Advanced Design Tools for Ocean Energy Systems Innovation, Development and Deployment

Deliverable D5.7

Logistics and Marine Operations Tools – Alpha version

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Author(s)	F. X. Correia da Fonseca, Luís Amaral, Manuel Rentschler, Filipe Arede, Paulo Chainho (WavEC), Yi Yang (AAU), Donald R Noble (UEDIN), Alexey Petrov (OCC), Vincenzo Nava (Tecnalia), Nicolas Germain (FEM), Nicolas Lariviere-Gillet (BV), Jillian Henderson, Ben Hudson (WES).
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EXECUTIVE SUMMARY

Deliverable D5.7 "Logistics and Marine Operation Tools – alpha version" of the DTOceanPlus project includes the details of the Deployment Design Tools module: "Logistics and Marine Operations" (LMO), and it represents the result of the work developed during tasks T5.2 and T5.8 of the project.

The Logistics and Marine Operations module is responsible for designing and planning the project lifecycle phases (installation, maintenance, decommissioning) of an ocean energy project. Reflecting the most recent experiences and best practices of the offshore wind sector, the LMO module produces integrated solutions in respect to logistic infrastructure, comprised of vessels, equipment and ports, as well as operation durations and costs based on introduced historical weather data.

Expanding on the previous DTOcean version, the LMO module was improved in respect to the vessel selection methodology and the waiting on weather algorithm, providing more meaningful results and a way to quantifying uncertainty. Preventive and corrective maintenance activities were included, namely tow to port maintenance options, and vessel, equipment and port data were updated. Additional flexibility was also implemented to provide the user a way to customise the operations according to their preferences. The development of LMO was carried out in close connection with task T6.4 in which tools for assessing for the reliability, availability, maintainability and survivability were developed.

The Business Logic of the code, which corresponds to the core functions of the LMO module, has been implemented in Python 3. An Application Programming Interface (API) was developed in OpenAPI and provided with the code, in order to interact and communicate with the other modules of the DTOceanPlus design suite. The Graphical User Interface (GUI) of the module is being developed in harmony with the other modules, in Vue.js, allowing the user to interact easily with the LMO tool, inputting data and visualising results. Preliminary unit tests were implemented to verify the Business Logic of the code and to contribute to the easy maintainability for future developments of the tool.

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ABBREVIATIONS AND ACRONYMS

ACCW	Average Climate Capture Width
ACE	Average Climate Capture Width per Characteristic Capital Expenditure
AHTS	Anchor Handling Tug Supply
ALF	Average Load Factor
API	Application Programming Interface
BIMCO	Baltic and International Maritime Council
BOM	Bill of Materials
BP	Bollard Pull
CCE	Characteristic Capital Expenditure
CCF	Cumulative Cash Flow
CD	Characteristic dimension
CLV	Cable Laying Vessel
CPX	Complexity Level of the module
CTV	Crew Transfer Vessel
DP	Dynamic Positioning
DPBP	Discounted Payback Period
DRP	Device Rated Power
DSV	Dive Support Vessel
EC	Energy Capture
ED	Energy Delivery
EPCI	Engineering, Procurement, Construction and Installation
ESA	Environmental and Social Acceptance
ET	Energy Transformation
FEED	Front-End Engineering Design
GRS	Global Renewable Shipbrokers
GUI	Graphic User Interface
HDD	Horizontal Directional Drilling
HFO	Heavy Fuel Oil
HTTP	HyperText Transfer Protocol
IRR	Internal Rate of Return
IMO	International Maritime Organisation
LCOE	Levelised Cost of Energy
LMO	Logistics and Marine Operations
LOA	Length Overall
MC	Machine Characterisation
MDO	Marine Diesel Oil
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
ND	Number of devices
NPV	Net Present Value
O&M	Operation and Maintenance
OCT	Open-Cut Trenching
OLC	Operational Limits and Conditions
PBP	Payback Period
PL	Project Life
PSV	Platform Support Vessel
PTO	Power Take-Off unit

RAMS	Reliability, Availability, Maintainability, Survivability
REST	Representational State Transfer
ROV	Remotely Operated Vehicle
SC	Site Characterisation
SFOC	Specific Fuel Oil Consumption
SG	Stage Gate
SI	Structured Innovation
SK	Station Keeping
SLC	System Lifetime Costs
SOV	Service Operation Vessel (also referred to as Field Support Vessel)
SPEY	System Performance and Energy Yield
T&I	Transportation and Installation
TEA	Techno-economic Assessment
TEC	Tidal Energy Converter
TIP	Total Installed Power (of vessel)
TRL	Technology Readiness Level
TT	Technology Type (Tidal or Wave Energy Device)
VC	Vessel Combination
WEC	Wave Energy Converter
WOW	Waiting on Weather

1. INTRODUCTION

1.1 SCOPE AND OUTLINE OF THE REPORT

Deliverable D5.7 "Logistics and Marine Operations Planning – Alpha version" of the DTOceanPlus project includes the details of the Deployment Design Tools module: "Logistics and Marine Operations", hereinafter referred to as LMO or Logistics module, and it represents the result of the work developed during task T5.8 of the project. This document serves as the technical manual of the alpha version of the LMO module, describing the data requirements, main functionalities, user interfaces and relevant technical details. The alpha version of the LMO is a fully functional version in terms of the implementation of calculations covered by the LMO module, i.e. the Business Logic, with limited functionality in terms of Graphical User Interface (GUI), which will be further developed during the integration phase.

This document summarises:

1. The supporting theory, definitions, and underlying assumptions behind the Logistics and Marine Operations module (Section 2).
2. The use cases and the functionalities of the Logistics and Marine Operations module (Section 3).
3. The actual implementation of the module, describing the architecture of the tool, the technologies adopted for the implementation and the results of the testing (Section 4).
4. A set of extensive examples, to provide the reader with an overall view of the capabilities of the module (Section 5).

1.2 SUMMARY OF THE DTOCEANPLUS PROJECT

The Logistics and Marine Operations module belongs to the design suite of tools "DTOceanPlus" [1] developed within the EU-funded project DTOceanPlus (https://www.dtoceanplus.eu/).

DTOceanPlus aims to accelerate the commercialisation of the Ocean Energy sector by developing and demonstrating an open source suite of design tools for the selection, development, deployment and assessment of ocean energy systems (including subsystems, energy capture devices and arrays).

At a high level, the suite of tools developed in a modular fashion for integrated purpose in DTOceanPlus will include:

- **Structured Innovation Tool (SI)**, for concept creation, selection, and design.
- **Stage Gate Tool (SG)**, using metrics to measure, assess and guide technology development.
- Deployment Tools, supporting optimal device and array deployment:
  - *Site Characterisation (SC)*, to characterise the site, including met-ocean, geotechnical, and environmental conditions;
  - *Machine Characterisation (MC):* to characterise the prime mover;
  - *Energy Capture (EC)*, to characterise the device at an array level;
  - *Energy Transformation (ET)*, to design PTO and control solutions;

- *Energy Delivery (ED)*, to design electrical and grid connection solutions;
- *Station Keeping (SK)*, to design moorings and foundations solutions;
- *Logistics and Marine Operations (LMO)*, to design logistical solutions operation plans related to the installation, operation, maintenance, and decommissioning operations.

- **Assessment Tools**, to evaluate projects in terms of key parameters:
  - *System Performance and Energy Yield (SPEY)*, to evaluate projects in terms of energy performance;
  - *System Lifetime Costs (SLC)*, to evaluate projects from the economic perspective;
  - *System Reliability, Availability, Maintainability, Survivability*† *(RAMS)*, to evaluate the reliability aspects of a marine renewable energy project;
  - *Environmental and Social Acceptance (ESA)*, to evaluate the environmental and social impacts of a given wave and tidal energy projects.

These will be supported by underlying common digital models and a global database, as shown graphically in Figure 1.1.

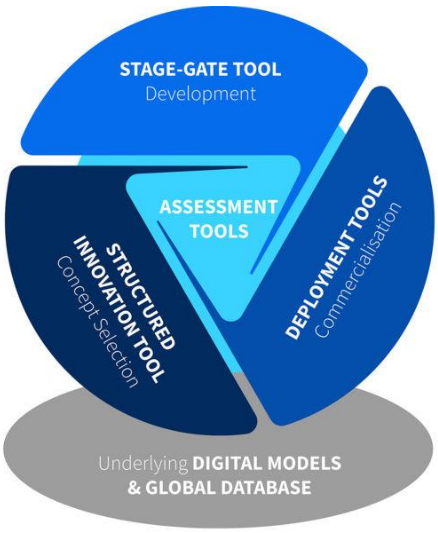


FIGURE 1.1 REPRESENTATION OF DTOCEANPLUS TOOLS

2. BACKGROUND

2.1 OPERATING PRINCIPLE OF THE LOGISTICS AND MARINE OPERATIONS MODULE

The Logistics and Marine Operation (LMO) module is responsible for designing logistical solutions for the installation, Operation and Maintenance (O&M), and decommissioning phases of Ocean Energy projects. Logistic solutions consist of an operation plan and an optimal combination of vessels, equipment and ports that minimise the costs of each operation individually, reducing capital and operational expenditures simultaneously (CAPEX and OPEX).

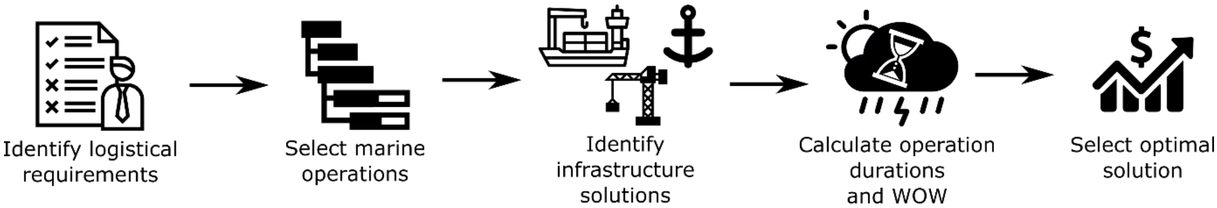


FIGURE 2.1 OPERATING PRINCIPLE OF THE LMO MODULE

The operating principle behind the LMO module, as schematised in Figure 2.1, is common to all three phases (installation, O&M and decommissioning) of the project.

In a first stage, the Logistics module compiles from the other modules and user inputs, information about the devices and subsystems that must be installed, maintained, and decommissioned throughout project lifetime. These are transformed into project logistic requirements (e.g. 50 mooring lines with a given weight, diameter, and length, need to be installed) and relevant marine operations to be carried out are identified (e.g. moorings installation).

Secondly, the identification of feasible infrastructure solutions is initiated. Vessels, ports and equipment are not only required to meet minimum individual prerequisites for their purpose (e.g. sufficient vessel deck area, terminal dry dock requirements, adequate Remotely Operated Vehicles (ROV) depth rating, etc.), but also to be combined into a compatible solution (e.g. vessel must be suitable to transport equipment, port water depth must be compatible with vessel draft, etc.).

Next, for each potential logistic solution, defined by an operation plan and an infrastructure solution, the operation durations and waiting on weather (WOW) estimates are calculated based on past met-ocean conditions. Once the total durations are calculated, the total costs of the operation, for each logistic solution, can be calculated based on the daily costs of the infrastructure solutions. Finally, the logistic solution associated with the lowest operation costs can now be selected as the optimal solution.

2.2 INSTALLATION

2.2.1 COMPONENTS AND INSTALLATION OPERATIONS

The installation of all subsystems and components related to a given offshore renewable energy farm is typically grouped into large operations according to component types, transport methodology, vessel requirements and installation sequence.

Within the context of DTOceanPlus, eight different installation operations were considered for installing all the envisaged component types, as shown in Table 2.1 Considered installation operationsTable 2.1.

TABLE 2.1 CONSIDERED INSTALLATION OPERATIONS

Name of installation operation	Component types to be installed
Foundation installation	▸ Gravity-based anchors ▸ Pile anchors and foundations ▸ Suction caissons (anchors and foundations)
Mooring installation	▸ Mooring lines ▸ All anchors except pile and suction anchors.
Support structure installation	▸ Jacket ▸ Gravity-based structures ▸ Tripod
Collection point installation	▸ Subsea hub ▸ Surface-piercing offshore substations ▸ Floating offshore substations
Device installation	▸ Floating WEC ▸ Bottom-fixed WEC ▸ Floating TEC ▸ Bottom-fixed TEC
Export cable installation	▸ Includes cables and connectors ▸ Static and dynamic cables/segments. ▸ May include split pipes if needed
Array cable installation	▸ Includes cables and connectors ▸ Static and dynamic cables/segments. ▸ May include split pipes if needed
External protections installation	▸ Concrete mattress ▸ Rock bags ▸ Rocks

In DTOceanPlus, it is assumed that each installation operation is singular and thus responsible for installing all components associated with the operation in question. In other words, for a given floating wave energy farm with floating collection points, it is assumed there will only be one "*Mooring installation"* operation, which will only end after having installed every single mooring line of the farm. Multi-phase installation projects are thus, not considered within the scope of DTOceanPlus. The project commissioning date is assumed to be the end date of the last installation operation.

2.2.2 SEQUENCE OF OPERATIONS

For an offshore renewable energy project, the exact sequencing of the installation operations is project specific, many times with multiple operations being carried out in parallel. Still, there are physical constraints that impose that some systems are installed before others. One example is the case of foundations which are necessarily installed before the device and frequently before everything else. When designing the sequence of installation operations, the following motivations come into play:

1) Cable connections using dry-mate connectors must be performed in a dry-environment, on deck of the installation vessel.
2) Dynamic cables (or cables with dynamic segments) should not be installed without performing the connection. This means that in theory, dynamic cables should be installed after the floating elements (device or collection point) they are connected to.
3) Devices and collection points installed on the seabed should be lowered just once during installation.
4) Surface piercing fixed elements (e.g. fixed offshore wind), are commonly installed before cables for asset safety reasons.

In DTOceanPlus, flexibility related to specifying operation sequences was provided to the user. Building on the reasons stated above, the LMO module proposes operation precedence rules for different device and collection point topologies, and cable connectors. In Table 2.2, four typical operation sequences are presented (Seq 1, Seq 2, Seq 3 and Seq 4), and then expanded in Table 2.3. However, the user may change the operation sequence, and in case any violation to the stated rules occurs, a warning will be presented.

TABLE 2.2 OPERATION PRECEDENCE RULES FOR INSTALLING OFFSHORE RENEWABLE ENERGY FARMS

		Device: Bottom-fixed		Floating Device
		Dry-mate	Wet-mate *(or I-tube/J-tube)*	Wet-mate / Dry-mate
Collection point: Surface Piercing	Wet-mate / Dry-mate	Seq 1[1]	Seq 2[2]	Seq 2[3]
Collection point: Seabed	Dry-mate	Seq 3	Seq 4	Seq 4
	Wet-mate *(or I-tube/ J-tube)*	Seq 1	Seq 2	Seq 2

[1] E.g. Wave-roller: although no collection point was installed, the installation approach followed this principle.
[2] E.g. Fixed offshore wind
[3] E.g. Wind Float Atlantic (according to initial installation plan) [2]. The Pelamis technology would have also followed this operation sequence since the mooring and cable connection are coupled.

TABLE 2.3 INSTALLATION OPERATION SEQUENCE CONSIDERED

Seq 1	Seq 2	Seq 3	Seq 4
Foundation installation ↓ Moorings installation ↓ Support structures installation ↓ Collection point installation ↓ Export cable installation ↓ Array cable installation ↓ Post-lay cable burial ↓ External protections ↓ Device installation	Foundation installation ↓ Moorings installation ↓ Support structures installation ↓ Collection point installation ↓ Device installation ↓ Export cable installation ↓ Array cable installation ↓ Post-lay cable burial ↓ External protections	Foundation installation ↓ Moorings installation ↓ Support structures installation ↓ Export cable installation ↓ Array cable installation ↓ Post-lay cable burial ↓ External protections ↓ Collection point installation ↓ Device installation	Foundation installation ↓ Moorings installation ↓ Support structures installation ↓ Device installation ↓ Export cable installation ↓ Array cable installation ↓ Post-lay cable burial ↓ External protections ↓ Collection point installation

2.3 MAINTENANCE

Operation and Maintenance (O&M) activities in offshore renewable energy projects have considerable impact on the cost of energy. For offshore wind, a more mature sector, these activities make up about one third of the overall costs, which is considerably higher than for onshore wind projects[3] The O&M costs are mostly made up of spare or replacement parts, vessel and technician hiring, and downtime which is significantly affected by the site accessibility.

In order to guarantee that infrastructure and devices are operating in good conditions over extended periods of time, maintenance activities must be carried out. There are many ways of classifying maintenance activities. In the perspective of project planning, maintenance activities can be broadly classified into two types: corrective maintenance and preventive maintenance. Corrective maintenance actions are scheduled as a response to a failure, whilst preventive maintenance tasks, are intended to prevent occurrence of a problem in the first place.

Preventive maintenance and corrective maintenance are sometimes referred to as "planned" and "unplanned" maintenances, respectively. As the names suggest, the main difference between planned and unplanned maintenances consists on whether they can be planned ahead, or if they are scheduled as a reaction to a situation [4], [5]. The preventive maintenance can be further divided into time-based maintenance, predictive maintenance, condition-based maintenance, and risk-based maintenance (see Figure 2.2).

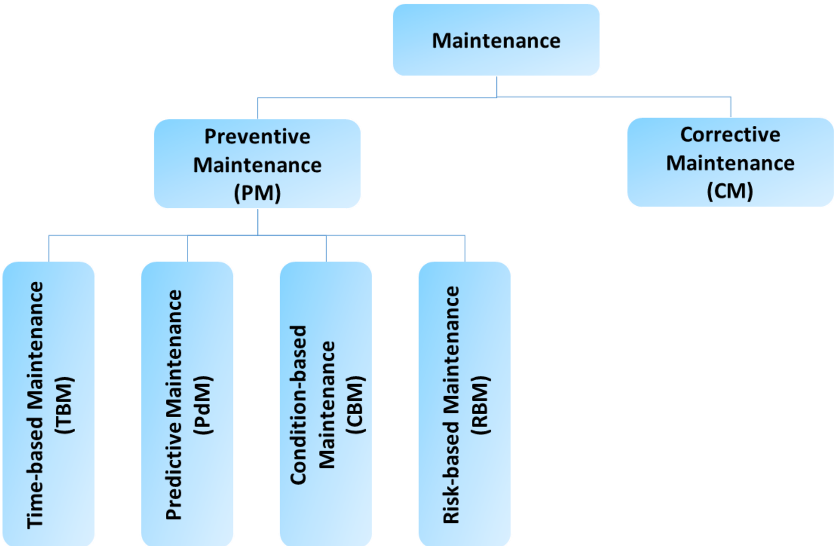


FIGURE 2.2 BREAKDOWN OF MAINTENANCE INTERVENTION TYPES

2.3.1 PREVENTIVE MAINTENANCE

2.3.1.1 TIME BASED

Time-based maintenance, also known as periodic-based/calendar maintenance, is a traditional maintenance strategy. In the framework of time-based maintenance, the maintenance interval is predetermined based upon the knowledge/ prior information on the damage evolution. The replacement of collapsed components or the repair of failed components should be conducted at a fixed time interval, regardless of its condition.

The purpose of time-based maintenance is to protect an infrastructure/ facility from the failures of wearing components with predictable mean time between failure (MTBF).

In some traditional industries, e.g. naval architecture, oil& gas, sub-sea, regulatory bodies and third-party certification societies have clear requirements on the time-based inspection/ maintenance for primary structures. For example, offshore jacket structures and ship structures should be subject to special inspections every five years. In the renewable industries, e.g. wind energy, marine energy, there are often similar regulatory/ compulsory requirements on the time-based inspections.

Time-based maintenance is considered in the Logistics and Marine Operations module.

2.3.1.2 CONDITION BASED MAINTENANCE

Condition-based maintenance is a maintenance strategy that recommends maintenance actions based on the information depicting the current condition of a structure/ device. Generally, the information stems from three resources, namely an inspection database, the condition-monitoring system and the physics-based deterioration model characterizing the damage propagation and/or the laboratory tests. The physics-based deterioration model parameters can be updated according to the obtained monitoring information. The updating process can help better understand the uncertainties embedded in the transformation/ link between the monitoring information and the physical damage.

The condition-based maintenance has gained the popularity recently since some failure modes give the syndromes of degradation through indicators such as component vibrations and temperature. In nature, the intrinsic properties of structures/ facilities are associated with features, which can be quantified by some physical variables, e.g. vibration frequencies/ modes/ amplitudes, temperature, oil particles, stiffness, damage sizes, etc. With the aim to obtain these indicators, advanced online monitoring data acquisition systems should be installed to sample these indicators on time. There are some successful applications of on-line monitoring (Supervisory control and data acquisition (SCADA)) in the gearboxes of wind turbines.

Condition-based maintenance is not considered within the scope of DTOceanPlus.

2.3.1.3 PREDICTIVE MAINTENANCE

Both condition-based and predictive maintenance rely on data from sensors that are monitoring the components. However, while condition-based maintenance uses conditions or thresholds to identify when it is time to perform maintenance, predictive maintenance tries to predict into the future when the components will require servicing. Predictive maintenance relies on advanced statistical methods, such as machine learning, analysing patterns across all sensors to generate one multivariate prediction model. Predictive maintenance can [6]:

- Minimise the number of unexpected breakdowns and maximise asset uptime which improves asset reliability;

- Reduce operational costs by optimising the time you spend on maintenance work (in other words, doing maintenance only when needed to do it practically eliminates any chance of wasting time doing excessive maintenance);
- Improve project economic viability by reducing long-term maintenance costs and maximising production hours.

In most cases, sensors are attached to the concerned structures/ facilities to measure the damage indirect indicators (vibration frequencies/ modes/ amplitudes, temperature, and stiffness) or detect the direct indicators (oil particles and damage sizes).

On one hand, the collected data can indicate the current condition of the infrastructures/ devices. On the other hand, these data can also be used to predict the damage indicator trend which indirectly indicate the physical damage evolution, based upon predictive algorithms. These algorithms can be divided into two major categories, namely physics-based and data-driven. The physics-based method investigates the mechanism of failure/collapse of materials and generally provides a closed-form predictive formula to predict the damage propagation for the identified failure mode (e.g. crack propagation). This method has been widely used in welded steel structures, e.g. ship hull structures, jacket structures and wind turbine steel foundations. The data-driven methods can build up a link between the observations (damage indicators) and the physical deterioration, instead of using a closed-form physical model. This method requires a huge amount of data to train the model. The training process guides the model to build up the links between the observations and the states of damage. Typically, the data-driven models include Markovian model (can be extended to Hidden Markov, Hidden Semi-Markovian models), Artificial neural networks, Support Vector Machines, Bayesian networks.

Sensors that enable predictive maintenance lie outside the DTOceanPlus scope, which renders impossible the implementation of predictive maintenance strategies.

2.3.1.4 RISK-BASED MAINTENANCE

Risk-based maintenance is an extension of predictive maintenance, and can be broken down into three main modules, see Figure 2.3:

1. Risk determination, which consists of risk identification and estimation:
    - Failure scenario identification: a failure scenario is a description of a series of events which may lead to a system failure. It may contain a single event or a combination of sequential events. Usually, a system failure occurs as a result of interacting sequence of events.
    - Consequence assessment: consequence analysis involves assessment of likely consequences if a failure scenario does materialise.
    - Probabilistic failure analysis: the objective is to calculate the probability of failure of each failure event by using classic algorithms, e.g. fault tree, reliability diagram, Bayesian network.
2. Risk evaluation and acceptance analysis;
    - Set up the risk acceptance criteria;
    - Comparison of risks based upon the acceptance criteria
3. Maintenance planning considering risk factors

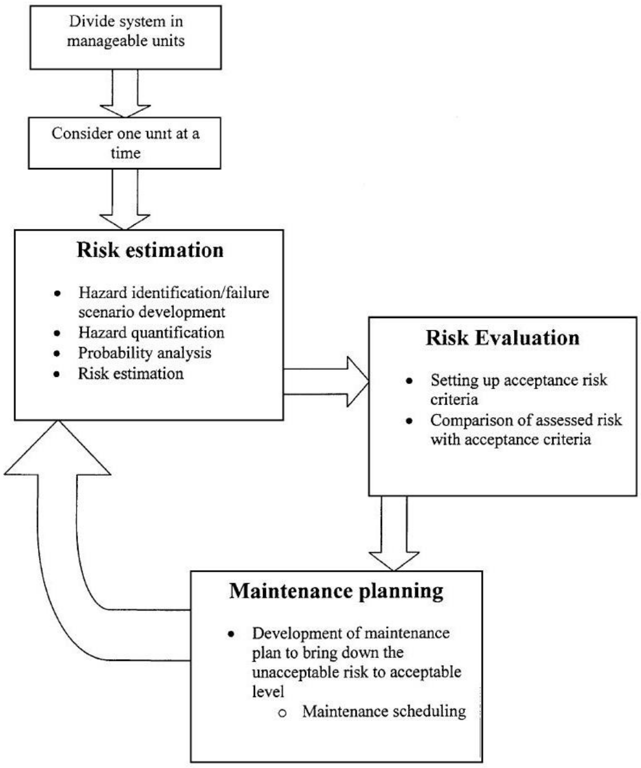


FIGURE 2.3 ARCHITECTURE OF RBM METHODOLOGY[7]

Risk-based maintenance was not implemented in DTOceanPlus.

2.3.2 CORRECTIVE MAINTENANCE

Corrective maintenance is scheduled as a response to a component failure, which may require repairing or replacing the component in question. Corrective maintenance is unplanned and results in a longer downtime which takes significantly long time for the maintenance team to restore the device in problem. Corrective maintenance may be further decomposed in "on demand" which consists in scheduling maintenance after component failure, and in "batch wise corrective maintenance" which consists in allowing for multiple components to fail before engaging in maintenance activities. In the context of DTOceanPlus, only "corrective maintenance on demand" will be implemented.

Any given component may have different failures modes. According to the Offshore and Onshore Reliability Data (OREDA)'s failure classification [8], failures may be classified according to "critical" and "non-critical" ("critical failures", "degraded failures" and "incipient failures"). A critical failure is a sudden failure which causes a given component to no longer be able to operate, while for non-critical failures, the component may still operate imperfectly or partially.

In the context of DTOceanPlus, only critical failures are considered, i.e., failures that cause the component to stop working.

2.4 DECOMMISSIONING

The decommissioning activities of the offshore oil and gas sector began over thirty years ago, and specialised techniques that have been developed are still evolving today. Since then, over 4,000 structures have been dismantled in the Gulf of Mexico, and over 150 in the North Sea. Despite the fact that few offshore wind projects have been dismantled to date, it is expected that the volume of decommissioning work will rapidly ramp up in the years to come as more commercial offshore wind projects reach the end of their operation lifetimes [9].

Although the decommissioning of ocean renewable farms is still a far distant future, it will be an inevitable phase of the project. In respect to pilot projects, the decommissioning is a near future reality that must be planned for due to its potential impact on the total costs of the project.

The general principle is that the installed infrastructure must be removed from the ocean when decommissioning. Similarly to offshore wind, wave and tidal energy projects will most likely be dismantled by the reverse of the installation procedure. The removal of the foundations is not as clear, as it will depend on the foundation type.

Whether power cables should be removed or not is subject of a lot of discussion, depending on the interpretation of the regulations, best practices and trade-offs between short-term costs and long-term liabilities. Export and inter-array cables are typically buried over one meter below the seabed, having limited environmental and pollution impacts and safety risks. Removing buried cables can be extremely expensive. In general, cables can be partially or entirely removed, although this will generally depend on whether the cable is buried or not [10]. It may be considered that the recovery is only necessary in key areas such as cable crossings [11]. Given the large uncertainty related to the decommissioning of subsea power cables, in the context of DTOceanPlus, it is assumed that they are left in situ.

The assumptions related to the decommissioning of ocean renewable energy projects are listed in Table 2.4.

TABLE 2.4 DECOMMISSIONING PROCEDURES FOR DIFFERENT SUBSYSTEMS OF OCEAN ENERGY PROJECTS

Component	Decommissioning procedure
Device	Complete removal from site following the reverse sequence of tasks carried out during the installation. Lifted from the seabed or foundations and either transported on the vessel deck or wet-towed to shore.
Collection point	Complete removal from site following the reverse sequence of tasks carried out during the installation. Lifted from the seabed or foundations and either transported on the vessel deck or wet-towed to shore.
Moorings	Mooring retrieval depends on anchor type. Drag anchors will be recovered by applying tension in the opposite direction to the setting direction at a high angle.

Component	Decommissioning procedure
Piled foundations (piles, pile anchors, jackets)	Cut pile below the seabed level, lift to deck, and transport it or wet-tow it, mirroring the installation phase.
Gravity based foundations and anchors	Lift structure from the seabed to the vessel deck or de-ballast and float it to shore.
Suction piles and anchors	Remove by creating overpressure in the caisson to release them from seabed.
Export and inter-array cables	Abandon them in situ.

Based on the identified decommissioning procedures for the different systems, a generic sequence of decommissioning operations is proposed, as shown in Table 2.5.

TABLE 2.5 OPERATION PRECEDENCE RULES FOR DECOMMISSIONING A GENERIC OCEAN ENERGY FARM

Decommissioning sequence
Device removal ↓ Collection point removal ↓ Support structures removal ↓ Moorings and anchors removal ↓ Foundations removal

2.5 BACKGROUND ON VESSELS

Vessel selection is a fundamental step in the planning stage of any offshore project and a major cost driver of the installation and maintenance of offshore renewable energy farms. In DTOceanPlus, the selection of vessels is a two-phase process. In the first phase, default vessel combinations are retrieved for a given operation and filtered according to user preferences and operation requirements. In the second phase, for each possible vessel combination listed in the vessel combination matrix, vessel entries are extracted from the vessel database, and evaluated in respect to their technical parameters and according to their roles as specified in the vessel combination matrix. The iterative process of removing unsuitable solutions is achieved through running feasibility functions as seen in Figure 2.4.

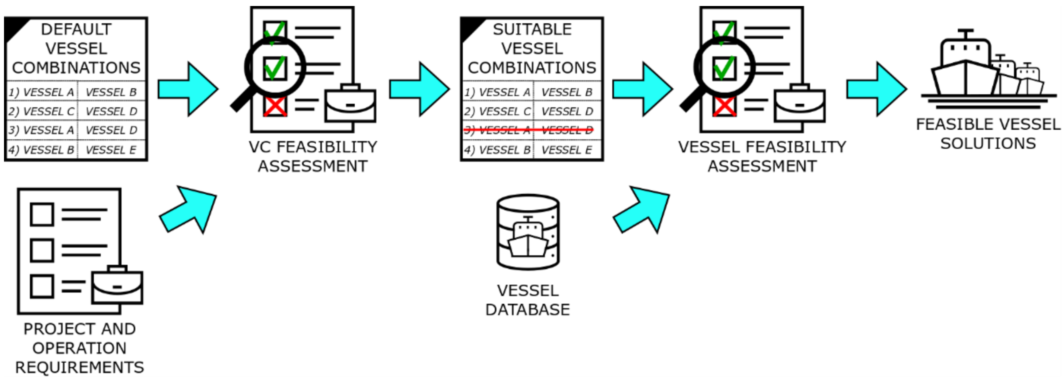


FIGURE 2.4 VESSEL PRE-SELECTION PROCESS

2.5.1 DEFAULT VESSEL COMBINATIONS

There are numerous approaches to carry out any given offshore operation such as the installation of an ocean energy device. The device may be transported on deck of a large crane vessel, or it may be loaded to a transport barge, which would in turn be towed by a Tug or Anchor Handling Tug vessel (AHTS) . In some instances, the device can be structurally designed to be wet-towed directly to site. Low draft devices may be transported to site using a semi-submersible vessel, capable of ballasting down and submerging its deck to load and unload the device from/to the water.

Different operation strategies and methods require different combinations of vessels playing different roles and consequently, with different technical requirements. Based on previous experience in relevant offshore projects, a vessel combination (VC) table was compiled, featuring different combinations of vessels for each operation types and transportation methods. In Table 2.6, nine vessel combinations (VC) are presented for a device installation operation (see the appendix ANNEX I: VESSEL COMBINATIONS for the full table of vessel combinations for each operation).

