruption have been developed by WavEC Offshore Renewables. Nevertheless, due to time constraints related to the testing, verification, validation and integration of the installation module into the full suite of DTOcean design tools it could not be released in the first version of the software package. Additionally, historical time-series met-ocean data could also be randomized using forecasting techniques to better reflect projections of future conditions at the site. Directionality of met-ocean parameters could also be taken into account. Finally, further statistical results could be exploited from the weather window functions to present a more comprehensive view of the weather risk to the user.

- On the “vessel cost” and “equipment cost” function: here more detailed breakdown of the cost factors leading to the daily-rates of usage and other fixed fees could be implemented to echo the contractual terms typically stipulated under Engineering, Procurement, Construction and Installation (EPCI) and Original Equipment Manufacturers (OEMs) agreement. Alternative chartering strategies could also be implemented
- On the “port cost” calculation: due to the large diversity of costing methods throughout the European ports, the first release version of DTOcean simply takes a percentage of the expenditures at sea (due to vessels and equipment). This could also be replaced by a more aggregated approach trying to reflect the main approaches to consider when estimating the port charges a project developer will be subject to.
- On the “optimization method”: in a first approach, it was decided to apply the optimization routine on a logistic phase per logistic phase basis. In other words, the optimal logistic solution try to optimize use of same vessel for different operations
- Developing dedicated “procurement and port management” functions;
- Developing tailored-made “logistic risk” functions: while originally envisioned to be part of the first release of the DTOcean tool, several constraints have prevented the implementation of dedicated logistic risk functions as part of the overall logistic functions (see section 2.12 of Deliverable 5.6). However, the framework for the development of algorithm quantifying the risk value associated with marine operations has been documented in this section 2.12 of Deliverable 5.6.

The above list of suggested upgrades for the logistic functions does not pretend to be exhaustive. Depending on the profile of the end-user and the objectives sought when using these early-stage decision-supporting numerical tools, alternative directions of modifications of the logistic functions may be more relevant. One key advantage of the DTOcean software package is its open-source nature. This gives shared-access to the wider community to directly build upon existing programming code. There are at least two fundamental interrogations to be weighted when developing further the logistic functions:

- Tradeoff between “user requirements” - how much burden is acceptable for the user in terms of input data provision? And, “flexibility of the tool” –
- At which project planning and development stage does the tool should be useful?

For instance, let us imagine that an advanced user would like to improve the tool in a way that it would be better suited for short-term planning of marine operations, i.e a few hours/day before going to sea. In this situation, a detailed engineered planning is likely to be known notably in terms of procedure and infrastructure envisioned for a given marine operation.

In terms of weather window predictions, it can be envisaged to couple time-series delivered by multi-body dynamic simulations of offshore operations with:

- actual working restrictions physically meaningful derived from existing standards (e.g maximum accelerations tolerated during personnel transfer or maximum tension variations during lifting)
- actual weather forecasting data for the site considered.

Uncertainties associated to these parameters (e.g weather forecast and could also be accounted for. While such an upgrade would require an in-depth re-shaping of the presently implemented weather window function, the structure of the overall installation and O&M modules can still serve as a useful basis for making this effort.