TABLE 2.6 VESSEL COMBINATION MATRIX (VC) TABLE FOR A DEVICE INSTALLATION OPERATION

VC ID	Operation Name	Description	Transportation	Qty	Main vessel role	Qty	Tow vessel role	Qty	Support vessel role
VC_001	Device Installation	Device	On deck Transportation	1	Propelled crane vessel	-	-	-	-
VC_002	Device Installation	Device	On deck Transportation	1	Jack-up Vessel	-	-	-	-
VC_003	Device Installation	Device	On deck Transportation	1	SOV Gangway / Accommodation	-	-	-	-
VC_004	Device Installation	Device	Dry tow Transportation	1	Non propelled crane Vessel	1	Tug	-	-
VC_005	Device Installation	Device	Dry tow Transportation	1	Transport Barge	1	Tug	-	-
VC_006	Device Installation	Device	Dry tow Transportation	1	Semi-submersible	1	Tug	-	-
VC_007	Device Installation	Device	Wet tow Transportation	-	-	1	AHTS / Tug	1	Multicat
VC_008	Device Installation	Device	Wet tow Transportation	-	-	2	AHTS / Tug	1	Multicat
VC_009	Device Installation	Device	Wet tow Transportation	-	-	3	AHTS / Tug	1	Multicat

It is possible to observe that different operation strategies require different quantities and types of vessels under different roles. The vessel's role throughout the operation plan affects the criteria according to which each vessel will be evaluated. Three main vessel roles are identified: main vessel, tow vessel and support vessel:

- Main vessels are vessels that play a main role in the operation, either by lifting, transporting on deck, or installing a cable, for example. Depending on the vessel type and operation plan, these vessels are assessed in respect to their deck area, crane lifting capacity, anchor handling capacity, jack-up operating depth, etc.
- Tow vessels: Tow vessels are only responsible for towing a device or structure (wet-tow), or a non-propelled barge (dry tow). These vessels are only assessed in respect to their ability to safely carry out the tow, which is partially expressed by its bollard pull.
- Support vessels: Support vessels are vessels that are required for controlling marine traffic, assist device positioning or support some lifts but do not play a main role in the operation itself.

The vessel combination table is also used to firstly discard unsuitable vessel combinations that do not meet project requirements or user preferences, such as considering or not wet-tow as a possibility. Vessel types listed on the pre-selection of vessel combinations will be further evaluated in the subsequent vessel selection stage: vessel feasibility.

2.5.2 VESSEL FEASIBILITY ASSESSMENTS

Having defined the combinations of vessel(s) that are suitable for carrying out each operation, it should be ensured that the vessel specifications satisfy the physical and technical characteristics of the components to be installed, maintained, or decommissioned, as well as site requirements.

For each suitable vessel combination, the vessel pre-selection algorithm searches in vessel cluster database for vessels of the specified type that could perform the tasks associated with the attributed roles. In order to judge the vessel eligibility for a given operation, feasibility functions are used, which relate technical requirements to the parameters of the vessel databases. Simple mathematical and Boolean formulations filter out the maritime infrastructure non-complying with the logistic requirements. A given vessel is considered "feasible" if it is capable of performing the minimum work threshold (e.g. vessel has sufficient deck space to transport at least one device at the time).

While constructing these feasibility functions, it became obvious that some assumptions were required to simplify the process's complexity while maintaining physical meaningfulness. For instance, the available inputs does not inform the Logistics module about the accurate optimal deck layout when transporting components/subsystems together with the required equipment to site. Therefore, if nothing is mentioned, it was assumed that all elements are laid on their two principal dimensions and no vertical stacking of components/equipment is considered.

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, a safety factors of 20% is applied for the feasibility functions implemented in the logistics module.

2.5.3 VESSEL DATABASE

Given the rapid expansion of the offshore wind sector in the last few years, offshore service vessel owners have been working on building larger and more advanced offshore service vessels and adapting their existent fleet to meet the needs of the market. Following the progressive increase in size of devices being installed, vessel owners have been dimensioning their vessels for larger lifting capacities, deck areas and cargo carrying capacity [12].

The ability to propose meaningful vessel solutions for the different lifecycle phases of an offshore renewable energy project relies on the ability to access relevant and up-to-date technical and financial data from vessels that are representative of the current offshore vessel market. However, such information is typically sensitive and not freely available.

In DTOcean 1.0 and 2.0 releases[13], vessel selection relied on a database of 70 real world vessels, featuring some main vessel characteristics and vessel charter costs estimates. The vessel selection algorithm would then run on a vessel-by-vessel approach: unsuitable vessels that could not perform the operation (e.g. due to insufficient crane lifting capacity) would be discarded, and operation plans would be designed for each suitable vessel candidate, scheduling the operation and calculating operation durations, waiting on weather, and operating costs. Despite its data completeness and decent size, a seventy vessels database constitutes an extremely small and potentially unrepresentative sample of the entire population of offshore vessels relevant to offshore renewable projects.

In DTOceanPlus, a vessel cluster database was developed to be used in the context of the LMO module. This database was the result of a statistical analysis performed on an original vessel database from **GRS Offshore**[4], comprised of 14,847 vessels and 46 technical parameters relevant to offshore renewable projects. Vessels were grouped according to type (e.g. AHTS, Tug) and then similar vessels were clustered together according to their most important characteristics (e.g. deck area, bollard pull, gross tonnage, crane lift capacity). A more in-depth description is presented in Appendix: ANNEX II: CLUSTER ANALYSIS.

Vessels of the database were divided into 15 main types, as shown in Table 2.7.

[4] Global Renewable Shipbrokers (GRS) Offshore is a shipbroker firm with extensive experience in vessel chartering and consulting for offshore renewable energy projects.
GRS's collaboration with DTOceanPlus provided access to their database and expert support in identifying vessel cost drivers. https://www.grs-offshore.com/en/

TABLE 2.7 VESSEL TYPES CONSIDERED IN DTOCEANPLUS

Vessel type	Main Capabilities	Example
Anchor Handling Tug Supply (AHTS)	➢ Anchor Handling ➢ Towing ➢ Firefighting ➢ On deck transportation	 **AHTS**
Non-Propelled Barge	➢ Pontoon deck ➢ Transport of devices, foundations, and equipment ➢ Towed to site	 **NON-PROPELLED BARGE [14]**
Cable Layer (CLV)	➢ Underwater cable lay operations ➢ Dynamic Positioning (DP) system ➢ ROV equipped ➢ Cable turntable (carrousel)	 **'WILLEM DE VLAMINGH' [15]**
Crew Transfer Vessel (CTV)	➢ Crew transfer between shore/ vessel to a device/substructure ➢ High service speed (27-55 km/h [12, p. 35]) ➢ Transport of tools, luggage and small size spare parts ➢ Maximum sailing distance of 30 nautical miles for an associated Hs of 1.5 m [16].	 **CTV NEXT TO AN OFFSHORE WIND TURBINE TRANSITION PIECE**
Dredging Vessel	➢ Dredging operations ➢ Land reclamation ➢ Depth clearance maintenance ➢ Marine construction	 **TSHD[5] 'LEIV EIRIKSSON' [15]**
Dive Support Vessel	➢ Diving operations (O&M or inspection) ➢ ROV operations	 **GUARD VESSEL 'CONSTRUCTOR' [17]**

[5] Trailing Suction Hopper Dredger

Vessel type	Main Capabilities	Example
Jack-Up Crane Vessel	➢ Heavy duty crane operations ➢ Self-elevating to a height above waterline ➢ Installation of substructures, top structures and foundations ➢ Not subjected to wave induced motions ➢ High charter costs	 **JACK-UP CRANE VESSEL 'VOLE AU VENT' [15]**
Guard Vessel	➢ Monitoring of marine traffic near the construction site, visually, with radar and AIS. ➢ Able to stay offshore for long periods of time (>30 days) ➢ Great seaworthiness and high transit speeds	 **GUARD VESSEL 'VIVRE-G'[18]**
Multicat	➢ Multi-purpose workboat for offshore works, transport, and dredging. ➢ Rectangular deck pontoon, flat hull ➢ Support vessel on large projects ➢ Main vessel on small dimension projects ➢ Especially suited for shallow waters	 **MULTICAT [15]**
Crane Vessel	➢ Vessels for lifting and transporting heavy offshore structures ➢ Equipped with heavy lift cranes ➢ Frequently limited deck area ➢ Propelled or Non-propelled	 **HEAVY LIFT CRANE VESSEL 'RAMBIZ' [15]**
Platform Supply Vessel (PSV)	➢ Transport of components, equipment, and crew ➢ Free deck area for transport of components ➢ Recent generation with high service speed and low fuel consumptions [19].	 **PSV BY "WÄRTSILA' [19]**

Vessel type	Main Capabilities	Example
Rigid Inflatable Boat (RIB)	➢ Maneuverability ➢ Fast deployment ➢ O&M operations	 RIGID INFLATABLE BOAT [20]
Rock Dumper	➢ Post cable lay operations ➢ Scour protection installation ➢ ROV equipped	 ROCK DUMPER [15]
Service Operation Vessel	➢ Crew Transfer ➢ O&M operations ➢ Flotel ➢ Cargo carrying capacity ➢ High service speed ➢ Gangway equipped or relevant.	 SOV [21]
Survey Vessel	➢ Survey operations ➢ Marine site characterisation ➢ ROV equipped	 SURVEY VESSEL 'SEABED STINGRAY' [22]
Tugboat	➢ High power-tonnage ratio ➢ High manoeuvrability ➢ Towing operations ➢ High bollard pull coefficient	 TUGBOAT TOWING A BARGE AND A RIB [15]

2.5.4 VESSEL DYNAMIC POSITIONING

A vessel's station keeping capability when carrying out potentially hazardous offshore operations is fundamental, not only for safety (e.g. collision, diving operations) but also for operability (e.g. piling, drilling, ROV operations). Dynamic Positioning (DP) systems are computer-controlled systems capable of automatically maintaining vessel's position and heading using its own propellers and thrusters. The use of dynamic positioning systems has become standard for newly built construction vessels, whilst older commercial vessels have been retrofitted [23].

According to the International Maritime Organization (IMO), DP-systems may be classified according to Table 2.8, and are mostly divided according to system redundancy [24]:

TABLE 2.8 VESSEL DYNAMIC POSITIONING EQUIPMENT CLASSES

Description	IMO DP Class
Manual position control and automatic heading control under specified maximum environmental conditions.	[-][6]
Automatic and manual position and heading control under specified maximum environmental conditions. No redundancy: Loss of position may occur in the event of a single fault.	Class 1 (DP-1)
Automatic and manual position and heading control under specified maximum environmental conditions. Redundancy: Loss of position shall not occur from a single fault of an active system (generator, thruster, switchboards, remote controlled valves), but may occur after failure of static components such as cable, pipeline or manual valves.	Class 2 (DP-2)
Automatic and manual position and heading control under specified maximum environmental conditions. Redundancy: Loss of position shall not occur from a single failure, active and static, and should be able to withstand a fire or floor in any one compartment.	Class 3 (DP-3)

In the O&G sector, there are clear standards prescribing vessel requirements in terms of DP system for typical offshore operations (see Table 2.9). Despite specific standards not existing for offshore renewable energy projects, including offshore wind and ocean energy, it may be assumed that most operations will require DP-2, although this requirement may be relaxed.

[6] Sometimes referred to as DP-0

TABLE 2.9 DP REQUIREMENTS TABLE AS RECOMMENDED BY DNVGL-OS-H203 STANDARDS [25]

ACTIVITY	CLASS
a) Manned underwater operations where loss of position entails a high risk for divers or diver platforms.	3
b) Other manned underwater operations where loss of position entails risk for divers or diver platforms.	2
c) Support vessels for manned underwater operations conducted from work boats where loss of position for the support vessel has direct consequences for the work boat.	2
d) Drilling and well activities where well control is handled by a DP facility	3
e) Facilities that produce hydrocarbons	3
f) Flotels with gangway connected Two reference systems may be accepted for arrival and departure.	3
g) All activities within the safety zone Two reference systems may be accepted for arrival and departure. The need for relative position reference system(s) shall be evaluated considering the facilities displacements and the minimum clearance to the facility.	2
h) Activities with limited clearance to the facility where the vessel represents a risk to the facility The requirement applies if the vessel exceeds the vessel size the facility is designed for with regard to withstanding a collision and is working with a limited clearance to facility. Two reference systems may be accepted for arrival and departure. The need for relative position reference system(s) shall be evaluated considering the facilities displacements and the minimum clearance to the facility.	3
i) Loading operations from FSUs and FPSOs The requirement applies to the tank vessel	2
j) Loading operations from buoys (quick release available)	1
k) Other well activities The requirement applies to well maintenance facilities if well control is handled by another facility	2
l) Shallow drilling if one does not expect to encounter hydrocarbons and emergency disconnect is feasible in case of drift-off.	1
Notes to the table 1) For dynamic positioning, consideration should be given to the reference systems' limitations as regards reliability, accessibility and quality. 2) High risk as mentioned in a), means the cases when the diver does not have an unrestricted return to the diving bell, or where loss of the vessel's position can lead to loss of or damage to the diving bell, and possibly the associated bottom weight. 3) The requirement to equipment class 3 as mentioned in d), does not apply to all drilling and well activities. For shallow drilling, other requirements in the table may be relevant, such as the requirements in h), l) and emergency disconnect response time. Well activities that require equipment class 3 are e.g. well intervention including wire line operations. Other well activities as mentioned in k) may be well stimulations and unmanned underwater operations, including the use of remote-controlled sub-sea vessels or sub-sea tools.	

2.5.5 VESSEL FUEL CONSUMPTION

Offshore vessels require significant amounts of engine power to operate, particularly when in harsh offshore environments. Fuel consumption has not only a significant impact on total costs of the operation, but also on the emissions and carbon footprint associated with the project.

Vessel total fuel consumption is affected by several factors such as engine power, number of engines (main and auxiliary), engine efficiency, operation duration, mobilised ancillary equipment, transit speed and durations, and weather conditions to name a few. In DTOceanPlus, the average vessel fuel consumption per day can be estimated for a given vessel based on the following formula:

$$Fuel\ consumption\ (ton/day) = TIP \times ALF \times SFOC \times 24 \times \left(\frac{1}{1000^2}\right), \quad (1)$$

where TIP is the total installed power of the vessel (in kW), ALF is the average load factor[7] (equal to 80% as per GRS Offshore recommendations), and SFOC is specific fuel oil consumption[8] (in g/kWh) [26] taken as 210 g/kWh according to GRS Offshore recommendation.

When at port, most vessels will have their auxiliary engines running at a low load factor albeit fuel consumption is not zero. Still, given the difficulty in estimating the vessel fuel consumption during waiting on weather at port, it is assumed that the total fuel consumption associated with a given operation can be calculated by summing the average hourly fuel consumptions of each vessel involved in a given operation and multiplying it by the duration of the operation minus the waiting on weather duration (at port).

2.5.6 VESSEL COST MODELLING

In an offshore renewable energy project, total vessel cost can be attributed to vessel charter rates, and fuel expenditures from operating the vessels.

$$Total\ running\ cost\ \left(€/_{day}\right) = Vessel\ charter\ rate\ \left(€/_{day}\right) + Fuel\ Oil\ Expenditure\ (€/_{day}) \quad (2)$$

2.5.6.1 VESSEL DAILY CHARTER RATES IN DTOCEANPLUS

The vessel chartering cost depends on several influencing factors. Vessel characteristics and capabilities have a primary impact on the costs, although several surrounding market conditions, which can often be hard to specify in detail, can also play a large part. Contract durations and contract different contracting set-ups also play a role. Smaller tonnage vessels like CTVs, Survey vessel and Tugs are usually chartered out on a time charter basis (e.g. BIMCO[9] Supply time) which allows a clear

[7] The average load factor corresponds to the average engine load experienced by the vessel's engine plant, considering the entire offshore project, including transits, service and stays at port.
[8] The specific fuel oil consumption represents the amount of fuel necessary for an engine to produce 1 kWh of electrical energy.
[9] Baltic and International Maritime Council

understanding of the vessel day rate. Contrastingly, larger vessels such as crane vessels, cable laying vessels and jack-up vessels in general, are mainly contracted as a part of comprehensive service agreements such as EPCI[10] or T&I[11] contracts (e.g. FIDIC [12]or Logic). In both cases, average daily charter costs that exclude consumables such as fuel and harbour costs, were estimated.

In respect to vessel characteristics, factors such as vessel size, vessel age, crane capacity, deck area, engine power, and dp equipment, to name a few, have an impact on the final vessel costs. Leveraging on the guidance from **GRS Offshore** shipbrokers, for each vessel type, major vessel charter cost drivers were identified. For simplicity vessel charter costs were modelled as a function of a single parameter for each vessel type. Cost functions that model charter day rates for the different vessel types were then derived, based on a curve fitting applied to database points gathered from: i) DTOcean, ii) from a WavEC's inhouse database, iii) cost figures provided by ECN and GRS Offshore, iv) from expert experience. Different regression models including linear, polynomial, exponential, logarithmic and piecewise regressions have been adjusted to find an optimal fit based on the R-squared coefficient, while eliminating fits that result in cost inflections within the analysed domain.

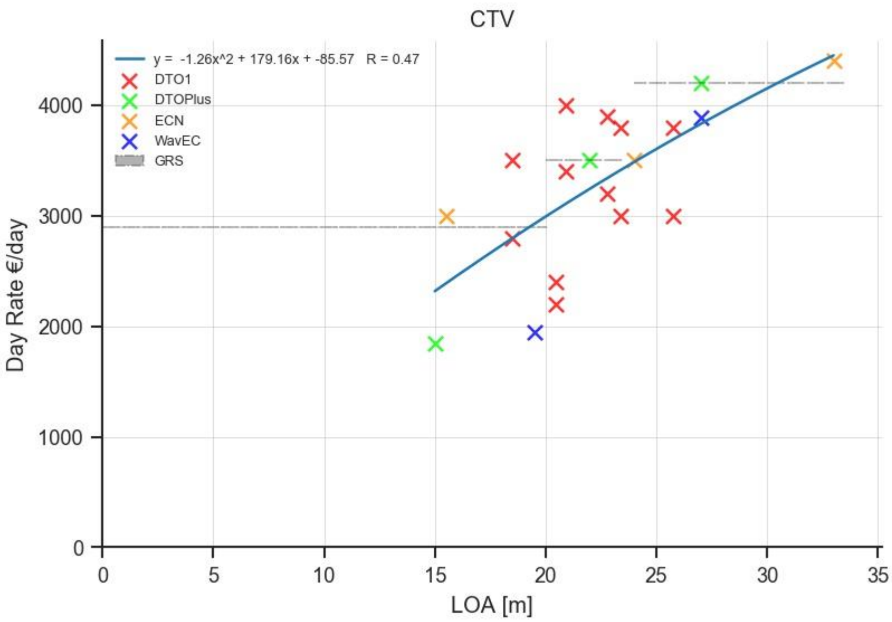


FIGURE 2.5 REGRESSION OF THE CHARTER DAILY RATES FOR CREW TRANSFER VESSELS

2.5.6.2 FUEL OIL COST IN DTOCEANPLUS

In order to estimate fuel costs, a reference price for the marine diesel oil (MDO) in the port of Rotterdam was taken as 515 €/ton [47]. However, this value may be modified by the user to reflect different fuel prices or even other fuel types such as heavy fuel oil (HFO).

[10] EPCI stands for Engineering, Procurement, Construction and Installation, a common form of contracting within the offshore construction sector.
[11] Transportation and Installation
[12] Fédération Internationale Des Ingénieurs-Conseils

$$Fuel\ costs\ \left(\frac{€}{day}\right) = \ Fuel\ consumption\ (ton\ /\ day) \times fuel\ price\ (€\ /ton) \tag{3}$$

2.6 OPERATION METHODS

2.6.1 TRANSPORT AND LOAD-OUT METHODS

Devices and subsystems must be transported from port to site in one of three ways: i) on deck of the main vessel, ii) dry-towed, i.e., on deck of a non-propelled barge that is subsequently towed by a tug or AHTS, and iii) wet-towed, which consists of placing the floating component in the water and towing it to site with a tug or AHTS. The first two methods are defined as "dry transport", while the latter is defined as "wet transport"

Depending on the transportation method, devices and subsystems must be loaded from the quay site onto vessels, put afloat via quays, dry docks or other launching facilities such a slipways or syncrolifts [27]. In DTOcean, the load-out methods were mainly considered for devices only, although this affects every subsystem[28]. Four load-out methods are therefore considered in DTOceanPlus:

- *Lifted load out*: this is perhaps the most common method employed for MRE devices and subsystems. Devices are lifted onto the vessel (or barge) deck by means of shore-based cranes or cranes installed on the transportation vessel.
- *Float-away load out*: the device is assembled in a dry dock facility. Once completed the dry dock is flooded or ballasted down in the case of floating dry docks. The structure that floats under its own buoyancy is then towed away by tugs or an AHTS. This is mostly applicable to floating devices and floating collection points.
- *Trailer load out*: multi-wheel hydraulic trailers are brought underneath the sub-structure/device. The structure/device is then lifted onto the deck of the transportation vessel which is placed against the quay wall.
- *Skidded/railed load out*: initially the structure is placed upon steel rails. It is then pushed or pulled by winches onto the deck of the transportation vessel which has to be equipped with skidded beams to take the structure to its final position.

TABLE 2.10 TRANSPORTATION AND LOAD-OUT METHODS FOR DIFFERENT COMPONENT TYPES

Component	Transportation method	Load-out method
Devices	Dry (on deck or dry-tow)	Lifted†, Trailer, skidded
	Wet (if selected by the user)	Lifted†, Trailer, skidded, float-away
	Dry (on deck or dry-tow)	Lifted†, Trailer, skidded
	Wet (if selected by the user)	Lifted†, Trailer, skidded
Moorings	Dry (on deck of an AHTS)	Lifted†, Trailer, skidded
Support structures	Dry (on deck or dry-tow)	Lifted†, Trailer, skidded
Collection point	Dry	Lifted†, Trailer, skidded
	Wet (if floating collection point, and "wet-tow" is selected by the user)	Lifted†, Trailer, skidded, float-away
Export cable	Dry (on the vessel's cable reel)	Lifted†, Trailer, skidded

Component	Transportation method	Load-out method
Array cable	Dry (on the vessel's cable reel)	Lifted†, Trailer, skidded
External protections	Dry (on deck)	Lifted†, Trailer, skidded

† denotes default values in case not specified by the user.

2.6.2 TOWING

The decision to transport any component by the means of towing depends on different factors. The decision between dry-towing and on deck transportation is mostly economical: for large devices, the costs of chartering a transport barge and a sufficiently powerful towing tug might be significantly lower than chartering a large vessel with sufficient deck area. However, opting for a wet-tow transport method is more complex as it must be incorporated in the structural design of the components. Still, towing components to site will require vessels with lower lifting capacity and, consequently, may result in lower charter costs.

In fixed offshore wind, most transportation is dry (either on deck or dry-tow), although in some cases, pile foundations (monopiles) have been wet-towed to site [29]. Floating offshore platforms may be towed to site, depending on their topology and stability. In case of wave and tidal energy converters, both floating (e.g. IDOM's MARMOK-A5 prototype [27-28], Pelamis [32], and Orbital Marine's SR1-2000[33]), and bottom-fixed concepts (e.g. Wave Roller [34]) have been wet-towed to site.

Both dry- and wet-tows impose bollard pull requirements of the towing vessel. In DTOceanPlus, the estimation of the required pulling force for towing a given structure or barge was implemented to support the tug vessel selection for wet and dry tows.

2.6.2.1 BOLLARD PULL REQUIREMENTS

Bollard Pull (BP) corresponds to the pulling capability (at zero speed) of a vessel. Bollard pull is a selling point for Tug vessels, which are optimised for towing and/or stranding other vessels, transport barges, platforms, and floating devices. It follows that the tug is required to have sufficient power to overcome the hull resistance of the tug itself and the hydrodynamic resistance of towed barge/structured, the latter being referred as the towline pull required. The towline pull required (F_{TR}) must be calculated taking into consideration the wind, wave drift and current forces acting on the towed platform.

In the context of DTOceanPlus, tow operations are designed according to DNV standards [35] as an unrestricted marine operation. It follows that the selected tug vessel must have sufficiently large bollard pull to hold position (zero towing speed) when exposed to the following weather conditions:

1. Towing speed = 0 knots
2. Wind speed of 20 m/s
3. Significant wave height equal to 5 m
4. Current speed of 0.5 m/s.

In a dry-tow, one or multiple tugs are towing a barge where the device or subsystems are placed.

TUG EFFICIENCY

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} can be estimated for good ocean-going tugs according to the following equation [35]:

$$T_{Eff} = 80 - \left(18 - 0.0417 \times LOA_{vessel} \times \sqrt{BP_{vessel} - 20}\,\right) \times (H_s - 1) \tag{4}$$

where

- T_{Eff} is the tug's efficiency in %.
- LOA = tug length overall in meters (using 45 m for LOA > 45 m)
- BP = Static continuous bollard pull in tonnes (with BP > 20 tonnes, and using 100 when BP >100 tonnes)
- H_s = significant wave height (with 1 m < Hs < 5 m).

Note that all tugs will generally have very low efficiencies with H > 5 m since they should be protecting their towing gear. Tugs with less sea-kindly characteristics will have significantly lower values of T_{Eff} in all sea states.

ENVIRONMENTAL LOADS

The towline pull required (F_{TR}) must be calculated taking into consideration the wind, wave drift and current forces acting on the towed platform.

- WAVE DRIFT FORCE

At zero forward speed, the wave resistance force, or wave drift, F_{wd} (in kN) can be estimated with a simplified expression which will provide conservative results in most cases [36]:

$$F_{wd} = \frac{1}{8} \cdot \rho_{sw} \cdot g \cdot R^2 \cdot B \cdot {H_s}^2 \cdot 10^{-3} \tag{5}$$

Where, ρ_{sw} is the sea water density (kg/m^3), *R* is the reflection coefficient, *B* is the breadth of the towed object (m), Hs is the significant wave height (m) and *g* is the gravitational acceleration constant (m/s^2).

TABLE 2.11 REFLECTION COEFFICIENTS FOR DIFFERENT BARGE OR STRUCTURE SHAPES

Reflection coefficients	
Square face	R = 1.00
Condeep base	R = 0.97
Vertical cylinder	R = 0.88
Barge with raked bow	R = 0.67
Barge with spoon bow	R = 0.55 (default)
Ship bow	R = 0.45

- WIND RESISTANCE FORCE

The wind resistance force F_{wind}(in kN) can be estimated using a simplified equation as:

$$F_{wind} = \frac{1}{2} \cdot C_{shape} \cdot \rho_{air} \cdot A_{windage} \cdot V_w^2 \cdot 10^{-3} \tag{6}$$

Where C_{shape} is the (dimensionless) drag coefficient which can be estimated based on the towed object dimensions, ρ_{air} is the air density in kg/m³, $A_{windage}$ is the windage area normal to the wind direction, and V_w is the wind speed.

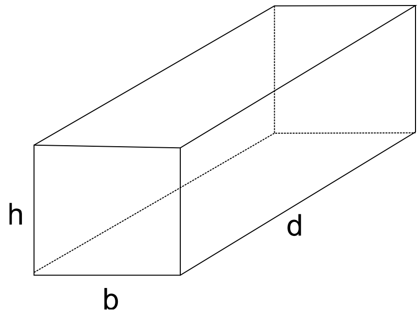
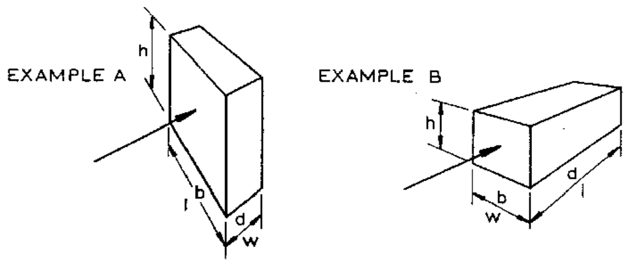
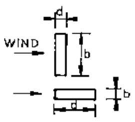
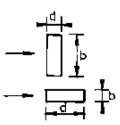


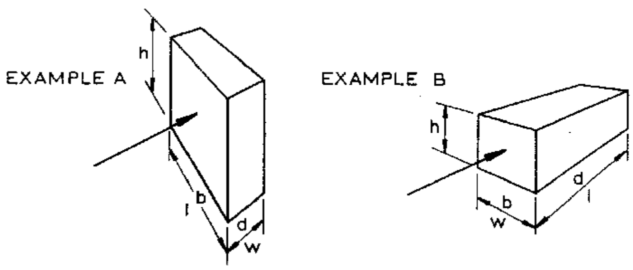
FIGURE 2.6 DIMENSIONS OF AN OBJECT TRANSPORTED ON DECK

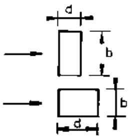
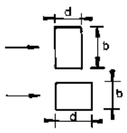
The shape coefficient for estimating wind loads (C_{shape}) can be estimated based on the device dimensions as shown in the table Table 2.12 [37].

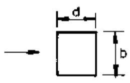
TABLE 2.12 SHAPE COEFFICIENT FOR CALCULATING WIND LOADS ON A THREE-DIMENSIONAL BODY PLACED ON AN HORIZONTAL SURFACE.
EXTRACTED FROM DNVGL-RP-C205 (CONTINUES IN NEXT PAGE)[37]



Plan shape	l/w	b/d	C for height/breadth ratio h/b				
			Up to 1	1	2	4	6
 WIND	≥ 4	≥ 4	1.2	1.3	1.4	1.5	1.6
		≤ 1/4	0.7	0.7	0.75	0.75	0.75
	3	3	1.1	1.2	1.25	1.35	1.4
		1/3	0.7	0.75	0.75	0.75	0.8



Plan shape	l/w	b/d	C for height/breadth ratio h/b				
			Up to 1	1	2	4	6
	2	2	1.0	1.05	1.1	1.15	1.2
		0.5	0.75	0.75	0.8	0.85	0.9
	1.5	1.5	0.95	1.0	1.05	1.1	1.15
		2/3	0.8	0.85	0.9	0.95	1.0

Plan shape	l/w	b/d	C for height/breadth ratio h/b						
			Up to 0.5	1	2	4	6	10	20
	1	1	0.9	0.95	1.0	1.05	1.1	1.2	1.4

b = the dimension of the member normal to the wind
d = the dimension of the member measured in the direction of the wind
l = the greater horizontal dimension.
w = the lesser horizontal dimension of a member

Example A: *l* = *b*, *w* = *d*. Example B: *w* = *b*, *l* = *d*.

- OCEAN CURRENT RESISTANCE FORCE

The underwater part of the hull of the barge or towed object experiences what is called as calm water resistance. This is the resistance a ship experiences when it is moving in water without waves. For the specified conditions, the tow is in the stall scenario, i.e. the tug and towed object/barge are not moving. Still, the current moving against the vessel creates the same effect as the vessel moving with the speed of the current in calm water.

  - DRY TOW: FRICTION DOMINATED DRAG

When towing a barge, it can be assumed that the drag force is dominated by friction forces on the hull. In order to estimate the friction forces, some auxiliary parameters such as the Reynolds number, the wetted area and the friction coefficients must be calculated according to [38].

The Reynolds number can be calculated, taking the kinematic viscosity of water, ν, as $1.2 \cdot 10^{-6}\ m^2/s$, L as the characteristic dimension and V_c as the current speed.

$$Re = \frac{V_c^2 \cdot L}{\nu} \tag{7}$$

The friction coefficient C_f can be calculated as,

$$C_f = \frac{0.075}{[\log_{10} Re - 2]^2} \tag{8}$$

In order to calculate the total friction coefficient C_{ft}, the additional friction caused by hull fouling can be estimated assuming a number of days since last dry docking, $N_{dayssincedrydock}$ as 100 days.

$$\Delta C_f = 0.008 \cdot N_{dayssincedrydock} \cdot C_f \tag{9}$$

$$C_{ft} = C_f + \Delta C_f + 0.0004$$

$$A_{w,total} = 0.92 \cdot vessel\_length \cdot (vessel\_beam + 1.81 \cdot \ vessel\_draft)$$

In the case of a barge, the total wet surface can be estimated as:

$$A_{w,total} = 0.92 \cdot vessel\_length \cdot (vessel\_beam + 1.81 \cdot \ vessel\_draft) \tag{10}$$

The friction resistance force caused by the ocean currents on the barge $F_{current}$ (in kN) can be calculated as:

$$F_{current\,drytow} = \frac{1}{2} \cdot \ C_{ft} \cdot \rho_{sw} \cdot \ A_{w,total} \cdot \ V_c^2 \cdot \frac{1}{1000} \tag{11}$$

- WET TOW: PRESSURE DOMINATED DRAG

When wet towing a component or device, it can be assumed that the drag force is dominated by pressure drag forces on the structure. In this case, it is required to estimate the dimensionless drag coefficient C_{drag}. ρ_{air} is the air density in kg/m^3, $A_{w,proj}$ is the projected wet area, normal to the current direction, and V_c is the current speed [36].

In order to estimate the drag coefficient of the towed object, it is assumed that the object has a cylindrical shape. In case of a wet tow of the device, the dimensions of the device as towed are introduced by the user (see Figure 2.6).

Drag coefficient on three-dimensional objects for steady flow C_{DS}.
Drag force is defined as $F_D = ½\rho C_{DS} S u^2$.

S = projected area normal to flow direction [m²].
R_e = uD/ν = Reynolds number where D = characteristic dimension.

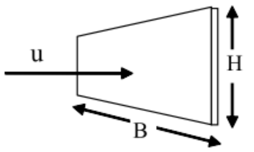
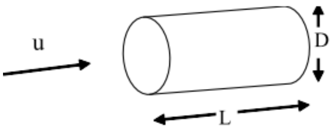
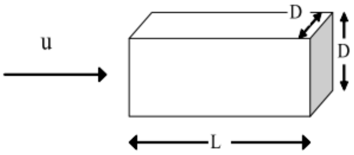
Geometry	*Dimensions*	C_{DS}
Rectangular plate normal to flow direction 	B/H 1 5 10 ∞	1.16 1.20 1.50 1.90 $R_e > 10^3$
Circular cylinder. Axis parallel to flow. 	L/D 0 1 2 4 7	1.12 0.91 0.85 0.87 0.99 $R_e > 10^3$
Square rod parallel to flow 	L/D 1.0 1.5 2.0 2.5 3.0 4.0 5.0	1.15 0.97 0.87 0.90 0.93 0.95 0.95 $R_e = 1.7 \cdot 10^5$

FIGURE 2.7 DRAG COEFFICIENT ON THREE-DIMENSIONAL OBJECTS FOR STEADY FLOWS

In order to estimate the drag coefficient, the characteristic dimension D can be defined as the maximum frontal dimension

$$D = \max\,(object.width, object.height) \tag{12}$$

The drag coefficient can be interpolated from the drag coefficient table in Figure 2.7.

$$C_d = \text{interpolation}(\frac{object.length}{D}, C_{DS}) \tag{13}$$

Once the object's frontal wet area is calculated, it is possible to estimate the current load, in kN, where V_c is the current speed and ρ_{sw} is the sea water density.

$$A_{w,normal} = object.width \cdot object.height \tag{14}$$

$$F_{current\,wettow} = \frac{1}{2} \cdot C_d \cdot \rho_{sw} \cdot A_{w,normal} \cdot V_c^2 \cdot \frac{1}{1000} \tag{15}$$

- REQUIRED BOLLARD PULL FORCE

The total resistance force (F_{TR}, in tonnes) can be calculated as:

$$F_{TR} = \frac{F_{wave} + F_{current} + F_{wind}}{g} \quad (16)$$

Finally, the required tug bollard pull (BP, in tonnes) can be calculated, where the T_{Eff} is the tug's efficiency:

$$BP = \frac{F_{TR}}{T_{Eff}} \cdot 10^{-3} \quad (17)$$

2.6.3 CABLE LANDFALL METHOD

The landfall of the export cable corresponds to the onshore transition section 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 equipment such as excavators and trench wall stabilization techniques such as cofferdams) which is then backfilled following the installation of the cable. The HDD method involves drilling 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.

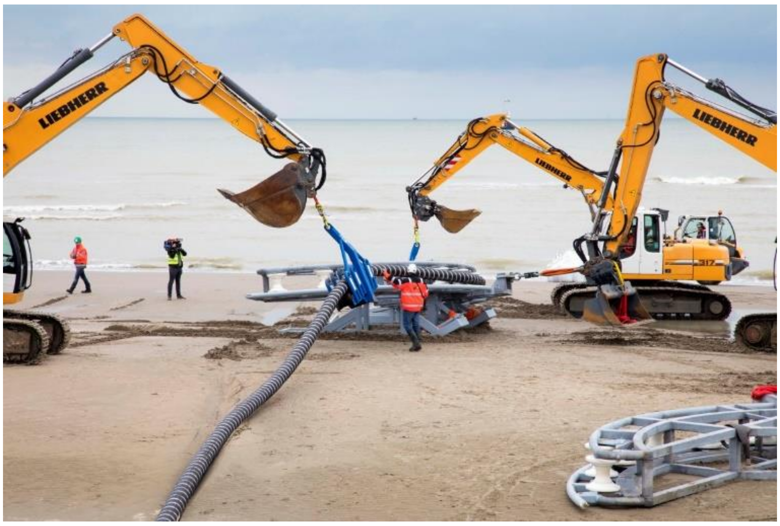


FIGURE 2.8 LANDFALL OF THE EXPORT CABLE OF A BELGIAN OFFSHORE WIND FARM IN ZEEBRUGGE[39]

The decision for the most suitable method is based on the results of a detailed design study by the installation contractor. The selection of the landfall method has an impact on the durations and procedures associated with the export cable installation operation. Based on these premises, the following assumptions were made:

- 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 prior to the export cable installation operation.
- Onshore work preparations are outside the DTOceanPlus scope. For this reason, the infrastructure necessary for carrying out this operation (e.g. winches, bulldozers, backhoes, dredgers, drilling rigs, drill pipes, storage areas, workshop facilities) will not be considered in the infrastructure solution.

2.7 ESTIMATING WAITING ON WEATHER CONTIGENCIES

2.7.1 OVERVIEW

Weather characterisation and weather window analysis are fundamental for operation design, vessel, and equipment selection as well as risks assessment in any offshore renewable energy Front-End Engineering Design (FEED) and pre-FEED study. Given that up to 73% of the total O&M costs can be attributed to vessel hiring costs [40], it follows that even modest reductions in operation durations may entail significant installation and maintenance cost-reductions[41]. Weather risk analysis may thus be used not only to estimate waiting times, but to weight the trade-offs between selecting cheaper vessel solutions that are more vulnerable to weather risks, and using heavy and less weather-sensitive equipment at the cost of more expensive daily hire rates [42].

In any offshore project, marine operations are inherently sensitive to weather conditions due to the potentially large accelerations imposed on the vessels, equipment, and structures, compromising asset integrity and health and safety. Such operations can only be carried out during sufficiently long periods of sufficiently calm weather that respect pre-defined operational limits and conditions (OLCs), commonly referred to as weather windows. OLCs may be expressed in terms of different combinations of environmental parameters such as wave height, wave period, wind speed, current speed, and even visibility/daylight [41]. Whenever the meteorological conditions violate the operational limits and conditions, the operation cannot be conducted and Waiting on Weather (WOW) is required. Given that in most projects, the vessel fleet must be chartered months in advanced, an operation's actual duration is consequently the result of its net duration and the waiting time during execution.

Cable laying and heavy crane lifting are good examples of exceptionally high-risk and weather-sensitive offshore work activities. These operations typically require specialised vessels with expensive daily charter rates, for the entire duration of the operation, waiting times included. These activities are generally planned for the good weather seasons, avoiding seasons with high probabilities of large waves and high wind speeds. However, in respect to maintenance, this is not always possible, as unforeseeable component failures may require prompt corrective maintenance during the harsh weather season.

In order to estimate the waiting on weather durations, the algorithm's underlying approach consists in attempting to schedule a given operation in each time-step of an historical timeseries of met-ocean conditions. Having specified the operation's list of activities, activity durations and weather restrictions, the algorithm attempts to iteratively initiate the operation for each timestep of the timeseries. In case both present and following timesteps are considered workable (i.e. OLCs are met) for a period that is longer than the whole operation duration, then the operation can be executed and identified as a possible solution. Otherwise, the timestep will be identified as unsuitable to initiate the operation (timestep feasibility and the iteration will jump to the following timestep. A compilation of scheduling solutions is finally obtained, as well as observed waiting on weather durations.

2.7.2 METHODOLOGY

At any given offshore location, the met-ocean conditions can be understood as a multivariate stochastic process[43]–[45], whereas each environmental parameter (wave height, wave period, wind speed, current speed) are interdependent and can be represented by different statistical distributions with joint probabilities but clear ensemble seasonal trends[46], [47]. However, even though cyclic patterns may be observed throughout the year (common knowledge shows that summer season is typically calmer than winter, although summer storms should not be overlooked), it may be reasonable to assume data stationarity for smaller time periods [48]. It is typically reasonable to assume data stationarity, i.e. the statistical properties of the met-ocean timeseries such as mean, variance, autocorrelation, etc. are constant, within fixed monthly blocks. This method is known as piecewise stationarity and consists of grouping the entire met-ocean timeseries by seasons or months and carrying out separate calculations.

Hindcast simulation, the most commonly adopted approach towards marine operation planning, consists in replicating the execution of a project subject to several years of historical met-ocean conditions. Met-ocean historical data typically includes an historical series of significant wave heights, wave periods, wind speeds, directions, and sometimes current speeds. Given the random nature of the weather conditions at a given location, a sufficiently large sample size is required to adequately capture the potentially large annual variability. More is better, although 20-years long continuous weather time series are a commonly accepted reference.

Given that maritime operations are usually planned on an hourly time frame, DNV standards recommend linearly interpolating the raw hindcast data when necessary to produce hourly time series, increasing resolution [36]. The met-ocean hourly time series can subsequently be analysed as a single continuous record.

Marine operations typically consist of a long sequence of activities, which make assessing weather risks and waiting times significantly more complex. Export cable installation operations may require a long sequence of activities such as vessel preparation, transit to site, Vessel positioning, cable laying and burial, to name a few [49], each of them associated with different net durations and operating limits.

For any given activity, the timestep workability $W_t(t)$ determines whether each timestep is considered workable, i.e. whether the environmental conditions registered during that specific timestep meet the activity's OLCs and restrictions. Timesteps considered workable take a workability value of one, otherwise they are zero.

$$W_t(t) = \begin{cases} 1, & \text{if } OLCs \text{ are met in } t \\ 0, & \text{otherwise} \end{cases} \tag{18}$$

For marine activities with time durations that exceed the timestep length (1 hour), timestep workability alone is insufficient to judge whether an operation could have been carried out from start to finish in a given time period such as a month. For an activity to be considered feasible, a sufficiently long sequence of workable timesteps is required. The timestep feasibility parameter $f_t(t)$ evaluates whether timestep t is suitable for starting the activity without violating the weather restrictions during the present and subsequent timesteps, for the whole duration of the activity. In case the operation may be started in timestep t, the feasibility parameter $f_t(t)$ takes a value of one, otherwise it takes a value equal to zero. This can be expressed by the equation below in equation (19), where *d* is the activity duration in hours:

$$f_t(t) = \prod_{i=t}^{i+(d-1)} W_t(i) \tag{19}$$

Considering an example operation comprised by a single activity, Act1, that is only restricted in wave height for simplicity, with a limit of 2.0 m Hs. In this case, the timestep workabilities and feasibilities of activity Act1 can be calculated as shown in Table 2.13. Workable (and feasible) timesteps are identified in green, while non-workable ones are coloured in red.

TABLE 2.13 EXAMPLE TIMESTEP WORKABILITY AND FEASIBILITY FOR ACTIVITY ACT1

Time step	Year	Month	Day	Hour	Hs	$W_t(t)$	$f_t(t)$
...	...	...	...	...	...	...	...
70	1992	1	15	5	1.5	1	1
71	1992	1	15	6	1.8	1	0
72	1992	1	15	7	1.9	1	0
73	1992	1	15	8	**2.1**	0	0
74	1992	1	15	9	1.9	1	1
75	1992	1	15	10	1.8	1	0
76	1992	1	15	11	1.9	**1**	0
77	1992	1	15	12	**2.1**	0	0
78	1992	1	15	13	1.9	1	0
79	1992	1	15	14	**2.1**	0	0
80	1992	1	15	15	**2.2**	0	0
81	1992	1	15	16	**2.1**	0	0
82	1992	1	15	17	1.9	1	0
...	...	...	...	...	...	...	...

As shown in Table 2.13, timestep feasibility is only equal to 1, when at least three consecutive timesteps (each timestep corresponds to an hour, totalling three hours, the duration of Act1) are workable.

Each unfeasible timestep (timestep feasibility $f_t(t) = 0$) entails waiting time. Considering the previous example, if the activity Act1 would have been scheduled for the 15th of January of 1992 at 6 AM (timestep 71), it can be observed that 3 hours of WOW would be required (until 9 AM, timestep 74). Assuming monthly stationarity, a list of waiting on weather times can thus be calculated for all timesteps of the timeseries, grouped by months and statistically treated. This is illustrated in Table 2.14.

TABLE 2.14 WAITING ON WEATHER CALCULATION

Timestep	$W_t(t)$	$f_t(t)$	WOW [hours]	Total duration [hours]
...	...	...	...	...
70	1	1	0	3
71	1	0	3	6
72	1	0	2	5
73	0	0	1	4
74	1	1	0	3
75	1	0	15	18
76	1	0	14	17
77	0	0	13	16
78	1	0	12	15
79	0	0	11	14
80	0	0	10	13
81	0	0	9	12
82	1	0	8	11
...	...	...	...	....
N-2	1	1	0	3
N-1	1	NA	NA	NA
N	1	NA	NA	NA

In Table 2.14, total duration is equal to the net duration of Act1 (3 hours) plus the WOW. The frequency of occurrence of waiting time can be quantified using a cumulative frequency analysis, where probabilities of not exceeding a given threshold are estimated. Waiting time observations can be grouped by months to ensure stationarity.

As the algorithm approaches the end of the met-ocean timeseries, the number of subsequent timesteps will decrease until it eventually becomes lower than the duration of the activity being scheduled. In that case, the activity feasibility cannot be assessed. As a result, those timesteps are defined as "NA" and are discarded from the statistical analysis.

Given that the monthly waiting on weather values are not normally distributed, statistical properties such as the median (p50) and the interquartile ranges (p75-p25) provide more meaningful way of estimating the expected value and quantifying data variability. In Figure 2.9, a hypothetical non-exceedance distribution is plotted for Act1, considering all WOW values that occurred in every February of the entire timeseries (typically 20 years of data). According to Figure 2.9, there is a 50% probability that the activity Act1 will have a waiting time equal or lower than approximately 28 hours. The p25 and p75 values are approximately equal to 22 and 38 hours, respectively. According to this interquartile distance, there is a 50% probability that in February, the waiting time for Act1 will fall between the [22-38 hours] range.

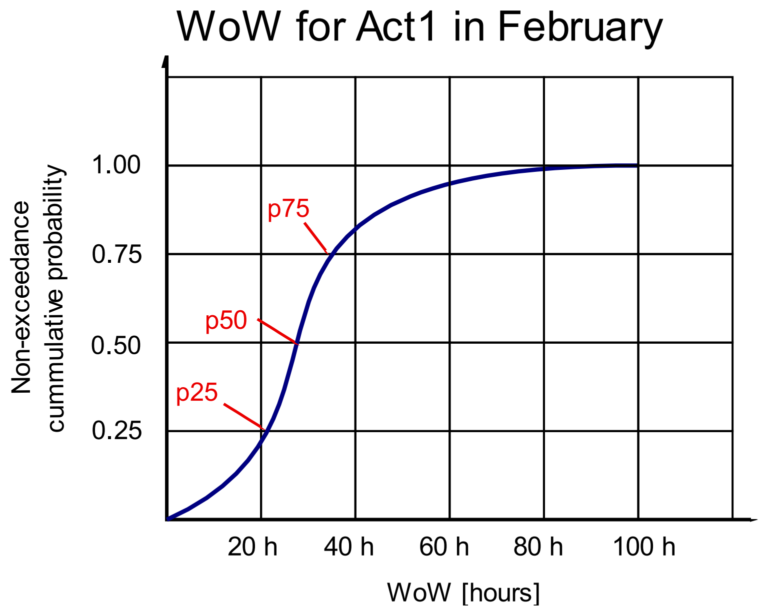


FIGURE 2.9 EXAMPLE NON-EXCEEDANCE PROBABILITY OF WAITING TIMES FOR A GIVEN MARINE ACTIVITY

Operations composed by multiple activities with different durations and weather restrictions can also be analysed. An illustrative example operation OPx composed by three activities (Act1, Act2 and Act3), with durations 3 hours, 4 hours, and 2 hours, respectively, can be considered. This adds a new complexity level to the tool.

TABLE 2.15 TIMESTEP WORKABILITY AND FEASIBILITIES FOR THREE DIFFERENT ACTIVITIES

Time step	$W_{1t}(t)$	$W_{2t}(t)$	$W_{3t}(t)$	$f_{1t}(t)$ (dur=3)	$f_{2t}(t)$ (dur=4)	$f_{3t}(t)$ (dur=2)
...	...	...	...	...	...	...
70	1	0	1	**1**	0	0
71	1	1	0	0	0	0
72	1	0	1	0	0	1
73	0	0	1	0	0	1
74	1	1	1	1	1	1
75	1	1	1	0	1	0
76	1	1	0	0	1	0
77	0	1	1	0	1	1
78	1	1	1	0	0	1
79	0	1	1	0	0	1
80	0	1	1	0	0	0
81	0	0	0	0	0	0
82	1	0	1	0	0	1
83	0	1	1	0	1	0
84	1	1	0	0	0	0
85	1	1	1	0	0	0
...	...	...	...	...	...	...

Given the precedence between activities, Act3 can only be carried out after Act2 has been completed, and Act2 after Act1. The process of scheduling an operation OPx, composed by multiple activities, as described in Table 2.15, is illustrated in Table 2.16. Analysing timestep 72, for example, it is possible to observe that the first activity could only have been started in timestep 74, so two hours of waiting (W, in red) would be needed. It also follows that when analysing timestep 72 as a potential start, previous timesteps are not defined (N.D.). The total waiting times and operation durations are then calculated as shown in the last column for illustrative purposes.

TABLE 2.16 ESTIMATION OF THE WAITING ON WEATHER AND OPERATION DURATION FOR ALL TIMESTEPS OF THE TIMESERIES

Time step		Subsequent timesteps															Tot WOW	Op. dur
		70	71	72	73	74	75	76	77	78	79	80	81	82	83	...		
Timestep under analysis	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	70	ACT1	ACT1	ACT1	W	ACT2	ACT2	ACT2	ACT2	ACT3	ACT3	X	X	X	X	X	1	10 h
	71	N.D.	W	W	W	ACT1	ACT1	ACT1	ACT2	ACT2	ACT2	ACT2	W	ACT3	ACT3	X	4	13 h
	72	N.D	N.D	W	W	ACT1	ACT1	ACT1	ACT2	ACT2	ACT2	ACT2	W	ACT3	ACT3	X	3	12 h
	73	N.D	N.D	N.D	W	ACT1	ACT1	ACT1	ACT2	ACT2	ACT2	ACT2	W	ACT3	ACT3	X	2	11 h
	74	N.D	N.D	N.D	N.D	ACT1	ACT1	ACT1	ACT2	ACT2	ACT2	ACT2	W	ACT3	ACT3	X	1	10 h
	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

2.8 APPROACH TO DOWNTIME ESTIMATION

2.8.1 HIERARCHY

Ocean renewable energy farms may be comprised of a very large number of systems, subsystems and components, interlinked in a complex manner. In DTOceanPlus, three major system can be identified: the Energy Transformation (ET) system (i.e. Power Take-Off units or PTOs), the Energy Delivery (ED) system (i.e. export cables, inter-array cables and collection points), and the Station Keeping (SK) system (i.e. moorings/foundations). Storing the information related to the relationships between systems, subsystems, and components, in a consistent, flexible and automatised manner, is fundamental to identify physical relationships between components in a farm, but also quantifying impacts of a given component failure in the energy production.

The hierarchy tree of a system/ subsystem is a digital representation of the working philosophy and the interrelationship between the units at different levels in this system/ subsystem. In the hierarchy, Boolean logic is used to define the relationships between components in respect to their impacts on the energy production of each device. In contrast to failure trees, the hierarchy models whether components are operational (1) or failed (0). This allows the quantification of the impacts of component critical failure on the system and identify which component critical failures generate critical failures at the system level, for each device.

The hierarchy tree is built following a bottom-up approach, analysing at the device level, whether a given component failure affects the ability of said device to deliver energy to the grid. Indivisible components are referred to as "Level 0" and have no "Children". The "child" column shows which components affect the operating state of a given system. In DTOceanPlus, hierarchy trees for the three described systems will be built by the three respective modules. The structure of the hierarchy is explained more in depth in [50].

2.8.1.1 ENERGY TRANSFORMATION HIERARCHY

Depending on the technology, ocean energy converters (OEC) may have one PTO per device (e.g. OWC spar buoy wave energy converter), or several. In some cases, PTOs may be installed in parallel and able to operate independently, even in case one of them fails (e.g. Pelamis). However, in some designs, PTOs may be interconnected in a way that if one PTO fails, then the entire device unit must be shutdown.

The Energy Transformation (ET) hierarchy describes the relationships between PTO sub-components (Mechanical Transformation, Electrical Transformation and Grid Conditioning), PTOs, devices and array [51]. In Figure 2.10, an example array of three devices with two independent PTOs each, is presented, while the corresponding hierarchy tree is shown in Table 2.17. In the ET hierarchy, the nodes ET1, ET2 and ET3 correspond to the ability of OEC1, OEC2 and OEC3, respectively, to produce energy.

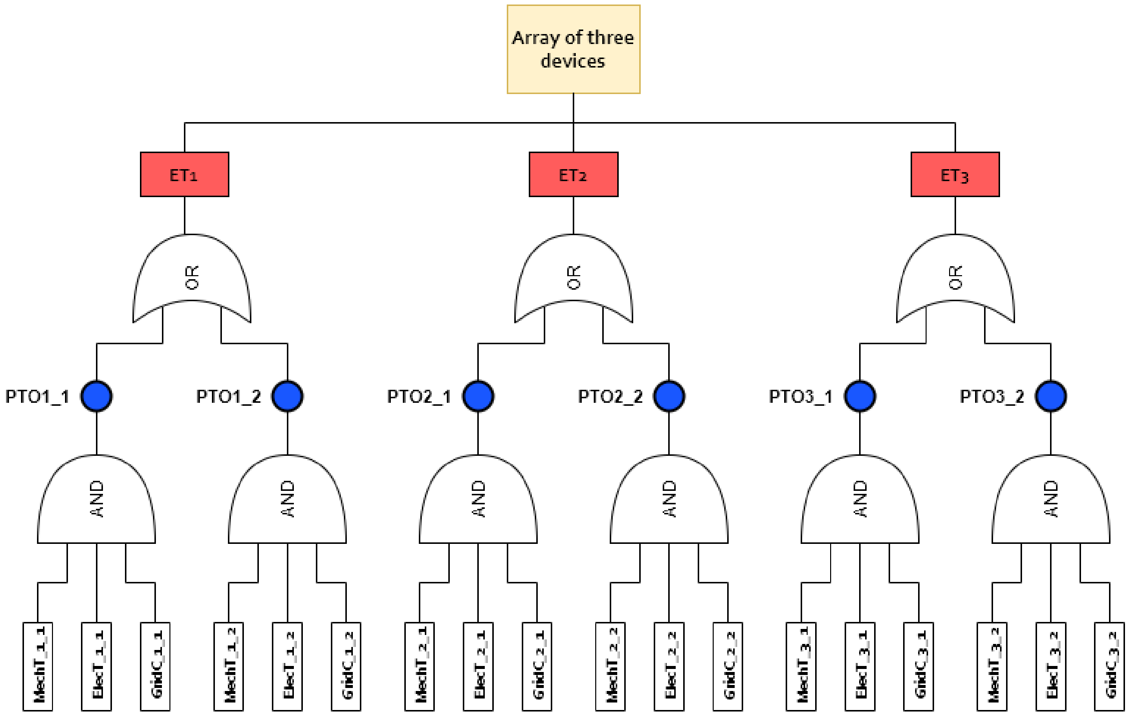


FIGURE 2.10. SCHEMATIC REPRESENTATION OF THE ENERGY TRANSFORMATION COMPONENTS IN AN ARRAY OF THREE DEVICES WITH TWO INDEPENDENT PTOS EACH

TABLE 2.17 ENERGY TRANSFORMATION HIERARCHY EXAMPLE

System	Name of Node	Design ID	Node Type	Category	Parent	Child	Gate Type	Failure Rate Minor repair [1/year]	Failure Rate Replacement [1/year]
ET	ET1	ET_01	System	Level 2	N/A	[PTO1_1, PTO1_2]	OR	N/A	N/A
ET	ET2	ET_01	System	Level 2	N/A	[PTO2_1, PTO2_2]	OR	N/A	N/A
ET	ET3	ET_01	System	Level 2	N/A	[PTO3_1, PTO3_2]	OR	N/A	N/A
ET	PTO1_1	ET_01	PTO	Level 1	ET1	[MechT_1_1, ElecT_1_1, GridC_1_1]	AND	N/A	N/A
ET	PTO1_2	ET_01	PTO	Level 1	ET1	[MechT_1_2, ElecT_1_2, GridC_1_2]	AND	N/A	N/A
ET	PTO2_1	ET_01	PTO	Level 1	ET2	[MechT_2_1, ElecT_2_1, GridC_2_1]	AND	N/A	N/A
ET	PTO2_2	ET_01	PTO	Level 1	ET2	[MechT_2_2, ElecT_2_2, GridC_2_2]	AND	N/A	N/A
ET	PTO3_1	ET_01	PTO	Level 1	ET3	[MechT_3_1, ElecT_3_1, GridC_3_1]	AND	N/A	N/A
ET	PTO3_2	ET_01	PTO	Level 1	ET3	[MechT_3_2, ElecT_3_2, GridC_3_2]	AND	N/A	N/A
ET	MechT_1_1	ET_01	Component	Level 0	PTO1_1	N/A	N/A	*value*	*value*
ET	MechT_1_2	ET_01	Component	Level 0	PTO1_2	N/A	N/A	*value*	*value*

System	Name of Node	Design ID	Node Type	Category	Parent	Child	Gate Type	Failure Rate Minor repair [1/year]	Failure Rate Replacement [1/year]
ET	MechT_2_1	ET_01	Component	Level 0	PTO2_1	N/A	N/A	*value*	*value*
ET	MechT_2_2	ET_01	Component	Level 0	PTO2_2	N/A	N/A	*value*	*value*
ET	MechT_3_1	ET_01	Component	Level 0	PTO3_1	N/A	N/A	*value*	*value*
ET	MechT_3_2	ET_01	Component	Level 0	PTO3_2	N/A	N/A	*value*	*value*
ET	ElecT_1_1	ET_01	Component	Level 0	PTO1_1	N/A	N/A	*value*	*value*
ET	ElecT_1_2	ET_01	Component	Level 0	PTO1_2	N/A	N/A	*value*	*value*
ET	ElecT_2_1	ET_01	Component	Level 0	PTO2_1	N/A	N/A	*value*	*value*
ET	ElecT_2_2	ET_01	Component	Level 0	PTO2_2	N/A	N/A	*value*	*value*
ET	ElecT_3_1	ET_01	Component	Level 0	PTO3_1	N/A	N/A	*value*	*value*
ET	ElecT_3_2	ET_01	Component	Level 0	PTO3_2	N/A	N/A	*value*	*value*
ET	GridC_1_1	ET_01	Component	Level 0	PTO1_1	N/A	N/A	*value*	*value*
ET	GridC_1_2	ET_01	Component	Level 0	PTO1_2	N/A	N/A	*value*	*value*
ET	GridC_2_1	ET_01	Component	Level 0	PTO2_1	N/A	N/A	*value*	*value*
ET	GridC_2_2	ET_01	Component	Level 0	PTO2_2	N/A	N/A	*value*	*value*
ET	GridC_3_1	ET_01	Component	Level 0	PTO3_1	N/A	N/A	*value*	*value*
ET	GridC_3_2	ET_01	Component	Level 0	PTO3_2	N/A	N/A	*value*	*value*

2.8.1.2 ENERGY DELIVERY HIERARCHY

The energy delivery hierarchy (ED) represents the component-to-component connection relationships and flow of electricity within the energy delivery network. The energy delivery hierarchy is comprised of physical components such as export and array cables, connectors, and collection points, that are organised in energy routes through which the energy generated by the OEC is passed before reaching the onshore landing point. Depending on the electrical connection layout, cable route redundancies may exist, namely if ring configurations are adopted [52].

In Figure 2.11, an example energy delivery connection layout is represented for a seven-device ocean energy farm, laid in two separate strings (rows) which are in turn connected to a collection point. In the ED hierarchy, the nodes ED1, ED2 and ED3 correspond to the ability of OEC1, OEC2 and OCE3, respectively, to successfully deliver their generated energy to the grid.

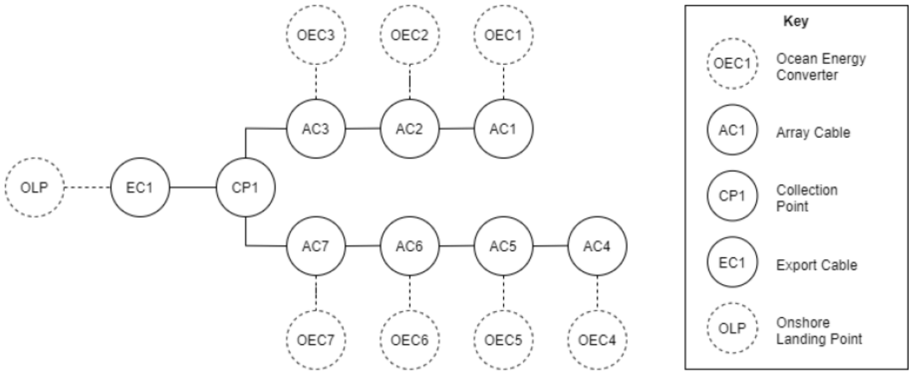


FIGURE 2.11 EXAMPLE ENERGY DELIVERY SOLUTION

TABLE 2.18 ENERGY DELIVERY HIERARCHY TREE EXAMPLE

System	Name	Design ID	Type	Category	Parent	Child	Gate	Failure Rate Minor [1/year]	Failure Rate Replacement [1/year]
ED	ED1	NotAppl	System	Level 2	[]	['Route1_1']	OR	NotAppl	NotAppl
ED	ED2	NotAppl	System	Level 2	[]	['Route2_1']	OR	NotAppl	NotAppl
ED	ED3	NotAppl	System	Level 2	[]	['Route3_1']	OR	NotAppl	NotAppl
ED	ED4	NotAppl	System	Level 2	[]	['Route4_1']	OR	NotAppl	NotAppl
ED	ED5	NotAppl	System	Level 2	[]	['Route5_1']	OR	NotAppl	NotAppl
ED	ED6	NotAppl	System	Level 2	[]	['Route6_1']	OR	NotAppl	NotAppl
ED	ED7	NotAppl	System	Level 2	[]	['Route7_1']	OR	NotAppl	NotAppl
ED	Route1_1	NotAppl	Energy route	Level 1	['ED1']	['AC1', 'AC2', 'AC3', 'CP1', 'EC1']	AND	NotAppl	NotAppl
ED	Route2_1	NotAppl	Energy route	Level 1	['ED2']	['AC2', 'AC3', 'CP1', 'EC1']	AND	NotAppl	NotAppl
ED	Route3_1	NotAppl	Energy route	Level 1	['ED3']	['AC3', 'CP1', 'EC1']	AND	NotAppl	NotAppl
ED	Route4_1	NotAppl	Energy route	Level 1	['ED4']	['AC4', 'AC5', 'AC6', 'AC7', 'CP1', 'EC1']	AND	NotAppl	NotAppl
ED	Route5_1	NotAppl	Energy route	Level 1	['ED5']	['AC5', 'AC6', 'AC7', 'CP1', 'EC1']	AND	NotAppl	NotAppl
ED	Route6_1	NotAppl	Energy route	Level 1	['ED6']	['AC6', 'AC7', 'CP1', 'EC1']	AND	NotAppl	NotAppl
ED	Route7_1	NotAppl	Energy route	Level 1	['ED7']	['AC7', 'CP1', 'EC1']	AND	NotAppl	NotAppl
ED	AC1	AC1	Component	Level 0	['Route1_1']	[]	NA	0.00024	0.00024
ED	AC2	AC2	Component	Level 0	['Route1_1', 'Route2_1']	[]	NA	0.00024	0.00024
ED	AC3	AC3	Component	Level 0	['Route1_1', 'Route2_1', 'Route3_1']	[]	NA	0.0004	0.0004

System	Name	Design ID	Type	Category	Parent	Child	Gate	Failure Rate Minor [1/year]	Failure Rate Replacement [1/year]
ED	AC4	AC4	Component	Level 0	['Route4_1']	[]	NA	0.00024	0.00024
ED	AC5	AC5	Component	Level 0	['Route4_1', 'Route5_1']	[]	NA	0.00024	0.00024
ED	AC6	AC6	Component	Level 0	['Route4_1', 'Route5_1', 'Route6_1']	[]	NA	0.00024	0.00024
ED	AC7	AC7	Component	Level 0	['Route4_1', 'Route5_1', 'Route6_1', 'Route7_1']	[]	NA	0.0004	0.0004
ED	CP1	CP1	Component	Level 0	['Route1_1', 'Route2_1', 'Route3_1', 'Route4_1', 'Route5_1', 'Route6_1', 'Route7_1']	[]	NA	0.03	0.03
ED	EC1	EC1	Component	Level 0	['Route1_1', 'Route2_1', 'Route3_1', 'Route4_1', 'Route5_1', 'Route6_1', 'Route7_1']	[]	NA	0.0048	0.0048

2.8.1.3 STATION KEEPING HIERARCHY

The Station Keeping hierarchy represents relationships between each device and the systems that hold the device in position. Station Keeping system consist of substructures and foundations, whilst for floating typologies it will consist of mooring systems. These systems may be simple or aggregated depending on the number of components. Aggregated station keeping systems may have different design configurations, sometimes with component redundancy. An obvious example is the case of a mooring system design with four mooring lines, where one line is redundant. In this case, the mooring system will still be operating, even if one mooring line fails. In this case, SK failure would occur only whenever two or more mooring lines collapse. The SK hierarchy tree, as outputted by the SK module, model these relationships.