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7 **APPENDICES**

7.1 INSTALLATION MODULES FLOWCHARTS

7.1.1 Device Installation Sequence

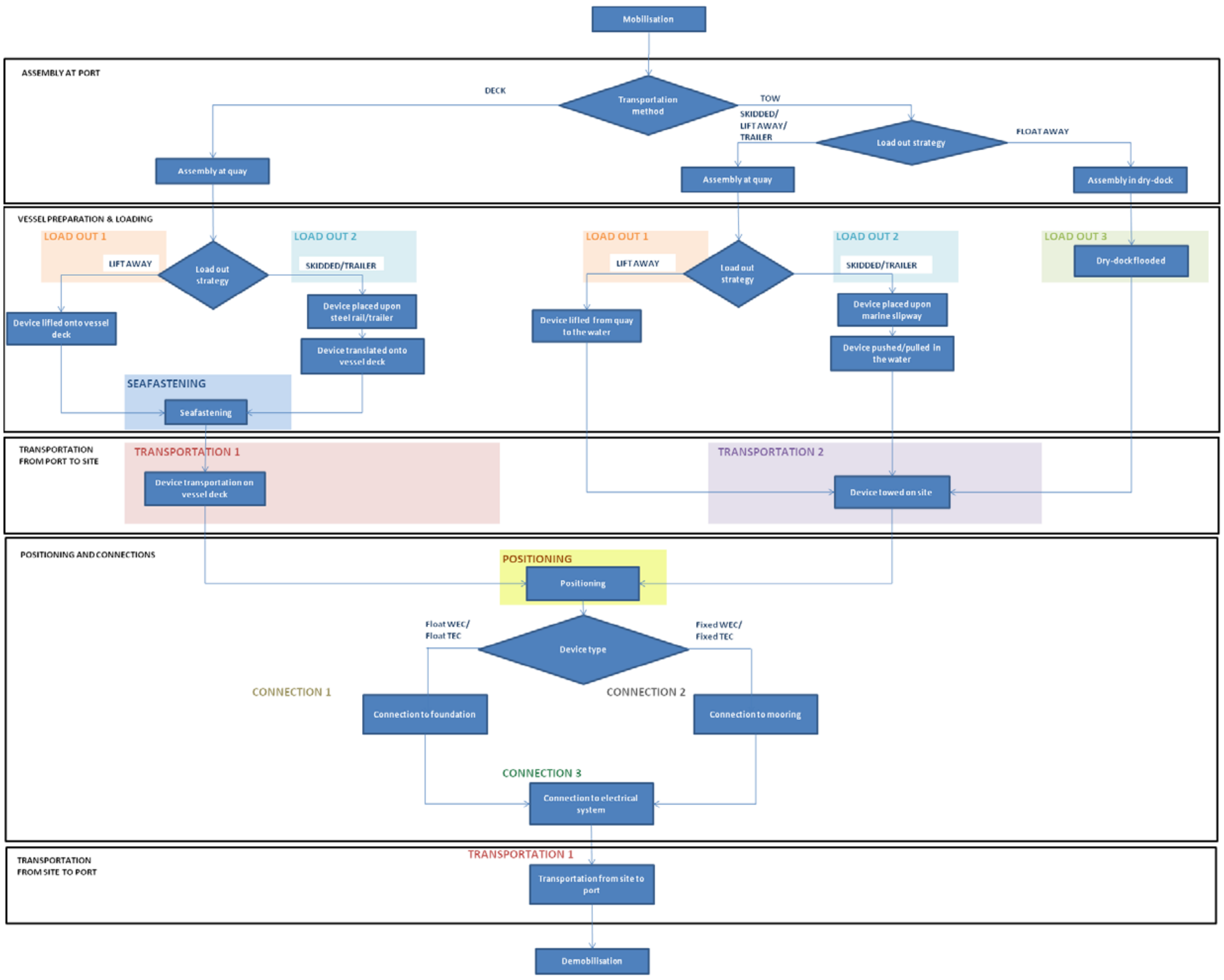

Figure 7-1 Operation Sequence for the installation of devices

7.1.2 *Mooring Installation Sequence*

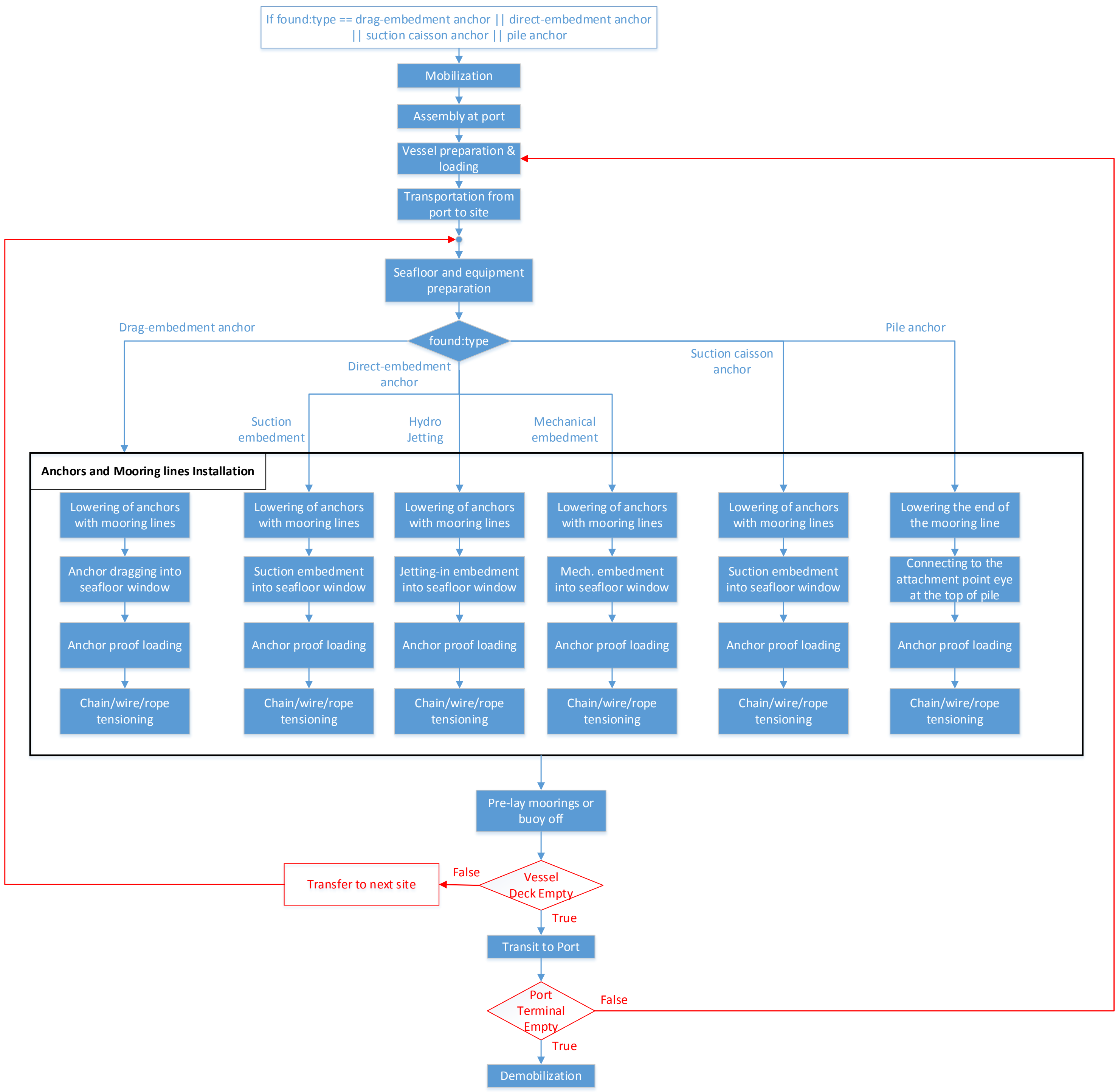

Figure 7-2 Mooring installation operation sequence

7.1.3 Gravity Based Structure Installation Sequence

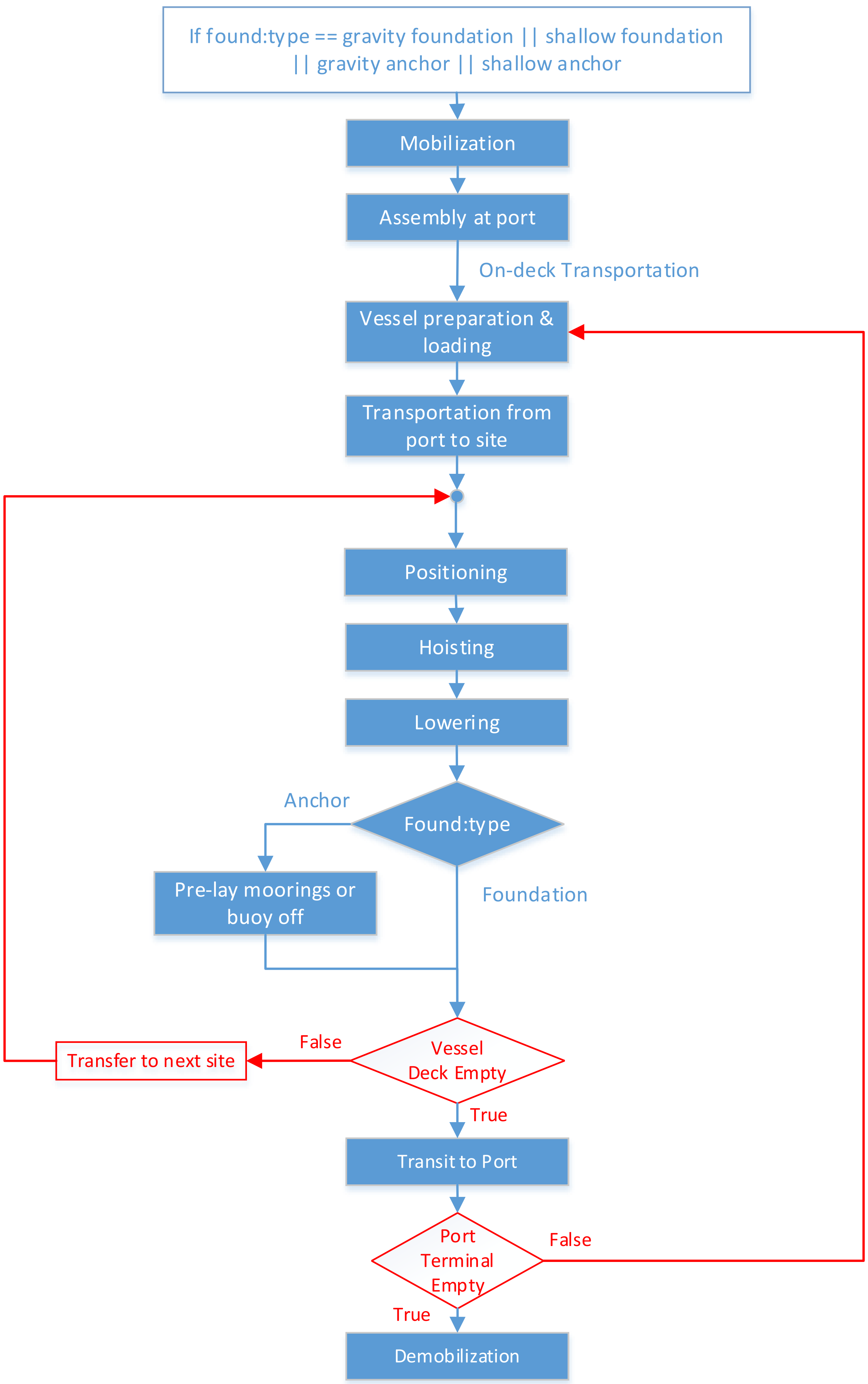

Figure 7-3 Gravity based structure installation operation sequence

7.1.4 *Driven Pile Installation Sequence*

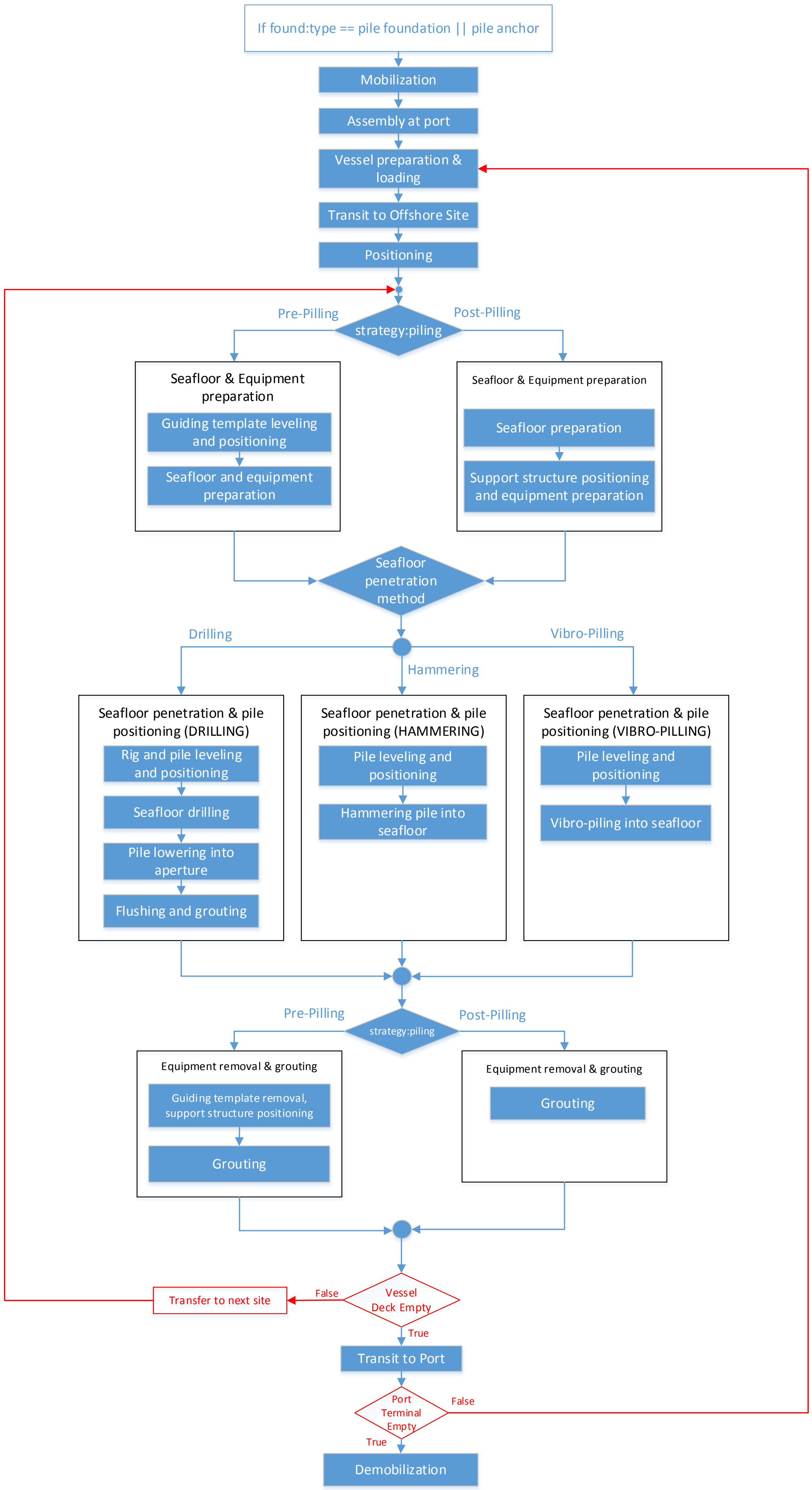

Figure 7-4 Driven pile installation operation sequence

7.1.5 *Static Export Cable Installation Sequence*

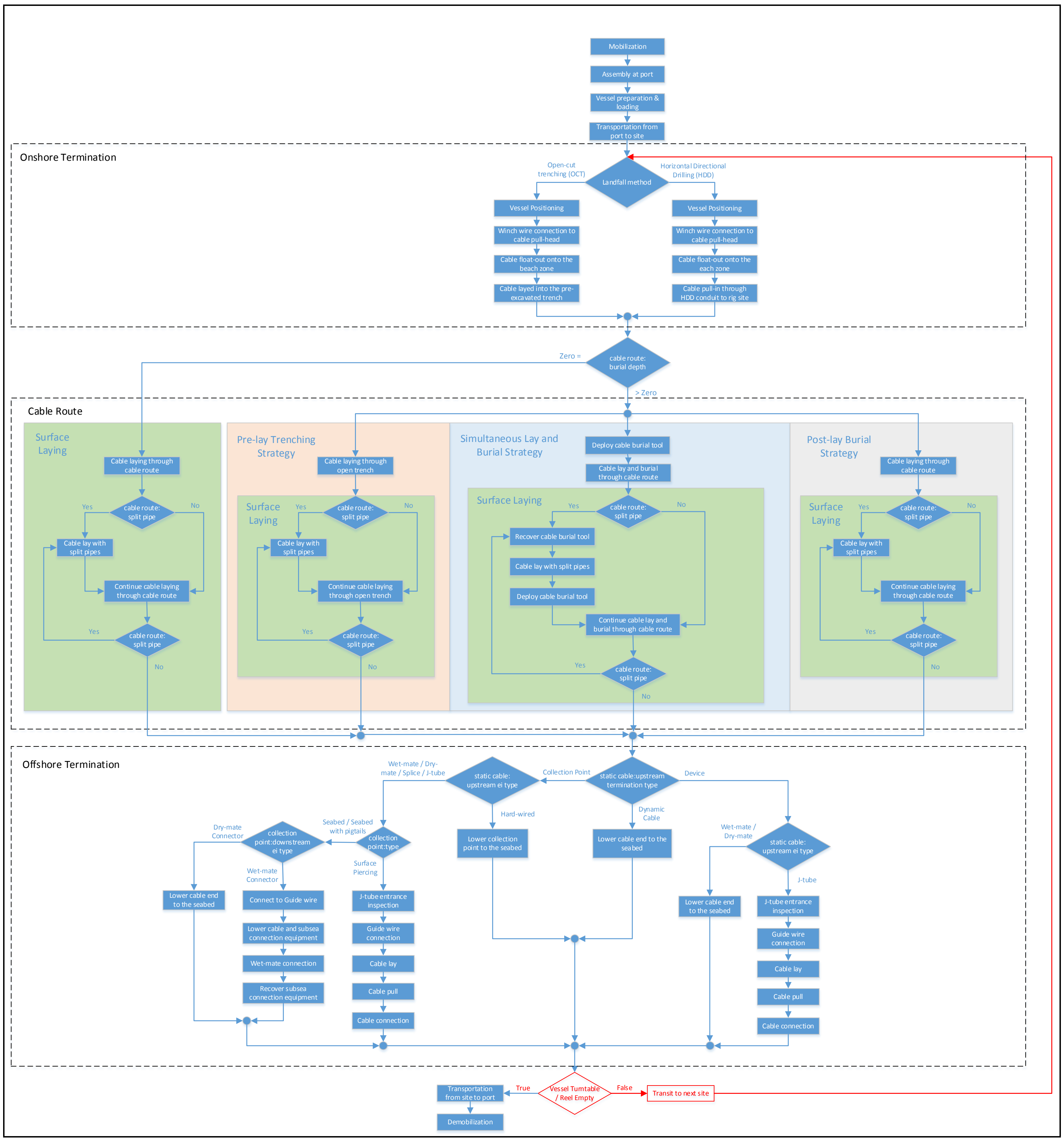

Figure 7-5 – Static Export Cable laying operation sequence

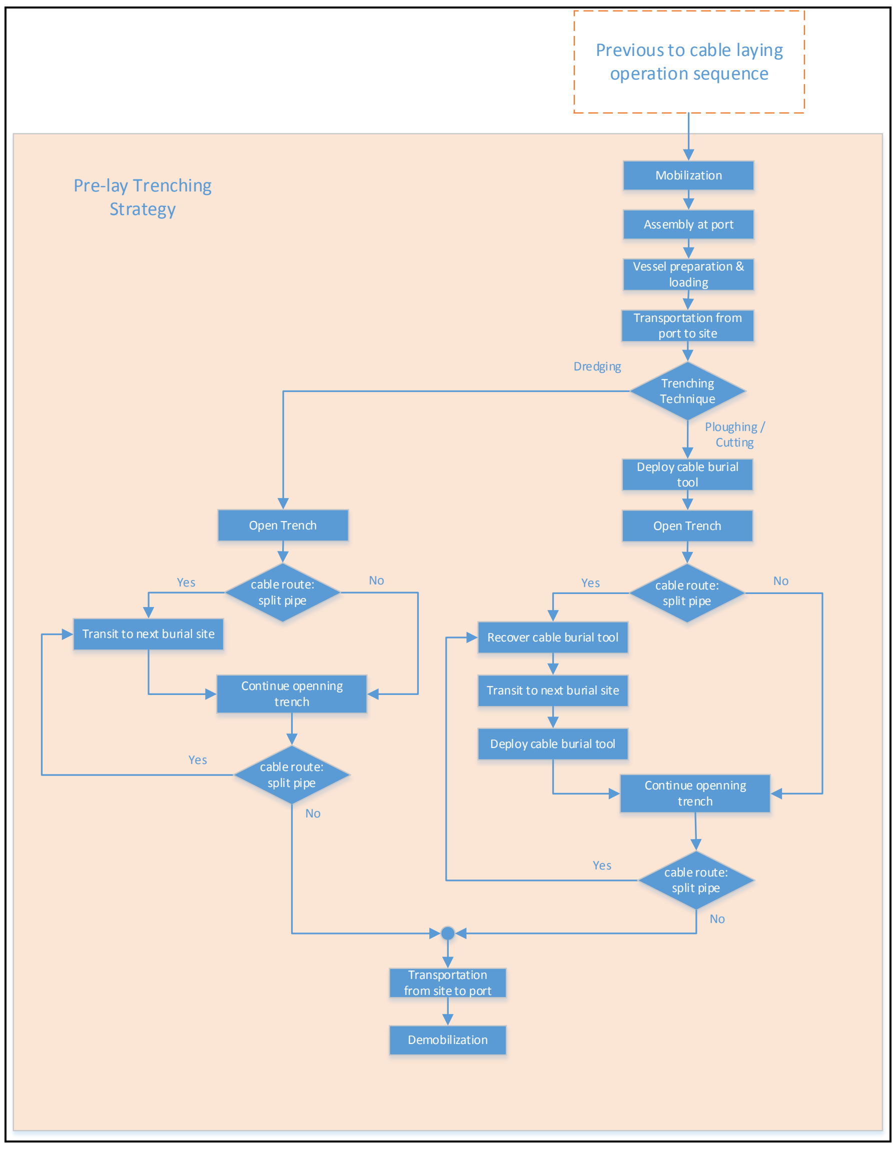

Figure 7-6 – Operation Sequence required by Pre-lay Trenching Strategy before cable laying

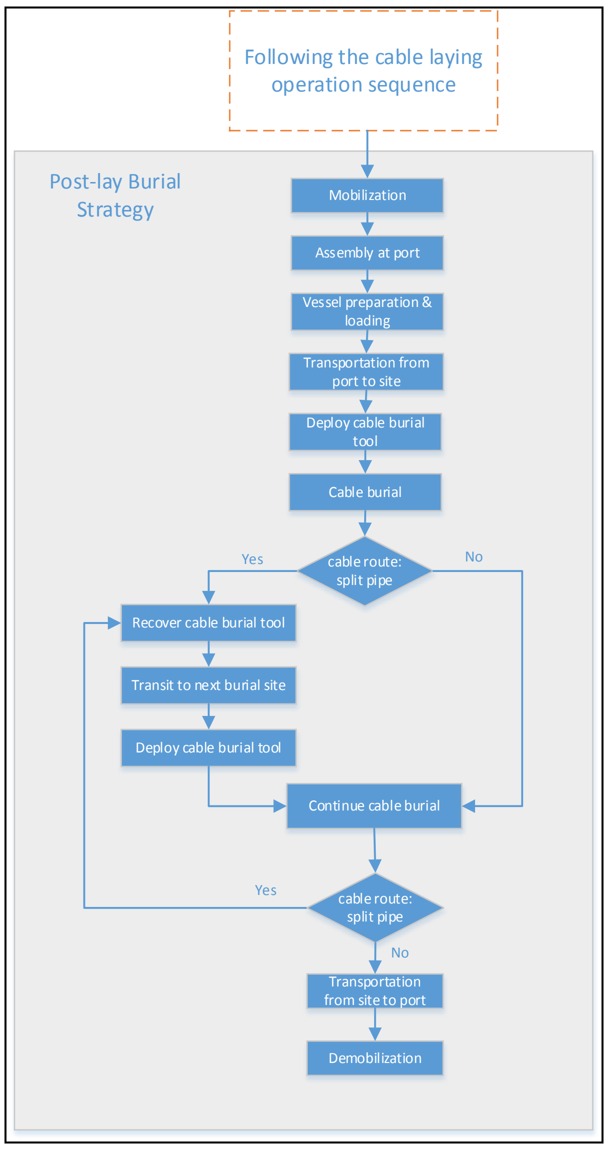

Figure 7-7 - Operation Sequence required by Post-lay Burial Strategy before cable laying

7.1.6 Static Array Cable Installation Sequence

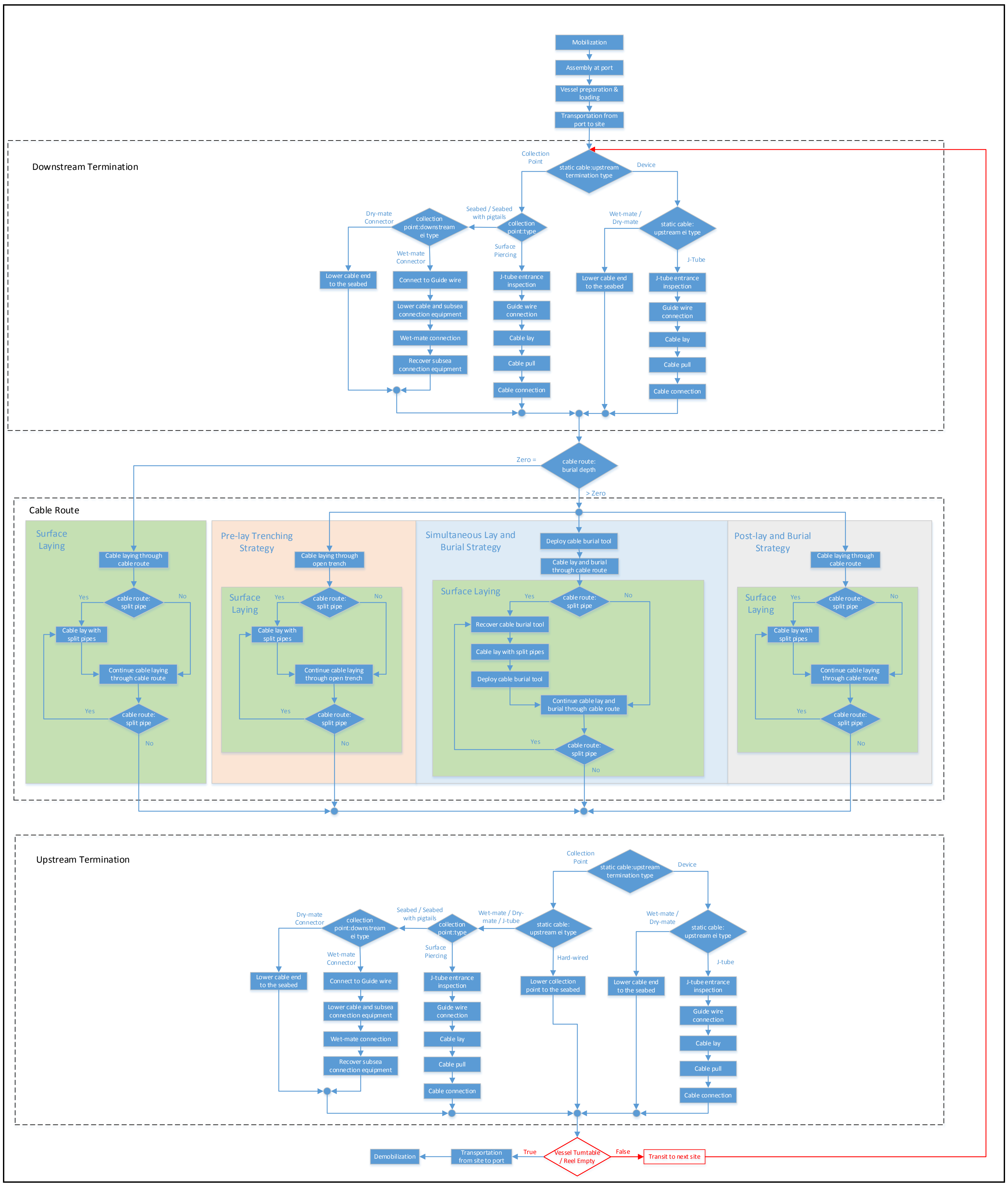

Figure 7-8 - Static Array Cable laying operation sequence

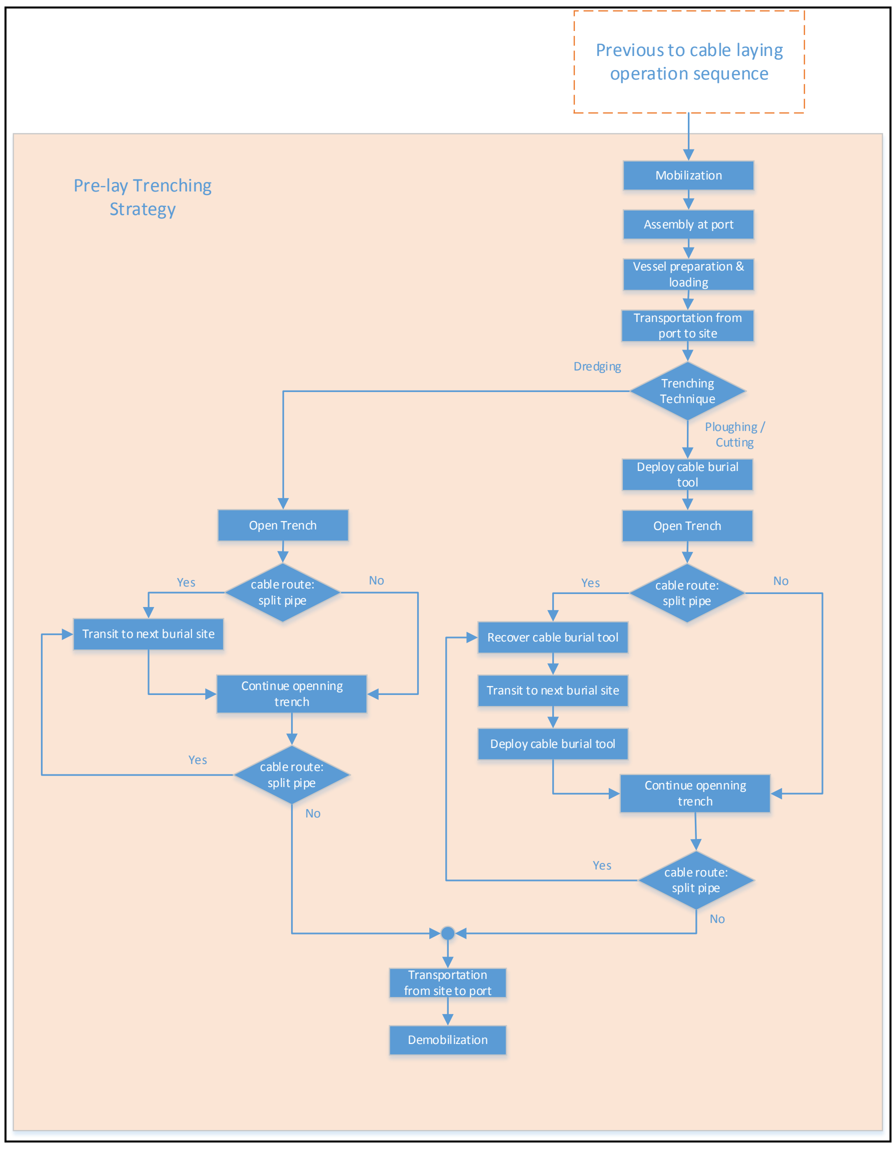

Figure 7-9 – Operation Sequence required by Pre-lay Trenching Strategy before cable laying

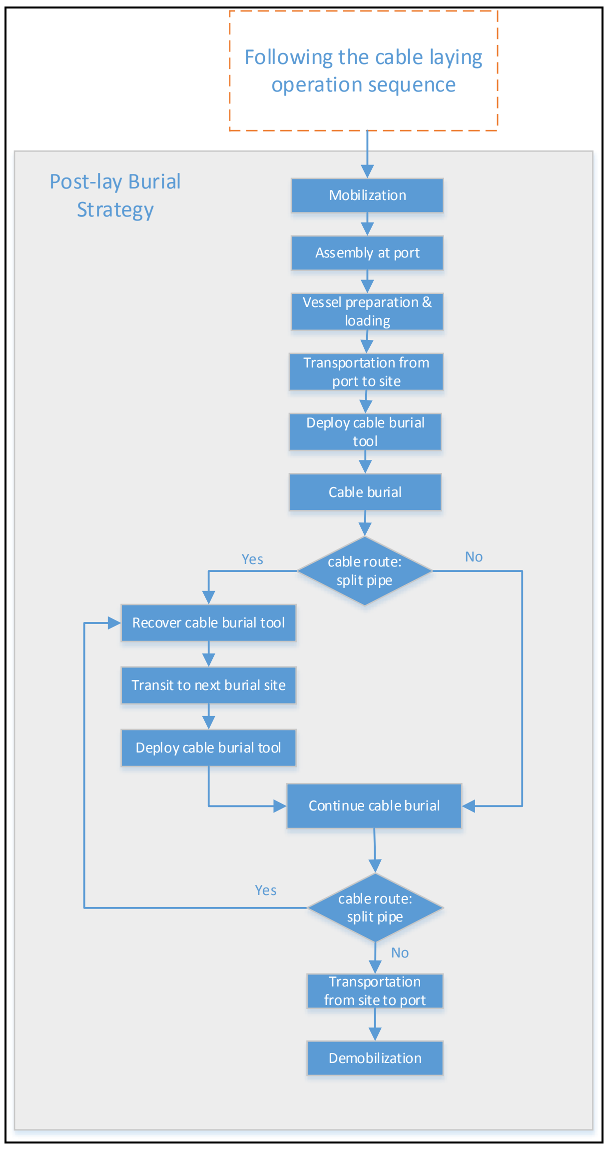

Figure 7-10 - Operation Sequence required by Post-lay Burial Strategy before cable laying