In Figure 2.12, a generic station keeping system, composed by three non-redundant mooring lines, is represented. The corresponding SK hierarchy tree is represented in Table 2.19, where the bottom node (SK0) represents the operating status of the station keeping system of OEC0.

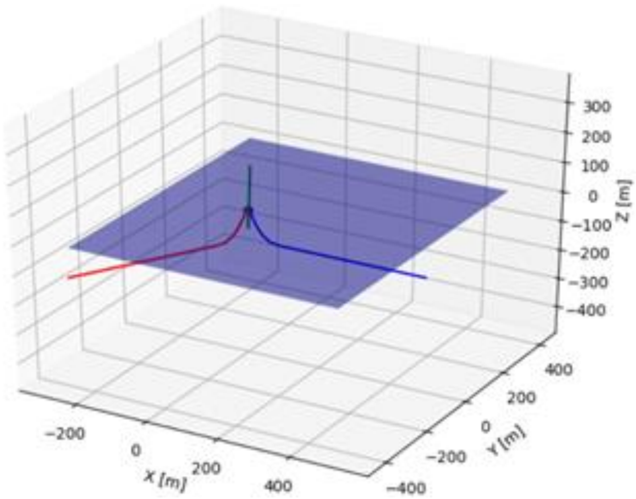


FIGURE 2.12 GENERIC STATION KEEPING SOLUTION COMPOSED OF THREE NON-REDUNDANT MOORING LINES FOR A SINGLE DEVICE

TABLE 2.19 STATION KEEPING HIERARCHY TREE

System	Name of node	Design ID	Node type	Node subtype	Category	Parent	Child	Gate	Repair	Replacement
SK	SK0_x	NA	System	stationkeeping	Level 2	SK0	[SK0_x_ml_0,SK0_x_ml_1,SK0_x_ml_2]	AND	NA	NA
SK	SK0_x_ml_0_seg_0	SK0_x_ml_0_seg_0	Component	line_segment	Level 0	SK0_x_ml_0	NA	NA	NA	0.00722
SK	SK0_x_ml_0_anchor_n_2_0	SK0_x_ml_0_anchor_n_2_0	Component	anchor	Level 0	SK0_x_ml_0	NA	NA	NA	0.000278
SK	SK0_x_ml_0	"NA"	System	mooring_line	Level 1	SK0_x	[SK0_x_ml_0_seg_0,SK0_x_ml_0_anchor_n_2_0]	AND	NA	NA
SK	SK0_x_ml_1_seg_0	SK0_x_ml_1_seg_0	Component	line_segment	Level 0	SK0_x_ml_1	NA	NA	NA	0.00722
SK	SK0_x_ml_1_anchor_n_2_0	SK0_x_ml_1_anchor_n_2_0	Component	anchor	Level 0	SK0_x_ml_1	NA	NA	NA	0.000278

System	Name of node	Design ID	Node type	Node subtype	Category	Parent	Child	Gate	Repair	Replacement
SK	SK0_x_ml_1	NA	System	mooring_line	Level 1	SK0_x	[SK0_x_ml_1_seg_0,SK0_x_ml_1_anchor_n_2_0]	AND	NA	NA
SK	SK0_x_ml_2_seg_0	SK0_x_ml_2_seg_0	Component	line_segment	Level 0	SK0_x_ml_2	NA	NA	NA	0.00722
SK	SK0_x_ml_2_anchor_n_2_0	SK0_x_ml_2_anchor_n_2_0	Component	anchor	Level 0	SK0_x_ml_2	NA	NA	NA	0.000278
SK	SK0_x_ml_2	NA	System	mooring_line	Level 1	SK0_x	[SK0_x_ml_2_seg_0,SK0_x_ml_2_anchor_n_2_0]	AND	NA	NA
SK	SK0	NA	System	stationkeeping	Level 3	NA	[SK0_x]	AND	NA	NA

2.8.2 ENERGY PRODUCTION TREES

Throughout an ocean energy farm lifetime, downtime may occur either due to component failure, or due to a maintenance activity that requires shutting off one or multiple devices. Both scenarios result in losses of energy production, or downtime.

Energy production trees are what allow to calculate, for each timestep of a timeseries, how much energy is being produced, and consequently estimate downtime. Since devices may have more than one PTO, it must be considered that energy is produced at a PTO level and delivered to the grid whenever all conditions are met. The energy production tree can be produced aggregating all the information from the hierarchy trees provided by ET, SK, and ED.

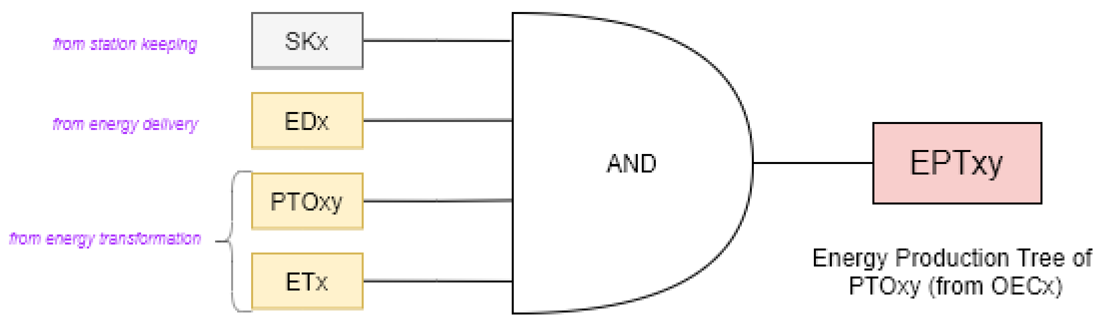


FIGURE 2.13 ENERGY PRODUCTION TREE FOR PTO1 (OF OEC1)

The energy generated by a given PTO may be delivered to the onshore landing point if and only if:

1. The energy delivery system corresponding to that specific device (OECx) is operational (EDx is working).
2. The station keeping system corresponding to that specific device (OECx) is operational (SKx is working)
3. PTO in question is operational (PTOxy)
4. The energy transformation system corresponding to that device (OECx) is operational (if the device's PTOs are not independent, PTO13 may have failed, causing ET1 to fail, even though PTO11 is operational and not requiring maintenance)

Based on these requirements, as represented in Figure 2.13, a logical equation (Boolean) can be used to evaluate the energy production (and delivery to grid) of each PTO in a given ocean energy farm:

$$EPT_{x,y} = SK_x \times ED_x \times PTO_{xy} \times ET_x$$

Where $EPT_{x,y}$ will be 1 or 0 in case energy is being delivered to the grid or not, respectively.

2.9 KEY ASSUMPTIONS AND EXCLUSIONS

- The project commissioning date is assumed to be the end date of the last installation operation.
- Infrastructure solutions are produced for each operation, which means that for different operations, different port terminals may be selected as optimal solutions for each operation. However, the user may force a given port terminal to be considered throughout the project.
- For the installation and decommissioning operations, feeder-solutions, where a main vessel is stationed at site whilst a feeder barge or PSV travels back and forth from port to site in order to transport components, has not been considered in this version of the Logistics module.
- In the foundation installation operation, it is assumed that a single piling method is used for installing every single pile foundation/anchor.
- The infrastructure pre-selection functionality evaluates whether at least one device or subsystem can be installed/maintained/decommissioned using the specified infrastructure solution.
- Multi-phase installation projects are not considered within the scope of DTOceanPlus.

3. USE CASES AND FUNCTIONALITIES

The Logistics and Marine Operation Planning (LMO) module is responsible for:

- Producing a solution in terms of logistical infrastructure (vessels, ports, and equipment) for all stages (installation, O&M and decommissioning) of a wave or tidal renewable energy project at different levels of aggregation (array, energy capture devices, and subsystems).
- Producing an installation plan, with discriminated sequence of operations and activities, featuring durations, cost estimates and weather restrictions
- Producing a maintenance plan, based on the system reliability information, hierarchical relationships between components, and failure events generated by the RAMS module, as well as the impacts of failure scenarios or maintenance activities on the energy production at the array level.
- Compute a maintenance plan based on component list and user preferences.
- Produce an (optional) decommissioning plan, detailing the sequence of operations and activities, featuring operation durations, cost estimates and weather restrictions.

3.1 THE USE CASES

In Deliverable D5.1 [53], the Technical requirements of the LMO module were presented, and the use cases were listed for the different types of users. In this section, the use cases are described from an operational perspective, in respect to what the user decides to do and which modules to run.

In this generic use case, the user is able to:

1) Run LMO as part of the set of Deployment Design tools of DTOceanPlus.
2) Run LMO within the framework of the Stage Gate (SG) or Structured Innovation (SI) Design tools.
3) Use LMO in standalone mode.

By considering the three Use cases above mentioned, Table 3.1 summarises the dependencies of LMO from/to other modules in DTOceanPlus.

TABLE 3.1 DEPENDENCIES OF LMO FROM/TO OTHER MODULES IN DTOCEANPLUS

Modules that provide services that LMO consumes	Modules that are consuming services from LMO
Site Characterisation (SC)	Energy Delivery (ED) through a shared function
Energy Capture (EC)	System Performance and Energy Yield (SPEY)
Machine Characterisation (MC)	Reliability, Availability, Maintainability, and Survivability (RAMS)
Energy Transformation (ET)	System Lifetime Costs (SLC)
Energy Delivery (ED)	Environmental and Social Acceptance (ESA)
Station Keeping (SK)	Stage Gate (SG)
RAMS (shared function)	Structured Innovation (SI)

3.1.1 USE CASE AS A PART OF THE SET OF DEPLOYMENT DESIGN TOOLS

In this case, the user will run one or more Deployment Design tools and then he/she will run the LMO module to calculate a logistic solution for each phase of the project. This is represented in Figure 3.1. The numerical results as well as the graphs/diagrams will be shown to the user.

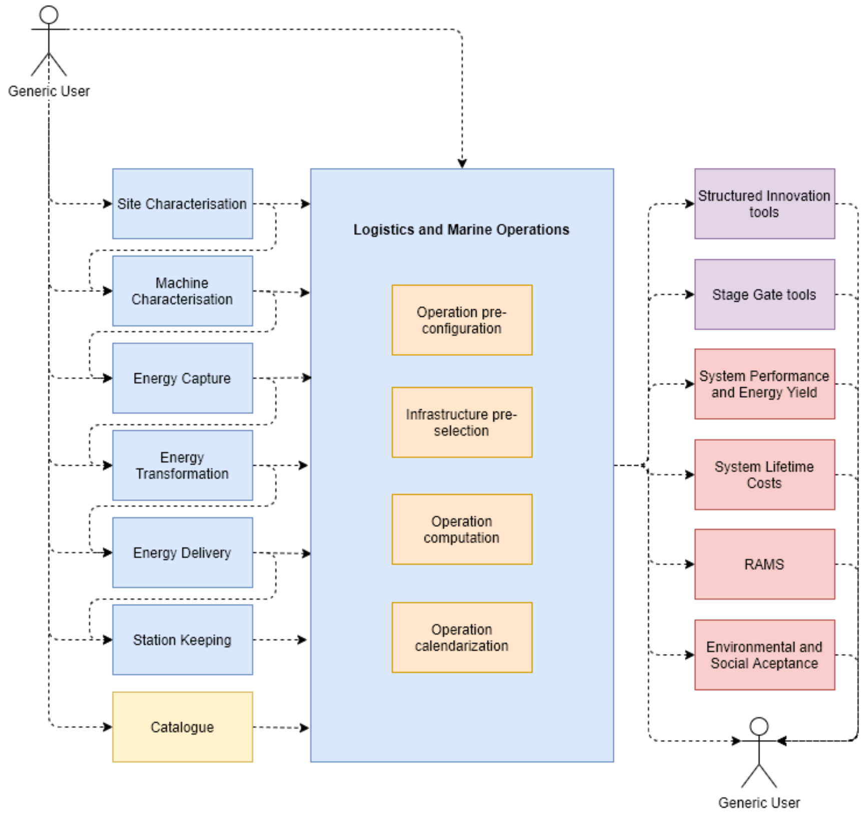


FIGURE 3.1 USE CASE FOR USING THE LOGISTICS AND MARINE OPERATIONS MODULE AFTER RUNNING THE DEPLOYMENT DESIGN TOOLS.

3.1.2 USE CASE WITHIN THE FRAMEWORK OF SG/SI DESIGN TOOLS

In this case, the LMO module will be run within the framework of the Stage Gate or Structured Innovation design tools, as seen in Figure 3.2. The following steps are identified for this use case:

1) The user runs the framework of the SI/SG tools.
2) The SI/SG tools will require information from the Assessment tools.
3) The LMO module will provide required design parameters, if available, or
4) The LMO module will prompt the user to provide information and run the LMO module.
5) LMO will provide required design parameters to the Assessment modules.
6) The assessments are sent back to SI/SG tools to complete their framework.
7) The SI/SG tools will process and show the outcome to the user.

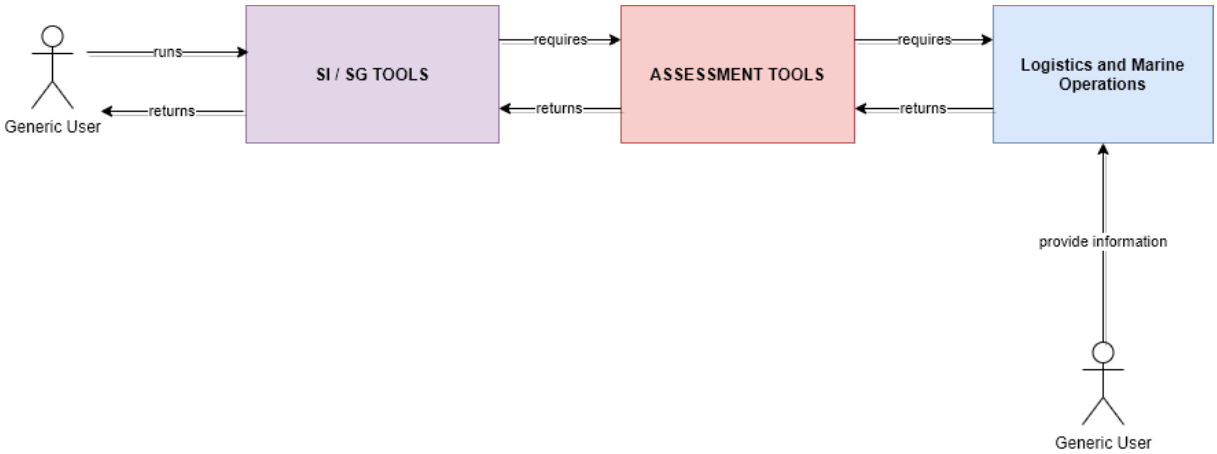


FIGURE 3.2 USE CASE FOR USING THE LOGISTIC AND MARINE OPERATIONS TOOLS WITHIN THE FRAMEWORK OF SG/SI DESIGN TOOLS.

3.1.3 STANDALONE MODE

In this case, the user only wants to run the LMO module in order obtain optimal logistic solutions in terms of vessel fleet, port and equipment selection as well as operation scheduling and costs. In this case, the user will be required to provide every input and will be presented with the overall results of the design process, as illustrated in Figure 3.3.

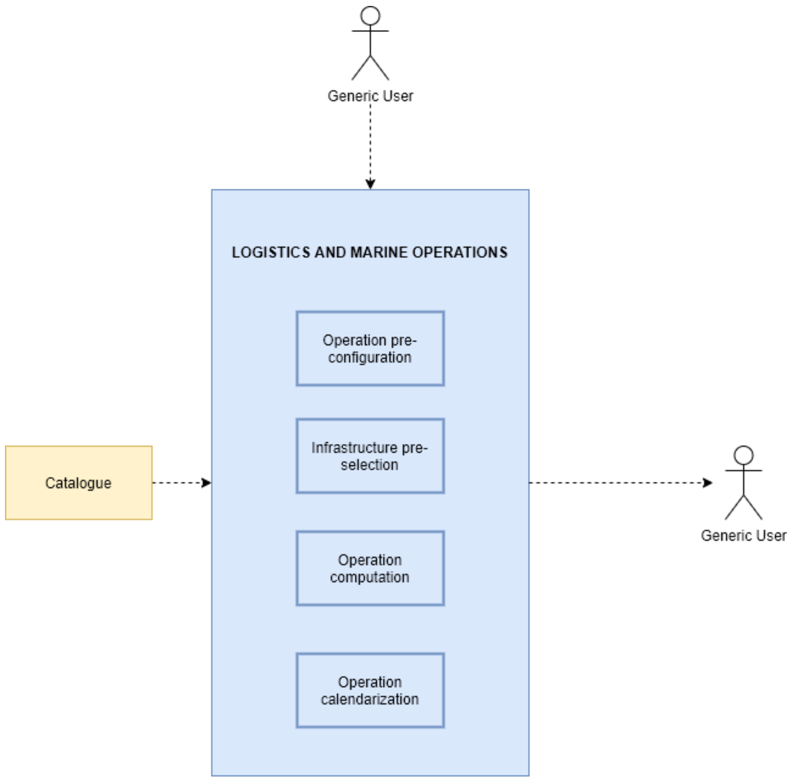


FIGURE 3.3 USE CASE FOR USING THE LOGISTIC TOOLS IN STANDALONE MODE.

3.2 THE FUNCTIONALITIES AT DIFFERENT LEVELS OF COMPLEXITY

The LMO module was developed to design logistic solutions for technologies and projects at different stages of development. However, at the different stages of the technology development process, the amount of available information and data will change. In DTOceanPlus, the method used by each module will change to align with this detail.

To ensure consistency with the other tools, three levels of complexity (CPX1, CPX2 and CPX3) have been developed for the Logistics module. The LMO module will have two design modes, a low complexity (CPX1) and a full complexity (CPX2-3). In the full complexity mode, the main differences between complexity CPX2 and CPX3 are the certainty of the inputs and whether default values are assumed in the intermediate stage instead of requesting these from the user. Alternatively, the simplified mode (CPX1) can be used for early stage technologies, at lower Technology Readiness Levels (TRL) 1-3, or whenever limited information is available about the technology design and project specifics. The simplified mode may also be used to provide a quick and rough estimate for higher TRL projects. In Table 3.2, the main differences in respect to the inputs and outputs of the LMO module for the different complexity levels are presented.

TABLE 3.2 MAIN DIFFERENCES IN THE INPUTS AND OUPUTS OF THE LMO MODULE AT DIFFERENT LEVELS OF COMPLEXITY

Input/output	Simplified process	Full complexity calculation process	
	CPX1 Simple	CPX2 Medium	CPX3 Complex
Transportation method	Assumed dry	Assumed dry	User input (default dry).
Cable burial method	Ignored (Surface lay)	Consider	Consider
Cable Landfall method	Assumed OCT	Assumed OCT	User input
Consider post-lay cable burial	Ignored	False	User input
Load-out method	Ignored	Assumed "lift"	User input
Load-out from vessel deck method	Lift	Lift	User input (default lift)
Piling method	Assumed hammering. Soil type ignored.	Calculated	User preferences, Calculated
External protections	Ignored	User/ED input	User/ED input
Met-ocean timeseries	Reduced Hs timeseries	Full timeseries (Hs,Tp,Ws,Cs)	Full timeseries (Hs,Tp,Ws,Cs)
Site bathymetry	Average value	Detailed bathymetry	Detailed bathymetry
Vessel route	Assumed straight line from port to site	Calculated	Calculated

Input/output	Simplified process	Full complexity calculation process	
	CPX1 Simple	CPX2 Medium	CPX3 Complex
Start date	Ask month to user	Ask specific date to user	Ask specific date to user
Export cable route	Based on cable length	Detailed input from ED	Detailed input from ED
Installation operation sequence	Assumed	Default/User input	Default/User input
Topside inspections requirement	Assumed True	User specified	User specified
Bollard pull calculation for vessel selection during wet-tows	Ignored	Calculated	Calculated

3.3 FUNCTIONALITIES OF THE FULL COMPLEXITY LOGISTICS MODULE

As shown in Figure 3.4, the LMO module has four major functionalities, which are common to all three project phases:

1. **Operation pre-configuration**: The operation pre-configuration functionality is responsible for identifying operations associated with the project and for translating component attributes (e.g. mass, dimensions) and operation methods (e.g. transport: wet-tow) into infrastructure requirements (e.g. vessel deck area) and operation sequence. This functionality is further divided into three sub-functionalities, related to the three lifecycle phases.
2. **Infrastructure pre-selection:** This functionality is common to all three phases of the project and consists firstly of pre-selecting vessels, equipment, and port terminals that independently comply with operation requirements, and then match pre-selections into multiple combined solutions.
3. **Operation computation:** This functionality, common to all three phases of the operation, is responsible for analysing the pre-selected infrastructure combinations, defining activity sequences (e.g. number of transits port-site) and calculate expected operation durations and waiting on weather for different months of the year. Based on operation durations and selected infrastructure, the operation costs are calculated for each infrastructure solution and a cost-optimal solution is selected for each individual operation.
4. **Operation calendarization:** This functionality is responsible for scheduling the list of optimal operations, as calculated by the previous functionality, as a sequence. This functionality slightly varies with logistic phase: for the maintenance phase it also is responsible for calculating operation's downtime.

These functionalities are shown in Figure 3.4

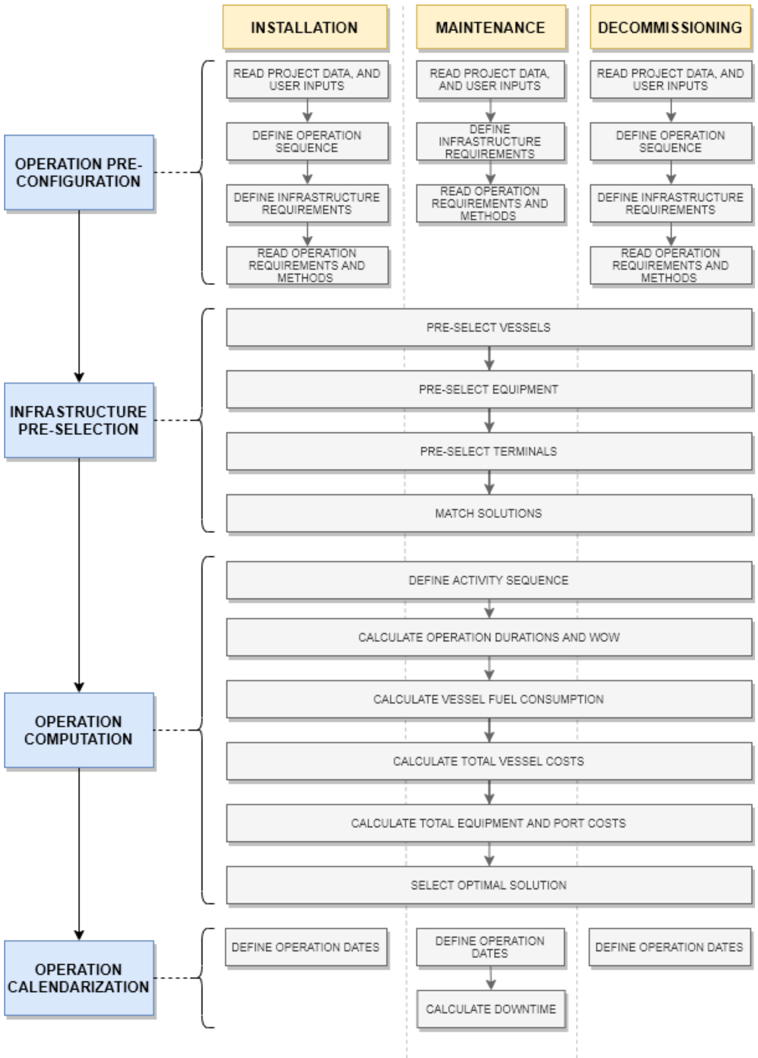


FIGURE 3.4 MAIN FUNCTIONALITIES OF THE LOGISTICS MODULE AT FULL COMPLEXITY

3.3.1 OPERATION PRE-CONFIGURATION

The first step in the operation planning is identifying which operations are required and in what sequence, when it comes to installing, maintaining, and decommissioning an ocean energy farm. The second step is identifying what are the requirements in terms of vessels, port terminals and equipment. The operation pre-configuration is responsible for outputting the following:

- Operation list: what operations should be scheduled
- Operation sequence: in what order should the operations be scheduled
- Methods: defined techniques for carrying out a given task (e.g. pilling method, cable burial method)
- Requirements: compiled requirements such as lifting, area, vessel DP, to name a few.

3.3.1.1 INPUTS

TABLE 3.3 INPUT TABLE FOR THE OPERATION PRE-CONFIGURATION FUNCTIONALITY

Variable name	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
hierarchy_et	Hierarchy datafile from the energy transformation system	ET	Pandas	[-]
hierarchy_ed	Hierarchy datafile from the energy delivery system	ED	Pandas	[-]
hierarchy_sk	Hierarchy datafile from the station keeping system	SK	Pandas	[-]
bom_et	BOM datafile from the energy transformation system	ET	Pandas	[-]
bom_ed	BOM datafile from the energy delivery system	ED	Pandas	[-]
bom_sk	BOM datafile from the station keeping system	SK	Pandas	[-]
metocean_timeseries	Timeseries of met-ocean conditions	SC	Pandas	[-]
farm_bathymetry	Bathymetry data at farm site location	SC	Dictionary	[-]
seabed_type	Soil type	SC	Dictionary	[-]
OEC.drymass	Dry mass of device	MC	Float	kg
OEC.dimensions	Dimensions of device (OEC.width, OEC.length, OEC.height)	MC	Float	m
OEC.draft_towing	Device's draft while towing (only for floating and wet-tow transport)	User	Float	m
farm_layout	Farm layout	EC	Dictionary	[-]
ndevices	Number of devices	EC	Integer	[-]
OEC.type	Device topology (Wave/tidal, bottom-fixed/floating)	EC	String	[-]
PTO.mech.drymass	Mass of the Mechanical Transformation component of the PTO	ET	Float	kg
PTO.elect.drymass	Mass of the Eletrical Transformation component of the PTO	ET	Float	kg
PTO.grid.drymass	Mass of the Grid Conditioning component of the PTO	ET	Float	kg
cables	Cable data, including length, type, connectors and route	ED	Dictionary	[-]
collection_point	Collection point data, including type, coordinates, and dimensions.	ED	Dictionary	[-]
mooring_line	Mooring line data, including type, material, and dimensions.	SK	Dictionary	[-]
anchor	Anchor data, including dimensions, dry mass, position.	SK	Dictionary	[-]
seabed_connection	Umbilical cable seabed connection coordinates	ED	Dictionary	[-]
Installation.sequence	Pre-defined installation operation sequence	User input/LMO	List	[-]
Decom.sequence	Pre-defined decommissioning operation sequence	LMO	List	[-]
install_ext_protect	Boolean that defines whether cable external protections (rock bags, concrete mattresses) will be installed	User input/ED	Boolean	[-]
cable_post_burial	Boolean that defines whether cable burial should be carried out in a separate operation after laying on the seabed	User input	Boolean	[-]
port_max_dist	Maximum allowable distance, in straight line, between port and site	User input	Integer	m
project_life	Project lifetime in years	User input	Integer	[years]
installation_start_date	Format: "DD/MM/YYYY"	User input	String	[-]

Variable name	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
opx.method[burial]	Selected cable burial method (ploughing, jetting, cutting)	ED/user	String	[-]
opx.method[pilling]	In CPX3, the user may specify the piling method. Otherwise, it is defined internally in LMO(hammering"; "drilling"; "vibro-piling")	User	String	[-]
op.methods[transport]	Dry or wet transport method (default: dry)	User input	String	[-]
op.methods[landfall]	The landfall method for the export cable installation is dependent on the soil type (default: "OCT")	User input	String	[-]
OEC.topside	Is the device's PTO above the sea surface?	User input	Boolean	[-]
OEC.ttp	Consider tow-to-port maintenance for the device?	User input	Boolean	[-]
cp.type	Collection point type (substation or hub)	ED	String	[-]
pilling	Pile equipment catalogues	Catalogue	Dictionary	[-]

3.3.1.2 OUTPUTS

OPERATION IDENTIFICATION AND SEQUENCE

Based on the components listed in the hierarchy, the necessary installation, maintenance and decommissioning operations can be defined.

- INSTALLATION

For the installation, an operation sequence is proposed to the user, who may modify the operation sequence according to their preferences but within a logical range of possible solutions. The user is also able to remove installation operations, namely cable installations, which would be irrelevant when installing devices in test-sites that already have the electrical infrastructure in place. Still, if the user removes any operation, a warning is presented explaining that the results may be unrealistic.

TABLE 3.4 OPERATION PRE-CONFIGURATION OUTPUTS FOR INSTALLATION OPERATIONS

Requirement	Inputs	Function
List of installation operations	Hierarchy_ET Hierarchy_ED, Hierarchy_SK Ndevices cp.type	*If ndevices>0:* *opx_list.append("device installation")* *If hierarchy_ED includes "array cable":* *opx_list.append("array cable installation")* *If hierarchy_ED includes "export cable":* *opx_list.append("export cable installation")* *If hierarchy_ED includes "collection point":* *If not all cp's are "hub":* *opx_list.append("collection point installation")* *if "moorings" in hierarchy_SK:* *opx_list.append("moorings installation")* *if "pile" or "suction caisson" in hierarchy_SK:* *opx_list.append("foundation installation")* *if "support structure" in hierarchy_SK:* *opx_list.append("support structure installation")* *if "install_ext_protect" = True:* *opx_list.append("external protection installation")*

Requirement	Inputs	Function
Operation sequence suggestion[13]	List of installation operations Device connector type (dry/wet) User introduced sequence	Seq1 = ["Foundation installation"," Moorings installation", "Support structures installation", "Collection point installation", Device installation", "Export cable installation", "Array cable installation", "Post-lay cable burial", "External protections"] Seq2 = ["Foundation installation"," Moorings installation", "Support structures installation", "Collection point installation", "Export cable installation", "Array cable installation", "Device installation", "Post-lay cable burial", "External protections"] Seq3 = ["Foundation installation"," Moorings installation", "Support structures installation", "Device installation", "Export cable installation", "Array cable installation", "Collection point installation", "Post-lay cable burial", "External protections"] Seq4 = ["Foundation installation"," Moorings installation", "Support structures installation", "Array cable installation", "Post-lay cable burial", "External protections", "Collection point installation", "Device installation"]

- MAINTENANCE

Two types of maintenance are considered in the full complexity of LMO: preventive (time-based maintenance) and corrective.

- PREVENTIVE

The identification of preventive maintenance activities that will be carried out throughout the project lifetime is achieved in three steps:

i) read component list in the farm,
ii) read maintenance catalogue, which lists preventive maintenance periodicity, number of technicians and impacts of maintenance on energy production, per operation type, and
iii) estimate number of preventive maintenance interventions until the end of project lifetime specified by the user.

TABLE 3.5 PREVENTIVE MAINTENANCE OPERATIONS EXTRACTED FROM MAINTENANCE CATALOGUE

ID	Operation name	Operation type	Periodicity (years)	Number technicians	Energy power shutdown
op10	Preventive Maintenance	Topside inspection	1	2	Yes
op11	Preventive Maintenance	Underwater inspection	2	2	Yes
op12	Preventive Maintenance	Moorings inspection	3	2	Yes
op13	Preventive Maintenance	Array cable inspection	3	2	Yes
op14	Preventive Maintenance	Export cable inspection	5	2	No

[13] This sequence is based on pre-defined precedence rules between operations, defining the overall order of the installation operations to carry out. Depending on the farm design, the final installation operation sequence is likely to not feature every single operation listed.

As defined in LMO, "topside inspections" correspond to visual inspections of components that are above the sea level. This preventive maintenance covers devices and collection points (surface piercing and floating) that are above sea level. In contrast, underwater inspection is carried out to the hull of the devices and collection points, as well as foundations, using ROVs or divers. Finally, the "Moorings inspection", "Array cable inspection", and "export cable inspection" operations are visual inspections carried out underwater using ROVs or divers, to the moorings, array cables and export cables, respectively. Preventive maintenance operations are defined in the catalogue, and in some cases, it is assumed that they will require shutting down the specific device for safety reasons. However, the user may modify these assumptions according to their preferences and best knowledge.

TABLE 3.6 OPERATION PRE-CONFIGURATION OUTPUTS FOR PREVENTIVE MAINTENANCE OPERATIONS

Requirement	Inputs	Function
List of preventive maintenance operations	Hierarchy_ET Hierarchy_ED, Hierarchy_SK OEC.topside cp.type	*If OEC.topside==True* *opx_list.append("Topside inspection")* *If hierarchy_ED includes "array cable":* *opx_list.append("array cable inspection")* *If hierarchy_ED includes "export cable":* *opx_list.append("export cable inspection")* *If hierarchy_ED includes "collection point":* *If cp.type=="hub"* *opx_list.append("Underwater inspection")* *else:* *opx_list.append("Topside inspection")* *if "moorings" in hierarchy_SK:* *opx_list.append("Moorings inspection")* *if "pile" or "suction caisson" in hierarchy_SK:* *opx_list.append("Underwater inspection")* *if "support structure" in hierarchy_SK:* *opx_list.append("Underwater inspection")*

- CORRECTIVE

The identification of corrective maintenance activities that will be carried out throughout the project lifetime is also achieved in three steps:

i) read component list in the farm,
ii) estimate time-to-failure (TTF) data using a RAMS shared function[50] and identify which components are likely to failure throughout the specified project lifetime,
iii) read maintenance catalogue which lists corrective maintenance activities per component type.

TABLE 3.7 CORRECTIVE MAINTENANCE OPERATIONS EXTRACTED FROM MAINTENANCE CATALOGUE

ID	Operation name	Operation type	Periodicity (years)	Number technicians	Energy power shutdown
op15	Corrective Maintenance	Device retrieval	NA	6	NA
op16	Corrective Maintenance	Device repair at port	NA	6	NA
op17	Corrective Maintenance	Device redeployment	NA	6	NA
op18	Corrective Maintenance	Device repair on site	NA	6	NA
op19	Corrective Maintenance	Mooring line replacement	NA	6	NA
op20	Corrective Maintenance	Cable replacement	NA	6	NA
op21	Corrective Maintenance	Cable repair	NA	6	NA

For corrective maintenance, the list of corrective maintenance interventions that are likely to be scheduled during project lifetime can be defined as:

TABLE 3.8 OPERATION PRE-CONFIGURATION OUTPUTS FOR CORRECTIVE MAINTENANCE OPERATIONS

Requirement	Inputs	Function
List of corrective maintenance operations	Hierarchy_ET Hierarchy_ED, Hierarchy_SK OEC.topside	*If TTF[component]<= project_lifetime* *Include maintenance_operation*

- DECOMMISSIONING

Decommissioning operations are defined as follows:

TABLE 3.9 OPERATION PRE-CONFIGURATION OUTPUTS FOR DECOMMISSIONING OPERATIONS

Requirement	Inputs	Function
List of decommissioning operations	List of project components	*If ndevices>0:* *opx_list.append("device removal")* *If "collection point" is in hierarchy_ED:* *opx_list.append("collection point removal")* *if "moorings" is in hierarchy_SK:* *opx_list.append("moorings removal")* *if "support structure" is in hierarchy_SK:* *opx_list.append("support structure removal")* *if "pile" or "suction caisson" is in hierarchy _SK:* *opx_list.append("foundation removal")*
Sequence of decommissioning operations	List of decommissioning operations	Seq1 = ["Device removal", "Collection point removal", "Support structures removal"," Moorings removal", "foundations removal"]

OPERATION METHODS

Operation methods describe how the operation should be carried out. Four overall methods, as well as defaults, are defined as shown in Table 3.10. In Table 3.14, the different operation methods are interconnected to the operations considered in LMO.

TABLE 3.10 OPERATION METHODS

Method	Source	Function
Transportation method	User inputs	Default: dry transport ("on deck" or "dry tow", both will be evaluated) *options: "dry"; "wet"*
Load-out method	User inputs	Default: "lift" *options: "lift"; "float"; "skidder"; "railed"*
Load-out from vessel deck method	User inputs	Default: "lift" *options: "lift"; "launch"*
Piling method	LMO/User inputs	*options: "hammering"; "drilling"; "vibro-piling"*
Cable burial method	ED / user inputs	*options: "ploughing"; "jetting"; "cutting"*
Post laying burial	LMO/User inputs	*Default: False* *Options: True, False.*
Cable landfall method	User input	Default: *OCT* *options: "HDD", "OCT".*
Tow-to port maintenance method	User input	Default: *False* *options: True, False*

CABLE BURIAL METHOD

In DTOceanPlus, the cable route is an output of the electrical system design, produced by the ED module, which must take into consideration soil type and existing cable burial tools and methods. For this reason, the cable burial method is specified by ED. In case LMO is run in standalone mode, the cable burial method is asked to the user, assumed ploughing as a default.

- EXPORT CABLE LANDFALL METHOD

The selection of the landfall method has an impact on the durations and procedures associated with installing the export cable.

TABLE 3.11 OPERATION REQUIREMENTS DEFINITION IN RESPECT TO CABLE LANDFALL

Requirement	Inputs	Function
Export cable landfall method	User input	*op.methods[landfall]="OCT" or "HDD".*

- PILING METHOD

In offshore renewable energy projects, piles have been used as foundations and anchors for devices and substations. Depending on the seabed soil type, different piling techniques are available, with different equipment requirements, restrictions and environmental impacts. In DTOceanPlus, three piling methods are considered: i) hammering, ii) drilling, and iii) vibro-driving.

A fourth method is reserved for suction caissons (suction piles and suction anchors), and large steel cylinders with an open bottom. These are installed by firstly penetrating the seabed under their own weight, and then finally embedding through suction using a remote-operated vehicle (ROV) to pump water out of the cylinder's interior. For the different soil categories as defined by the Site Characterisation module [54], different vertical penetration speeds were compiled and adapted in Table 3.12 from DTOcean D5.6 [49].

TABLE 3.12 PILING SPEEDS FOR DIFFERENT PILING METHODS AND SOIL TYPES

Soil type	Vertical penetration speed per method in m/h			
	hammering	drilling	Vibro-drilling	Suction (for suction anchors and piles)
rocks	0	0.3	0	0
pebbles	0	0.25	0	0
gravels	5	0	75	0
sands	10	0	150	300
Fine sands	20	0	300	200
mud	10	0.6	75	150

In the full complexify version of the LMO module, the piling method is a user input. In case one piling method is specified, it is assumed that every pile in the project will be installed using the specified piling method. If the specified piling method is not suitable for installing every single pile, due to differences in the soil type for each pile location, a warning will be shown to the user. In case the piling method is not specified by the user, hammering is selected as default.

The duration of installing each pile will then be calculated taking into consideration the soil type, the piling method (and consequently the vertical penetration speed of selected piling method) and the pile penetration depth.

TABLE 3.13 OPERATION REQUIREMENTS DEFINITION IN RESPECT TO PILING OPERATION

Requirement	Inputs	Function
Piling operation duration	*pile.bathymetry* *pile.soiltype* *op.method[piling]*	$piling.duration[method] = piling.speed[method, soil] \times pile.penetration$

TABLE 3.14 COMPILATION OF OPERATION METHODS PER OPERATION TYPE

Operation	Transported components	Transport methods	Load-out methods	Piling/ cable burial/landfall methods
Foundation installation	Foundations, pilling equipment	Dry/ wet	*"lift"*†; *"float"*; *"skidder"*; *"railed"*	Piling methods: *"hammering"*†; *"drilling"*; *"vibro-piling"*
Moorings installation	Moorings	Dry	*"lift"*	N/A
Support structures installation	Support structure	Dry	*"lift"*†; *"float"*; *"skidder"*; *"railed"*	N/A
Collection point installation	Collection point	Dry/ wet (floating cp)	*"lift"*†; *"float"*; *"skidder"*; *"railed"*	N/A
Export cable installation	Cable	Dry	N/A	Cable burial method: *"ploughing"*†; *"jetting"*; *"cutting"* Cable landfall:

Operation	Transported components	Transport methods	Load-out methods	Piling/ cable burial/landfall methods
				"OCT"†*; "HDD"*
Array cable installation	Cable	Dry	N/A	Cable burial method: *"ploughing"*†*; "jetting"; "cutting"*
Post-lay cable burial	Cable burial tool	Dry	*"lift"*	Cable burial method: *"ploughing"*†*; "jetting"; "cutting"*
External protection installation	Concrete mattress or rock bags	Dry	*"lift"*	N/A
Device installation	Device	Dry/ wet	*"lift"*†*; "float"; "skidder"; "railed"*	N/A
Topside inspection	N/A	N/A	N/A	N/A
Underwater inspection	ROV	Dry	N/A	N/A
Mooring inspection	N/A	Dry	N/A	N/A
Array cable inspection	ROV	Dry	N/A	N/A
Export cable inspection	ROV	Dry	N/A	N/A
Device retrieval	Device	Dry/ wet	*"lift"*	N/A
Device repair at port	N/A	NA	N/A	N/A
Device redeployment	Device	Dry/ wet	*"lift"*	N/A
Device repair on site	N/A	NA	N/A	N/A
Mooring line replacement	Mooring line	Dry	N/A	N/A
Cable replacement[14]	Cable	Dry	N/A	N/A
Cable repair	Cable	Dry	N/A	N/A
Decommissioning device	Device	Dry/ wet	N/A	N/A
Decommissioning collection point	Collection point	Dry/ wet	N/A	N/A
Decommissioning moorings	Moorings	Dry	N/A	N/A
Decommissioning foundations	Foundations	Dry	N/A	N/A

† denotes methods selected as default.

PORT TERMINAL REQUIREMENTS DEFINITION

For each operation, the operation requirements related to port terminals are defined as described in Table 3.15.

[14] It is assumed that in case of failure, array cables will be replaced, while export cables will be repaired.

TABLE 3.15 OPERATION REQUIREMENTS DEFINITION IN RESPECT TO PORT TERMINAL CAPABILITIES

Requirement	Variable	Inputs	Function
Filter according to dry-dock capabilities	*op.requirements [drydock]*	LMO	*True if op.method[load_out] =="float", else False*
Filter according to marine slipway	*op.requirements [slipway]*	LMO	*True if op.method[load_out]== "skidded" or "railed", else False*
Filter according to previous experience in MRE projects	*op.requirements [experience]*	User input	*Default: False* *options: "True"; "False"*
Filter according to sufficient area	*op.requirements [filter_term_area]*	User input	*Default: False* *options: "True"; "False"*
Filter according to terminal crane capabilities	*op.requirements [filter_term_crane]*	User input	*Default: False* *options: "True"; "False"*
Filter according to terminal quay load capabilities	*op.requirements [filter_term_load]*	User input	*Default: False* *options: "True"; "False"*
Filter according to maximum distance to site	*op.requirements [filter_max_dist]*	User input	*Default:* $op.requirement[filter\_max\_dist] = 2000000$
Port terminal draught requirements	*op.requirements [port_mindepth]*	OEC.draft_tow	*if op.transport=="wet" & op.name="device installation":* $op.requirement[port\_mindepth] = OEC.draft\_tow$
Area requirement	*op.requirements [area]*	OEC.length, OEC.width, Sub.length Sub.width	*if op.name=="device installation":* $op.requirement[area] = max(OEC.length \times OEC.width)$ *else:* $op.requirement[area] = max(sub.length \times sub.width)$
Lifting power requirement	*op.requirements [lift]*	OEC.drymass Sub.drymass	*if op.name="device installation":* $op.requirement[lift] = OEC.drymass$ *else:* $op.requirement[lift] = sub.drymass$
Quay soil load/strength requirement	*op.requirements [load]*	OEC.length, OEC.width, OEC.drymass Sub.length Sub.width Sub.drymass	*if op.name="device installation":* $op.requirement[load] = (OEC.drymass)/(1000 \times (OEC.length \times OEC.width))$ *else:* $op.requirement[load] = (sub.drymass)/(1000 \times (sub.length \times sub.width))$

EQUIPMENT REQUIREMENTS DEFINITION

For each operation, the operation requirements in terms of equipment requirements per operation type are described in Table 3.16. ROV requirements per operation type are compiled in Table 3.17.

TABLE 3.16 OPERATION REQUIREMENTS DEFINITION IN RESPECT TO EQUIPMENT CAPABILITIES

Requirement	Inputs	Function
		ROV (all)
ROV class requirement	*op.name*	*According to Table 3.17*
Maximum depth at farm	OEC.bathymetry, Sub.bathymetry	*if op.name="device installation":* $op.requirements[depth\_max] = \max(OEC.bathymetry)$ *else:* $op.requirements[depth\_max] = \max(sub.bathymetry)$
Minimum depth at farm		*if op.name="device installation":* $op.requirements[depth\_min] = \min(OEC.bathymetry)$ *else:* $op.requirements[depth\_min] = \min(sub.bathymetry)$
		DIVERS (all)
Maximum water depth	OEC.bathymetry, Sub.bathymetry	*if op.name="device installation":* $op.requirements[depth\_max] = \max(OEC.bathymetry)$ *else:* $op.requirements[depth\_max] = \max(sub.bathymetry)$
Maximum cable burial depth	Cable.bathymetry	$op.requirements[cable\_depth] = \max(cable.burial\_depth)$
		PILING EQUIPMENT (foundations installation)
Crane lift requirement	Sub.drymass	$op.requirements[lift] = sub.drymass$
Maximum depth of piles	Sub.bathymetry	$op.requirements[depth\_max] = \max(sub.bathymetry)$
Maximum penetration depth of piles	Sub.burial_depth	$op.requirements[pilling\_max] = \max(sub.burial\_depth)$
Maximum diameter of piles	Sub.diameter	$op.requirements[object\_diameter\_max] = \max(sub.diameter)$
Minimum diameter of piles		$op.requirements[object\_diameter\_min] = \min(sub.diameter)$
		BURIAL EQUIPMENT (export and array cable installation)
Maximum depth at farm location	Cable. bathymetry	$op.requirements[depth\_max] = \max(cable.bathymetry)$
Maximum cable burial depth	Cable.burial_depth	$op.requirements[cable\_depth] = \max(cable.burial\_depth)$
Maximum cable diameter	Cable.diameter	$op.requirements[cable\_diameter\_max] = \max(cable.diameter)$
Minimum cable diameter		$op.requirements[cable\_diameter\_min] = \min(cable.diameter)$
Cable minimum bending radius	Cable.mbr	$op.requirements[mbr] = \max(cable.mbr)$

TABLE 3.17 ROV TYPE REQUIREMENTS PER OPERATION TYPE.

Operation	Conditions	ROV requirements
Foundations installation	Suction caisson, with ROV (default)	Work class
	Otherwise	Inspection class
Moorings and Anchors Installation	Anchor previously installed	Work class
	Otherwise	Inspection class
Support structure installation	Always	Inspection class
Export cable installation	Wet-mate connection	Work class
	Otherwise	Inspection class
Inter-array cable installation	Wet-mate	Work class
	Otherwise	Inspection class
Collection point installation	Wet-mate connection	Work class
	Otherwise	Inspection class

Operation	Conditions	ROV requirements
Device installation	Wet-mate connection	Work class
	Always	Inspection class
Post-lay cable trenching	Always	Cable Burial ROVs
External protection installation	Always	Inspection class
Topside inspection	N/A	N/A
Underwater inspection	Always	Inspection class
Mooring inspection	Always	Inspection class
Array cable inspection	Always	Inspection class
Export cable inspection	Always	Inspection class
Device retrieval	N/A	N/A
Device repair at port	N/A	N/A
Device redeployment	N/A	N/A
Device repair on site	N/A	N/A
Mooring line replacement	Always	Inspection class
Cable replacement	Always	Inspection class
Cable repair	Always	Inspection class
Decommissioning device	Always	Inspection class
Decommissioning collection point	Always	Inspection class
Decommissioning support structure	Always	Inspection class
Decommissioning moorings	Always	Inspection class
Decommissioning foundations	Always	Inspection class

VESSEL REQUIREMENTS DEFINITION

The definition of vessel requirements is compiled as seen in Table 3.18.

TABLE 3.18 OUTPUT VESSEL REQUIREMENTS

Requirement	Inputs	Function
Area requirement	*OEC.length*, *OEC.width*, *Sub.length* *Sub.width*	*if op.name=="device installation":* $op.requirements[area] = max(OEC.length \times OEC.width)$ *else:* $op.requirements[area] = max(sub.length \times sub.width)$
Lifting power requirement	*OEC.drymass* *Sub.drymass*	*if op.name="device installation":* $op.requirements[lift] = OEC.drymass$ *else:* $op.requirements[lift] = sub.drymass$
Deck strength requirement	*OEC.drymass* *Sub.drymass* *OEC.length* *OEC.width* *Sub.length* *Sub.width*	*if op.name="device installation":* $op.requirements[load] = (OEC.drymass)/(1000 \times (OEC.length \times OEC.width))$ *else:* $op.requirements[load] = (sub.drymass)/(1000 \times (sub.length \times sub.width))$
Maximum cargo on deck	*OEC.drymass* *Sub.drymass*	*if op.name="device installation":* $op.requirements[dwat] = OEC.drymass$ *else:* $op.requirements[dwat] = sub.drymass$

Requirement	Inputs	Function
Maximum depth requirement	*OEC.bathymetry* *Sub.bathymetry*	$op.requirements[depth\_max] = \max(\text{OEC. bathymetry}, \text{Sub. bathymetry})$
Minimum depth requirement		$op.requirements[depth\_min] = \min(\text{OEC. bathymetry}, \text{Sub. bathymetry})$
Largest object requirement	*OEC.length* *OEC.base_are* *Sub.length* *Sub.base_area*	$op.requirements[largest\_object] = \max\begin{pmatrix} base\_area * length, \\ for\ every\ component \end{pmatrix}$
Vessel DP required	*op.dp*	According to Table 2.9
Turntable capacity	*Cable.diameter* *Cable.length*	*if op.name="cable installation":* $op.requirements[turn\_storage] =$ $\max\begin{pmatrix} (cable.diameter^2) \times cable.length \\ for\ every\ cable \end{pmatrix}$
Turntable storage	*Cable.drymass* *Cable.length*	*if op.name="cable installation":* $op.requirements[turn\_capacity] =$ $\max\begin{pmatrix} (cable.drymass) \times cable.length \\ for\ every\ cable \end{pmatrix}$
ROV	*op.name* *op.description*	According to Table 3.17
Number of passengers	*op.name*	*if "maintenance" in op.name:* *if "preventive" in op. name:* $op.requirements[passengers] = 2$ *else if "corrective" in op. name:* $op.requirements[passengers] = 6$

- VESSEL DP REQUIREMENTS

A vessel Dynamic Positioning (DP) requirement table was created for DTOceanPlus (see Section 2.5.4), describing the DP requirement per offshore operation. As a default, it was assumed that a DP-2 vessel requirement was necessary for any of the considered offshore operations, except for topside inspections. However, table Table 3.19 will be included in a catalogue and values may be edited by the user when running LMO.

TABLE 3.19 VESSEL DP REQUIREMENTS FOR THE OFFSHORE OPERATIONS IN DTOCEANPLUS

Phase	Operation	DP class
Installation	Foundations installation	2
	Moorings Installation	2
	Support structure installation	2
	Collection point installation	2
	Device installation	2
	Export cable installation	2
	Inter-array cable installation	2
	Post-lay cable trenching	2
	External protection installation	2

Phase	Operation	DP class
Maintenance	Topside inspection	1
	Underwater inspection	2
	Mooring inspection	2
	Array cable inspection	2
	Export cable inspection	2
	Device retrieval	2
	Device redeployment	2
	Device repair on site	2
	Mooring line replacement	2
	Array cable replacement	2
	Export cable repair	2
Decommissioning	Foundations removal	2
	Moorings removal	2
	Support structure removal	2
	Collection point removal	2
	Device removal	2

FEASIBILITY FUNCTION COMPILER

Regardless of the operation methods and requirements, port terminals and vessels will always be assessed in terms of feasibility, and consequently feasibility functions for these infrastructures will always run. However, equipment feasibility functions will only run in case the equipment has been specified as a requirement for the specific operation. This is the case of ROVs, divers, piling equipment, cable burial equipment and external protections. Table 3.20 presents all conditions to run feasibility functions.

TABLE 3.20: CONDITIONS TO RUN FEASIBILITY FUNCTIONS

Feasibility function	Conditions to be run
Vessels Combinations (VC)	Always
Terminals	Always
Vessels	Always
ROVs	$True, if\ op.requirements[\text{"}rov\text{"}]\ != \text{None}$ $False, else$
Divers	$True, if\ op.requirements[\text{"}divers\text{"}]\ != \text{None}$ $False, else$
Piling Equipment	$True, if\ op.name = \text{"foundation installation" AND "pile"}\ in\ \text{objects}$ $True, if\ op.name = \text{"support structure" AND "pile"}\ in\ \text{objects}$ $False, else$
Burial Equipment	$True, if\ op.name = \text{"cable installation" AND "simultaneous burial"}\ in\ op.description$ $True, if\ op.name = \text{"post-lay burial"}$ $False, else$
External Protection equipment	$True, if\ op.name = \text{"cable external protection"}$ $False, else$

3.3.2 INFRASTRUCTURE PRE-SELECTION

As previously described, the selection of vessels, equipment and ports for a given operation is a holistic process. Vessels, ports, and equipment are firstly individually evaluated in terms of their ability to carry out a given operation. Then, feasible vessel combinations, feasible port terminals and feasible equipment are matched and integrated into combined feasible infrastructure solutions. These combined infrastructure solutions can later on be assessed in terms of operation durations and costs, and the cost-optimal solution can be selected.

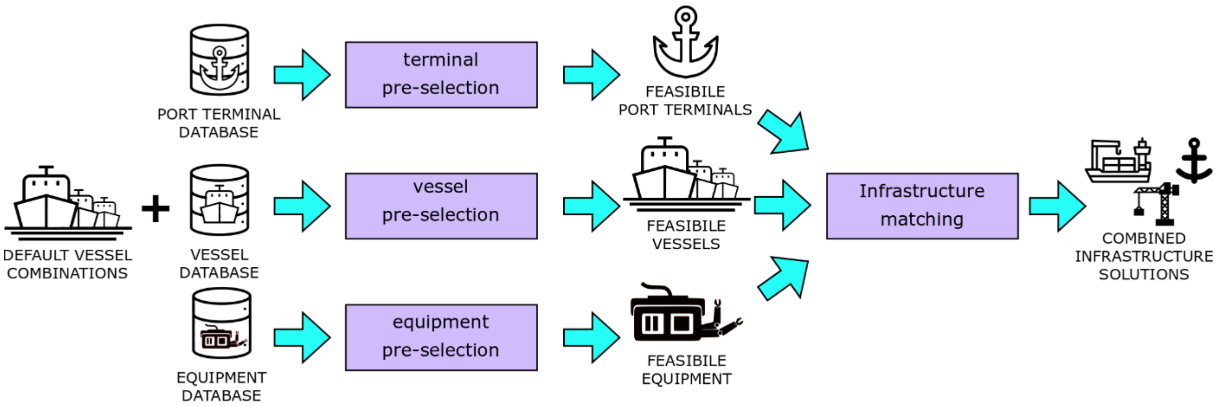


FIGURE 3.5 SCHEMATIC REPRESENTATION OF THE INFRASTRUCTURE PRE-SELECTION FUNCTIONALITY

The infrastructure pre-selection occurs at an operation level, where logical functions relate operation, component characteristics and project 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 pre-selection functions only deal with the interactions between maritime infrastructure and physical elements of the ocean energy array, the "infrastructure matching" functions verify the compatibility between each pre-selected maritime infrastructure type. The matching functions therefore ensure that no conflicts arise from selecting each combination of port/vessels/equipment together.

3.3.2.1 TERMINAL PRE-SELECTION

Port terminal pre-selection is simple: terminals listed in the terminal database are evaluated according to project and previously defined operation requirements.

In DTOceanPlus, the port terminal database is an expanded and updated version of the DTOcean database, and consists of 203 terminals and 21 parameters, namely name, type, country, location, terminal entrance width, draught, maximum load, and terminal area, to name a few.

INPUTS

The inputs of the terminal pre-selection functionality are listed in Table 3.21.

TABLE 3.21: INPUT TABLE FOR TERMINAL PRE-SELECTION FUNCTIONALITY

Variable name	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
op.requirements	Pre-configured operation requirements	LMO	Dictionary	[-]
op.methods	Pre- configured operation methods	LMO	Dictionary	[-]
terminals_database	Database with all terminals available	Catalogue	Dictionary	[-]

OUTPUTS

PORT FEASIBILITY FUNCTIONS

The main port feasibility functions are presented in Table 3.22.

TABLE 3.22 PORT FEASIBILITY FUNCTIONS

Requirement	Inputs	Function
Port maximum distance	*op.requirements[port_max_dist]* *terminal.coordinates*	$if\ terminal.distance \leq op.requirements[port\_max\ \_dist]:$ $terminal\_feasible = \mathrm{True}$ $else, terminal\_feasible = \mathrm{False}$
Relevant experience in MRE projects	*op.requirements[experience]* *terminal.past_experience*	$if\ op.requirements[experience] = \mathrm{True}:$ $if\ terminal.past\_experience = \mathrm{True}:$ $terminal\_feasible = \mathrm{True}$ $else, terminal\_feasible = \mathrm{False}$ $else, terminal\_feasible = \mathrm{True}$
Dry-dock capabilities	*op.requirements[dry_dock]* *terminal.dry_dock*	$if\ op.requirements[dry\_dock] = \mathrm{True}:$ $if\ terminal.dry\_dock = \mathrm{True}:$ $terminal\_feasible = \mathrm{True}$ $else, terminal\_feasible = \mathrm{False}$ $else, terminal\_feasible = \mathrm{True}$
Marine slipway capabilities	*op.requirements[slip]* *terminal.slipway*	$if\ op.requirements[slip] = \mathrm{True}:$ $if\ terminal.slipway = \mathrm{True}:$ $terminal\_feasible = \mathrm{True}$ $else, terminal\_feasible = \mathrm{False}$ $else, terminal\_feasible = \mathrm{True}$
Crane lifting capabilities	*op.requirements[lift]* *op.methods[load_out]* *op.methods[transport]* *terminal.gantry_lift* *terminal.tower_lift*	$if\ op.methods[load\_out] = 'lift'\ \mathbf{AND}$ $op.methods[transport] = 'wet':$ $if\ terminal.gantry\_crane \geq$ $op.requirements[lift]\ \mathbf{OR}$ $terminal.tower\_crane \geq op.requirements[lift]:$ $terminal\_feasible = \mathrm{True}$ $else, terminal\_feasible = \mathrm{False}$ $else, terminal\_feasible = \mathrm{True}$

Requirement	Inputs	Function
Area capabilities	*op.requirements[terminal_area]* *op.requirements[area]* *terminal.area*	$if\ op.requirements[terminal\_area] = \text{True}:$ $\quad if\ terminal.area \geq op.requirements[area]:$ $\quad\quad terminal\_feasible = \text{True}$ $\quad else, terminal\_feasible = \text{False}$ $else, terminal\_feasible = \text{True}$
Load capabilities	*op.requirements[terminal_load]* *op.requirements[strength]* *terminal.load*	$if\ op.requirements[terminal\_load] = \text{True}:$ $\quad if\ terminal.load \geq op.requirements[strength]:$ $\quad\quad terminal\_feasible = \text{True}$ $\quad else, terminal\_feasible = \text{False}$ $else, terminal\_feasible = \text{True}$
Port terminal draught requirements	*op.requirements[port_mindepth]*	$c\_ukc = UKC\_contigency$[15] $\times\ op.requirements[port\_mindepth]$ $if\ term.draught \geq op.requirements[depth\_min] \times u\_ukc:$ $\quad term\_feasible = \text{True}$ $else, term\_feasible = \text{False}$

3.3.2.2 EQUIPMENT PRE-SELECTION

The Logistic and Marine Operations module is responsible for selecting the required equipment to carry out a given operation. Six main types of equipment are considered in DTOceanPlus and listed in an equipment catalogue.

TABLE 3.23 EQUIPMENT TYPES

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 Bag
Piling equipment	Hammer
	Drilling Rigs
	Vibro-driving

[15] The under keel clearance (UKC) allowance is normally fixed to a minimum of 10% of the ship draft, which means that the *UKC_contigency* is fixed to 1.10. Source: https://safeshippingbc.ca/?page_id=231

The equipment selection process consists of identifying previously specified equipment needs and proposing the cheapest equipment for a given operation.

INPUTS

TABLE 3.24 INPUT TABLE FOR EQUIPMENT PRE-SELECTION FUNCTIONALITY

Variable name	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
op.requirements	Operation requirements	Operation	Dictionary	[-]
rov_database	Database with all ROVs available	Catalogue	Dictionary	[-]
divers_database	Database with all divers available	Catalogue	Dictionary	[-]
piling_database	Database with all piling equipment available	Catalogue	Dictionary	[-]
burial_database	Database with all burial equipment available	Catalogue	Dictionary	[-]

OUTPUTS

ROV AND DIVERS

The pre-selection of ROVs and divers is achieved as described in Table 3.25

TABLE 3.25 ROV AND DIVERS PRE-SELECTION FUNCTIONALITY

Requirement	Inputs	Function
ROV class	*op.requirements[rov]* *rov.class*	$if\ op.requirements[rov] = rov.class:$ $rov\_feasible = \text{True}$ $else, rov\_feasible = \text{False}$
ROV depth capabilities	*op.requirements[depth_max]* *rov.max_depth*	$if\ rov.max\_depth \geq op.requirements[depth\_max]:$ $rov\_feasible = \text{True}$ $else, rov\_feasible = \text{False}$
Divers depth capabilities	*op.requirements[depth_max]* *divers.max_depth*	$if\ divers.max\_depth \geq op.requirements[depth\_max]:$ $divers\_feasible = \text{True}$ $else, divers\_feasible = \text{False}$

PILING EQUIPMENT

The pre-selection of ROVs and divers is achieved as described in Table 3.26.