7.1.7 *Dynamic Cable Installation Sequence*

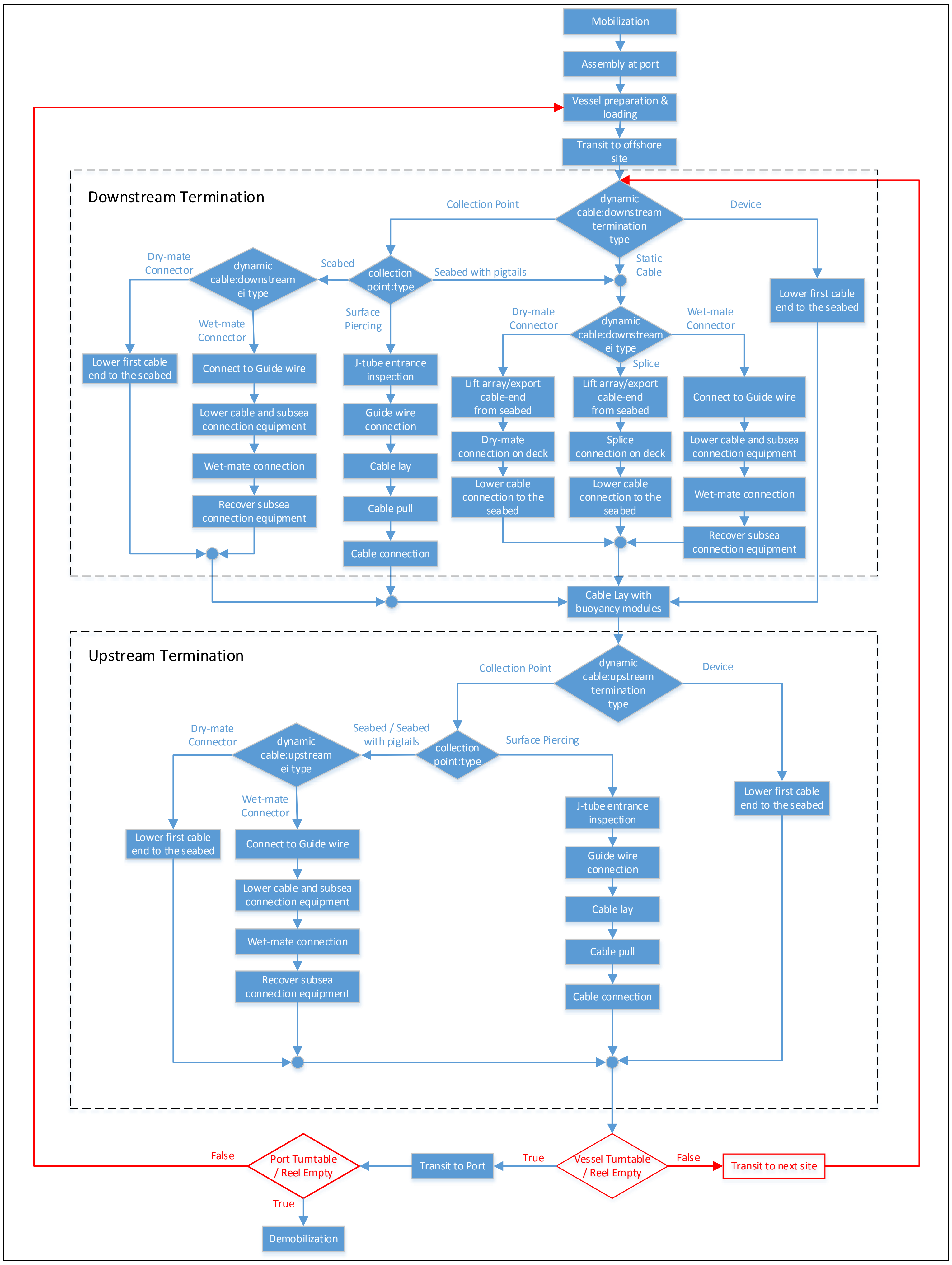

Figure 7-11 – Dynamic cable installation operation sequence

7.1.8 Collection Points Installation Sequence

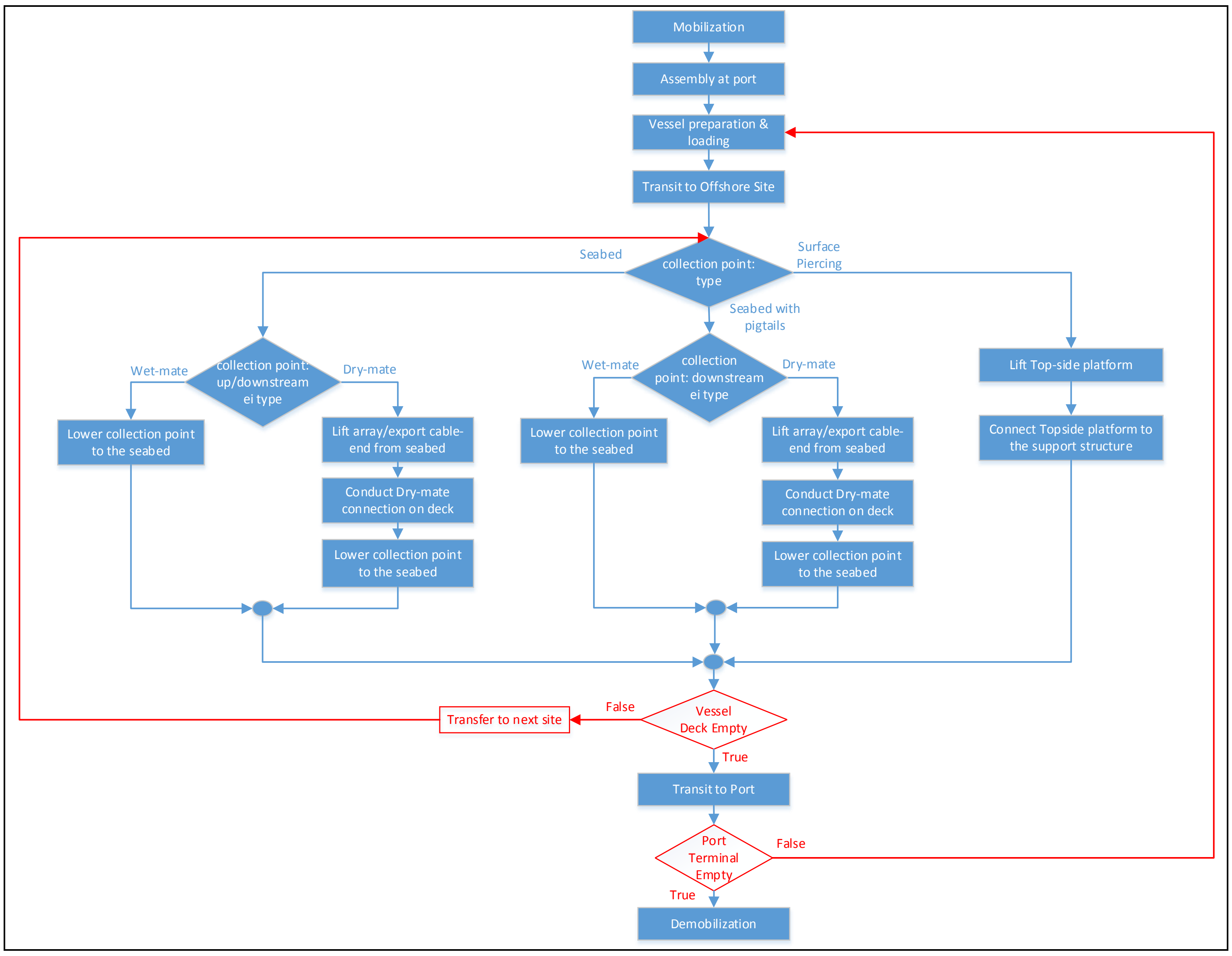

Figure 7-12 – Collection Point installation operation sequence

7.1.9 External Cable Protection Installation Sequence

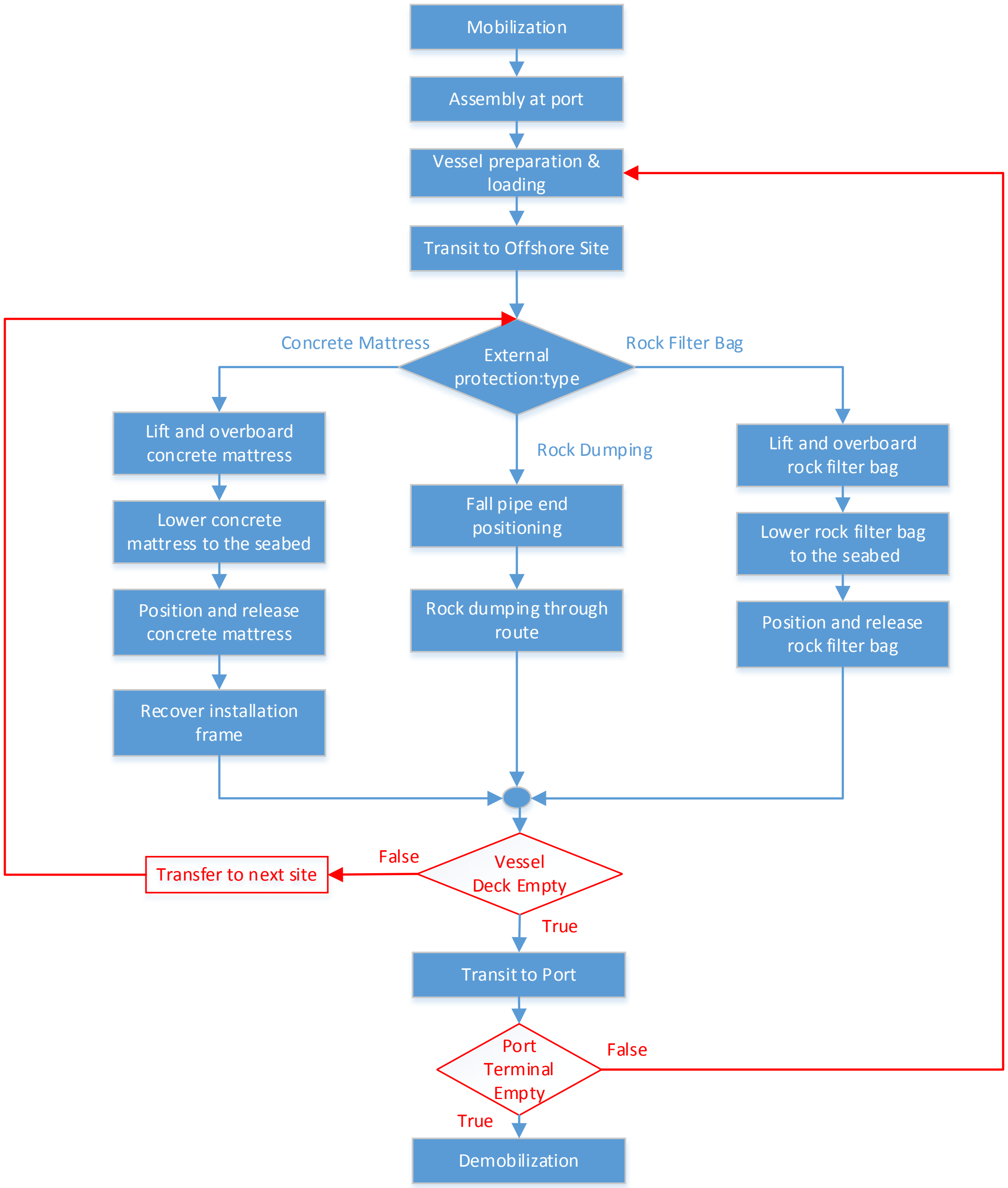

Figure 7-13 External Cable Protection installation operation sequence

7.2 DISTANCE CALCULATOR ALGORITHM

The ship routing routine is used to calculate distance between two points connected by sea. This is used in the port installation routine to assess the closest feasible port and also in the performance routine to assess the time required for a vessel to travel between two coordinates.

The implementation of this routine required data of the European coastline, which was obtained using ArcGis data, with a given grid resolution. Data consisted of latitude and longitude coordinates of every point in the grid that consisted of sea mass point. The scope of the grid was such to encompass the entire European coastline including Island (see Figure 7-14). The resolution was set as 0.04 differences both in latitude and longitude.

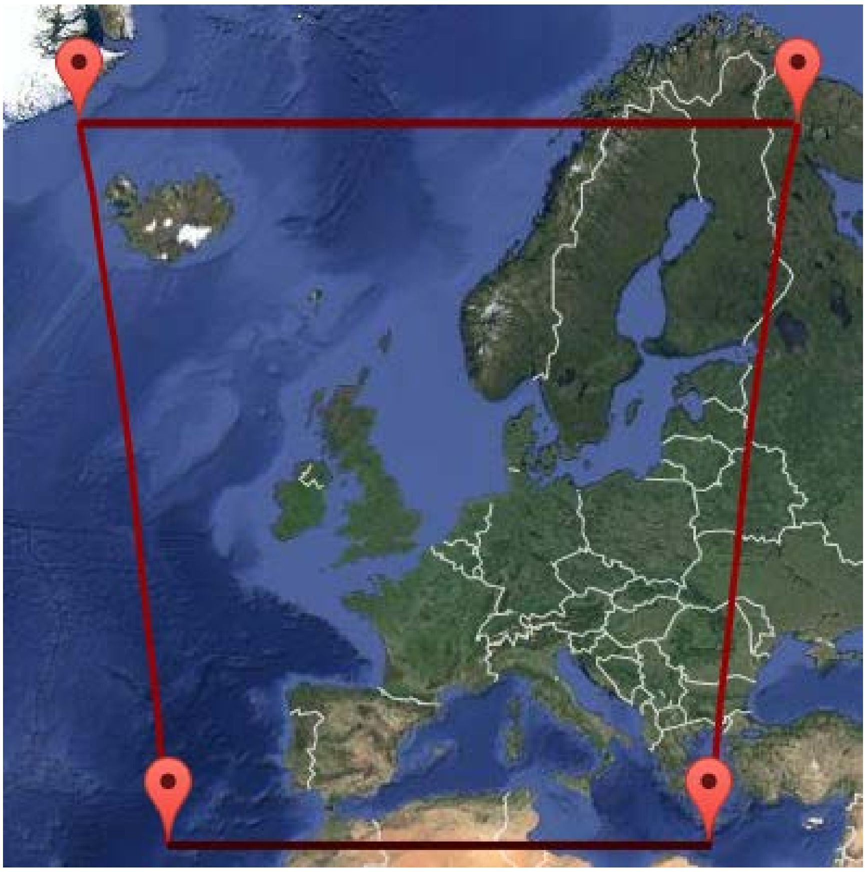

Figure 7-14 Scope of the grid for the ship routing algorithm problem

This data points were then implemented in the form of a graph, a Python structure of the *networkx* Python package, transforming each data point to a node with a connection, if so existing, to the nearby nodes of the grid.

Two different graph neighbour definitions were used: a four-direction and a eight-direction graph (see Figure 7-15). This two are compared in terms of computational time and distance accuracy when compared to available data of travel distance between ports.

To calculate the optimal path between two points the *dijkstra optimization algorithm* is used through the *dijkstra_path* library of the *networkx* Python package, which returns a list containing the points which comprise the shortest route.

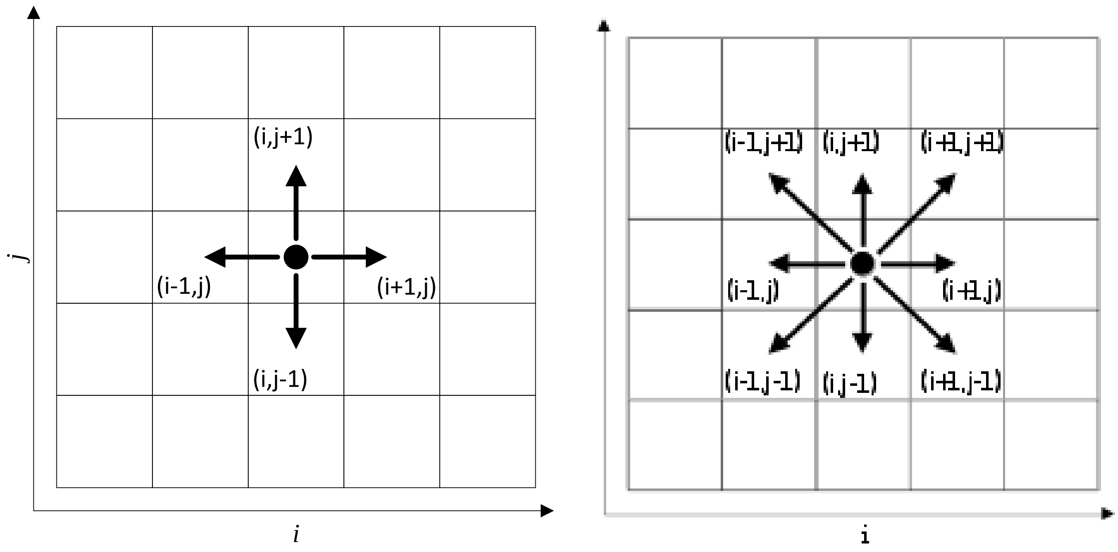

Figure 7-15 Creation of the graph based on connections between sea points.

In Figure 7-16 and Figure 7-17 the comparison of results of a case example test between the port of Barcelona, Spain and the port of Dundee, UK is presented. The impact in the obtained route and respective route length can be seen.

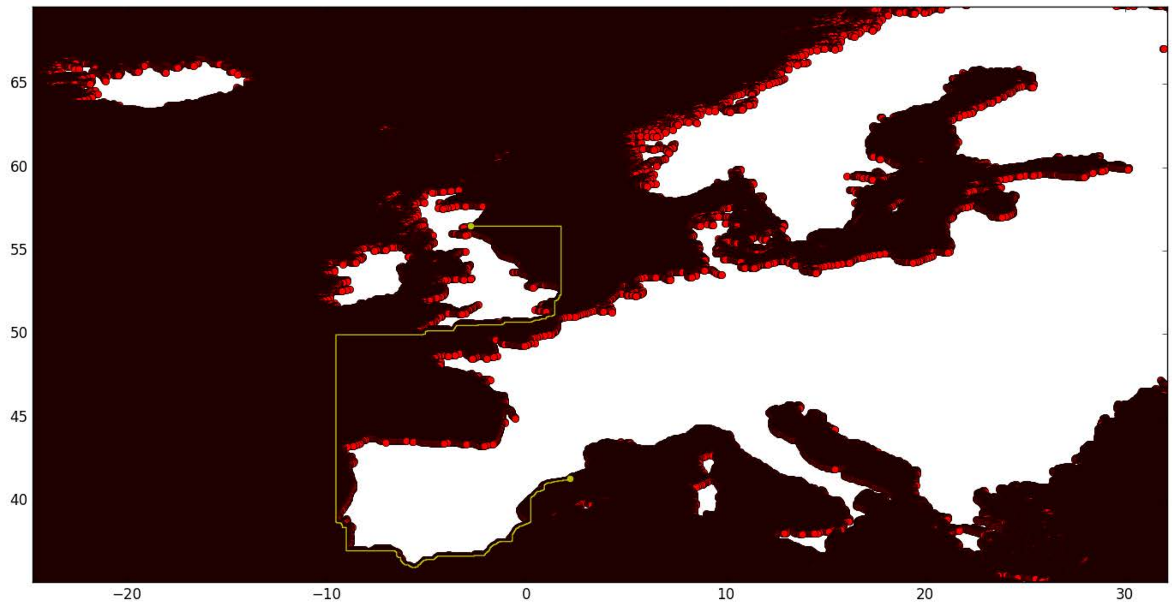

Figure 7-16 Route shipping connection between the port of Barcelona and the port of Dundee for the four-direction graph.

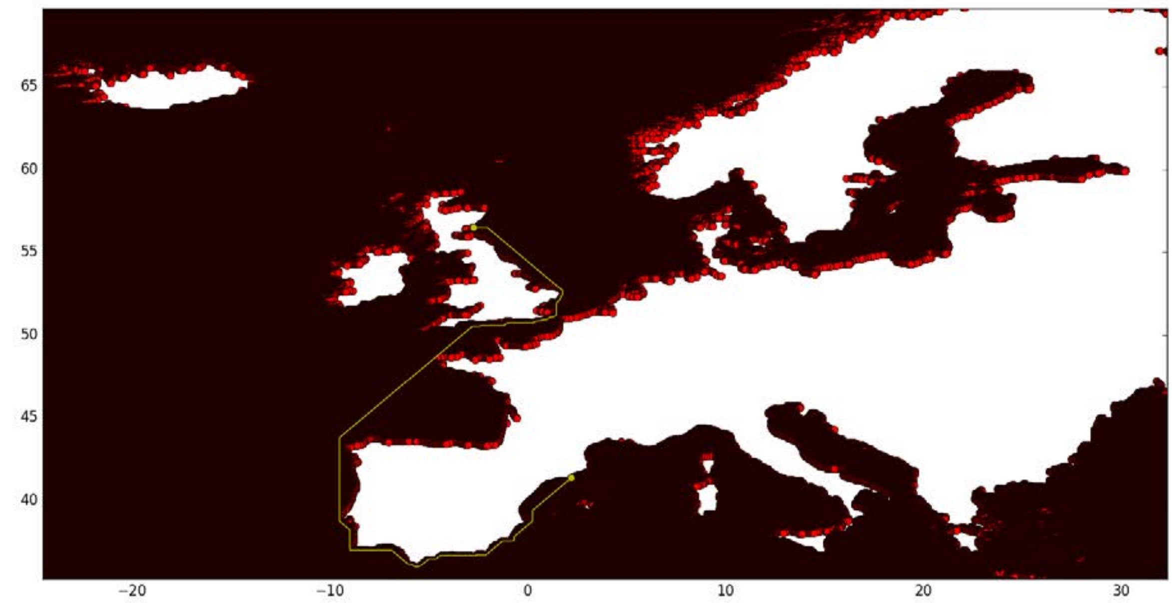

Figure 7-17 Route shipping connection between the port of Barcelona and the port of Dundee for the eight-direction graph.

The routine was tested using the *timeit* Python module in order to assess the duration of the running of the code. The connection between different points also assessed and the corresponding distance and duration of the run analysed. Results for the test connection of different ports are summarize in Table 7-1 and Table 7-2**.**

Table 7-1 Route shipping connection between different ports for the four-direction graph

Origin	Destination	Distance[km]	Duration[s]	Ref.[km]	Diff[km]	Diff[%]
Sines	V. do Castelo	522	10	445	77	17,30
Sines	Barcelona	1810	18	1465	345	23,55
Dundee	Barcelona	4983	57	3972	1011	25,45

Table 7-2 Route shipping connection between different ports for the eight-direction graph.

Origin	Destination	Distance[km]	Duration[s]	Ref.[km]	Diff[km]	Diff[%]
Sines	V. do Castelo	450	14	445	5	1,12
Sines	Barcelona	1487	22	1465	22	1,50
Dundee	Barcelona	4097	61	3972	125	3,15

It can be seen that there is little increase in the computational time, when using the more accurate eight-direction graph when compared to the four-direction graph, but there is significant increase in accuracy with an error decrease from around 20% to 2%.

It can also be seen that the relationship between computation time and the distance between points is approximately linear as long there is no great mass of land to contour, which in that case, it can increase. But since the start and end points will be project specific, there is little significance of these results in terms of characterising the performance of the DTOcean tool.

As stated before, the routine is used both at an initial stage of the Installation Phase, to assess the closest feasible port. After excluding non-feasible port, based on port and device or element characteristics, the remaining ones are assessed in distance to the position of the first device of the array to be installed. The port with the least distance will be chosen as the installation port.

Besides this, the routine is callable in the performance stage, to assess the vessel transit time between the port and the lease installation area, and between any two elements, such as devices or foundations.

The routine is also used for the O&M module for the choice of the inspection and maintenance port.

7.3 LANDFALL ONSHORE OPERATIONS COSTS

<table>
<tr><th></th><th colspan="3">HDD - Horizontal Directional Drilling
(user option)</th><th colspan="2">OCT - Open Cut Trenching
(default choice)</th></tr>
<tr><td rowspan="4">Model default Inputs
(user should be able to bypass any of these inputs)</td><td colspan="2">Conduit diameter [mm]</td><td>cable outer diameter × 1.5 [19]</td><td rowspan="2">Construction time [days]</td><td rowspan="2">Default input:
60 days

User bypass Input:
Construction time</td></tr>
<tr><td colspan="2">Borehole diameter [mm]</td><td>Conduit diameter × 1.5 [20]</td></tr>
<tr><td colspan="2">Land cable lenght [m]
(between onshore jointing pit and onshore substation)</td><td>1000 meters</td><td rowspan="2">Land cable lenght [m]
(between onshore jointing pit and onshore substation)</td><td rowspan="2">1000 meters</td></tr>
<tr><td colspan="2">Borehole length [m]</td><td>lenght between:
[landing point, minimum water depth of 8 meters]</td></tr>
<tr><td rowspan="4">Cost assumptions
(based on industrial expertize)</td><td colspan="2">Mobilization / Demobilization and site preparation</td><td>50.000 €</td><td>Excavator day rate</td><td>1750-2250€/day</td></tr>
<tr><td colspan="2">Land cable supply and installation
(includes cable cost and installation works)</td><td>125€/m</td><td>Land cable supply and installation
(includes cable cost and installation works)</td><td>125€/m</td></tr>
<tr><td rowspan="2">Borehole drilling costs</td><td>Borehole Diameter
0 < D < 300 mm</td><td>Cost per meter:
1150€/m</td><td rowspan="2">Construction and reinstatement works
(includes digging the trench and constructing an onshore jointing pit)</td><td rowspan="2">120.000 €</td></tr>
<tr><td>Borehole Diameter
300 < D < 500 mm</td><td>Cost per meter:
1700-2200€/m</td></tr>
<tr><td>Total Costs</td><td colspan="3">$(mob/demob\ and\ site\ preparation)$
$+\ (land\ cable\ lenght$
$\times\ land\ cable\ supply\ and\ installation\ )$
$+\ (borehole\ lenght \times borehole\ drilling\ costs)$</td><td colspan="2">$(construction\ time \times excavator\ dayrate)$
$+\ (land\ cable\ lenght$
$\times\ land\ cable\ supply\ and\ installation\ )$
$+\ (construction\ and\ reinstatement\ works)$</td></tr>
</table>

[19] See DNV Subsea power cables in shallow waters guidelines [8]

[20] See DNV Subsea power cables in shallow waters guidelines [8]

7.4 BOLLARD PULL & TOWING SPEED

<u>Objective:</u> Determine the appropriate tugboat to tow an object (barge, WEC, TEC) from a point A to a point B

The reference certification institution DNV has proposed a Bollard Pull (BP) criterion to do that selection which seems well-established and accepted by the industry. The method consists of estimating the required tug bollard pull based on calculated required towing force and tug efficiency in a given set of environmental conditions (wind, current and wave). In the end, one compares this required BP value to the actual BP value indicated in the towing boat specifications sheet.

7.4.1 DNV pollard pull method

7.4.1.1 Requirements

According to the VMO (Veritas Marine Operations) rules for towing [72], the towing force (continuous bollard pull of the towing vessel) for **open sea towing,** shall be sufficient to **maintain zero speed under the following environmental conditions**:

- Sustained wind velocity: 20 m/s
- Head current velocity: 0.5 m/s
- Significant wave height: 5 m

The above environmental conditions should be seen as the worst case scenario and hence the directionality of the wave and wind should be chosen as the most adverse for the given towing boat and object towed.

Moreover, towing force for coastal towing, and towing **in narrow or shallow waters** representing a danger for grounding, shall be sufficient to maintain a speed over ground, in safe direction, of **minimum 2 knots** under defined environmental conditions. An additional check with the vessel towed at a speed of 2 knots should be done.

Furthermore, the ISO 29400 standard [20], provides the relationship between F_{PR}, the minimum towline pull required, expressed in kilonewtons, and the continuous static bollard pull, F_{BP}, of the tug(s) is given by the following Formula:

$$F_{PR} = \sum F_{BP} \frac{T_{eff}}{100}$$

Where:

- T_{eff} is the tug efficiency in the sea conditions [%]
- F_{BP} is the continuous static bollard pull of each tug [kN]
- $F_{BP} \frac{T_{eff}}{100}$ is the contribution to the F_{PR} of each tug [kN]

The tug efficiency, T_{eff}, depends on the size and configuration of the tug, the sea state considered and the towing speed achieved. In the absence of alternative information, T_{eff} may be estimated according to
Table *7-3*.

Table 7-3 Estimation of the tug efficiency (based on experience in the Noth Sea) [20]

Continuous static bollard pull F_{BP} [kN]	**Tug efficiency for various sea conditions** T_{eff} [%]		
	Calm	$H_s = 2m$	$H_s = 5m$
$F_{BP} \leq 300$	80	$50 + F_{BP}/10$	$F_{BP}/10$
$300 < F_{BP} < 900$	80	80	$30 + 0.75[(F_{BP}/10) - 30]$
$F_{BP} \geq 900$	80	80	75

7.4.1.2 Environmental force calculations

The calculations of the required bollard pull are based on DNV Rules for Planning and Execution of Marine Operations [72]*, DNV RP-H103* [18] *and DNV OS-C301* [73].

Three main environmental forces required for the required bollard pull calculation are: Wind, Current and Wave Drift forces. The equations for calculating these forces are detailed in [18] and [73] and summarized as follows:

Wind Force:
The formula for the wind force is shown below:

$$F_W = \frac{\frac{1}{2}.C_S.C_h.\rho_A.V_W^2.A_W}{g}$$

Where:

- F_W = Wind force [ton]
- C_s = Shape coefficient
- C_h = Height coefficient
- ρ_A = Density of air [t/m^3]
- V_W = Wind velocity [m/s]
- A_W = Projected area of all exposed surfaces [m^2]
- g = Gravity [m/s^2]

C_h and C_s are respectively height and shape coefficient. These coefficients can be found in the following Table 7-4 and Table 7-5:

Table 7-4 Wind force shape coefficient C_s [73] Section B105

Shape	**Cs**
Spherical	0.40
Cylindrical	0.50

Large flat surface (hull, deckhouse, smooth under-deck areas)	1.00
Drilling derrick	1.25
Wires	1.20
Exposed beams and girders under deck	1.30
Small parts	1.40
Isolated shapes (crane, beam, etc.)	1.50
Clustered deckhouses or similar structures	1.10

Table 7-5 Wind force height coefficient C_h [73] Section B105

Height above sea level (meters)	Ch
0 - 15.3	1.00
15.3 - 30.5	1.10
30.5 - 46.0	1.20
46.0 - 61.0	1.30
61.0 -76.0	1.37
76.0 - 91.5	1.43
91.5 - 106.5	1.48
106.5 - 122.0	1.52
122.0 - 137.0	1.56
137.0 - 152.5	1.60
152.5 - 167.5	1.63
167.5 - 183.0	1.67
183.0 - 198.0	1.70
198.0 - 213.5	1.72
213.5 - 228.5	1.75
228.5 - 244.0	1.77
244.0 - 256.0	1.79
Above 256	1.80

Considering the inputs to the installation module, it appears unrealistic to measure the height above sea level of a device during towing or to assume the most shape for a given WEC or TEC.

Current Force:
The formula for calculating the current force is shown below:

$$F_C = \frac{\frac{1}{2}.\rho_W.C_d.V_C^2.A_C}{g}$$

Where:

- F_C= Current force [ton]

- ρ_W = Density of water [t/m^3]
- C_d = Current force coefficient
- V_C = Current velocity [m/s]
- A_C = Wetted surface area of hull [m^2]
- g = Gravity [m/s^2]

APPENDIX B of [18] provides Drag coefficients related to the geometry of the tow object.

Wave Drift Force:
The formula for wave drift force at zero towing speed is shown below:

$$F_{Wd} = \frac{1}{8} . \rho_W . R^2 . B . H_S^2$$

Where:
- F_{Wd} = Wave drift force [ton]
- ρ_W = Density of water [t/m^3]
- R = Reflection coefficient
- B = Breadth of towed object [m]
- H_s = Significant waveheight [m]

Table 7-6 Typical reflection coefficients [18] Section 7.2.6.4

Typical reflection Coefficients	R
Square Face	1.00
Condeep Face	0.97
Vertical Cylinder	0.88
Barge with Raked Bow	0.67
Barge with Spoon Bow	0.55
Ship Bow	0.45

The wave drift force increases linearly with the towing speed according to the formula [18] (Section 7.2.6.5):

$$F_{Wd}(U) = F_{Wd}(0) + U . B_{11} \quad [N]$$

Where B_{11} (kg/s) is the wave drift damping coefficient and U (m/s) the towing speed. For more information on wave drift damping reference is made to DNV-RPC205 [74].

Total resistance:

$$R_{TOT} = F_W + F_C + F_{Wd}$$

7.4.2 Required bollard pull

The relation to satisfy, both to maintain zero speed under open sea environmental conditions and the additional check with the vessel towed at a speed of 2 knots in shallow/narrow water, is:

$$\mathrm{BP}.\eta > \mathrm{R_{TOT}} \quad => \quad \mathrm{BP} > \frac{\mathrm{R_{TOT}}}{\eta}$$

With:

- η = Tug efficiency [%]
- BP: Tug bollard pull [ton]
- BP.η = Required bollard pull [ton]

Formally, there is no minimum size and length of a tug, but vessels for open sea towage shall not have any service restrictions [75]. Note that the VMO Rules [76] penalize tugs of less than 45m length with respect to towing efficiency:

$$\gamma = 0.75(1 - \gamma_L)$$

Where:

- γ: tug efficiency factor [%]
- γ_L: tug length factor, $\gamma_L = \left(1 - \frac{L}{45}\right)^2$ [m]
- L: tug length [m], not to be taken more than 45m
- A tug efficiency factor of 0.75 as recommended for offshore tows in [72]

7.4.3 Application to the DTOcean installation module WP5

7.4.3.1 Required bollard pull to tow a barge

INPUT/Parameters:

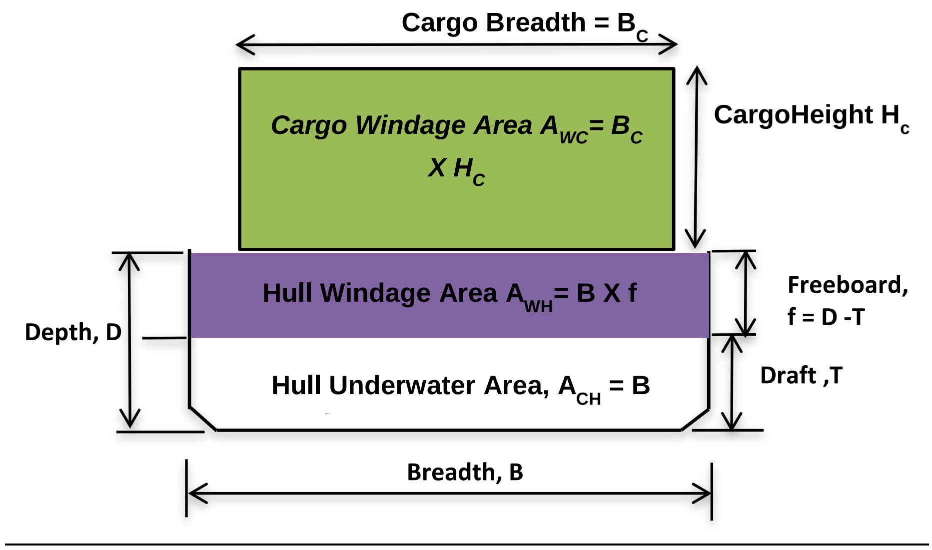

Figure 7-18 Profile of a vertical cross-section of a barge towing a rectangular shaped cargo

The notation system adopted herein is summarized in the following tables:

GENERAL			
Parameter	**Notation**	**Value**	**Units**
Air Density	ρ_a	1,225	kg/m^3
Sea Water Density	ρ_w	1025	kg/m^3
Acc. Due to Gravity	g	9,81	m/s^2

SEA STATE			
Parameter	**Notation**	**Value**	**Units**
Wave Height	H_S		m
Current Speed	V_C		m/s
Wind Speed	V_W		m/s

BARGE			
Parameter	**Notation**	**Value**	**Units**
Length	L		m
Breadth	B		m
Depth	D		m
Draft (Mid)	T		m
Freeboard	f		m
Hull Windage Area	$A_{WH} = B X f$		m^2
Hull Underwater Area	$A_{CH} = B X T$		m^2
Current Drag Coefficient (Hull)	C_D		

TUG			
Parameter	**Notation**	**Value**	**Units**
Actual Bollard Pull of Tug	BP_T		T
Tug Efficiency	η	0,75	

CARGO			
Parameter	**Notation**	**Value**	**Units**
Breadth Overall	B_c		m
Height Overall	H_c		m
Height Coefficient	Ch		See Table 1
Shape Coefficient	Cs		See Table 2
Cargo Windage Area	$A_{WC} = B_C \times H_C$	0,00	m^2

Environmental resistance:

- **Wind resistance: F_W**

Wind resistance for Hull: $F_{WH} = \frac{1}{2}.\rho_A.V_W^2.A_{WH}$

Note: It is assumed that the C_h=1 and C_s =1 for the hull area exposed to wind (height<15,3m and large flat structure)

Wind resistance for Cargo: $F_{WC} = \frac{1}{2}.\rho_A.V_W^2.A_{WC}.C_hC_s$

Note: If it's possible, the different contribution of the cargo can be identified with each Wind Force Shape Coefficient (C_s) Wind Force Height Coefficient (C_h) applied, and then be summed up as follows: $\sum_i A_{WCi}.C_{hi}C_{si}$

In the frame of DTOcean, the barge cargos that could be characterized (in terms of projected area, height, and shape) are:

- The transported object: WEC, TEC, foundations, piles, support structure, equipment...
- The facilities on the barge: Realistically, it seems impossible to have an acceptable rough assumption of the deck lay-out which is totally unknown and not reasonable to ask for inputs. However, the cranes, especially in case of crane barges, may be characterized. For that, the height and projected area of the on-board crane must be calculated. This would imply the addition of the following parameters in the vessel database: Number of crane, boom length [m], minimum crane radius [m] as a strict minimum.