TABLE 3.26 PILING EQUIPMENT PRE-SELECTION FUNCTIONALITY

Requirement	Inputs	Function
Depth rating (m)	Maximum water depth at foundation location (m): *op.requirements[depth_max]* *piling.max_depth*	$if\ piling.max\_depth \geq op.requirements[depth\_max]$: $piling\_feasible = \text{True}$ $else, piling\_feasible = \text{False}$
	$if\ op.methods[piling] = 'hammer'$	
Equipment Type	*piling.type*	$if\ piling.type = 'hammer'$ $piling\_feasible = \text{True}$ $else, piling\_feasible = \text{False}$
Pile sleeve diameter (m)	*piling.hammer_max_diam* *piling.hammer_min_diam* *op.requirements[obj_diameter_max]* *op.requirements[obj_diameter_min]*	$if\ piling.hammer\_max\_diam \geq op.requirements[obj\_diameter\_max]$ **AND** $piling.hammer\_min\_diameter \leq op.requirements[obj\_diameter\_min]$: $piling\_feasible = \text{True}$ $else, piling\_feasible = \text{False}$
	$if\ op.methods[piling] = 'drilling'$	
Equipment Type	*piling.type*	$if\ piling.type = 'drilling'$ $piling\_feasible = \text{True}$ $else, piling\_feasible = \text{False}$
Pile sleeve diameter (m)	*piling.drilling_max_diam* *piling.drilling_min_diam* *op.requirements[obj_diameter_max]* *op.requirements[obj_diameter_min]*	$if\ piling.drilling\_max\_diam \geq op.requirements[obj\_diameter\_max]$ **AND** $piling.drilling\_min\_diameter \leq op.requirements[obj\_diameter\_min]$: $piling\_feasible = \text{True}$ $else, piling\_feasible = \text{False}$
Penetration depth (m)	*piling.drilling_max_depth* *op.requirements[piling_max]*	$if\ piling.drilling\_max\_depth \geq op.requirements[piling\_max]$: $piling\_feasible = \text{True}$ $else, piling\_feasible = \text{False}$
	$if\ op.methods[piling] = 'vibro'$	
Equipment Type	*piling.type*	$if\ piling.type = 'drilling'$ $piling\_feasible = \text{True}$ $else, piling\_feasible = \text{False}$
Pile sleeve diameter (m)	*piling.vibro_max_diam* *piling.vibro_min_diam* *op.requirements[obj_diameter_max]* *op.requirements[obj_diameter_min]*	$if\ piling.vibro\_max\_diam \geq op.requirements[obj\_diameter\_max]$ **AND** $piling.vibro\_min\_diameter \leq op.requirements[obj\_diameter\_min]$: $piling\_feasible = \text{True}$ $else, piling\_feasible = \text{False}$
Pile maximum weight (kg)	*piling.vibro_max_weight* *op.requirements[lift]*	$if\ piling.vibro\_max\_weight \geq op.requirements[lift]$: $piling\_feasible = \text{True}$ $else, piling\_feasible = \text{False}$

BURIAL EQUIPMENT

TABLE 3.27 CABLE BURIAL EQUIPMENT PRE-SELECTION FUNCTIONALITY

Requirement	Inputs	Function
Depth rating (m)	Maximum water depth of cables (m): *op.requirements[depth_max]* *burial.max_depth*	$if\ burial.max\_depth \geq op.requirements[depth\_max]$: $burial\_feasible = \text{True}$ $else, burial\_feasible = \text{False}$
Cable diameter (mm)	Maximum cable diameter (mm): *op.requirements[cable_diameter_max]* *burial.max_cable_diam*	$if\ burial.max\_cable\_diam \geq op.requirements[cable\_diameter\_max]$: $burial\_feasible = \text{True}$ $else, burial\_feasible = \text{False}$
Cable minimum bending radius (m)	Maximum minimum bending radius (m): *op.requirements[mbr]* *burial.max_cable_bend*	$if\ burial.max\_cable\_bend \geq op.requirements[mbr]$: $burial\_feasible = \text{True}$ $else, burial\_feasible = \text{False}$
$if\ op.methods[burial] = 'ploughing'$		
Ploughing capabilities	*burial.capabilities_ploughing*	$if\ burial.capabilities\_ploughing = \text{True}$ $burial\_feasible = \text{True}$ $else, burial\_feasible = \text{False}$
Ploughing depth rating (m)	*burial.max_depth_ploughing* *op.requirements[cable_depth]*	$if\ burial.max\_depth\_ploughing \geq op.requirements[cable\_depth]$ $burial\_feasible = \text{True}$ $else, burial\_feasible = \text{False}$
$if\ op.methods[burial] = 'jetting'$		
Jetting capabilities	*burial.capabilities_jetting*	$if\ burial.capabilities\_jetting = \text{True}$ $burial\_feasible = \text{True}$ $else, burial\_feasible = \text{False}$
Jetting depth rating (m)	*burial.max_depth_jetting* *op.requirements[cable_depth]*	$if\ burial.max\_depth\_jetting \geq op.requirements[cable\_depth]$ $burial\_feasible = \text{True}$ $else, burial\_feasible = \text{False}$
$if\ op.methods[burial] = 'cutting'$		
Cutting capabilities	*burial.capabilities_cutting*	$if\ burial.capabilities\_cutting = \text{True}$ $burial\_feasible = \text{True}$ $else, burial\_feasible = \text{False}$
Cutting depth rating (m)	*burial.max_depth_cutting* *op.requirements[cable_depth]*	$if\ burial.max\_depth\_cutting \geq op.requirements[cable\_depth]$ $burial\_feasible = \text{True}$ $else, burial\_feasible = \text{False}$

3.3.2.3 VESSEL PRE-SELECTION

In DTOceanPlus, the vessel pre-selection functionality consists of pre-selecting vessels that comply with the identified vessel combinations for the operation in question and that can fulfil the vessel requirements previously identified in the Operation pre-configuration feasibility.

INPUTS

TABLE 3.28 INPUT TABLE FOR VESSEL PRE-SELECTION FUNCTIONALITY

Variable name	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
vc	Vessels Combinations database	LMO	Catalogue	[-]
ve	Vessels database	LMO	Catalogue	[-]
vc_feasible	Feasible Vessel Combinations	LMO	Catalogue	[-]
ve.bollard	Vessel bollard pull capabilities	Catalogue	Float	ton
ve.LOA	Vessel Length Overall	Catalogue	Float	m
ve.beam	Vessel beam	Catalogue	Float	m
ve.draft	Vessel draft	Catalogue	Float	m
ve.free_deck	Vessel free deck area	Catalogue	Float	m^2
ve.deck_str	Vessel deck strength	Catalogue	Float	ton/m^2
ve.crane_lift	Vessel crane maximum lifting capability	Catalogue	Float	ton
ve.DP	Vessel Dynamic Positioning system rating	Catalogue	Int	[-]
ve.type	Vessel type	Catalogue	String	[-]
ve.jup_max_water	Vessel jack up maximum operational water depth	Catalogue	Float	m
ve.totalcablestorage	Vessel turntable loading capacity	Catalogue	Float	ton
ve.turn_diameter_inner	Inner diameter vessel turn table	Catalogue	Float	m
op.name	Operation name	LMO	string	[-]
op.description	Operation description	LMO	string	[-]
op.requirements	Operation requirements	LMO	Dictionary	[-]
op.requirements[dp]	DP requirements for the operation	LMO	Int	[-]
op.requirements[bp]	Required vessel bollard pull	LMO	Float	ton
op.requirements[mindepth]	Minimum water depth at site	LMO	Float	m
op.requirements[maxdepth]	Maximum water depth at site	LMO	Float	m
op.methods	Operation methods	LMO	Dictionary	[-]
numberobjectsondeck	Maximum number of items (piles, devices) on deck	LMO	Int	[-]
ve_Te	Tug efficiency. Hard coded as 0.75	LMO	Float	[-]
UK_contigency	Under keel clearance contingency, set as 10% of draft.	LMO	Float	[-]

OUTPUTS

VC FEASIBILITY

The vessel combination table is also used to firstly discard unsuitable vessel combinations that do not meet project requirements or user preferences, such as considering or not wet-tow as a possibility. For each operation, default vessel combinations are stored in the catalogues, although the user may make modifications in the GUI when running the module. Vessel types listed on the pre-selection of vessel combinations will be further evaluated in the subsequent vessel selection stage: vessel feasibility.

TABLE 3.29 VESSEL COMBINATION FEASIBILITY FUNCTIONS

Requirement	Inputs	Function
Filter by VC name	*op.name* *vc.type*	$if\ vc.type = op.name$ $vc\_feasible = \mathrm{True}$ $else, vc\_feasible = \mathrm{False}$
Filter by VC description	*op.description* *vc.description*	$if\ vc.description = op.description$ $vc\_feasible = \mathrm{True}$ $else, vc\_feasible = \mathrm{False}$
Filter by transportation method	*op.methods* *op.transport* *vc.transportation*	$if\ op.methods[transport] = 'dry':$ $if\ vc.transportation = 'on\ deck'\ \boldsymbol{OR}\ 'dry\ tow':$ $vc\_feasible = \mathrm{True}$ $else, vc\_feasible = \mathrm{False}$ $if\ op.methods[transport] = 'wet':$ $if\ vc.transportation = 'wet\ tow':$ $vc\_feasible = \mathrm{True}$ $else, vc\_feasible = \mathrm{False}$

TUG BOLLARD PULL

The required tug bollard pull is calculated following the theory described in Section 2.6.2.

TABLE 3.30 TUG BOLLARD PULL CALCULATION FUNCTIONS

Requirement	Inputs	Function
R coefficient and considered beam [m]	*op.transport* object.width[16] object.length object.height	*If ve.transport=="dry tow":* $B = ve.beam$ $h = ve.draft$ $R\_coef = 0.67$ *elseif ve.transport=="wet tow":* $B = object.width$ $d = object.length$ $h = object.height$ $R\_coef = 1.00$
Windage area [m²]	*object.width* *object.height* *no_structures*	*If ve.transport=="dry tow":* $A\_windage = (object.\mathrm{width} \times object.\mathrm{height}) \times no\_structures$ *elseif ve.transport=="wet tow":* A_windage =0
Shape Coefficient	*B (beam)* *d (length)* *h (height)*	Interpolation of Table 2.12 using the *sk.learn* library.
Wet frontal area of barge or object towed [m²]	*B* *h*	*If ve.transport=="dry tow":* $A\_wet\_frontal = B \times h$ *elseif ve.transport=="wet tow":* $A\_wet\_frontal = B \times h$

[16] Object may refer to OEC in case of a device installation operation, to pile in case of a foundation installation or (floating) substation in case of floating collection point installation.

Requirement	Inputs	Function
Drag Coefficient	*object.width* *object.height*	Interpolation of Figure 2.7Table 2.12 using the *sk.learn* library.
Wave drift load [kN]	$Hs = 5m$ $g = 9.81 m/s^2$	$f\_wave = \frac{1}{8} \cdot rho\_sw \cdot g \cdot R\_coef^2 \cdot B \cdot Hs^2 \cdot \frac{1}{1000}$
Wind load [kN]	C_shape $A\_windage$ $wind\_speed = 20\ m/s$ $rho\_air = 1.225\ kg/m^3$	$f\_wind = \frac{1}{2} \cdot C\_shape \cdot rho\_air \cdot A\_windage \cdot wind\_speed^2 \cdot \frac{1}{1000}$
Current load [kN]	*current_speed=0.5m/s* *rho_sw = 1020 kg/m³*	$f\_current = \frac{1}{2} \cdot C\_drag \cdot rho\_sw \cdot A\_wet\_frontal \cdot current\_speed^2 \cdot \frac{1}{1000}$
Total resistance force [ton]	*f_wave,* *f_current* *f_wind* $g = 9.81 m/s^2$	$f\_towline\_pull = \frac{f\_wave + f\_wind + f\_current}{g}$
Required bollard pull [ton]	*Tug_efficiency* *f_towline_pull*	$BP\_required = \frac{f\_towline\_pull}{T\_eff} * 10^{-3}$

INSTALLATION FUNCTIONS

- FOUNDATIONS, SUPPORT STRUCTURE, COLLECTION POINT AND DEVICE

Vessel feasibility functions used for pre-selecting vessels for the installation of foundations, support structures, collection points and devices are listed in Table 3.31.

TABLE 3.31 VESSEL FEASIBILITY FUNCTIONS FOR THE INSTALLATION OF FOUNDATIONS, SUPPORT STRUCTURES, COLLECTION POINTS, DEVICES, AND (CABLE) EXTERNAL PROTECTIONS

Requirement	Inputs	Function
Deck area [m²]	*op.requirements[area]* *ve.free_deck*	$if\ vessel.free\_deck \geq op.requiremnts[area]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Deck strength [t/m²]	*op.requirements[strength]* *ve.deck_str*	$if\ vessel.deck\_str \geq op.requiremnts[strength]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Crane capabilities [ton]	*op.requirements[lift]* *ve.crane_capacity*	$if\ vessel.crane\_capacity \geq op.requiremnts[lift]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Dynamic positioning	*op.requirements[dp]* *ve.dp*	$if\ vessel.dp \geq op.requiremnts[dp]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Jack-up capabilities	*op.requirements[depth_max]* Jack-up vessel legs operating depth (m): *ve.jup_capabilities*	$if\ vessel.jup\_capabilities = True$: $if\ vessel.jup\_max\_water \geq op.requirements[depth\_max]$: $vessel\_feasible = \text{True}$ $else, vesse\_feasible = \text{False}$

Requirement	Inputs	Function
	ve.jup_max_water	$else, vessel\_feasible = \text{True}$
Depth clearance [m]	*op.requirements[depth_min]* *ve.draft*	$c\_ukc = UKC\_contigency^{17} \times ve.draft$ $if\ vessel.draft * c\_ukc \leq op.requirements[depth\_min]$: $vessel\_feasible = \text{True}$ $else, vesse\_feasible = \text{False}$
ROV capabilities	*op.requirements[rov]* *vessels.rov_ready*	$if\ op.requiremnts[rov]\ is\ not\ \text{None}$: $if\ vessels.rov\_ready = \text{True}$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$ $else, vessel\_feasible = \text{True}$
Type	*vc.type* *vessel.type*	$if\ vessel.type = vc.type$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
$if\ vessel.type = 'tug'\ \textbf{OR}\ 'ahts'\ \textbf{OR}\ op.methods[transport] = 'wet'$		
Bollard pull [ton]	*ve.bollard_pull* *ve.type* *op.methods[transport]*	$if\ \ BP\_required^{18}(obejct) \leq vessel.bollard\_pull$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$

- MOORINGS INSTALLATION

Vessel feasibility functions used for pre-selecting vessels for the installation of mooring systems are listed in Table 3.32.

TABLE 3.32 VESSEL PRE-SELECTION FUNCTIONS FOR MOORING INSTALLATION

Requirement	Inputs	Function
Deck area [m²]	*op.requirements[area]* *ve.free_deck*	$if\ vessel.free\_deck \geq op.requiremnts[area]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Deck strength [t/m²]	*op.requirements[strength]* *ve.deck_str*	$if\ vessel.deck\_str \geq op.requiremnts[strength]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Crane capabilities [ton]	*op.requirements[lift]* *ve.crane_capacity*	$if\ vessel.crane\_capacity \geq op.requiremnts[lift]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Dynamic positioning	*op.requirements[dp]* *ve.dp*	$if\ vessel.dp \geq op.requiremnts[dp]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Depth clearance [m]	*op.requirements[depth_min]* *ve.draft*	$c\_ukc = UKC\_contigency \times ve.draft$ $if\ vessel.draft * c\_ukc \leq op.requirements[depth\_min]$: $vessel\_feasible = \text{True}$

[17] The under keel clearance (UKC) allowance is normally fixed to a minimum of 10% of the ship draft, which means that the *UKC_contigency* is fixed to 1.10. Source: https://safeshippingbc.ca/?page_id=231
[18] According with Table 3.30

Requirement	Inputs	Function
		$else, vesse\_feasible = \text{False}$
ROV capabilities	*op.requirements[rov]* *ve.rov_ready*	$if\ op.requiremnts[rov]\ is\ not\ \text{None}:$ $\quad if\ vessels.rov\_ready = \text{True}:$ $\quad\quad vessel\_feasible = \text{True}$ $\quad else, vessel\_feasible = \text{False}$ $else, vessel\_feasible = \text{True}$
Type	*vc.type* *ve.type*	$if\ vessel.type = vc.type:$ $\quad vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$

- EXPORT AND INTER-ARRAY CABLE INSTALLATION

Vessel feasibility functions used for pre-selecting vessels for the installation of export and inter-array cables are listed in Table 3.33.

TABLE 3.33 VESSEL PRE-SELECTION FUNCTIONS FOR EXPORT AND INTER-ARRAY CABLE INSTALLATIONS

Requirement	Inputs	Function
Deck area [m²]	*op.requirements[area]* *ve_deck*	$if\ vessel.free\_deck \geq op.requiremnts[area]:$ $\quad vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Deck strength [t/m²]	*op.requirements[strength]* *ve.deck_str*	$if\ vessel.deck\_str \geq op.requiremnts[strength]:$ $\quad vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Crane capabilities [ton]	*op.requirements[lift]* *ve.crane_capacity*	$if\ vessel.crane\_capacity \geq op.requiremnts[lift]:$ $\quad vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Dynamic positioning	*op.requirements[dp]* *ve.dp*	$if\ vessel.dp \geq op.requiremnts[dp]:$ $\quad vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Depth clearance [m]	*op.requirements[depth_min]* *ve.draft*	$c\_ukc = UKC\_contigency \times\ ve.draft$ $if\ vessel.draft * c\_ukc \leq$ $op.requiremnts[depth\_min]:$ $\quad vessel\_feasible = \text{True}$ $else, vesse\_feasible = \text{False}$
ROV capabilities	*op.requirements[rov]* *ve.rov_ready*	$if\ op.requiremnts[rov]\ is\ not\ \text{None}:$ $\quad if\ vessels.rov\_ready = \text{True}:$ $\quad\quad vessel\_feasible = \text{True}$ $\quad else, vessel\_feasible = \text{False}$ $else, vessel\_feasible = \text{True}$
Turntable capacity	*op.requirements[turn_capacity]* *ve.turn_capacity*	$if\ vessel.turn\_capacity$ $\quad\quad \geq op.requiremnts[turn\_capacity]:$ $\quad vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Turntable storage [ton]	*op.requirements[turn_storage]* *ve.turn_storage*	$if\ vessel.turn\_storage$ $\quad\quad \geq op.requiremnts[turn\_storage]:$ $\quad vessel\_feasible = \text{True}$

Requirement	Inputs	Function
		$else, vessel\_feasible = \text{False}$
Turntable inner diameter [m]	*op.requirements[mbr]* *ve.turn_diam_inner*	$if\ vessel.turn\_diam\_inner \geq 2 * op.requiremnts[mbr]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Type	*vc.type* *ve.type*	$if\ vessel.type = vc.type$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$

MAINTENANCE FUNCTIONS

Vessel feasibility functions used for pre-selecting vessels for the carrying out O&M interventions are listed in Table 3.34.

TABLE 3.34 INFRASTRUCTURE PRE-SELECTION FUNCTIONS FOR MAINTENANCE OPERATIONS

Requirement	Inputs	Function
Deck area [m²]	*op.requirements[area]* *ve.free_deck*	$if\ vessel.free\_deck \geq op.requiremnts[area]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Deck strength [t/m²]	*op.requirements[strength]* *ve.deck_str*	$if\ vessel.deck\_str \geq op.requiremnts[strength]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Crane capabilities [ton]	*op.requirements[lift]* *ve.crane_capacity*	$if\ vessel.crane\_capacity \geq op.requiremnts[lift]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Dynamic positioning	*op.requirements[dp]* *ve.dp*	$if\ vessel.dp \geq op.requiremnts[dp]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Jack-up capabilities	*op.requirements[depth_max]* Jack-up vessel legs operating depth (m): *ve.jup_capabilities* *ve.jup_max_water*	$if\ vessel.jup\_capabilities = True$: $if\ vessel.jup\_max\_water \geq op.requirements[depth\_max]$: $vessel\_feasible = \text{True}$ $else, vesse\_feasible = \text{False}$ $else, vessel\_feasible = \text{True}$
Depth clearance [m]	*op.requirements[depth_min]* *ve.draft*	$c\_ukc = UKC\_contigency \times ve.draft$ $if\ vessel.draft * c\_ukc \leq op.requirements[depth\_min]$: $vessel\_feasible = \text{True}$ $else, vesse\_feasible = \text{False}$
ROV capabilities	*op.requirements[rov]* *ve.rov_ready*	$if\ op.requiremnts[rov]\ is\ not\ \text{None}$: $if\ vessels.rov\_ready = \text{True}$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$ $else, vessel\_feasible = \text{True}$

Requirement	Inputs	Function
Turntable capacity [m³]	*op.requirements[turn_capacity]* *ve.turn_capacity*	$if\ vessel.turn\_capacity \geq op.requiremnts[turn\_capacity]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Turntable storage [ton]	*op.requirements[turn_storage]* *ve.turn_storage*	$if\ vessel.turn\_storage \geq op.requiremnts[turn\_storage]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Turntable inner diameter [m]	*op.requirements[mbr]* *ve.turn_diam_inner*	$if\ vessel.turn\_diam\_inner \geq 2 * op.requiremnts[mbr]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Type	*vc.type* *ve.type*	$if\ vessel.type = vc.type$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$

DECOMMISSIONING FUNCTIONS

Vessel feasibility functions used for pre-selecting vessels for the decommissioning operations are listed in Table 3.35.

TABLE 3.35 INFRASTRUCTURE PRE-SELECTION FUNCTIONS FOR DECOMMISSIONING OPERATIONS

Requirement	Inputs	Function
Deck area	*op.requirements[area]* *ve.free_deck*	$if\ vessel.free\_deck \geq op.requiremnts[area]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Maximum cargo on deck	*op.requirements[dwat]* *ve.dwat*	$if\ vessel.dwat \geq op.requiremnts[dwat]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Deck strength [t/m²]	*op.requirements[strength]* *ve.deck_str*	$if\ vessel.deck\_str \geq op.requiremnts[strength]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Crane capabilities	*op.requirements[lift]* *ve.crane_capacity*	$if\ vessel.crane\_capacity \geq op.requiremnts[lift]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Dynamic positioning	*op.requirements[dp]* *ve.dp*	$if\ vessel.dp \geq op.requiremnts[dp]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Jack-up capabilities	*op.requirements[depth_max]* Jack-up vessel legs operating depth (m): *ve.jup_capabilities* *ve.jup_max_water*	$if\ vessel.jup\_capabilities = True$: $if\ vessel.jup\_max\_water \geq op.requirements[depth\_max]$: $vessel\_feasible = \text{True}$ $else, vesse\_feasible = \text{False}$ $else, vessel\_feasible = \text{True}$
Depth clearance	*op.requirements[depth_min]* *ve.draft*	$c\_ukc = UKC\_contigency \times ve.draft$ $if\ vessel.draft * c\_ukc \leq op.requirements[depth\_min]$: $vessel\_feasible = \text{True}$ $else, vesse\_feasible = \text{False}$

Requirement	Inputs	Function
ROV capabilities	*op.requirements[rov]* *ve.rov_ready*	$if\ op.requiremnts[rov]\ is\ not$ None: $if\ vessels.rov\_ready =$ True: $vessel\_feasible =$ True $else, vessel\_feasible =$ False $else, vessel\_feasible =$ True
Type	*vc.type* *ve.type*	$if\ vessel.type = vc.type$: $vessel\_feasible =$ True $else, vessel\_feasible =$ False

3.3.2.4 INFRASTRUCTURE MATCHING

Once the feasible infrastructure has been pre-selected, compatibility checks can ensue to ensure that compatible vessel, equipment and port terminal solutions are produced for each operation. In Figure 3.6, a schematic representation of the infrastructure matching process is presented, where independently feasible but incompatible infrastructure solutions are discarded.

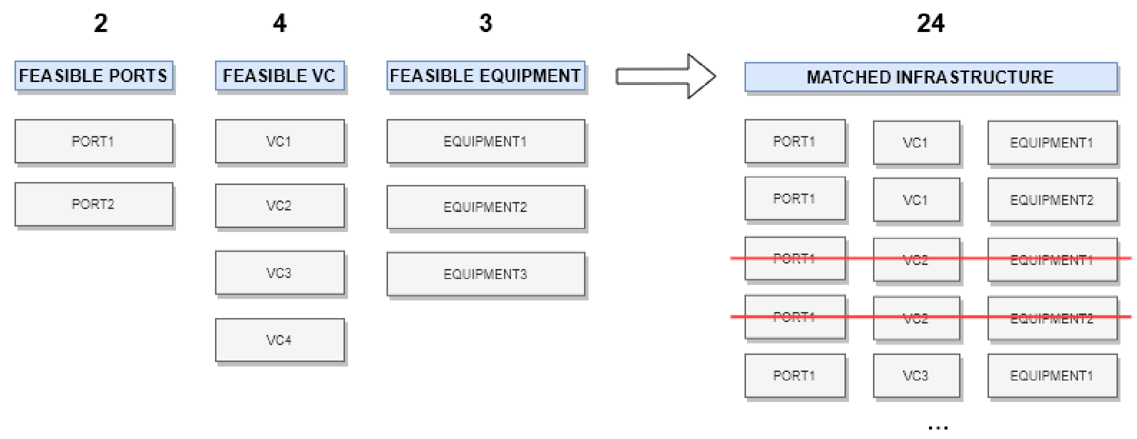


FIGURE 3.6 SCHEMATIC REPRESENTATION OF THE MATCHING OPERATING PRINCIPLE

INPUTS

TABLE 3.36: INPUT TABLE FOR THE INFRASTRUCTURE MATCHING FUNCTIONALITY

Variable name	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
feasible_solutions.vessel_main *feasible_solutions.vessel_tow* *feasible_solutions.vessel_support*	Feasible combination of vessels after pre-selection	LMO	Pandas	[-]
feasible_solutions.terminal	Feasible port terminals after pre-selection	LMO	Pandas	[-]
feasible_solutions.equip_burial *feasible_solutions.equip_piling* *feasible_solutions.equip_rov* *feasible_solutions.equip_divers*	Feasible equipment after pre-selection	LMO	Pandas	[-]

OUTPUTS

VESSEL-EQUIPMENT MATCHING FUNCTIONS

Matching functions to evaluate compatibility between pre-selected vessels and equipment are described in Table 3.27Table 3.37.

TABLE 3.37 VESSEL-EQUIPMENT MATCHING FUNCTIONALITY ACCORDING TO DEFINED REQUIREMENTS

Requirement	Inputs	Function
Vessel deck area	Mattress dimensions (m) Rock bag dimensions (m) Vessel deck space (m^2)	$deckfull == false$ $if\ ROV.exists:$ $ROV.area = ROV.width \times ROV.length$ $equipment.area = append(ROV.totalarea)$ $if\ sum(equipment.area) \geq vessel\_deck\_space$ $deckfull == True$ $if\ mattress.exists\ and\ deckfull == false:$ $mattress.maxstackedheight = np.floor(\frac{2.0}{mattress.thickness})$ $mattress.maxstackeddeckload = np.floor(\frac{max\_deck\_load}{mattress.load})$ $mattress.maxstacked$ $= \min(mattress.maxstackedheight, mattress.maxstackedload, mattress.number)$ $mattress.pilenumber = np.ceil(\frac{mattress.number}{mattress.maxstacked})$ $mattress.totalarea = mattress.pilenumber \times mattress.area$ $if\ sum(equipment.area) \geq vessel\_deck\_space$ $deckfull == True$ $equipment.area = append(mattress.totalarea)$ $if\ sum(equipment.area) \leq vessel\_deck\_space$ $if\ rockbags.exists:$ $rockbags.maxstackedheight = np.floor\left(\frac{2.0}{rockbags.thickness}\right)$ $rockbags.maxstackeddeckload = np.floor(\frac{max\_deck\_load}{mattress.load})$ $rockbags.maxstacked$ $= \min(rockbags.maxstackedheight, rockbags.maxstackedload, rockbags.number)$ $rockbags.pilenumber = np.ceil(\frac{rockbags.number}{rockbags.maxstacked})$ $rockbags.totalarea = mattress.pilenumber \times mattress.area$ $equipment.area = append(rockbags.totalarea)$ $sum(equipment.area) \leq vessel\_deck\_space$
Vessel max cargo	Vessel max cargo (t), Mattress mass (t) Rock bag mass (t)	$equipment.mass$ $= mattress.number \times mattress.mass$ $+ rockbag.number \times rockbag.mass + ROV.mass$ $sum(equipment.mass) \leq vessel\_max\_cargo$

Requirement	Inputs	Function
Max Deck Load [t/m²]	Mattress dimensions (m), Mattress mass (t) Rock bag dimensions (m), Rock bag mass (t) Max Deck Load (t/m²)	$if\ mattress.exists:$ $\frac{mattress.maxstacked \times mattress.mass}{mattress.area} \leq max\_deck\_load$ $if\ rockbags.exists:$ $\frac{rockbags.maxstacked \times rockbags.mass}{rockbags.area} \leq max\_deck\_load$ $if\ ROV.exists:$ $\frac{ROV.mass}{ROV.area} \leq max\_deck\_load$
Vessel Lift capabilities	Mattress mass (t) Rock bag mass (t) Max crane lift (t),	$mattress.mass \leq max\_crane\_lift$ $rockbag.mass \leq max\_crane\_lift$ $ROV.mass \leq max\_crane\_lift$

TERMINAL-VESSEL MATCHING FUNCTIONS

TABLE 3.38 TERMINAL-VESSEL MATCHING FUNCTIONS ACCORDING TO DIFFERENT REQUIREMENTS

Requirement	Inputs	Function
Port terminal depth capabilities	Device dimensions, Vessel dimensions	$c\_ukc = UKC\_contigency \times ve.draft$ $if\ op.transport = "dry":$ $ve.draft * c\_ukc \leq term.draught$
Port terminal entrance width	Terminal width, Device dimensions, Vessel dimensions	$\max(ve.\_beam) \leq term.width$
Terminal Quay length	Terminal data Vessel data	$term.length \geq ve.LOA$
Ability to accommodate Jack Up vessel	Port suitability for jack-up (-) Vessel type (-)	$if\ ve.type == \text{"jack up"}:$ $term.jackupsuitable == True$

3.3.3 OPERATION COMPUTATION

3.3.3.1 ACTIVITY SEQUENCE DEFINITION

Once feasible port-vessel-equipment solutions have been identified, it is now necessary to define the activity sequence, which include the number of trips to port taking into consideration the number of components to transport, their dimensions and the vessel deck area.

INPUTS

TABLE 3.39: INPUT TABLE FOR ACTIVITY SEQUENCE DEFINITION FUNCTIONALITY

Variable name	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
graph_map	Graph representing distances by sea	LMO	NetworkX.Graph	[-]
Farm_coord_UTM	Site coordinates in UTM	SC	Dictionary	[-]
Activities database	Database with all operations possible activities	Catalogues		[-]
op.devices	Devices to install/maintain/decommission in this operation	LMO	List	[-]
op.sub	Sub-components to install/maintain/decommission in this operation	LMO	List	[-]
op.cables	Cables to install/maintain in this operation	LMO	List	[-]
op.methods	Operations methods	LMO	Dictionary	[-]
op.requirements	Operation requirements	LMO	Dictionary	[-]

The activity sequence definition is divided in two steps:

- Finding a port-site route;
- Identifying and defining activities to be preform for a given set of possible activities.

PORT-SITE ROUTE FINDER

Vessel routes were defined considering the A* (A-star) algorithm. This algorithm is commonly employed to find the shortest path between two given points in space due to its computation speed in this specific scenario [55].

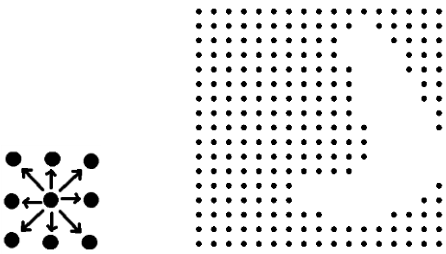


FIGURE 3.7 NODE WEIGHTING (LEFT) AND LAND REPRESENTATION (RIGHT).

A map of Europe was generated using a python tool denominated "Basemap" from the Matplotlib library[56], where land and water areas are identified. Based on this map, a python graph using

NetworkX python library [57] was generated in order to run the A* algorithm. A graph[19] with one million nodes (1000x1000) was created, where each node represents a geographical point. To represent distances, edges between nodes were created.