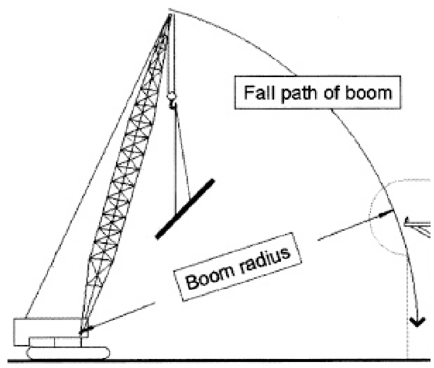

Figure 7-19 Schematic of a typical mobile as used on floating barges

Total wind resistance: $F_W = F_{WH} + F_{WC}$

- **Current resistance: F_C**

$$F_C = \frac{1}{2} . \rho_W . C_D . V_C^2 . A_{CH}$$

Table 7-7 Drag coefficient for different hull types [77]

Hull Type	**Cd**
SPOON BOW / FAIRED STERN	0.20
SPOON BOW / RAKED STERN	0.35

- **Wave Drift resistance: F_D**

$$\mathrm{F_D} = \frac{1}{8} . \rho_\mathrm{W} . \mathrm{R}^2 . \mathrm{B} . \mathrm{H}_\mathrm{S}^2$$

Note: We assumed that for the test at 2 knots speed, the wave drift dumping coefficient has very little impact on the wave drift resistance.

Total resistance: $\mathrm{R_{TOT}} = \mathrm{F_W} + \mathrm{F_C} + \mathrm{F_D}$

Condition to respect: $\mathrm{BP} > \frac{\mathrm{R_{TOT}}}{\eta}$ for the 0 knot and 2 knots test.

For the check at 2 knots, the test can be done in less harsh conditions. An option can be to consider an average value of the Wind Speed, Current Speed, and Significant Have Height from the time series, or in the worst case, considering the most adverse environmental condition during the transit route. Nevertheless, the towing speed has a significant impact on the minimum required bollard pull. Choosing the worst environmental conditions instead of an average value can also lead to not representative required bollard pull and misleading calculations.

7.4.3.2 Required bollard pull to tow a device

For towing a device, exactly the same methodology should be used: Calculate the induced resistance from current, waves and wind. And, including a tug efficiency factor, compare it to the tugboat bollard pull.

Calculating within the WP5 the total resistance on the tow device would be a task more difficult than for the barge, that have in general a common shape. For each device, the geometry is different, and manufactures would probably have a better expertise and evaluation of the resistance of their device to wind, current and wave.

The total resistance of the device (to wind, current and wave) could be an optional end-user input. In a first approach, it is, however, preferable to not increase the level of details in the requested inputs. Therefore, this option is left opened for future version of the installation module that may be upgraded due to the open-source nature of the DTOcean tool. As the environmental conditions during the transit route are unknown, the total resistance of the device could be realized for the following commonly used conditions:

Towing speed (Device speed)	0 knot
Wind velocity	20 m/s
Current velocity	1 m/s
Significant Wave Height	5 m

7.4.4 Conclusion

The feasibility function to select which tugboat (or Anchor Handling Vessel) is suitable to tow a device or a barge to the site location is a complex and challenging problem:

- The calculation to determine the required bollard pull can be done in the case of tow device if the manufacturer provides the information about the resistance to wind, current and wave in specific environmental conditions. This input was not anticipated because it seems quite delicate to obtain. Hence, the first version of the installation module will simply perform a direct, rough comparison of the total dry mass of the device against the bollard pull to verify its suitability (based on recommendations from offshore marine contractors for rough first approximation)
- The calculation in case of tow barge can also be done, even if the cargo characterization can be tricky with the data available in the vessel database. In the future, a sensibility test should be done between a real crane barge profile, with all the different projected areas along the height, and a rough evaluation of the barge cargo, based only on the shape of the crane(s). The first version of the installation module will simply perform a direct rough comparison of the total dry mass of the towed barge against the bollard pull to verify its suitability (based on recommendations from offshore marine contractors for very rough first approximation)

Further research on the towing speed regulation in the European seas and ocean would be necessary although the maximum towing speed is an input of the vessel database. Unfortunately, it has been difficult to find good references for these values to-date. Based on general reading and communications from offshore experienced persons, it is likely that the towage speed is not to be greater than 10 knots.

7.4.5 References

[1] DNV Rules for Planning and Execution of Marine Operations, 1996 Revision, January 2000.

[2] DNV RP-H103, Modelling and Analysis of Marine Operations, April 2011.

[3] DNV-OS-C301, Stability and Watertight Integrity, DNV, April 2011.

[4] IMO, Guidelines for Safe Ocean Towing, London, December 1998

[5] Global Maritime Scotland Ltd, Haewene Brim Bollard Pull Calculations, June 2013

[6] DNV Towing recommendation, Rolf Hilmar Hansen, Norway, 1 Paper No 7

[7] GL Noble Denton, Technical Policy Board Guidelines for Marine Transportations, March 2010

[8] China Classification Society, Guidelines for Towage at Sea, 2011

[9] DNV-RP-C205, Environmental Conditions and Environmental Load, October 2010

7.5 DRILLING PENETRATION RATE

This appendix is a concise literature overview of drilling penetration rate equations. Having a rate of penetration for drilling operation allows the estimation of the time to install drilling piles at a given depth. The difficulty lies in selecting the most adequate equation available in the literature and, if necessary, adapts it to the input available on DTOcean tools.

7.5.1 Preliminary concepts

WOB (kg): It is the abbreviation for "Weight on Bit". It represents the amount of weight applied onto the bit, that is then transferred to the formation (soil) which in turn is the energy created together with string speed that advances drill string. It is measured through the drilling line, usually by means of having attached a strain-gauge which measures the magnitude of the tension in the line itself, and gives the weight reading based on the calibration. This sensor measures a unique value, which is the overall weight (Hook-load) of the string including the weight of the block and Top Drive System (TDS). For all of these circumstances correct calibration is required in order to have proper reading for this drilling parameter.

RPM (revo/min): This parameter stands for "revolution per minute". It represents the rotational speed of the drill string. With the invention of TDS; the reading is directly linked to the electronics of the unit itself. It is considered that the measurements for this parameter are accurate as long as the acquisition system set-up has been thoroughly made up.

ROP (m/hour): Rate of Penetration (ROP). It is measured through the relative change of the position of the block in time. Accurate calibrations are very important in order to have a representative ROP parameter.

7.5.2 Introduction

There are many factors known to be affecting the ROP. From those parameters directly influencing how fast a well can be drilled, they can be divided in two main categories [1]:

- Controllable factors are the factors which can be instantly changed such as weight on bit, bit rotary speed, hydraulics.
- Environmental factors on the other hand are not controllable such as formation properties, drilling fluids requirements. (The reason that drilling fluid is considered to be an environmental factor is due to the fact that a certain amount of density is required in order to obtain certain objectives such as having enough overpressure to avoid flow of formation fluids).

ROP performance is a function of the controllable and environmental factors. Due to the complexity of an analytical understanding, the ROP mechanism of drilling operations, industry pioneers have adopted empirical approaches by quantifying the effects of the controllable parameters on ROP performance, more than the analytical model implementation for the understanding of rate of penetration in the industry of drilling.

7.5.3 Definition of the concepts

The most important variables affecting the ROP that have been identified and studied include [2]: (1) **bit type**, (2) **formation characteristics**, (3) **drilling fluid properties**, (4) **bit operating conditions (bit weight and rotary speed)**, (5) **bit tooth wear** and (6) **bit hydraulics**.
A considerable amount of experimental work has been done to study the effect of these variables on drilling rate. In most of this experimental work the effect of single variable was studied while holding the other variables constant.

- **Bit Type**

The bit type selected has a significant effect on the ROP. For rolling cutter bits, the initial penetration rates for shallow depths are often highest when using bits with long teeth and a large cone offset angle. However, these bits are practical only in soft formations because of a rapid tooth wear and sudden decline in penetration rate in harder formations. The lowest cost per foot drilled usually is obtained when using the longest tooth bit that will give a tooth life consistent with the bearing life at optimum bit operating conditions. The diamond and PDC bits are designed for a given penetration per revolution by the selection of the size and number of diamonds or PDC blanks. The width and number of cutters can be used to compute the effective number of blades. The length of the cutters projecting from the face of the bit (less the bottom clearance) limited the depth of the cut.

- **Formation Characteristics**

The elastic limit and ultimate strength of the soil conditions are two key formation properties affecting the ROP. It is mentioned that the crater volume produced beneath a single tooth is inversely proportional to both the compressive strength of the rock and the shear strength of the rock. The permeability of the formation also has a significant effect on the ROP. In permeable rocks, the drilling fluid filtrate can move into the rock ahead of the bit and equalize the pressure differential acting on the chips formed beneath each tooth. It also can be argued that the nature of the fluid contained in the pore space of the rock also affects this mechanism since more filtrate volume would be required to equalize the pressure in a rock containing gas than in a rock containing liquid. The mineral composition of the rock also has some effect on penetration rate.

- **Drilling Fluid Properties**

The properties of the drilling fluid reported to affect the penetration rate include (l) density, (2) rheological flow properties, (3) filtration characteristics, (4) solids content and size distribution, and (5) chemical composition. Penetration rate tends to decrease with increasing fluid density, viscosity, and solids content, and tends to increase with increasing filtration rate. The density, solids content, and filtration characteristics of the mud control the pressure differential across the zone of crushed rock beneath the bit. The fluid viscosity controls the parasitic frictional losses in the drill string and, thus, the hydraulic energy available at the bit jets for cleaning. There is also experimental evidence that increasing viscosity reduces penetration rate even when the bit is perfectly clean. The chemical composition of the fluid has an effect on penetration rate, such that the hydration rate and bit balling tendency of some clays are affected by the chemical composition of the fluid.

- **Bit Operating condition (WOB and Rotary speed)**

The effect of bit weight and rotary speed on the ROP has been studied by numerous authors both in the laboratory environment and in the field. Typically plot of penetration rate vs bit weight obtained experimentally with all other drilling variables held constant has the characteristic shape shown in the figure bellow**.** No significant penetration rate is obtained until the threshold bit weight is applied (Point a). Penetration rate then increases rapidly with increasing values of bit weight for moderate values of bit weight (Segment ab). Linear curve is often observed at moderate bit weights (Segment be). However at higher values of bit weight subsequent increase in hit weight causes only slight improvements in penetration rate (Segment cd). In some cases decrease in penetration rate is observed at extremely high values of bit weight (Segment de). This type of behavior often is called bit floundering. The poor response of penetration rate at high values of bit weight usually is attributed to less efficient bottom hole cleaning at higher rates of cuttings generation or to complete penetration of the cutting element into the hole bottom.

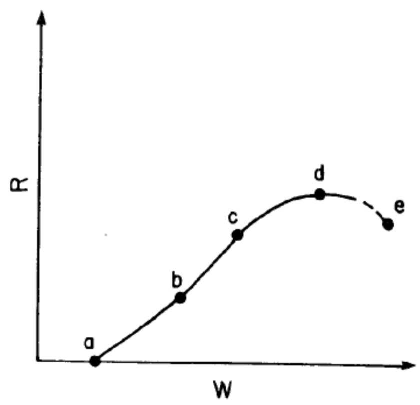

Figure 7-20 Typical response of penetration rate to increasing bit weight

A typical plot of penetration rate vs rotary speed obtained with all other drilling variables held constant is shown in the above figure**.** Penetration rate usually increases linearly with rotary speed at low values of rotary speed. After a certain rotary speed value, the increase in ROP decelerates as rotation speed is increased (Segment b-c). After point-c, rotation speed has a very slight influence on ROP. The poor response of penetration rate at high values of rotary speed usually is also attributed to less efficient bottom hole cleaning.

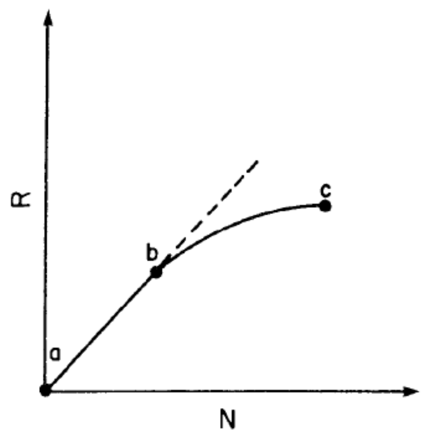

Figure 7-21 Typical response of penetration rate to increasing rotary speed

- **Bit Tooth Wear**

Most bits tend to drill slower as the drilling time elapses because of tooth wear. The tooth length of milled tooth rolling cutter bits is reduced continually by abrasion and chipping. The teeth are altered by hard facing or by case-hardening process to promote a self-sharpening type of tooth wear. However, while this tends to keep the tooth pointed, it does not compensate for the reduced tooth length. The teeth of tungsten carbide insert-type rolling cutter bits and PDC bits fail by breaking rather than by abrasion. Often, the entire tooth is lost when breakage occurs. Otherwise, reductions in the ROP due to bit tooth wear occur.

- **Bit Hydraulics**

Significant improvements in penetration rate could be achieved by a proper jetting action at the bit. The improved jetting action promoted better cleaning of the bit face as well as the hole bottom. There exists an uncertainty on the selection of the best proper hydraulic objective function to be used in characterizing the effect of hydraulics on penetration rate. Bit hydraulic horsepower, jet impact force, Reynolds number, etc, are commonly used objective functions for describing the influence of bit hydraulics on ROP.

7.5.4 Literature overview: penetration rate models

There exists a wide range of penetration rate models that can be found in the literature. There are three most widely used models for estimating the ROP; i) Maurer, ii) Galle and Woods, and iii) Bourgoyne and Young [1]

7.5.4.1 Maurer's model

Maurer's [3] method is based on a theoretical penetration equation for roller cone bits as a function of WOB, RPM, bit size and rock strength. The governing equation is based on observations such as the amount the crater cutter can create, rock strength related considerations.
Working relation assuming that the hole is subject to perfect hole cleaning circumstances. The rate of drilling equation expressed as given in equation:

$$\frac{dF}{dt} = \frac{4}{\pi d_b^2} \frac{dV}{dt}$$

Where, *F* is the distance drilled by bit, *t* is time, *V* is volume of rock removed, and d_b is diameter of the bit.

7.5.4.2 Galle and Woods' model

Galle and Woods [4] investigated the best selection effect of WOB and RPM. They presented graphs for the best selection of the drilling parameters combination. In [4], it is shown that drilling costs can be reduced when using their method. Galle and Wood are few of the first researchers who have been investigating the effect of best constant bit weight and rotary speed for lowest cost; developing mathematical relations.
The drilling rate equation is given by:

$$\frac{dF}{dt} = C_{fd} \frac{\overline{W}^k r}{a^p}$$

Where:

- C_{fd} is the formation drillability parameter
- $a = 0.028125h^2 + 6.0h + 1$ with *h* the bit tooth dullness (fractional tooth height worn away)
- k = 1.0 (for most formations), 0.6 (for very soft formations), 1,5 (for very hard formation) [5]
- p = 0.5 (for self-sharpening or chipping type bit tooth wear)
- *N* is the rotary speed
- *r* is a function of *N* defined by:

$$r_{\text{hard formations}} = [e^{-\frac{100}{N^2}} N^{0,428} + 0,2N\left(1 - e^{-\frac{100}{N^2}}\right)]$$
$$r_{\text{soft formations}} = [e^{-N^2} N^{0,75} + 0,5N\left(1 - e^{-\frac{100}{N^2}}\right)]$$

- $\overline{W} = \frac{7,88WOB}{d_b}$ with d_b diameter of the bit

7.5.4.3 Bourgoyne and Young's model

Bourgoyne and Youngs' [6] method is the most widely used drilling optimization method since it is based on statistical synthesis of the past drilling parameters which is usually known by drilling rig operators. A linear penetration model is being introduced and multiple regression analysis over the introduced rate of penetration equation is being conducted. For that reason this method is considered to be the most suitable method for the real-time drilling optimization.

$$\frac{dF}{dt} = e^{(a_1 + \sum_{j=2}^{8} a_j x_j)}$$

$a_1 = formation\ strength\ coefficient$

$a_2 = normal\ compactation\ coefficient$
$x_2 = 8000 - D$

$a_3 = under\ compactation\ coefficient$
$x_3 = D^{0,69}(g_p - 9)$

$a_4 = pressure\ differential\ coefficient$
$x_4 = D(g_p - \rho_C)$

$a_5 = WOB\ coefficient$

$$x_5 = \ln(\frac{\frac{W}{d_b} - (\frac{W}{d_b})_t}{4 - (\frac{W}{d_b})_t})$$

$a_6 = RPM\ coefficient$

$$x_6 = \ln(\frac{N}{60})$$

$a_7 = Tooth\ wear\ coefficient$
$x_7 = -h$

$a_8 = hydraulic\ coefficient$

$$x_8 = \frac{\rho q}{350 \mu d_n}$$

Where:

- **a_1 to a_8 = constants based on local drilling conditions**
- *D* depth of borehole, [L], ft (m)
- g_p pore pressure gradient of the formation, [M/L^3], ppg (sg)
- ρ_c equivalent circulating mud density at the hole bottom [M/ L^3], ppg (sg)
- *W* weight on bit [ML/T^2], 1000 lbf (N)
- d_b diameter of the bit [L], in (mm)

- N rotary speed [T^{-1}], rpm (-)
- h bit tooth dullness, fractional tooth height worn away
- ρ drilling fluid's density [M/T^3], ppg (kg/m^3)
- q volumetric flow rate [L^3/T], gpm (l/m)
- μ apparent viscosity at 10,000 sec^{-1} [M/LT], cp (Pa.s)
- d_n equivalent bit nozzle diameter [L], in (mm)

To acquire the constants a_1 through a_8, detailed drilling data obtained in the area must be used for computation. This is beyond the scope of the DTOcean project.

It should be noted that Galle & Woods and Bourgoyne & Young models both take in account the tooth dullness and have defined Rate of Dulling and Bearing life equation

7.5.5 Selection of a model for the installation module WP5

a. <u>Bourgoyne and Young model</u>

One of the most frequently used models for estimation of drilling penetration rate is the **Bourgoyne and Young model**. This model relates the penetration rate to several drilling parameters. There are eight unknown constants in this model. Bourgoyne and Young have proposed multiple regression analysis for obtaining these constants. Because the constant values obtained by multiple regression analysis are sometimes meaningless and are not in the recommended ranges, other methods for determining these coefficients are suggested (ex [1] and [7]). A set of possible answers is chosen from the recommended bounds:

Coefficients	Lower bound	Upper bound
a_1	0.5	1.9
a_2	0.000001	0.0005
a_3	0.000001	0.0009
a_4	0.000001	0.0001
a_5	0.5	2
a_6	0.4	1
a_7	0.3	1.5
a_8	0.3	0.6

Figure 7-22 Bourgoyne and Young recommended bounds for each coefficient [7]

<u>Conclusion:</u> Interesting equation to do optimization of the parameters in order to obtain the optimal rate of penetration. Unfortunately, DTOcean's objective is to apply a direct calculation knowing pre-set values for these parameters rather than doing an optimization. Moreover, this equation takes too many hardly accessible parameters into consideration. For the DTOcean WP5 application, it would mean 1) collect all these parameters, 2) do a multiple regression to have the coefficient, 3) once the

ROP obtained, deduce the time for the drilling operation. This will not be implemented in the first version of the installation module

b. Galle and Woods

Galle and Woods' parameters could be accessible to evaluate the rate of penetration. However, one assumption required is that there is no tooth wear during the time of drilling, the equation become:

$$\frac{dF}{dt} = C_{fd}\bar{W}^k r$$

Conclusion: The determination of the C_{fd} constant (formation drillability parameter) remains an issue. This constant is based on local drilling conditions, and no typical values has been found in the literature. It will not be possible to implement this model in the installation module.

c. Maurer's model

Maurer's model, as Galle and Woods' model, could be used for determining the rate of penetration using relatively simple parameters apart from the volume of rock removed per unit of time.

Conclusion: Volume of rock removed is a parameter difficult to obtain knowing only the input of DTOcean. Moreover, that equation suggest that drilling operation are achieved only for rocky seabed types although any soil type conditions are assumed to be suitable for drilling in DTOcean. Some experts argue that the equation remains valid in various formations. This model will also not be implemented in the installation module.

7.5.6 Going further

- Galle and Woods' model seems to be the most appropriate model for DTOcean WP5 uses. Few and accessible parameters can be used to determine the rate of penetration. The idea would be to determine typical C_{fd} for different type of soil drilled (and make the assumption that the type of soil doesn't vary along the drilled hole).

- Looking further into the technical specifications given by specialists of foundation engineering machinery (e. g. [8]), and deduce from it a possible rate of penetration. In fact, some of the necessary parameters to run the previous models are not always available on the drilling equipment technical specifications. Consequently, it would be almost impossible to collect these parameters from the equipment database and input them in one of the above models.

7.5.7 *Conclusion*

The ROP equations found in the literature are relevant to predict on optimization of the parameters influencing the rate of penetration. This approach is hardly applicable to the WP5 module as we want to determine the time of drilling operation based on fixed parameters given by the drilling equipment technical specifications.

Nevertheless, looking into these input parameters, real-time optimization makes sense during drill operation by controlling the drilling assistance control and regulating the input parameter (RPM, ROP) threw the penetration.

7.5.8 *References*

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[8] https://www.bauer.de/export/shared/pdf/bma/bma_Maritime_Ansicht.pdf

[9] https://www.bauer.de/en/bma/customers/2014/08-2014/08_2014_1.html

7.5.9 *Annex: BAUER Electronic Assistants in Rotary Drilling Rigs example*

Control between 3 parameters (speed of rotation, rate of penetration, crowd pressure/force) where the regulation is done automatically.

1. First, the operator inputs the geometrical data of the drill on the touchscreen via a data entry form. From these data, the program calculates the perfect fill level for one drill flight and the optimum penetration rate
2. In the next step, the rig operator selects a speed of rotation for the drill and then activates the automatic control
3. During drilling, the electronic control automatically regulates the ratio of **crowd pressure and rate of penetration**. The operator can, however, intervene at any time by varying one of the parameters (**fill level, speed of rotation, rate of penetration**).

If the speed of rotation is too high relative to the rate of penetration, then there is a danger that soil is extracted laterally from the ground into the auger and the surrounding soil is loosened. If, on the other hand, the speed of rotation is too low relative to the rate of penetration, the soil immediately adjacent to the drill is not sheared off and the drill pulls itself into the ground because of the so-called "corkscrew effect" and ultimately becomes stuck. The available pull may, in certain circumstances, not be sufficient to extract the drill from the ground.

Considering that values of the physical parameters change threw the penetration by automatically regulation, it is not possible to take fixed value coming from the equipment technical specification and apply an equation to determine a fixed rate of penetration.

7.6 PILE HAMMERING DRIVABILITY ANALYSIS

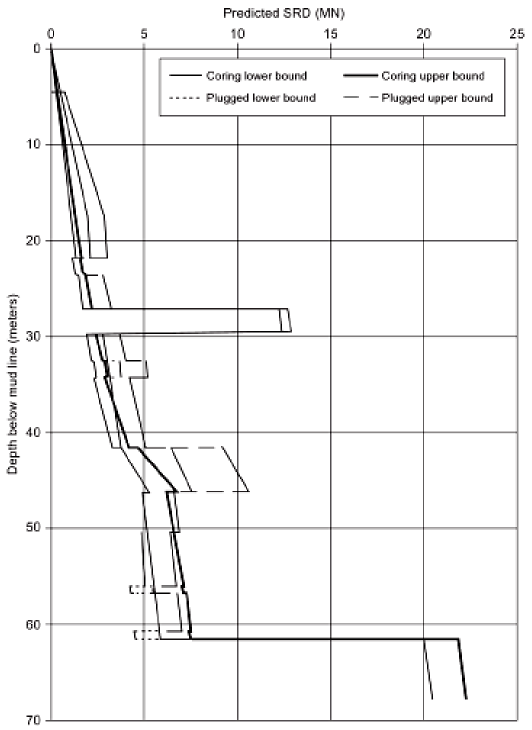
7.6.1 Introduction

When offshore piles are to be installed to substantial penetration depths, or when the soil conditions are such that the piles will have to penetrate dense sand layers or other strong soils, a question can arise whether the piles can be installed to the required penetration depth by means of hammers.

Answering this question may be developed by a **pile drivability analysis**. The analysis of pile drivability consists of three phases or steps: [1]

1) Evaluation of the Soil Resistance to Driving (SRD)
2) Wave Equation Analysis
3) Estimate blow count versus pile penetration

The first step is to evaluate the specific soil conditions at the location to estimate the resistance that the soil will offer to the forced penetration of the pile (provides graph of SRD versus penetration depth, see Figure bellow (left)). The second step is to use an analysis based on the one-dimensional wave equation to estimate the resistance that can be overcome by the particular hammer-pile-soil system (provides graph of blow count versus SRD, see Figure bellow (right)). The third step compiles the two previous steps to compare the resistance the hammer-pile-soil system can overcome with the resistance that the soil can offer (Figure 7-24 provides graph of blow count versus penetration depth). This last phase gives an indication whether the pile can be driven to the desired penetration. Moreover, if the hammer is able to drive the pile to the desired depth, an integration of the curve giving the blow count versus penetration depth will provide the total number of blow to get to this depth. Dividing this number by the blow per minute (parameter given by the hammer constructor, see Figure 7.25), an estimation of the global time of driving can be obtained (more details is part 3).



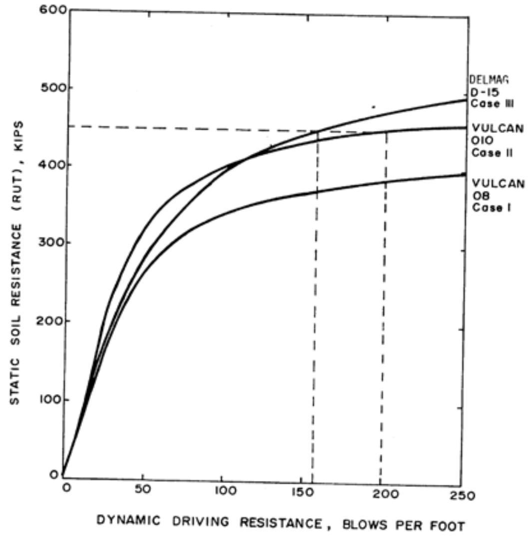


Figure 7-23 Example of Soil Resistance to Driving function of depth (left) and example of blow count vs SRD for three different hammers [1]

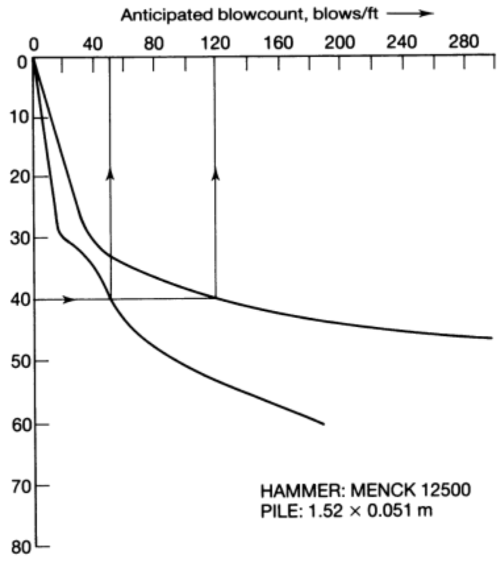


Figure 7-24 Example of blow count versus penetration depth [3]

Model	D6-32	D8-22	D12-42	D19-42	D25-32	D30-32
Approx. Piston Weight (kg) **Approx. Anvil Weight (kg)**	600 185	800 185	1.280 300	1.820 354	2.500 662	3.000 662
Blows per minute[1] Minimum (1/min) Maximum (1/min)	 39 52	 37 52	 37 52	 37 52	 37 52	 37 52
Energy per blow[2] **(adjustable)** Maximum (kNm) Minimum (kNm)	 17,0 9,6	 25,4 12,8	 40,4 20,3	 57,6 29,1	 79,0 40,0	 94,9 48,0
Consumption[3] Diesel Fuel (l./hr.) Lubrication Oil (l./hr.)	 3,70 0,25	 3,80 0,5	 4,5 0,5	 7,6 0,6	 8,0 1,0	 10,0 1,0
Capacity Diesel Fuel (l.) Lubrication Oil (l.)	 19 5	 20 6	 24 6.5	 75 19	 67 19	 67 19
Weight[3] Hammer (kg) Hammer, Standard Operating (kg)	 1.620 2.340	 1.815 2.426	 2.600 3.220	 3.795 4.400	 5.610 6.710	 6.110 7.210

Figure 7-25 BAUER group diesel hammers specification - D30-32 typically used for installing concrete cylinder piles and steel pipe piles in offshore marine construction [5]

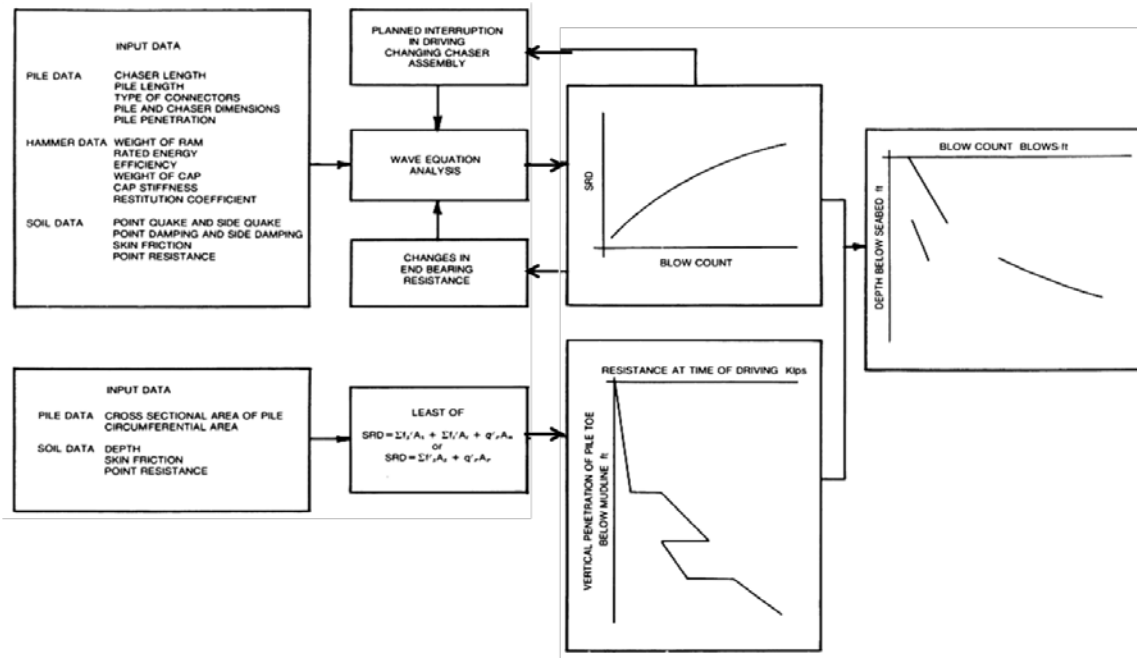


Figure 7-26 Schematic summary of the pile drivability analysis process [3]

Engineers should be aware that a drivability analysis does not necessarily produce a definite answer to the pile drivability question. Considerable engineering judgment is required for all three steps of a drivability analysis, and everyone making a drivability analysis may not arrive at exactly the same conclusions. A drivability analysis should be made for each specific combination of hammer, pile and soil conditions being considered for a project.

The presentation of the three phases of the pile drivability analysis is provided in the following sections:

7.6.2 Evaluation of the soil resistance to driving (SRD)

Predicting the SRD for offshore pile has been a challenging task. Several methods (Stevens et al. (1982), Puech et al. (1990), Colliat et al. (1993)) have been proposed. Methods for evaluating the SRD differ depending on whether the soil is **cohesive** (Ex: Semple and Gemeinhardt method (1981)) or **cohesionless** (Ex: API procedure (1984)).

Moreover, the soil resistance to driving can be divided into two types of resistance: one component of **shaft resistance** (resistance along the pile, which represent the skin friction multiply by the pile surface area), and one component of **end bearing** on pile wall area (which represent the resistance at the tip of pile). The two components are then combined to give a total driving resistance (Toolan and Fox, 1977).

The soil resistance force consists of two components [4], one depends on pile displacement, and the other depends on pile velocity (see Figure below). Pile displacement component models static soil behavior, and it is assumed to increase linearly up to a limiting deformation, which is **the quake**. Deformation beyond the quake requires no additional force. The pile velocity component models depend on soil damping characteristics where the relationship between soil resistance and velocity is linear and the slope of such relationship is the **damping constant**. Quake and damping constants are required for both skin friction and end-bearing components. *Table 7-8* and *Table 7-9* give recommended soil parameters from two different sources, which should be altered depending on local experience.

Table 7-8 Recommended soil parameter for Wave Equation (Globe, Rausche, Likins and Associated, Inc 1988)

Table 6-2
Recommended Soil Parameters for Wave Equation (Copyright permission, Goble, Rausche, Likins and Associates, Inc. 1988)

	Damping Constants J_c, seconds/ft (seconds/m)		Quake ρ_u, inches (mm)	
Soil	Skin	Tip	Skin	Tip[1]
Cohesionless	0.05 (0.16)	0.15 (0.50)	0.10 (2.54)	B_b / 120
Cohesive	0.30 (0.90)	0.15 (0.50)	0.10 (2.54)	B_b / 120

[1] Selected tip quake should not be less than 0.05 inch. B_b is the effective tip (base) diameter; pipe piles should be plugged.

Table 7-9 Dynamic soil parameters analysis (after Roussel, 1979)

	Quake (mm)		Damping Factors (s/m)	
	Side, Q_s	Point, Q_p	Side, J_s	Point, J_p
CLAY				
Soft	5.08	5.08	0.26	0.66
Firm	3.81	3.81	0.23	0.50
Stiff	2.54	2.54	0.20	0.50
Very stiff	2.54	2.54	0.16	0.50
Hard	2.54	2.54	0.10	0.50
SAND	2.54	2.54	0.26	0.50

The variability of the soil condition across the site and some anticipated variation in hammer performance are likely to influence the apparent driving resistance. Furthermore, the driving resistance during continuous driving is known to be considerably lower than when driving is restarted after an interruption long enough to allow soil set-up. To account these factors, **upper-bound** and **lower-bound** SRD profiles an be formulated [2] (based on the recommendation of Stevens et al. (1982)) for a given design soil profile.