Each node only has connections to adjacent nodes, and weights are attributed to each node's edges corresponding to the distance that they represent in the globe. Land areas are considered obstacles and therefore land were deleted (see Figure 3.7). Once the NetworkX graph is created, the A* algorithm (implemented in NetworkX library) is run and the shortest path from site to terminal is achieved.

For example, considering the unreal case with a site in Greek coast and a port in the Baltic sea, the vessel route given by the algorithm would be the one presented in Figure 3.8.

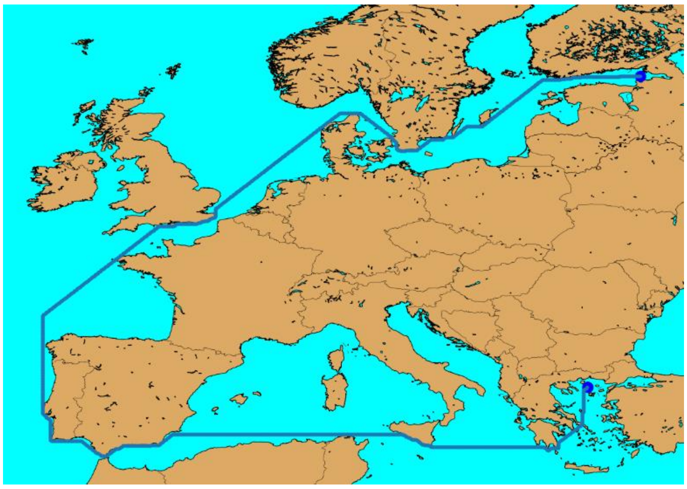


FIGURE 3.8 VESSEL ROUTE EXTREME EXAMPLE FOR DEMONSTRATION PURPOSES.

ACTIVITY SEQUENCE DEFINER

A logistic operation is subdivided in logistical activities. An activity is characterised by:

- *id* – activity unique identification number;
- *name* – activity summary description;
- *duration* – duration (in hours) of the activity;
- *OLC* – operation limit criteria. Limit wave height (Hs), wave peak period (Tp), wind speed (Ws) and current speed (Cs)
- *location* – where the activity takes place: Mobilization, Port or Sea.

The *duration* attribute may be fixed or dynamic. It is fixed for activities with a constant duration such as "positioning", and variable for durations that depend on speed (e.g. transit).

[19] Note: Europe's graph representation is saved as a pickle file in order to reduce the computation effort of creating the graph.

Since an operation have multiple manners to be accomplished, for each logistic operation, a Flowchart was design. All the activities that may occur for a given operation, are contemplated in the flowchart. An example of a flowchart is presented in Figure 3.9.

Besides activities, the flowchart also depicts certain conditions (static and dynamic) that will decide if the operation should follow one path or another.

- *static conditions* – when the operation is defined, these conditions are already "known" since it is related to the operation methods, requirements and components design.
- *dynamic conditions* – these conditions vary since they are related with the number of components at quay or on deck at the time of evaluation of the condition.

To turn flowcharts code "readable", spreadsheets representing them were elaborated (see Table 3.40).

For activities, each row should have: *id*, *name*, *op_id*, *next_activity*, *duration* (or *speed)*, OLCs and *location*. If the no OLC is defined the activity will have no weather restrictions and, if *next_activity* is empty that activity will be considered as the last activity of that operation.

For conditions, all the above columns should be filled with exception for *duration/speed*, OLCs and *location* and column *next_activity* should contain all possible next activities separated by a semicolon (A1;A2;A3). An extra column called *options* must not be empty: this column defines the options that are considered and evaluated.

Using Figure 3.9 and Table 3.40 as an example to give a picture of what is described above. If, at a certain point, condition "cond_methods:foo" is to be evaluated and "foo" method is "method1" (*op.methods['foo'] = method1*) the activity after "Transit to site" will be "Install component method 1".

These tables are stored as a catalogue of activities.

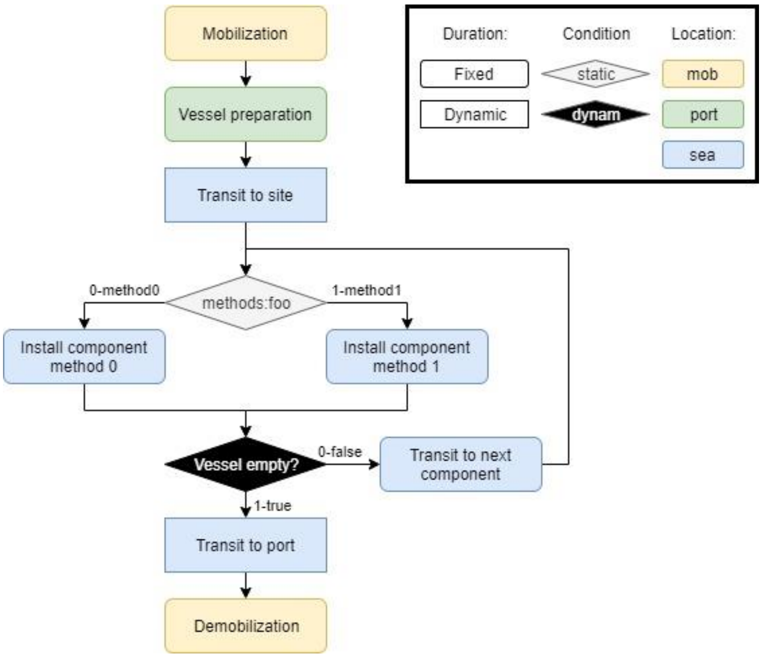


FIGURE 3.9 EXAMPLE OF AN OPERATION FLOWCHART.

TABLE 3.40 FLOWCHART REPRESENTED AS A SPREADSHEET.

ID	Name	Op ID	Next activity	Duration	Speed	Hs	Tp	Ws	Cs	Location	Options
OP01_A1	Mobilization	OP01	OP01_A2	24	-	-	-	-	-	mob	
OP01_A2	Vessel preparation	OP01	OP01_A3	8	-	-	-	-	-	port	
OP01_A3	Transit to site	OP01	OP01_C1		transit	3.0	18	-	-	sea	
OP01_C1	**cond**_methods: foo	OP01	OP01_A4;OP01_A5								0-method0; 1-method1
OP01_A4	Install component method 0	OP01	OP01_D1	4	-	2.0	-	12.5	-	sea	
OP01_A5	Install component method 1	OP01	OP01_D1	3	-	2.0	-	-	1.2	sea	
OP01_D1	**dynam**_vessel empty?	OP01	OP01_A6; OP01_A7								0-false; 1-true
OP01_A6	Transit to next component	OP01	OP01_C1	0.2	-	3.0	18	-	-	sea	
OP01_A7	Transit to port	OP01	OP01_A7		transit	3.0	18	-	-	sea	
OP01_A7	Demobilization	OP01		24	-	-	-	-	-	mob	

OUTPUTS

The output is simply a list with all the activities to be performed, excluding conditions. For example, for the installation of two floating devices, the activities list could be:

TABLE 3.41: EXAMPLE OF LIST OF ACTIVITIES FOR THE INSTALLATION OF PILES

Activity ID	Activity name	Duration [h]	OLC [Hs, Tp, Ws, Cs]
OP05_A0	Mobilisation	48.0	[-, -, -, -]
T_A4_1	Lift item from the quay to the water	2.0	[-, -, 12.5, -]
T_A9_1	Item towed on site	20.6	[1.5, 15, -, -]
OP05_A1_1	Vessel positioning	1.0	[2.5, -, -, -]
OP05_A3_1	Connection to mooring	2.0	[1.5, 12, -, -]
OP05_A19_1	Transit from site to port	5.1	[3.0, 20, -, -]
T_A4_2	Lift item from the quay to the water	2.0	[-, -, 12.5, -]
T_A9_2	Item towed on site	20.6	[1.5, 15, -, -]
OP05_A1_2	Vessel positioning	1.0	[2.5, -, -, -]
OP05_A3_2	Connection to mooring	2.0	[1.5, 12, -, -]
OP05_A19_2	Transit from site to port	5.1	[-, -, -, -]
OP05_A20	Demobilisation	48.0	[-, -, -, -]

3.3.3.2 OPERATION DURATION AND WAITING ON WEATHER

Once the exact sequence of activities has been defined for a given operation, featuring the transits to port and detailing the net durations and weather restrictions, the operation duration and waiting on weather contingencies may be estimated using the method described in Section 2.7.

At this stage, the algorithm has not yet defined the dates of each operation and for that reason, the algorithm estimates the expected operation duration and waiting on weather for all twelve months of the year. Later, the list of durations for each month will be used when assembling the operation plan in the operation calendarization functionality.

INPUTS

The following inputs, compiled in Table 3.42, are required to enable calculation of operation duration and WoW

TABLE 3.42 INPUT TABLE FOR OPERATION DURATION AND WAITING ON WEATHER CALCULATIONS

Variable name	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
metocean_timeseries	Met-ocean timeseries	SC	Dictionary	[m,s,m/s,m/s]
installation.solution_list	Installation operations solution, including infrastructure and operation durations	LMO	Dictionary	[-]
maintenance.solution_list	Maintenance operations solution, including infrastructure and operation durations	LMO	Dictionary	[-]
decom.solution_list	Decommissioning solution, including infrastructure and operation durations	LMO	Dictionary	[-]

OUTPUTS

The following outputs are produced by the algorithm in respect to the operation duration.

TABLE 3.43 OUTPUTS OF THE OPERATION COMPUTATION FUNCTIONALITY

Variable name	Description of the Input Quantity	Data Model	Units
op.dur_p50	Array of expected operation durations including WOW for the twelve months of the year.	List	[h,h,h,h,...,h]
op.dur_p25	Array of expected operation durations including WOW for the twelve months of the year.	List	[h,h,h,h,...,h]
op.dur_p75	Array of expected operation durations including WOW for the twelve months of the year.	List	[h,h,h,h,...,h]
op.wow_p50	Array of expected WOW for the twelve months of the year.	List	[h,h,h,h,...,h]
op.wow_p25	Array of expected WOW for the twelve months of the year.	List	[h,h,h,h,...,h]
op.wow_p75	Array of expected WOW for the twelve months of the year.	List	[h,h,h,h,...,h]

3.3.3.3 VESSEL FUEL CONSUMPTION AND CHARTER COSTS

Based on the selected infrastructure and estimated operation durations including weather contingencies, the operation costs can be calculated for each potential solution.

INPUTS

TABLE 3.44 INPUT TABLE FOR CORE FUNCTIONALITY

Variable name	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
mdo_price	Price of the Marine Diesel Oil fuel. Default: 515€/ton [58]	Catalogue	Float	€/ton
SFOC	Specific Fuel Oil Consumption. Default: 210 g/kWh	LMO	Float	g/kWh
ALF	Vessel average load factor throughout operation. Default: 0.8	LMO	Float	[-]
ve.type	Type of vessel	Catalogue	String	[-]
ve.TIP	Vessel Total Installed Power	Catalogue	Float	kW
ve.LOA	Vessel Length Overall	Catalogue	Float	m
ve.bollard	Vessel Bollard Pull	Catalogue	Float	ton
ve.turn_storage	Vessel turntable storage	Catalogue	Float	ton
ve.service_speed	Vessel service speed	Catalogue	Float	knots
ve.beam	Vessel beam/width	Catalogue	Float	m
ve.draft	Vessel draft	Catalogue	Float	m
ve.crane_capacity	Vessel crane lifting capacity	Catalogue	Float	ton
ve.free_deck	Vessel deck area	Catalogue	Float	m^2
ve.rock_capacity	Vessel rock carrying capacity	Catalogue	Float	ton
ve.passengers	Vessel maximum number of passengers	Catalogue	Int	[-]
op.duration	Operation duration	LMO	Int	hours

OUTPUTS

VESSEL FUEL CONSUMPTION DAILY CONSUMPTION

The daily fuel consumption of vessel ve in tons/hour can be calculated as:

$$ve.fuel\_cons\_daiily = \text{ve}.TIP \times ALF \times 24 \times SFOC \times \left(\frac{1}{1000^2}\right) \quad (20)$$

VESSEL FUEL DAILY COSTS

The hourly fuel costs of vessel ve, in Euros/hour, can be calculated as follows:

$$ve.fuel\_costs\_hourly = ve.fuel\_cons\_daily \times mdo\_price \quad (21)$$

VESSEL DAILY CHARTING COSTS

Based on the analysis described in Section 2.5.6.1, average daily vessel charter rates for different vessel types were derived through a regressive analysis of data from previous projects, and the output was compiled in Table 3.45.

TABLE 3.45 VESSEL DAILY CHARTER RATE COSTS IN EUROS

Vessel type	Input Parameter	Domain validity	Function
Tug	Bollard Pull (tonnes)	$13 \leq x < 25$	$chart\_costs = 151.34x - 467.47$
		$25 \leq x < 70$	$chart\_costs = 2.18x + 3261.61$
		$70 \leq x \leq 80$	$chart\_costs = 508.57x - 32186$
Multicat	LOA (m)	$21 \leq x < 28$	$chart\_costs = 63.23x + 1812.4$
		$28 \leq x < 35$	$chart\_costs = 916.74x - 22086$
		$35 \leq x \leq 42$	$chart\_costs = 10000$
AHTS	Bollard Pull (tonnes)	$70 < x \leq 338$	$chart\_costs = -8.3 \times 10^{-3}\, x^2 + 114.90\, x - 261.87$
CLV	Total cable storage (ton)	$565 \leq x \leq 10000$	$chart\_costs = 2.46 \times 10^{-4}\, x^2 + 7.25\, x + 53090$
CTV	LOA (m)	$15 \leq x \leq 33$	$chart\_costs = -1.26\, x^2 + 179.16\, x - 85.57$
DSV	LOA (m)	$35 \leq x \leq 150$	$chart\_costs = 4308.81\exp(0.02x)$
Guard Vessel	Service speed (knots)	$7 \leq x \leq 24$	$chart\_costs = 77.11x + 1345.48$
Non-propelled Transport Barge	Barge dimensions $(L \times B \times D)$	$1557 \leq x \leq 19950$	$x = ve.LOA \times ve.beam \times ve.draft$ $chart\_costs = 953.92\log(x) - 6761.18$
Jack up vessel	Crane lift capacity (tonnes)	$50 \leq x < 755$	$chart\_costs = 64.71x + 21448.41$
		$755 \leq x < 896$	$chart\_costs = 586.18x - 372275$
		$896 \leq x \leq 4400$	$chart\_costs = 26.83x + 128892$
Non-propelled crane vessel	Crane lift capacity (tonnes)	$4 \leq x \leq 3300$	$chart\_costs = -5.44 \times 10^{-3}\, x^2 + 64.41x - 6974.10$
Propelled crane vessel	Crane lift capacity (tonnes)	$4 \leq x < 500$	$chart\_costs = 26.15x + 5842.59$
		$500 \leq x < 1500$	$chart\_costs = 56.33x - 9254.94$
		$1500 \leq x < 3300$	$chart\_costs = 42.24x + 11871.96$

Vessel type	Input Parameter	Domain validity	Function
PSV	Free Deck Space (m²)	$30 \le x \le 5005$	$chart\_costs = 1.01x + 8970$
Rock Dumper	Stone cargo capacity (tonnes)	$5400 \le x \le 69212$	$chart\_costs = 3.99x + 69212.41$
SOV Accommodation	Number of passengers	$x < 60$	$chart\_costs = 12000$
		$x \ge 60$	$chart\_costs = 20000$
SOV with gangway	Number of passengers	$x < 60$	$chart\_costs = 24000$
		$x \ge 60$	$chart\_costs = 50000$
SOV gangway relevant	Number of passengers	$x < 60$	$chart\_costs = 24000$
		$x \ge 60$	$chart\_costs = 42000$
Survey vessel	LOA (m)	$23 \le x \le 56$	$chart\_costs = 333.33x - 4166.67$

OPERATION VESSEL COSTS

The total vessel cost can be calculated as follows:

$$op.vessel\_costs = \frac{op.duration}{24} \times \left(\sum_{ve}^{nvessels} ve.fuel\_costs\_daily + ve.chart\_costs \right) \quad (22)$$

3.3.3.4 EQUIPMENT COSTS

The equipment costs associated with a given operation are simply calculated by multiplying the operation duration by the sum of the daily renting cost of every equipment used in that operation.

INPUTS

TABLE 3.46 INPUT TABLE FOR CALCULATING EQUIPMENT COSTS

Variable name	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
equip.dailycosts	Equipment daily costs featured in equipment catalogue	Catalogue	[-]	€
equip.halfdaycosts	Equipment half daily costs featured in equipment catalogue	Catalogue	[-]	€
op.duration	Duration of the operation	LMO	Float	h
op.equipment	List of equipment IDs used during the operation	LMO	List of strings	[-]

OUTPUTS

The total equipment costs associated with a given operation can be calculated as follows:

$$op\_days = \begin{cases} ceil(op.duration), if\ (op.duration/24)\ \%\ 1 > 0.5 \\ int(op.duration), if\ (op.duration/24)\ \%\ 1 \le 0.5 \end{cases} \quad (23)$$

$$op\_half\_days = \begin{cases} 0, if\ (op.duration/24)\ \%\ 1 > 0.5 \\ 1, if\ (op.duration/24)\ \%\ 1 \leq 0.5 \end{cases}$$

$$op.equip\_cost = op\_days \times \sum_{i=1}^{N} equip.dailycosts[i] + op\_half\_days \times \sum_{i=1}^{N} equip.halfdaycosts[i]$$

3.3.3.5 SPARE PART COSTS

After component failure, the cost of the replacement component can be calculated taking as reference the costs of a new component, as defined in the Bill of Materials (BOM).

INPUTS

TABLE 3.47 INPUT REQUIREMENTS FOR CALCULATING THE SPARE PART COSTS

Variable name	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
BOM.ET	Bill of materials of Energy Transformation components	ET	Pandas	[-]
BOM.ED	Bill of materials of Energy Delivery components	ED	Pandas	[-]
BOM.SK	Bill of materials of Station Keeping components	SK	Pandas	[-]

OUTPUTS

- **COLLECTION POINT REPLACEMENT**

In case of failure, the collection point will be replaced. The main components of an offshore substation/hub are: transformer and switchgear. Given that the transformer accounts for about 86% of the total costs[59], it is possible to assume conservatively that the cost of collection point replacement will be equal to the total cost of the collection point as defined in the Bill of Materials.

$$op.replace\_costs = BOM\_ED.collection\_point \quad (24)$$

- **ARRAY CABLE REPLACEMENT**

In case of array cable failure, an experience in offshore wind projects has shown to be general practice to simply replace the array cable by a new one. In this sense, the cost of the array cable would be the same as shown in the Bill of Materials.

$$op.replace\_costs = BOM\_ED.array\_cable\_cost \quad (25)$$

- **EXPORT CABLE REPAIR**

When it comes to export cable failure, it is common practice to repair the cable which consists of cutting the damaged cable segment and replacing by a new cable segment. In this sense, it becomes necessary to estimate cable length.

The spare cable segment length should include twice the water depth, additional length to establish catenary lines, sufficient length to board the vessel before cable gantries, length to cut away during jointing, as well as safety margins [60]. For simplicity, cable replacement length, in m, can be estimated as follows:

$$cable.replace\_length = 2 \times cable.bathymetry + 20 \tag{26}$$

$$cable.replace\_costs = cable.replace\_length \times BOM\_ED.transmission\_costs \tag{27}$$

- **DEVICE REPAIR (PTO SUB-COMPONENT REPLACEMENT)**

As designed by the ET module, PTOs are comprised of three components: the mechanical transformation system (MechT), the electrical transformation unit (ElectT) and grid conditioning unit (GridC), which may fail independently. When one of these components fail, the replacement costs are calculated as follows:

$$op.replace\_costs[MechT] = BOM\_ET.MechT.costs \tag{28}$$

$$op.replace\_costs[ElectT] = BOM\_ET.ElectT.costs \tag{29}$$

$$op.replace\_costs[GridC] = BOM\_ET.GridC.costs \tag{30}$$

- **MOORING LINE REPLACEMENT**

In case of mooring line failure, it is assumed that the failed mooring line is replaced. The mooring line replacement part costs are simply based on the costs listed in the BOM.

$$op.replace\_costs[mooring] = BOM\_SK.mooring\_costs \tag{31}$$

3.3.3.6 PORT COSTS

The costs associated with port expenses are port specific and greatly vary according to type of contract, contract duration, leased storage area and equipment such as cranes. However, these costs are relatively small when compared to the total vessel costs. It has been found in the literature that expenditures associated with ports on average amount to about 0.5% of the total costs of offshore wind projects[57]. Based on this assumption, the port costs associated with a given operation are estimated as follows:

$$op.port\_costs = \frac{op.vessel\_costs + op.equip\_costs + op.sparepart\_costs}{199} \tag{32}$$

3.3.3.7 OPERATION COSTS AND FUEL

OPERATION TOTAL COSTS

The total costs of operation opx can be calculated as follows:

$$op.totalcosts = op.vessel\_costs + op.equip\_costs + op.port\_costs + op.sparepart\_costs \quad (33)$$

TOTAL OPERATION FUEL CONSUMPTION

The total fuel consumption in a given operation can be calculated as:

$$op.fuel\_cons = \frac{op.duration}{24} \times \sum_{ve}^{number\_vessels} ve.fuel\_cons\_daily \quad (34)$$

3.3.4 OPERATION CALENDARIZATION

Once the optimal solutions for each operation has been selected, the operation calendarization functionality is responsible for taking the optimal operation solutions previously computed and scheduling them on the project calendar. The outputs of this functionality slightly differ according to project lifecycle phase.

3.3.4.1 INSTALLATION

For the installation phase, based on the project start date specified by the user, the algorithm will schedule the installation operations according to the previously defined sequence and previously calculated durations and waiting on weather. In the end, the code will output a Gantt chart, featuring the optimal installation operations.

INPUTS

TABLE 3.48 INPUT TABLE FOR THE OPERATION CALENDARIZATION OF THE INSTALLATION PHASE

ID	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
Installation.operations	Sequence of optimal operations	LMO	List of Operation	[-]
proj_start_date	Project start date	User	String	DD/MM/YY

OUTPUTS

DEFINE OPERATION DATES

Based on the user specified project start date, the algorithm reads the expected operation duration of the first operation including WOW and schedules it. The algorithm then iteratively schedules each operation, taking into consideration the operation precedence rules and the month in which the operation is being scheduled.

TABLE 3.49 INSTALLATION OPERATION CALENDARIZATION

Dates	Inputs	Function
Start date operation 1	*Proj_start_date* *Installation.op[1].wow*	*Installation.op[1].start = Proj_start_date + Installation.op[1].wow[month]*
End date of operation 1	*Proj_start_date* *Installation.op[1].tot_dur*	*Installation.op[1].end = Proj_start_date + Installation.op[1].tot_dur[month]*
Start date of operation 2	*Installation.op[1].end* *Installation.op[2].wow*	*Installation.op[2].start = Installation.op[1].end + Installation.op[2].wow[month]*
End date of operation 2	*Installation.op[1].end* *Installation.op[2].tot_dur*	*Installation.op[2].end = Installation.op[1].end + Installation.op[2].tot_dur[month]*
Start date of operation n	*Installation.op[n-1].end* *Installation.op[n].wow*	*Installation.op[n].start = Installation.op[n-1].end + Installation.op[n].wow[month]*
End date of operation n	*Installation.op[n-1].end* *Installation.op[n].tot_dur*	*Installation.op[n].end = Installation.op[n-1].end + Installation.op[n].tot_dur[month]*

- **TOTAL INSTALLATION COSTS**

The total installation costs can be calculated as follows:

$$cost\_inst = \sum_{op=1}^{n\_op\_installation} op.costs \quad (35)$$

- **TOTAL INSTALLATION DURATION PER KW**

The total installation duration in hours per installed power can be calculated as follows.

$$installation.dur\_perkw = installation.duration/farm\_total\_power \quad (36)$$

3.3.4.2 MAINTENANCE

For the O&M phase, preventive and corrective maintenance interventions are scheduled based on periodicity requirements and failure events, respectively. Failure events are generated using a RAMS shared function, as described in [50]. In the end, the algorithm outputs operation dates, as well as downtime throughout project lifetime.

INPUTS

TABLE 3.50 INPUT TABLE FOR THE OPERATION CALENDARIZATION OF THE O&M PHASE

ID	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
hierarchy_et	Hierarchy datafile from the energy transformation system	ET	Pandas	[-]

ID	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
hierarchy_ed	Hierarchy datafile from the energy delivery system	ED	Pandas	[-]
hierarchy_sk	Hierarchy datafile from the station keeping system	SK	Pandas	[-]
maint.operations	Sequence of optimal operations	LMO	List of objects	[-]
maint.periodicity	Periodicity of preventive maintenance interventions per type	Catalogue	List of integrals	[h,h,h,..]
activity_durations	Durations of single maintenance activities	Catalogue	List of integrals	[h,h,h,..]
proj_start_date	Project start date	User	String	DD/MM/YY
proj_lifetime	Project lifetime (e.g. 20 years)	User	Int	Years
hierarchy_ET	Hierarchy of Energy Transformation components	ET	Pandas	[-]
hierarchy_ED	Hierarchy from Energy Delivery components	ED	Pandas	[-]
hierarchy_SK	Hierarchy from Station Keeping components	SK	Pandas	[-]
proj_com_date	Project commissioning date, or end date of the installation phase.	LMO	String	DD/MM/YY

OUTPUTS

DEFINE PREVENTIVE MAINTENANCE DATES

Preventive maintenance interventions are scheduled taking into consideration the commissioning date of the project (which is assumed to be the end date of the installation phase), and the periodicity requirements defined in the catalogue for each preventive maintenance type.

The algorithm assumes that preventive maintenance interventions would be planned for the best months of the year, while preventing that the maximum time interval between two consecutive interventions does not exceed the periodicity defined in the operations catalogue.

TABLE 3.51 PREVENTIVE MAINTENANCE INTERVENTIONS CALENDARIZATION

Requirement	Inputs	Function
Preventive operation date	*op.list,* *maint.type* *maint.periodicity* *proj_com_date*	*If first maintenance intervention:* *op.max_date[n]=proj_com_date+ maint.periodicity* *else:* *op.max_date[n]=op.end_date[n-1]+ maint.periodicity*

CALENDARISE FAILURES AND CORRECTIVE MAINTENANCE INTERVENTION DATES

Using a shared function from the RAMS module, a list of time to failures (TTF) in hours can be produced for each component of the farm, listed in the hierarchy. This list corresponds to the number of operating hours until component failure occurs. However, in case failure occurs, the time only restarts counting after the component has been serviced. This means that the length of time from the component failure until the moment where the component has been repaired has to be added to the

TTF value in order to correctly estimate the operating lifetime. This function is described in full detail in deliverable D6.3 RAMS – alpha version [50].

TABLE 3.52 CORRECTIVE MAINTENANCE INTERVENTIONS CALENDARIZATION

Requirement	Inputs	Function
Time to Failures disregarding maintenance	*hierarchy_et* *hierarchy_ed* *hierarchy_sk* *component_id*	*TTF[component_id] = [1000, 3500, 5000,…] in hours*
Maintenance intervention end date	*TTF, op.duration*[20]*[month]*	*op.end_date = op.may_start + op.duration[month]*
Time to failures taking into consideration maintenance events	*TTF_updated[component_id]*	*TTF_updated[component_id]=TTF[component_id]+op.duration*

As for all operations, the timeline of a corrective maintenance intervention is characterised by three dates. The first date corresponds to the time when the operation may start. Currently it is assumed, that this date corresponds to the moment of failure (instant failure detection, e.g. through online monitoring). The actual start date is set later and includes a statistical delay due to adverse metocean conditions (waiting on weather). The end date then is determined by adding the net operation duration to the actual start date, also seen in Table 3.52.

DONWTIME ESTIMATION

Failure events may generate downtime, periods of time where one or multiple devices cannot deliver their energy to de grid, until the failure is resolved. On the other hand, some preventive maintenance interventions may require shutting down the device for safety reasons, which would also result in downtime. Based on the simulated failure events and preventive and corrective maintenance interventions scheduled, downtime can be calculated with the Energy Production Tree concept, explained in Section 2.8.2, for each time step:

$$EPT[OECx] = hierarchy[SKx] \times hierarchy[EDx] \times hierarchy[PTOx] \times hierarchy[ETx] \tag{37}$$

Based on the previously defined failure events and maintenance operation dates, the energy production capability of each device will be assessed. In case the component failure or maintenance has no impact on the device's ability to produce and deliver its energy, the EPT will take a value equal to one and no downtime will be registered for that device. In the end, for each device, the number of downtime hours will be stored per month per year in a pandas dataframe.

[20] The Operations duration, as described in Section 2.7 and then in Section 3.3.3.2, include net duration and the waiting on weather contingency.

TOTAL MAINTENANCE COSTS

The total maintenance costs are calculated as the sum of all maintenance interventions scheduled throughout project lifetime.

$$cost\_maintenance = \sum_{op=1}^{n\_op\_maintenance} op.costs \tag{38}$$

TOTAL MAINTENANCE DURATION PER KW PER YEAR

The total maintenance duration in hours per installed power per year can be calculated as follows:

$$maintenance.dur\_perkwperyear = maintenance.totduration/farm\_total\_power \tag{39}$$

3.3.4.3 DECOMMISSIONING

For the decommissioning phase, the dismantling operations are scheduled taking into consideration the user specified project lifetime as well as the optimal decommissioning operation solutions previously calculated. Table 3.53 presents some of the inputs required.

INPUTS

TABLE 3.53 INPUT TABLE FOR THE OPERATION CALENDARIZATION OF THE DECOMMISSIONING PHASE

ID	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
decommissioning.operations	Sequence of optimal operations	LMO	List of objects	[-]
proj_start_date	Project start date	User	String	DD/MM/YY
proj_lifetime	Project lifetime (e.g. 20 years)	User	Int	Years
proj_com_date	Project commissioning date (end date of the installation phase).	LMO	String	DD/MM/YY

OUTPUTS

DEFINE OPERATION DATES

Decommissioning phase start date is calculated based on adding the project duration to the commissioning date. After the decommissioning start date, it is assumed that the devices completely stop producing energy.

TABLE 3.54 DECOMMISSIONING DATE DEFINITION FUNCTIONALITY

Requirement	Inputs	Function
Date of decommissioning phase start	*proj_com_date* *proj_lifetime*	*decom_start_date= proj_com_date+ proj_lifetime*

Requirement	Inputs	Function
End date of operation 1	*proj_com_date* *Decom.op[1].tot_dur*	*Decom.op[1].end = proj_com_date+ Decom.op[1].tot_dur[month]*
Start date of operation 2	*Decom.op[1].end* *Decom.op[2].wow*	*Decom.op[2].start = Decom.op[1].end + Decom.op[2].wow[month]*
End date of operation 2	*Decom.op[1].end* *Decom.op[2].tot_dur*	*Decom.op[2].end = Decom.op[1].end + Decom.op[2].tot_dur[month]*
Start date of operation n	*Decom.op[n-1].end* *Decom.op[n].wow*	*Decom.op[n].start = Decom.op[n-1].end + Decom.op[n].wow[month]*
End date of operation n	*Decom.op[n-1].end* *Decom.op[n].tot_dur*	*Decom.op[n].end = Decom.op[n-1].end + Decom.op[n].tot_dur[month]*

- **TOTAL DECOMMISSIONING COSTS**

The total costs of the decommissioning phases are calculated by summing the costs of all decommissioning operations.

$$cost\_decom = \sum_{op=1}^{n\_op\_decommissioning} op.costs \tag{40}$$

3.4 FUNCTIONALITIES OF THE SIMPLIFIED LOGISTICS MODULE

In the lowest complexity level (CPX1), the LMO module produces a generic logistic solution comprised of a selection of vessels, equipment and ports, and a simplified operation plan which include durations and rough estimates of waiting on weather contingencies. Some simplified assumptions are adopted as follows:

- Operation methods such as transportation, load-out at port, cable burial, and cable landfall methods are assumed.
- The infrastructure selection is based on a pre-defined combination of vessels for the required operations.
- Infrastructure solution matching is not carried out.