7.6.3 Wave equation analysis

The wave equation analysis is performed using a software program. The theory and application of the wave equation to pile driving problems has been described in number of papers (**Smith, 1962; Lowery et al., 1969; and Hirsch et al., 1975**). In the typical wave equation computer program, the pile, soil, and hammer system are modeled as a series of masses, springs, and dashpots in a one-dimensional analysis, as shown in Figure bellow

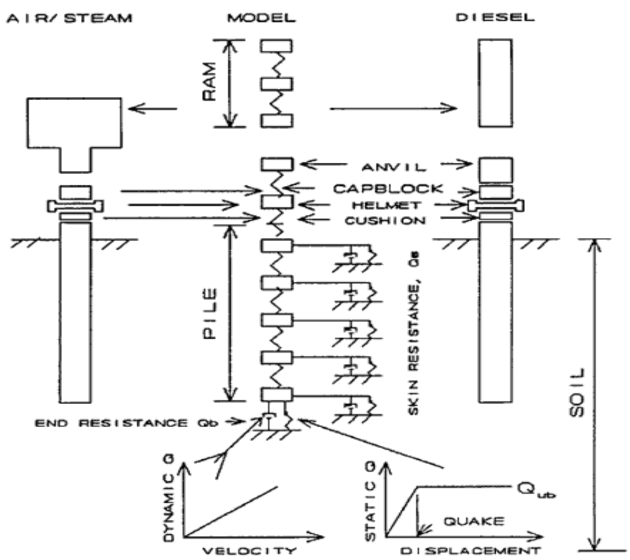


Figure 7-27 Soil, pile and hammer (stream and diesel) model

Owing the impact of the ram, a force wave starts traveling through the pile at a certain velocity (approximately 5000 m/s). The wave equation analysis then calculates for all elements in the system the corresponding velocities, displacements, and forces generated by the impact per time increment. The process is continued until the permanent set of the pile tip is achieved. This information then provides the expected blow count for a specified combination of **soil resistance, pile, and hammer characteristics** (Input parameters). The results from this analysis is then presented as curves of blow count values versus soil resistance at time of driving.

The INPUT parameters used depend mostly on the software program chosen to do the analysis. To give an idea, some typical parameters:

- **Soil resistance:**
  - Depth of pile embedment
  - Type of soil
  - Sketch of soil profile
  - Total soil resistance
  - Resistance at point of pile

- o Resistance on side of pile
- o Distribution of soil resistance on side of pile (on additional sheet)

- **Pile characteristics:**
  - o Material
  - o Unit weight
  - o Total length
  - o Cross-sectional area
  - o Modulus of elasticity

- **Hammer characteristics:**
  - o Type
  - o Rated energy
  - o Hammer efficiency
  - o Ram weight
  - o Anvil weight
  - o Capblock properties (material, modulus of elasticity, dimension, coefficient of restitution)
  - o Cushion properties (material, modulus of elasticity, dimension, coefficient of restitution)

7.6.4 Estimate blow count versus pile penetration depth

Blow count predictions are made combining the lower and upper bound SRD profiles and the wave equation results. The result is then presented as curves of blow count values versus pile penetration depth (see Figure 7-28). This curve can be integrated to obtain the total number of blow for a penetration depth required (see Figure 7-28), and then, a driving time estimation considering the (min/max) blow speed given by the hammer constructor.

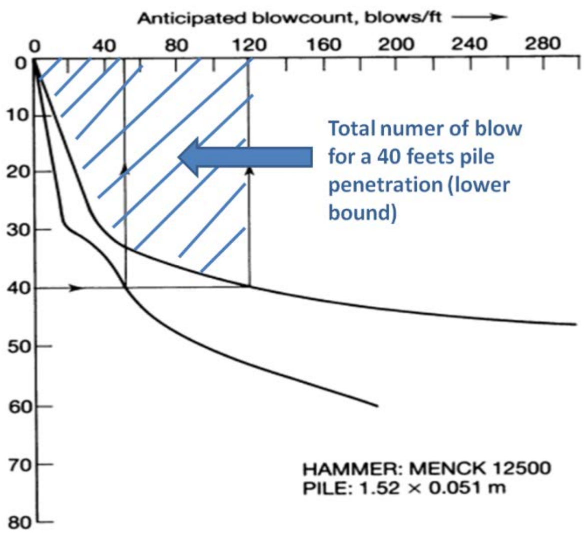


Figure 7-28 Calculation of the total number of blow

An example of the interpretation of the pile drivability analysis is given in Annex. This example is taken from a pile driving analysis by the wave equation made by the Department of Civil Engineering, Texas A&M University [2].

7.6.5 Application to the installation module DTOcean WP5

The pile drivability analysis previously depicted shows how cumbersome and time consuming this evaluation is, and thus, the impossibility to integrate it into the WP5 model.

Nevertheless, the pile drivability analysis is nowadays performed by commercial and user-friendly program (Ex: GRLWEAP, CAPWAP) and offer a practical and accurate method for pile drivability analysis. The program simulates the behavior of a pile and the surrounding soil under the impact of a pile driving hammer considering the soil layering and strength sensitivity.

To date, the GRLWEAP software is well-recognized by many experts as the most reliable predictor of dynamic pile driving stresses, hammer performance, and either blow count or bearing capacity of an impact driven pile.

7.6.6 References

[1]: Mohamed A. El-Reedy, Offshore Structures: Design, Construction and Maintenance, p272-287

[2] Department of Civil Engineering, Texas A&M University, Pile driving analysis by the wave equation

[3]: Hsai-Yang Fang, Foundation Engineering Handbook second edition, p700-702

[4]: Strandgaard T. and Vandenbulcke L., IBC's Wind Power Europe, Driving Monopile into Glacial Till

[5]:http://www.bauerpileco.com/export/sites/www.bauerpileco.com/documents/brochures/hammers-brochures/Offshore-Leads-2012.pdf

7.6.7 Annex: typical curves resulting from the wave equation analysis

The results of the wave equation analysis are presented in Figure 7-31 in the form of curves which enable the user to determine the blow count corresponding to any given resistance encountered by the pile. For example, according to the soil information given in Figure 7-29and Figure 7-30 , the resistance at a penetration of 110 feet will be 1360 kips. Entering this value in Figure 7-31 and projecting horizontally to curve 1 indicates a rate of penetration of around 96 blows per foot. Therefore, the contractor should have no difficulty in penetrating the sand lens.

At a penetration of 165 feet, the soils information of Figure 7-29 and Figure 7-30 indicates a resistance of around 1560 kips. Entering this value in Figure 7-31 and projecting horizontally to curve 2 also gives a blow count around 96 blows per foot, indicating no problems should arise in driving the pile to the required depth after penetrating the sand lens.

If a rate of penetration of around 360 blows per foot is assumed to be practical refusal, curve 2 of Figure 7-31 indicates that the Vulcan 020 hammer should be able to drive this pile to a final resistance to penetration of over 2200 kips. Thus, by using the soils information presented in Figure 7-29and Figure 7-30, it is seen that the pile could probably be driven to a final depth of penetration of over 175 feet. The slight change in penetration will affect the solution very little, and Figure 7-29 will be sufficiently accurate. However, should a major change in penetration be indicated, the problem should probably be re-run at the new penetration.

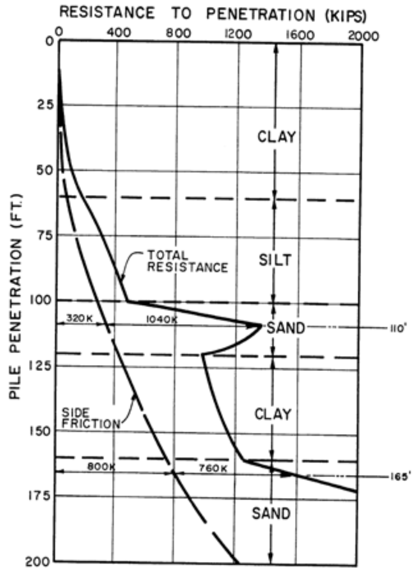


Figure 7-29 Resistance to the penetration versus pile penetration

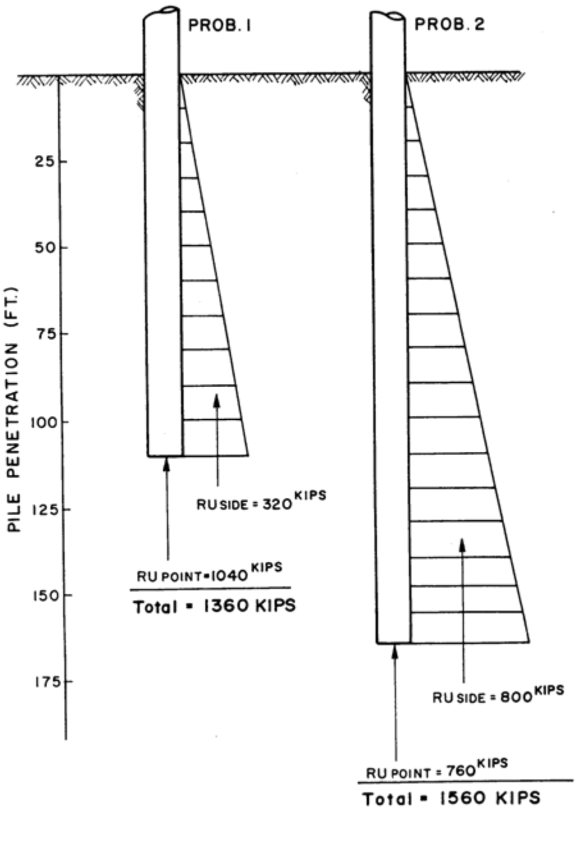


Figure 7-30 Total number of KIPS for two cases

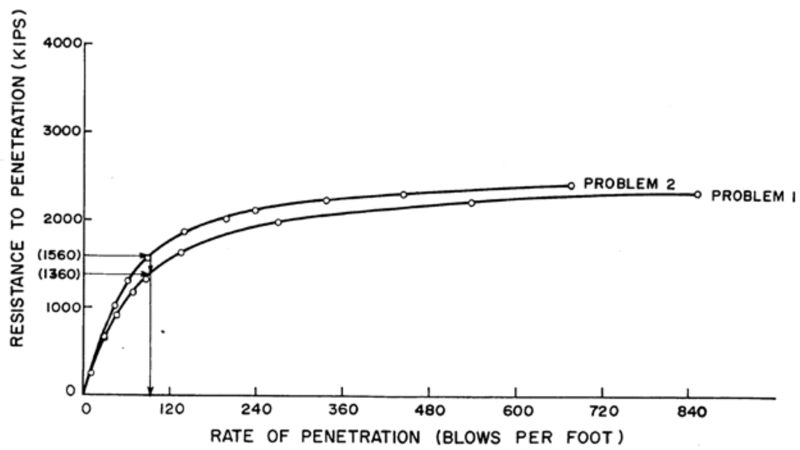


Figure 7-31 rate of penetration as function of the resistance to penetration

7.7 VESSEL AND EQUIPMENT TYPES CONSIDERED FOR THE ENVIRONMENTAL FUNCTIONS

Table 7-10 Environmental functions considered for each vessel type

Vessel Class	Vessel Type	Environmental functions
Barge for Deck Cargo	Barge	Chemical pollution
		Collision
		Footprint
		Noise
		Turbidity
Cable Laying Barge (CLB)	CLB	Chemical pollution
		Collision
		Footprint
		Noise
		Turbidity
Cable Laying Vessel	Cable Laying Vessel (CLV)	Chemical pollution
		Collision
		Noise
	Cable Repair Vessel	Chemical pollution
		Collision
		Noise
Crane Barge	Crane barge	Chemical pollution
		Collision
		Footprint
		Noise
		Turbidity
	Jack-up barge	Chemical pollution
		Collision
		Footprint
		Noise
		Turbidity
Crane Vessel	Crane Vessel	Chemical pollution
		Collision

		Footprint
		Noise
		Turbidity
	Jack-up Crane vessel	Chemical pollution
		Collision
		Footprint
		Noise
		Turbidity
FIT	HF4 - Installation vessel	Chemical pollution
		Collision
		Noise
	OH Installer - Installation Vessel	Chemical pollution
		Collision
		Noise
Offshore Service Vessel	Anchor Handling Vessel (AHT or AHTS)	Chemical pollution
		Collision
		Footprint
		Noise
		Turbidity
	Construction Support Vessel (CSV)	Chemical pollution
		Collision
		Noise
	Dive Support Vessel (DSV)	Chemical pollution
		Collision
		Noise
	Dredge	Chemical pollution
		Collision
		Footprint
		Noise
		Turbidity
	Fallpipe/Rock Dumping Vessel (RDV)	Chemical pollution
		Collision
		Footprint
		Noise
		Turbidity
	Multicat & workboat	Chemical pollution
		Collision
		Noise
	MultiPurpose Vessel (MPV)	Chemical pollution
		Collision
		Noise
	Supply vessel	Chemical pollution
		Collision
		Noise
Others	Helicopters	Collision
		Noise (Aerial)
Standby Vessel	accomodation barge	Chemical pollution
		Collision

		Footprint
		Noise
		Turbidity
	accomodation vessel	Chemical pollution
		Collision
		Footprint
		Noise
Tug	Tugboat	Chemical pollution
		Collision
		Noise
Windfarm maintenance	Crew Transfer Vessel (CTV)	Chemical pollution
		Collision
		Noise

Table 7-11 Environmental functions considered for each equipment type

Equipment Class	Equipment Type	Environmental functions
Cable Burial tools	Cable Burial Ploughs	Chemical pollution
		Collision
		Footprint
		Noise
		Turbidity
	Cable Burial ROV's	Footprint
		Noise
		Turbidity
Concrete matress installation	Concrete matress	Footprint
		Noise
		Reef effect
HDD rigs	HDD rigs	Chemical pollution
		Footprint
		Noise
		Turbidity
Piling equipment	Drilling rigs	Noise
	Hammer	Noise
		Turbidity
	Pile-Guide Frames	Footprint
	Vibro-driving	Noise
		Turbidity
ROV	Inspection	Noise
	Workclass	Noise
Subsea excavating tools	Subsea excavating	Chemical pollution
		Footprint
		Noise
		Turbidity
Tracked Cable Vehicles	Tracked Cable Vehicles	Chemical pollution
		Collision
		Footprint
		Noise
		Turbidity

7.8 LIST OF INPUTS TO THE INSTALLATION MODULE

7.8.1 END-USER INPUTS LIST

Table 7-12 Panda DataFrame containing all required "site" input data to WP5

DataFrame name	Input number	Parameter description	Python name	Unit	Format	Additional comments
site	0	Points of the grid UTM coordinate system in the lease area	x coord	[m]	float	UTM grid coordinate system - Spatial resolution: ΔX≤50 m ; Δy≤50 m
	1		y coord	[m]	float	
	2		zone	[-]	string	
	3	Bathymetry	bathymetry	m	float	Water depth at each point previously defined in 'points'. Water depth must be sufficient for the vessels and some operations are constrained by water depth
	4	Seabed Conditions - Geophysics/Geotechnics	soilt type	[-]	string	Soil type at each point previously defined in 'points' - Soil type list: Cohesionless (sands) -(loose sand; medium sand; dense sand) Cohesive (clays) - (very soft clay; soft clay; firm clay; stiff clay) Others - (hard glacial till; cemented; soft rock coral; hard rock; gravel cobble)

Table 7-13 Panda DataFrame containing all required "met-ocean" input data to WP5

DataFrame name	Input number	Parameter description	Python name	Unit	Format	Additional comments
met-ocean	0	Date and time of the measure met-ocean historical data	year	[-]	integer	
	1		month	[-]	integer	
	2		day	[-]	integer	
	3		hour	[-]	integer	
	4	Resource met-ocean data (wave): (Hs, Tp)	wave Hs	[m]	float	Weather window calculation - Time series of Hs, Tp, wind speed and current speed - One point only in the lease area but must be the same for all dataset - 1 hour resolution minimum - 1 year length minimum
	5		wave Tp	[s]	float	
	6	Resource met-ocean data (wind): wind speed	wind speed	[m/s]	float	
	7	Resource met-ocean data (tide): tidal speed	tide speed	[m/s]	float	

Table 7-14 Panda DataFrame containing all required "device" input data to WP5

DataFrame name	Input number	Parameter description	Python name	Unit	Format	Additional comments
device	0	Device type	type	[-]	string	List of device types: (float WEC; fixed WEC; float TEC; fixed TEC)
	1	Device dimensions	dimensions	[m]	float	Three main dimensions of the device such as length, width and heigth
	2	Device dry mass	dry mass	[kg]	float	
	3	Sub-system list	sub system list	[-]	string	List of the device sub-systems should always be: (A - hydro; B - PTO; C - control; D - support)
	6	Assembly Strategy of the sub-systems of one device	assembly strategy	[-]	text	Sequence and location (port or site) of assembly of the device sub-systems. Under square bracket = sub-systems intalled at port. Under parenthesis = sub-systems installed at site. Example: ([A,B,C], D) = Hydro & PTO & control assembled together at port and this sub-assembly is assembled to the support structure at site
	7	Estimated assembly duration of one device	assembly duration	[hour]	float	Time required to complete the assembly at port of one device
	8	Load-out strategy	load out	[-]	string	Load out type list: (skidded; trailer; float away; lift away) This defines what port characteristics are relevant for the load-out operation of the devices (e.g. dry-dock required, lifting capacities.. etc)
	9	Device and/or sub-assembly transportation method	transportation method	[-]	string	Transportation method list: (deck; tow) If all device sub-systems are assembled at port it is the full device transportation method otherwise it is the sub-assembly transportation method
	10	Required towing bollard pull of the device/sub-assembly	bollard pull	[ton]	float	Relevant only for towed device/sub-assembly

	11	Estimated overall duration of positioning and connection to moorings/foundations	connect duration	[hour]	float	This parameter defines the average on-site time required to position, hook up the device and connect it electrically
	12	Estimated overall duration of disconnection	disconnect duration	[hour]	float	This parameter defines the average on-site time required to disconnect the device for retrieval
	13	Operational Limit Conditions during the device positioning and connecting/disconnecting operation	max Hs	[m]	float	These parameters are used for the weather window calculation
	14		max Tp	[s]	float	
	15		max wind speed	[m/s]	float	
	16		max current speed	[m/s]	float	

Table 7-15 Panda DataFrame containing all required "sub_device" input data to WP5

DataFrame name	Input number	Parameter description	Python name	Unit	Format	Additional comment
Sub_device	0	Device sub-system ID	id	[-]	string	List of the device sub-systems should always be: (A - hydro; B - PTO; C - control; D - support structure)
	1	Device sub-system dimensions	length	[m]	float	Three main dimensions of each device sub-system such as length, width and heigth
	2		width	[m]	float	
	3		height	[m]	float	
	4	Device sub-system dry mass	sub system dry mass	[kg]	float	Dry mass of each device sub-system
	5	Assembly location of the device sub-system	assembly location	[-]	string	assembly location can be either: port (must take place at the installation port) ; site (must take place at the exploitation site); elsewhere (takes place before installation somewhere afar the port and the site)
	6	Estimated assembly duration of the device sub-system	assembly duration	[hour]	float	Time required to complete the assembly of one device sub-system

Table 7-16 Table format for the use of default values or methods for the time assessment and the OLC of each

logistic operations covered by the Installation and O&M modules

	id [-]	Logitic operation [-]	Time: value [h]	Time: function [-]	Time: other [-]	OLC: Hs [m]	OLC: Tp [s]	OLC: Ws [m/s]	OLC: Cs [m/s]
Mob	100	Mobilisation			vesselsDB['Mob time [h]']				
AssPort	101	Assembly at port	1						
TranPortSite	113	Transportation from port to site		transit_algorithm		vessel	vessel	vessel	vessel
TranSiteSite	115	Transportation from site to site		distance		vessel	vessel	vessel	vessel
Demob	116	Demobilisation			vesselsDB['Mob time [h]']				
SeafloorEquipPrep	117	Seafloor & equipment preparation	1			vessel	15	12,5	1,5
Grout	118	Grouting	0,5	grouting			15	12,5	1,5
VesPos	120	Vessel Positioning	6			vessel	vessel	vessel	vessel
PileDrill	302	Driven pile foundation or anchor seafloor penetration through drilling		penetration_time			15	12,5	1,5

		rig + positioning							
DevAssPort	**500**	Device assembly at port			device['assembly duration [h]']				
DeckTrans	**505**	Deck transportation		transit_algorithm		vessel	vessel	vessel	vessel
PosBFdev	**507**	On-site posisitioning and connection of bottom-fixed device			device['connect duration [h]']	device['max Hs [m]']	device['max Tp [s]']	device['max Ws [m/s]']	device['max Cs [m/s]']
Access	**600**	Access to the element			om['d_acc [hour]']	om['Hs_acc [m]']	om['Tp_acc [s]']	om['Ws_acc [m/s]']	om['Cs_acc [m/s]']
Maintenance	**601**	Inspection or Maintenance Operations			om['d_om [hour]']	om['Hs_om [m]']	om['Tp_om [s]']	om['Ws_om [m/s]']	om['Cs_om [m/s]']

Table 7-17 Vertical penetration rates default values for the various techniques to drive a foundation/anchor into the seafloor

	ls	**ms**	**ds**	**vsc**	**sc**	**fc**	**stc**	**hgt**	**cm**	**src**	**hr**	**gc**
Drilling rig [m/h]	0	0	0	0	0	0,65	0,5	0,25	0,5	0,375	0,25	0
Hammer [m/h]	20	15	5	15	12,5	7,5	4,5	0	0	0	0	5
Vibro driver [m/h]	375	250	75	175	75	0	0	0	0	0	0	75
ROV with suction pump [m/h]	375	250	100	200	100	0	0	0	0	0	0	0

ROV with jetting [m/h]	475	250	0	475	475	250	0	0	0	0	0	475

Table 7-18 Horizontal laying rates default values for the various techniques to lay and/or burry a static cable

	ls	ms	ds	vsc	sc	fc	sc	hgt	cm	src	hr	gc
Jetting [m/h]	250	200	0	475	475	250	0	0	0	0	0	0
Ploughing [m/h]	100	350	100	0	375	500	550	300	0	0	0	350
Cutting [m/h]	0	275	275	0	275	275	75	75	75	50	0	0
Dredging [m/h]	150	87,5	75	150	100	75	50	50	50	50	0	75

Table 7-19 Other default values considered in the installation module

	Default values
Surface laying [m/h]	1000
Installation of iron cast split pipes [m/h]	300
Loading rate [m/h]	450
Grout rate [m3/h]	20
Fuel cost rate [EUR/l]	1.5
Port percentual cost [%]	10
Comissioning time [weeks]	6
Cost Contingency [%]	10

7.8.2 UPSTREAM WPS INPUTS

Table 7-20 Panda DataFrame containing all required input data generated by WP2 to WP5

DataFrame name	Input number	Parameter description	Python name	Unit	Format	Additional comment
lay out	0	Device number	units	[-]	integer	

	1	Device ID number	device	[-]	string	Should be consistent with device ID used by all other WPs
	2	Position of devices in the UTM grid coordinate system	x coord	[m]	float	UTM grid coordinate system (x coord, y coord, zone)
	3		y coord	[m]	float	
	4		zone	[-]	string	

Table 7-21 Panda DataFrame containing all required input data "collection point" generated by WP3 to WP5

DataFrame name	Input number	Parameter description	Python name	Unit	Format	Additional comments
collection point	0	Collection point id number	id	[-]	integer	Identification number of the collection point
	1	Collection point type	type	[-]	string	Type list: (Seabed; Seabed with pigtails; Surface Piercing)
	2	Position of collection points	x coord	[m]	float	UTM grid coordinate system (x coord, y coord, zone)
	3		y coord	[m]	float	
	4		zone	[-]	string	
	5	Collection point dry mass	dry mass	[kg]	float	
	6	Collection point dimensions	width	[m]	float	
	7		length	[m]	float	
	8		height	[m]	float	
	9	Collection point electrical interfaces parameters	upstream ei type	[-]	string	- Type list: (wet-mate connector / dry-mate connector / splice / j-tube) - Depending on the Collection Point type, these assume: Seabed: onboard connectors (wet-mate/dry-mate) Seabed with pigtails: pigtails connectors (wet-mate/dry-mate/splice) Surface Piercing: J-tube interfaces (j-tube)
	10		upstream ei id	[-]	integer	Identification number of the upstream electrical interface of the collection point. If type == (wet-mate connector || dry-mate connector || splice): id should point to the 'connectors' dataframe if type == j-tube: id should point to the 'collection point' dataframe

	11		downstream ei type	[-]	string	- Type list: (wet-mate connector / dry-mate connector / j-tube / hard-wired cable) - Depending on the Collection Point type, these assume: Seabed: onboard connectors (wet-mate/dry-mate) or hard-wired interfaces (hard-wired cable) Seabed with pigtails: onboard connectors (wet-mate/dry-mate) or hard-wired interfaces (hard-wired cable) Surface Piercing: J-tube interfaces (j-tube)

	12		downstream ei id	[-]	integer	Identification number of the upstream electrical interface of the collection point.
						
						If type == (wet-mate connector || dry-mate connector):
						id should point to the 'connectors' dataframe
						if type == j-tube:
						id should be empty
						if type == hard-wired cable:
						id should point to the 'static cable' dataframe

	14	Number of Pigtails	nr pigtails	[-]	integer	
	15	Pigtails length	pigtail lenght	[m]	float	
	16	Pigtails diameter	pigtail diameter	[mm]	float	
	17	Pigtails cable dry mass	pigtail cable dry mass	[kg/m]	float	Cable dry mass per meter
	18	Pigtails total dry mass	pigtail total dry mass	[kg]	float	Dry mass of Individual pigtail cable plus the connector halve with end cap

Table 7-22 Panda DataFrame containing all required input data "dynamic cable" generated by WP3 to WP5

DataFrame name	Input number	Parameter description	Python name	Unit	Format	Additional comments
dynamic cable	0	Umbilical id number	id	[-]	integer	Identification number of the umbilical
	1	Umbilical dry mass	dry mass	[kg/m]	float	Umbilical dry mass per meter
	2	Umbilical total dry mass	total dry mass	[kg/m]	float	Dry mass of umbilical cable plus connector halves
	3	Umbilical length	length	[m]	float	
	4	Umbilical diameter	diameter	[mm]	float	
	5	Umbilical minimum bend radius (MBR)	MBR	[m]	float	

	6	Umbilical minimum breaking load (MBL)	MBL	[N]	float	
	7	Umbilical termination parameters	upstream termination type	[-]	string	Type list: (Device / Collection Point)
	8		upstream termination id	[-]	integer	Identification number of the upstream termination element of the umbilical. If type == device: id should point to the 'device' dataframe if type == collection point: id should point to the 'collection point' dataframe
	9		upstream termination x coord	[-]	float	UTM grid coordinate corresponding to the upstream termination of the umbilical
	10		upstream termination y coord	[-]	float	
	11		upstream termination zone	[-]	string	
	12		downstream termination type	[-]	string	Type list: (Device / Static Cable / Collection Point)

	13		downstream termination id	[-]	integer	Identification number of the downstream termination element of the umbilical.
						If type == device:
						id should point to the 'device' dataframe
						if type == static cable:
						id should point to the 'static cable' dataframe
						if type == collection point:
						id should point to the 'collection point' dataframe

	14		downstream termination x coord	[-]	float	UTM grid coordinate corresponding to the downstream termination of the umbilical
	15		downstream termination y coord	[-]	float	
	16		downstream termination zone	[-]	string	
	17	Umbilical electrical interface parameter	upstream ei type	[-]	string	Type list: (wet-mate connector / dry-mate connector / j-tube / hard-wired) - Depending on the downstream termination type, these assume: Device: onboard connectors (wet-mate/dry-mate) or a hard-wired umbilical Collection Point: onboard connectors (wet-mate/dry-mate) or (J-tube) interfaces for surface piercing collection points

	18		upstream ei id	[-]	integer	Identification number of the upstream electrical interface of the umbilical. If type == (wet-mate connector || dry-mate connector): id should point to the 'connectors' dataframe if type == hard-wired: id should point to the 'device' dataframe
	19		downstream ei type	[-]	string	Type list: (wet-mate connector / dry-mate connector / splice / j-tube) - Depending on the downstream termination type, these assume: Device: onboard connectors (wet-mate/dry-mate) Static Cable: seabed connector (wet-mate/dry-mate/splice) Collection Point: onboard connectors (wet-mate/dry-mate), pigtail connectors (wet-mate/dry-mate/splice) or (J-tube) interfaces for surface piercing collection points
	20		downstream ei id	[-]	integer	Identification number of the downstream electrical interface of the umbilical. If type == (wet-mate connector || dry-mate connector || splice): id should point to the 'connectors' dataframe if type == j-tube: id should point to the 'collection point' dataframe
	21	Buoyancy modules number	buoyancy number	[-]	integer	
	22	Buoyancy modules dimensions	buoyancy diameter	[m]	float	
	23		buoyancy length	[m]	float	
	24	Buoyancy modules weight	buoyancy weigth	[kg]	float	

Table 7-23 Panda DataFrame containing all required input data "static cable" generated by WP3 to WP5

DataFrame name	Input number	Parameter description	Python name	Unit	Format	Additional comments
static cable	0	Static cable id number	id	[-]	string	Identification number of the umbilical

	1	Static cable type	type	[-]	string	Type list: (array / export)
	2	Static cable dry mass	dry mass	[kg/m]	float	Umbilical dry mass per meter
	3	Static cable total dry mass	total dry mass	[kg]	float	Dry mass of static cable plus connector halves
	4	Static cable length	length	[m]	float	
	5	Static cable diameter	diameter	[mm]	float	
	6	Static cable minimum bend radius (MBR)	MBR	[m]	float	
	7	Static cable minimum breaking load (MBL)	MBL	[N]	float	
	8	Static Cable termination parameters	upstream termination type	[-]	string	Type list: (Device / Dynamic Cable / Collection Point)

	9		upstream termination id	[-]	integer	Identification number of the upstream termination element of the static cable.
						If type == device:
						id should point to the 'device' dataframe
						if type == static cable:
						id should point to the 'static cable' dataframe
						if type == collection point:
						id should point to the 'collection point' dataframe

	10		downstream termination type	[-]	string	Type list: (Device / Dynamic Cable / Collection Point / Landing Point)

	11		downstream termination id	[-]	integer	Identification number of the downstream termination element of the static cable.
						If type == device:
						id should point to the 'device' dataframe
						if type == dynamic cable:
						id should point to the 'dynamic cable' dataframe
						if type == collection point:
						id should point to the 'collection point' dataframe
						if type == landing point:
						id should be N/A

	12		upstream ei type	[-]	string	Type list: (wet-mate connector / dry-mate connector / splice / j-tube / hard-wired) Depending on the upstream termination type, the ei types can assume: Device: onboard connectors (wet-mate/dry-mate/ J-tube) Dynamic Cable: seabed connector (wet-mate/dry-mate/splice) Collection Point: onboard connectors (wet-mate/dry-mate) or (hard-wired) for seabed collection points and (J-tube) interfaces for surface piercing collection points

	13	Static Cable electrical interface parameters	upstream ei id	[-]	integer	Identification number of the upstream electrical interface of the static cable.
						
						If type == (wet-mate connector || dry-mate connector || Splice):
						id should point to the 'connectors' dataframe
						if type == hard-wired:
						id should point to the 'device' dataframe
						if type == j-tube:
						id should point to N/A

	15		downstream ei type	[-]	string	Type list: (wet-mate connector / dry-mate connector / splice / j-tube / NA) Depending on the upstream termination type, these assume: Device: onboard connectors (wet-mate/dry-mate/ J-tube) Dynamic Cable: seabed connector (wet-mate/dry-mate/splice) Collection Point: onboard connectors (wet-mate/dry-mate) or hard-wired for seabed collection points and J-tube interfaces (j-tube) for surface piercing collection points Landing Point: Electrical interfaces are not applicable (NA) for this termination

	16		downstream ei id	[-]	integer	Identification number of the downstream electrical interface of the static cable.
						
						If type == (wet-mate connector || dry-mate connector || Splice):
						id should point to the 'connectors' dataframe
						if type == j-tube:
						id should point to N/A
						if type == NA:
						id should point to N/A

Table 7-24 Panda DataFrame containing all required input data "cable route" generated by WP3 to WP5

DataFrame name	Input number	Parameter description	Python name	Unit	Format	Additional comments
cable route	0	Static cable id number	static cable id	[-]	integer	Identification number of the static cable
	1	Cable route UTM coordinates	x coord	[m]	float	UTM grid coordinate system (x coord, y coord, zone)
	2		y coord	[m]	float	
	3		zone	[-]	string	
	4	Soil type	soil type	[-]	string	Soil type corresponding to the UTM grid coordinate
	5	Soil bathymetry	bathymetry	[m]	float	Bathymetry corresponding to the UTM grid coordinate
	6	Burial depth	burial depth	[m]	float	The burial depth is defined from this cable grid coordinate until the next on the route.
	7	Split pipe required	split pipe	[-]	boolean	(Yes/No) : If the cable section starting from this grid point until the next requires the installation of split pipes

Table 7-25 Panda DataFrame containing all required input data "external protection" generated by WP3 to WP5

DataFrame name	Input number	Parameter description	Python name	Unit	Format	Additional comments
external protecti on	0	Type of protection element	type	[-]	string	Type list: (concrete matress / rock filter bag)

	1	Position of protection element	x coord	[m]	float	UTM grid coordinate system (x coord, y coord, zone)
	2		y coord	[m]	float	
	3		zone	[-]	string	

Table 7-26 Panda DataFrame containing all required input data "connectors" generated by WP3 to WP5

DataFrame name	Input number	Parameter description	Python name	Unit	Format	Additional comments
connectors	0	Electrical connector id number	id	[-]	integer	Identification number of the connenctor
	1	Electrical connector type	type	[-]	string	Type list: (wet-mate connector / dry-mate connector / splice connector)
	2	Electrical connector dry mass	dry mass	[kg]	float	
	3	Electrical connector dimensions	lenght	[m]	float	
	4		width	[m]	float	
	5		height	[m]	float	
	6	Electrical connector required mating / de-mating force	mating force	[N]	float	For wet-mate connectors, this data corresponds to the mating force required for the ROV manipulators to plug the connector.
	7		demating force	[N]	float	For wet-mate connectors, this data corresponds to the demating force required for the ROV manipulators to unplug the connector.

Table 7-27 Panda DataFrame containing all required "foundation" input data generated by WP4 to WP5

DataFrame name	Input number	Parameter description	Python name	Unit	Format	Additional comment
foundation	0	Device ID number	devices	[-]	string	Should be consistent with device ID used by all other WPs
	1	Foundation ID number	foundations	[-]	string	
	2	Foundations/anchors type	type	[-]	string	Foundation type list: (shallow foundation; gravity; pile; suction caisson; direct-embedment anchor; drag-embedment anchor)

	3	Foundations/anchors subtype	subtype	[-]	string	Foundation subtype list: (shallow foundation; concrete/steel composite structure with shear keys or concrete/steel composite structure without shear keys, gravity; concrete/steel composite structure, pile; pin pile or pipe pile, suction caisson; closed top, direct-embedment anchor; hammer driven, drag-embedment anchor; <anchor model specified in database>)
	5	Foundations/anchors coordinates	x coord	[m]	float	UTM grid coordinate system
			y coord	[m]	float	
			zone	[-]	string	
	6	Foundations/anchors dimensions	width	[m]	float	For all foundation types apart from piles and suction caissons three dimensions are specified (length, width and height). For piles and suctions caissons width=length=diameter.
			length	[m]	float	
			height	[m]	float	
	7	Foundation penetration depth	depth	[m]	float	Installation depth will be specified for all foundation types except gravity and shallow foundations
	8	Foundations/anchors dry mass	dry mass	[kg]	float	
	9	Foundation grout type	grout type	[-]	string	grout type list: TBC
	10	Foundation grout volume	grout volume	[m3]	float	

Table 7-28 Panda DataFrame containing all required “line” input data generated by WP4 to WP5

DataFrame name	Input number	Parameter description	Python name	Unit	Format	Additional comment
line	0	Device ID number	device	[-]	string	Should be consistent with device ID used by all other WPs
	1	Mooring line ID number	lines	[-]	string	The ID number of the line should match with the foundation ID number, i.e line001 of (device001) is attached to foundation001 (device001)
	2	Component list of the mooring system	component list	[-]	string	Anything between anchoring point and fairlead. Only one component list per device meaning there would necessarily be one mooring line type per device
	3	Type of mooring system	mooring system type	[-]	string	Mooring system type list: (taut; catenary)
	4	Mooring line length	line length	[m]	float	Cummulated length of all elements from the anchoring point to the fairlead

	5	Mooring line dry mass	line dry mass	[kg]	float	Cummulated dry mass of all elements from the anchoring point to the fairlead