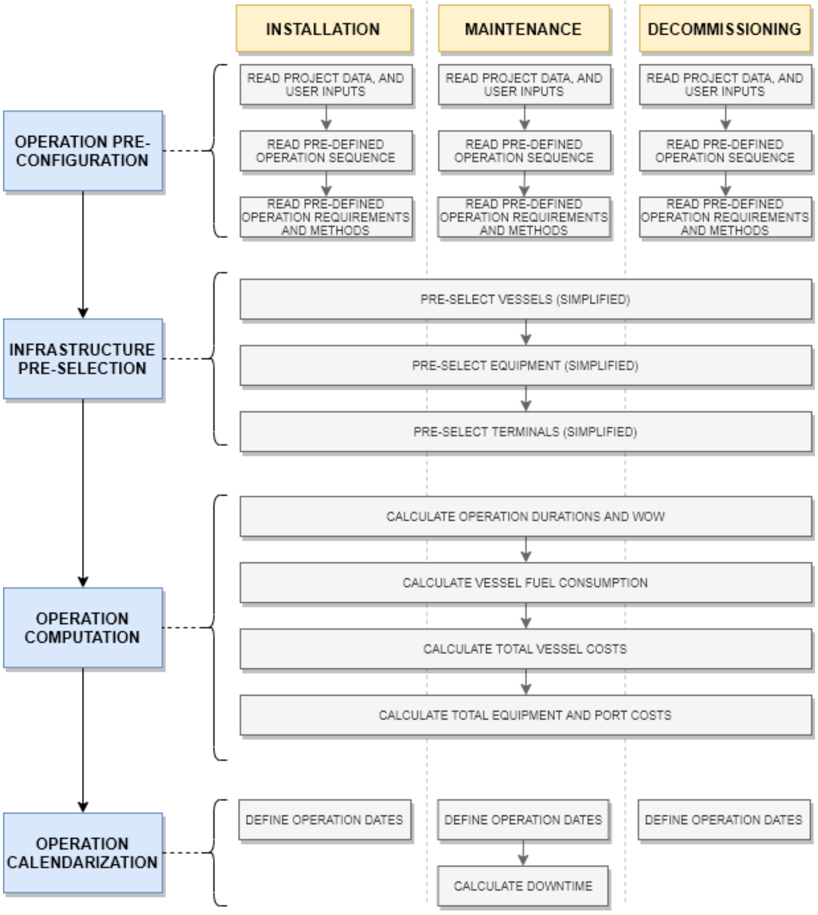


FIGURE 3.10 MAIN FUNCTIONALITIES OF THE LOGISTICS MODULE AT SIMPLIFIED COMPLEXITY

Similarly to the full complexity version, the simplified version of the LMO module keeps its four major functionalities, as shown in Figure 3.10, although with some simplifications:

1. **Operation pre-configuration**: For the low complexity level, the operation pre-configuration functionality identifies operation requirements and assumes pre-defined operation methods (e.g. transport: "dry").
2. **Infrastructure pre-selection:** In the simplified version of the module, this functionality is common to all three phases of the project and consists of selecting a pre-defined combination of vessels, equipment and ports terminal that comply with operation assumptions, although compatibility between vessels, ports and equipment are not assessed.
3. **Operation computation:** For the lowest complexity level, this functionality, common to all three phases of the operation, is responsible for analysing the pre-selected infrastructure combinations and calculating expected operation durations and waiting on weather for different months of the year. Based on operation durations and selected infrastructure, the operation costs are calculated for the pre-selected infrastructure solution.
5. **Operation calendarization:** In the simplified version of the Logistics module, the operation calendarization operates exactly in the same way as in the full complexity level. For more information see Section 3.3.4.

3.4.1 OPERATION PRE-CONFIGURATION

In the simplified version of the LMO code, some realistic assumptions are adopted to simplify the computation process and input requirements.

3.4.1.1 INPUTS

TABLE 3.55 INPUT TABLE FOR THE OPERATION PRE-CONFIGURATION FUNCTIONALITY AT CPX1

Variable name	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
hierarchy_et	Hierarchy datafile from the energy transformation system	ET	Pandas	[-]
hierarchy_ed	Hierarchy datafile from the energy delivery system	ED	Pandas	[-]
hierarchy_sk	Hierarchy datafile from the station keeping system	SK	Pandas	[-]
bom_et	Simplified BOM datafile from the energy transformation system	ET	Pandas	[-]
bom_ed	Simplified BOM datafile from the energy delivery system	ED	Pandas	[-]
bom_sk	Simplified BOM datafile from the station keeping system	SK	Pandas	[-]
Hs_timeseries	Met-ocean timeseries of Hs measurements (default site)	SC	Pandas	[-]

3.4.1.2 OUTPUTS

- **OPERATION IDENTIFICATION AND SEQUENCE**

TABLE 3.56 OPERATION PRE-CONFIGURATION OUTPUTS FOR INSTALLATION, MAINTENANCE AND DECOMMISSIONING OPERATIONS AT CPX1

Requirement	Inputs	Function
List of installation operations	*Hierarchy_ET* *Hierarchy_ED,* *Hierarchy_SK* *Ndevices* *cp.type*	*If ndevices>0:* *opx_list.append("device installation")* *If hierarchy_ED includes "array cable":* *opx_list.append("array cable installation")* *If hierarchy_ED includes "export cable":* *opx_list.append("export cable installation")* *If hierarchy_ED includes "collection point":* *If not all cp's are "hub":* *opx_list.append("collection point installation")* *if "moorings" in hierarchy_SK:* *opx_list.append("moorings installation")* *if "pile" or "suction caisson" in hierarchy_SK:* *opx_list.append("foundation installation")* *if "support structure" in hierarchy_SK:* *opx_list.append("support structure installation")*

Requirement	Inputs	Function
Operation sequence suggestion[21]	*None*	Seq1 = ["Foundation installation"," Moorings installation", "Support structures installation","Collection point installation", Device installation", "Export cable installation", "Array cable installation", "Post-lay cable burial", "External protections"]
List of preventive maintenance operations	Same as CPX2-3	*Same as CPX2-3.*
List of corrective maintenance operations	Same as CPX2-3	*Same as CPX2-3*
List of decommissioning operations	Same as CPX2-3	*Same as CPX2-3*
Decommissioning operations sequence	Same as CPX2-3	*Same as CPX2-3*

OPERATION METHODS

In the simplified version of the Logistics module, all operation methods are fixed as described in Table 3.57.

TABLE 3.57 OPERATION METHODS

Method	Source	Function
Transportation method	LMO	*Dry (on deck)*
Load-out method	LMO	*Ignored*
Load-out from vessel deck method	LMO	Lift
Piling method	LMO	*Hammering (soil ignored)*
Cable burial method	LMO	*ploughing*
Post laying burial	LMO	*False*
Cable landfall method	LMO	*OCT*

INFRASTRUCTURE REQUIREMENTS DEFINITION

Based on the available inputs at complexity level CPX1, the definition of the infrastructure requirements is presented in Table 3.58.

[21] This sequence is based on pre-defined precedence rules between operations, defining the overall order of the installation operations to carry out. Depending on the farm design, the final installation operation sequence is likely to not feature every single operation listed.

TABLE 3.58 OPERATION REQUIREMENTS DEFINITION IN RESPECT TO INFRASTRUCTURE CAPABILITIES

Requirement	Inputs	Function
	PORT TERMINALS	
Filter according to maximum Euclidean distance to site	*filter_max_dist*	$op.requirement[filter\_max\_dist] = 2000000$
	EQUIPMENT	
Maximum depth at farm	*OEC.bathymetry, Sub.bathymetry*	*if op.name="device installation":* $op.requirements[depth\_max] = \max(OEC.bathymetry)$ *else:* $op.requirements[depth\_max] = \max(sub.bathymetry)$
Minimum depth at farm		*if op.name="device installation":* $op.requirements[depth\_min] = \min(OEC.bathymetry)$ *else:* $op.requirements[depth\_min] = \min(sub.bathymetry)$
Cable burial depth	*Cable.bathymetry*	$op.requirements[cable\_depth] = \max(cable.burial\_depth)$
Crane lift requirement	*Sub.drymass*	$op.requirements[lift] = sub.drymass$
Maximum depth of piles	*Sub.bathymetry*	$op.requirements[depth\_max] = \max(sub.bathymetry)$
Maximum penetration depth of piles	*Sub.burial_depth*	$op.requirements[pilling\_max] = \max(sub.burial\_depth)$
Maximum diameter of piles	*Sub.diameter*	$op.requirements[object\_diameter\_max] = \max(sub.diameter)$
Minimum diameter of piles		$op.requirements[object\_diameter\_min] = \min(sub.diameter)$
Maximum depth at farm location	*Cable. bathymetry*	$op.requirements[depth\_max] = \max(cable.bathymetry)$
Maximum cable burial depth	*Cable.burial_depth*	$op.requirements[cable\_depth] = \max(cable.burial\_depth)$
Maximum cable diameter	*Cable.diameter*	$op.requirements[cable\_diameter\_max] = \max(cable.diameter)$
Minimum cable diameter		$op.requirements[cable\_diameter\_min] = \min(cable.diameter)$
	VESSELS	
Lifting power requirement	*OEC.drymass Sub.drymass*	*if op.name="device installation":* $op.requirements[lift] = OEC.drymass$ *else:* $op.requirements[lift] = sub.drymass$
Maximum depth requirement	*OEC.bathymetry Sub.bathymetry*	$op.requirements[depth\_max] = \max(\mathrm{OEC.\,bathymetry, Sub.\,bathymetry})$
Minimum depth requirement		$op.requirements[depth\_min] = \min(\mathrm{OEC.\,bathymetry, Sub.\,bathymetry})$

3.4.2 INFRASTRUCTURE PRE-SELECTION

In order to reduce the number of potential infrastructure solutions, in the simplified version of the LMO module, a pre-defined vessel combination is fixed for each operation type. Given the device's dimensions and project requirements, as well as the vessel roles defined in the vessel combination, vessels that do not comply with requirements are discarded. However, in this functionality, the infrastructure matching process is not carried out.

3.4.2.1 INPUTS

TABLE 3.59 INPUT TABLE FOR INFRASTRUCTURE PRE-SELECTION FUNCTIONALITY

Variable name	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
op.requirements	Operation requirements	LMO	Dictionary	[-]
op.methods	Operation methods	LMO	Dictionary	[-]
rov_database	Database with all ROVs available	Catalogue	Dictionary	[-]
divers_database	Database with all divers available	Catalogue	Dictionary	[-]
piling_database	Database with all piling equipment available	Catalogue	Dictionary	[-]
burial_database	Database with all burial equipment available	Catalogue	Dictionary	[-]
term_database	Database with all terminals available	Catalogue	Dictionary	[-]
op.name	Operation name	LMO	string	[-]
op.description	Operation description	LMO	string	[-]
vc_database	Vessels Combinations database	LMO	Catalogue	[-]
ve.database	Vessels database	LMO	Catalogue	[-]
vc_feasible	Feasible Vessel Combinations	LMO	Catalogue	[-]
op.dp_requirements	DP requirements for the operation	LMO	Int	[-]
op.bp_requirements	Required vessel bollard pull	LMO	Float	ton
op.site_min_depth	Minimum water depth at site	LMO	Float	m
op.site_max_depth	Maximum water depth at site	LMO	Float	m
op.site_loadout	Load-out method at site (Lift)	LMO	String	[-]
ve.LOA	Vessel Length Overall	Catalogue	Float	m
ve.beam	Vessel beam	Catalogue	Float	m
ve.draft	Vessel draft			m
ve.free_deck	Vessel free deck area	Catalogue	Float	m²
ve.deck_str	Vessel deck strength	Catalogue	Float	ton/m²
ve.crane_lift	Vessel crane maximum lifting capability	Catalogue	Float	ton
ve.DP	Vessel Dynamic Positioning system rating	Catalogue	Int	[-]
ve.type	Vessel type	Catalogue	String	[-]
ve.jup_max_water	Vessel jack up maximum operational water depth	Catalogue	Float	m
ve.totalcablestorage	Vessel turntable loading capacity	Catalogue	Float	Ton

Variable name	Brief Description of the Input Quantity	Origin of the Data	Data Model in LMO	Units
ve.turn_diameter_inner	Inner diameter vessel turn table	Catalogue	Float	m
numberobjectsondeck	Maximum number of items (piles, devices) on deck	LMO	Int	[-]
ve_Te	Tug efficiency. Hard coded as 0.75	LMO	Float	[-]
UK_contigency	Under keel clearence contingency, set as 10% of draft.	LMO	Float	[-]

3.4.2.2 OUTPUTS

TABLE 3.60 INFRASTRUCTURE PRE-SELECTION FUNCTIONALITY OUTPUTS

Requirement	Inputs	Function
		Ports
Port maximum distance	*op.requirements[port_max_dist]* *terminal.coordinates*	$if\ terminal.distance \leq op.requirements[port\_max\ \_dist]$: $terminal\_feasible = \text{True}$ $else, terminal\_feasible = \text{False}$
Area capabilities	*op.requirements[terminal_area]* *op.requirements[area]* *terminal.area*	$if\ op.requirements[terminal\_area] = \text{True}$: $if\ terminal.area \geq op.requirements[area]$: $terminal\_feasible = \text{True}$ $else, terminal\_feasible = \text{False}$ $else, terminal\_feasible = \text{True}$
		Equipment
ROV class	*op.requirements[rov]* *rov.class*	$if\ op.requirements[rov] = rov.class$: $rov\_feasible = \text{True}$ $else, rov\_feasible = \text{False}$
ROV depth capabilities	*op.requirements[depth_max]* *rov.max_depth*	$if\ rov.max\_depth \geq op.requirements[depth\_max]$: $rov\_feasible = \text{True}$ $else, rov\_feasible = \text{False}$
Depth rating (m)	Maximum water depth at foundation location (m): *op.requirements[depth_max]* *piling.max_depth*	$if\ piling.max\_depth \geq op.requirements[depth\_max]$: $piling\_feasible = \text{True}$ $else, piling\_feasible = \text{False}$
Pile sleeve diameter (m)	*piling.hammer_max_diam* *piling.hammer_min_diam* *op.requirements[obj_diameter_max]* *op.requirements[obj_diameter_min]*	$if\ piling.hammer\_max\_diam \geq op.requirements[obj\_diameter\_max]$ **AND** $piling.hammer\_min\_diameter \leq op.requirements[obj\_diameter\_min]$: $piling\_feasible = \text{True}$ $else, piling\_feasible = \text{False}$
Cable burial equipment depth rating (m)	Maximum water depth of cables (m): *op.requirements[depth_max]* *burial.max_depth*	$if\ burial.max\_depth \geq op.requirements[depth\_max]$: $burial\_feasible = \text{True}$ $else, burial\_feasible = \text{False}$

Requirement	Inputs	Function
Cable burial equipment cable diameter (mm)	Maximum cable diameter (mm): *op.requirements[cable_diameter_max]* *burial.max_cable_diam*	$if\ burial.max\_cable\_diam \geq op.requirements[cable\_diameter\_max]$: $burial\_feasible = \text{True}$ $else, burial\_feasible = \text{False}$
Cable burial equipment capabilities	*burial.capabilities_ploughing*	$if\ burial.capabilities\_ploughing = \text{True}$ $burial\_feasible = \text{True}$ $else, burial\_feasible = \text{False}$
Cable burial equipment Ploughing depth rating (m)	*burial.max_depth_ploughing* *op.requirements[cable_depth]*	$if\ burial.max\_depth\_ploughing \geq op.requirements[cable\_depth]$ $burial\_feasible = \text{True}$ $else, burial\_feasible = \text{False}$
		Vessels
Vessel Combination	*op.name* *vc.type*	*See* Table 3.61
Crane capabilities [ton]	*op.requirements[lift]* *ve.crane_capacity*	$if\ vessel.crane\_capacity \geq op.requiremnts[lift]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Dynamic positioning	*op.requirements[dp]* *ve.dp*	$if\ vessel.dp \geq op.requiremnts[dp]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Jack-up capabilities	*op.requirements[depth_max]* Jack-up vessel legs operating depth (m): *ve.jup_capabilities* *ve.jup_max_water*	$if\ vessel.jup\_capabilities = True$: $if\ vessel.jup\_max\_water \geq op.requirements[depth\_max]$: $vessel\_feasible = \text{True}$ $else, vesse\_feasible = \text{False}$ $else, vessel\_feasible = \text{True}$
Depth clearance [m]	*op.requirements[depth_min]* *ve.draft*	$c\_ukc = UKC\_contigency$[22] $\times\ ve.draft$ $if\ vessel.draft * c\_ukc \leq op.requirements[depth\_min]$: $vessel\_feasible = \text{True}$ $else, vesse\_feasible = \text{False}$
ROV capabilities	*op.requirements[rov]* *ve.rov_ready*	$if\ op.requiremnts[rov] == \text{"}work\text{"}$ $if\ vessels.rov\_ready = \text{True}$: $vessel\_feasible = \text{True}$
Vessel type	*vc.type* *ve.type*	$if\ vessel.type = vc.type$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$
Turntable storage [ton]	*op.requirements[turn_storage]* *vesturn_storage*	$if\ vessel.turn\_storage \geq op.requiremnts[turn\_storage]$: $vessel\_feasible = \text{True}$ $else, vessel\_feasible = \text{False}$

[22] The under keel clearance (UKC) allowance is normally fixed to a minimum of 10% of the ship draft, which means that the *UKC_contigency* is fixed to 1.10. Source: https://safeshippingbc.ca/?page_id=231

TABLE 3.61 DEFAULT VESSEL COMBINATIONS FOR THE DIFFERENT OPERATIONS IN CPX1

Operation name	Transport	No.	Main vessel	No.	Tow vessel	No.	Support vessel
Device installation	*On deck*	1	Propelled crane vessel	–	–	–	–
	Wet-tow	1	AHTS	–	–	–	–
Collection point installation	*On deck*	1	Propelled crane vessel	–	–	–	–
Foundation Installation	*On deck*	1	Propelled crane vessel	–	–	–	–
Cable installation (export and array)	*On deck*	1	Cable Laying Vessel	–	–	–	–
Moorings installation	*On deck*	1	AHTS	–	–	–	–
Support Structure Installation	*On deck*	1	Propelled crane vessel	–	–	–	–
Topside Inspection	*On deck*	1	CTV	–	–	–	–
Underwater Inspection	*On deck*	1	Diver support vessel	–	–	–	–
Mooring Inspection	*On deck*	1	Diver support vessel	–	–	–	–
Array Cable Inspection	*On deck*	1	Diver support vessel	–	–	–	–
Export Cable Inspection	*On deck*	1	Diver support vessel	–	–	–	–
Device Retrieval	*Wet-tow*	1	AHTS	–	–	–	–
Device Redeployment	*Wet-tow*	1	AHTS	–	–	–	–
Device Repair On Site	*On deck*	1	Propelled crane vessel	–	–	–	–
Mooring Line Replacement	*On deck*	1	AHTS	–	–	–	–
Cable Replacement	*On deck*	1	Cable Laying Vessel	–	–	–	–
Cable Repair	*On deck*	1	Cable Laying Vessel	–	–	–	–
Decommissioning device	*On deck*	1	Propelled crane vessel	–	–	–	–
	Wet-tow	1	AHTS	–	–	–	–
Decommissioning collection point	*On deck*	1	Propelled crane vessel	–	–	–	–
Decommissioning support structure	*On deck*	1	Propelled crane vessel	–	–	–	–
Decommissioning moorings	*On deck*	1	AHTS	–	–	–	–
Decommissioning foundations	*On deck*	1	Propelled crane vessel	–	–	–	–

3.4.3 OPERATION COMPUTATION

In complexity level CPX1 of the operation computation functionality, operations are not broken down into a sequence of activities. The transit distance from port to site is estimated as a straight line between the two coordinates. Net duration is calculated assuming a total duration and estimating the number of trips from port to site for transporting equipment. However, the remaining functionalities remain the same as in the full complexity version described in Section 3.3.3.

3.4.4 OPERATION CALENDARIZATION

The operation calendarization functionality operates exactly in the same way for both versions (full complexity and simplified) of the Logistics and Marine Operations module. For more information see Section 3.3.4.

4. THE IMPLEMENTATION

4.1 THE ARCHITECTURE OF THE TOOL

Each module of the DTOceanPlus suite of design tools is organised in three layers:

- The Business Logic (BL), including a set of modules, classes, libraries implementing all the functionalities of the modules
- The Application Programming Interface (API) that constitutes of the gate of the module to the other modules. LMO module will consume services from design modules and provide metrics for the SG, SI, SPEY, SLC, RAMS and ESA tools.
- The Graphic User Interface (GUI) which provides the means for interacting with the user, in respect to collecting inputs from the users and displaying results, besides exporting/importing data to/from files.

4.1.1 BUSINESS LOGIC

The architecture of the Business Logic of LMO is organised in order to differentiate the three project phases of a marine renewable energy project. Thus, the BL contains three independent classes: Installation, Maintenance and Decommissioning, one for each phase. Functionalities that are common to all three project phases are aggregated in a transversal class: Core Functionalities – Core.

- Core (see Figure 4.1)
- Installation (see Figure 4.2)
- Maintenance (see Figure 4.3)
- Decommissioning (see Figure 4.4)

The interactions between the classes above are represented in Figure 4.5. Functionalities related with Infrastructure Pre-Selection and Computation of Costs and Durations are comprised in class Core, while functionalities related with Operation pre-configuration and Operation Calendarization are integrated in the Installation, Maintenance and Decommissioning classes.

In the LMO module's business logic, classes were subdivided according to complexity levels (CPX1, CPX2, & CPX3) to be consistent with the other tools, as shown in Figure 4.1. With increasing complexity level, LMO will request inputs with an increasing level of detail from the user and will produce results with increased accuracy. These sub-classes have the same name of the parent class, adding the suffix "1", "2", or "3", according to the level of complexity (1-low; 2-mid; 3-high). Functionalities in complexities cpx2 and cpx3 are able to deal with data with different levels of uncertainty, producing more accurate results when more detailed data is provided.

Each class has several methods, each of them computing different quantities.

- Class Core (see Figure 4.1):
  - *run_feasibility_functions(operations),* select feasible infrastructure solutions of Vessels, Terminals, Equipment and Vessels Combinations;
  - *run_matchability_functions(operations)*, match feasible solutions. Check if a feasible vessel can port at a feasible terminal, etc. For each possible combination, an *operation.combination* is created.

    Note: the previous two functionalities are not available for the lowest complexity. In this case, a default combination will be considered
  - *define_activities(operations)*, define the operation activities considering each combination aspects[23];
  - *delete_combinations(operations)*, reduce computational effort related to calculating unnecessary waiting on weather outputs, impossible combinations, and combinations with very long net durations (not including waiting on weather) are discarded;
  - *check_workabilities(operations)* and *check_startabilities(operations)*, for each combination, for a given met-ocean timeseries, the workability and startability of each timestep is assessed;
  - *check_activities_waiting_time(operations)*, defines the waiting time per activity along the met-ocean timeseries;
  - *define_durations_waitings_timestep(opx)*, define the durations (at port, at sea, transit, etc.) and waiting time per timestep for each combination;
  - *get_statistics(df_values)*, based on these durations and waiting time per timestep, a statistical analysis is carried out and the expected operation duration, including waiting, for each month, is estimated (refer to Section 2.7 for more information).
  - *calculate_combinations_costs(feasible_sols, combination)*, considering the statistical values, the cost of the operation for each possible combination is assessed. Vessel charter and fuel costs, equipment costs and terminal costs are considered;
  - *optimal_solutions(operations)*, based on costs, the best combination is selected;
  - *operation_consumption(opx)*, for a given operation, this functionality calculates the total vessel consumption.

[23] Note: For complexity 1, operations are not broken down into activities.

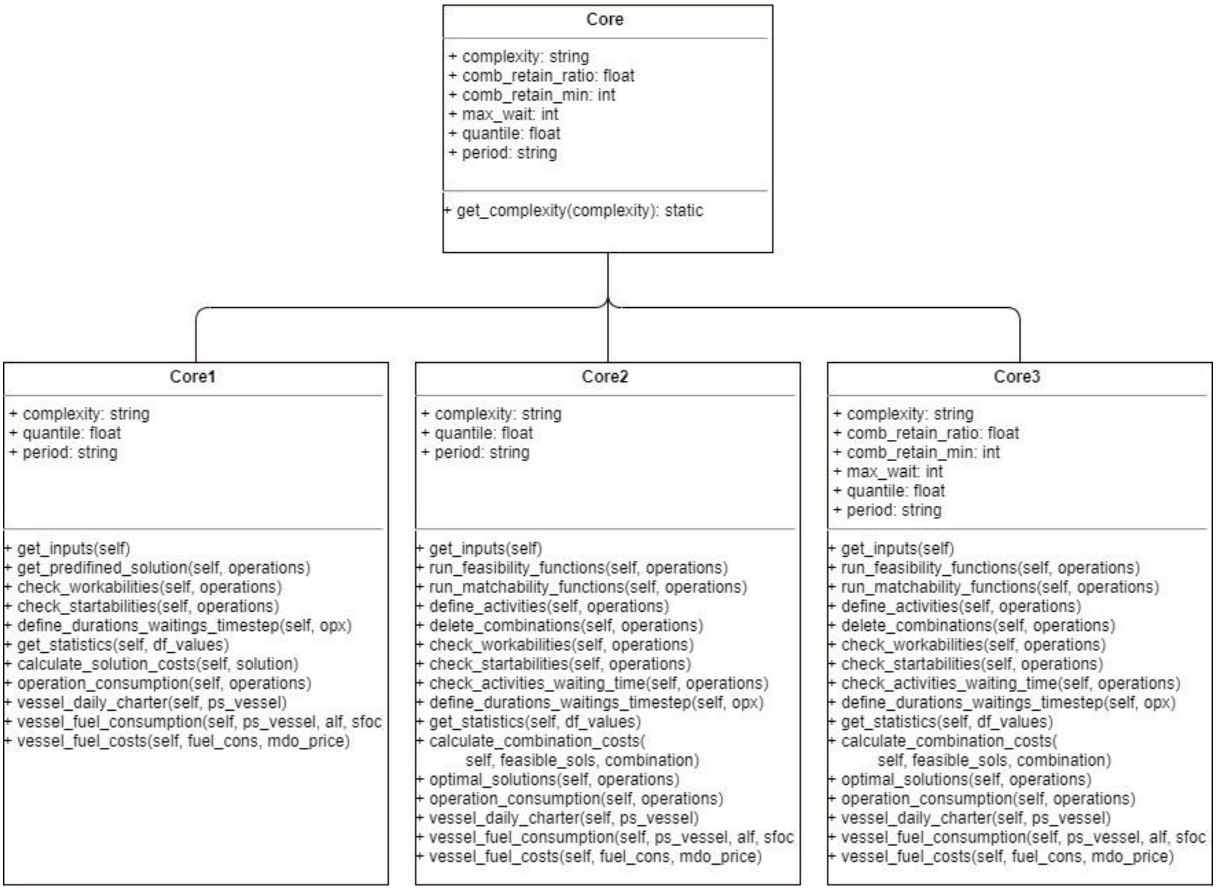


FIGURE 4.1 THE CORE CLASS AND METHODS FOR THE TWO LEVELS OF COMPLEXITY

- Class Installation (see Figure 4.2):
  - *define_objects()*, considering hierarchies and design inputs from other modules, a list of all components to installed is created (devices, foundations, moorings, etc.);
  - *define_cables()*, considering ED hierarchy and cables design, a list of cables to be installed is created;
  - *get_installation_operations_sequence()*, taking into account the characteristics of *Objects* and *Cables*, the sequence of operations to install every component is defined;
  - *set_installation_operations(dict_operations)*, creates *Operations* to be evaluated;
  - *allocate_site()*, allocate a *Site* (with coordinates and met-ocean timeseries) to the operations;
  - *update_operations_w_user_inputs()*, updates operations methods and requirements considering user inputs;
  - *define_operations_dates()*, considering *start_date* input and the operation sequence, operations dates are defines;
  - *build_output_table()*, considering the operations, builds a pandas DataFrame with the installation plan;
  - *vessel_consumption()*, returns the vessel consumption for installation phase;
  - *cost_metric()*, returns the installation costs.

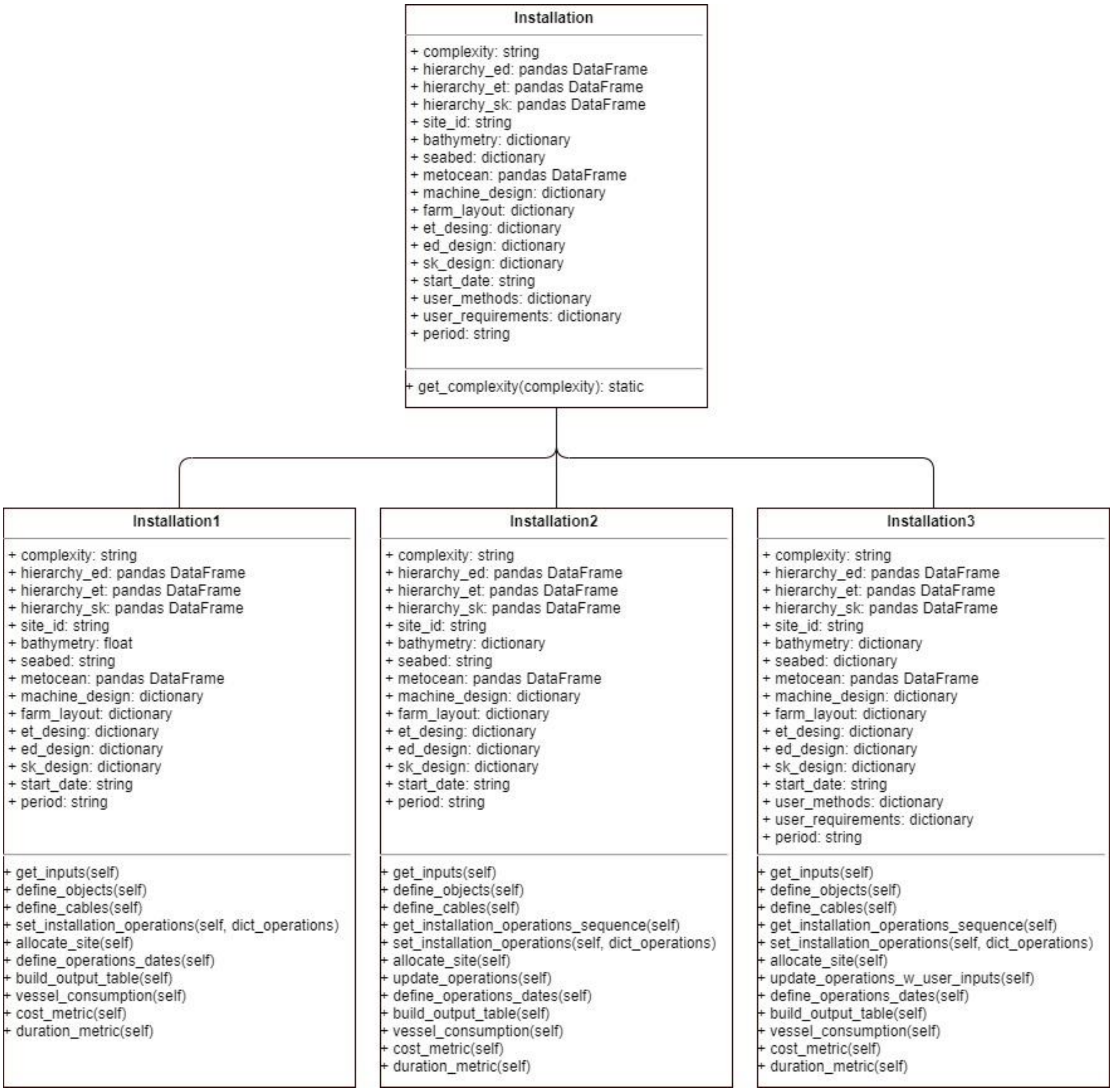


FIGURE 4.2 THE INSTALLATION CLASS AND METHODS FOR THE TWO LEVELS OF COMPLEXITY

- Class Maintenance (see Figure 4.3):
  - *define_objects()*, considering hierarchies and design inputs from other modules, a list of all components to installed is created (devices, foundations, moorings, etc.);
  - *define_cables()*, considering ED hierarchy and cables design, a list of cables to be installed is created;
  - *allocate_site()*, allocates a *Site* (with coordinates and met-ocean time series) to the operations;
  - *update_operations_w_user_inputs()*, updates operations methods and requirements considering user inputs;
  - *define_operations_dates()*, considering *start_date* input and the operation sequence, operations dates are defines;

- *build_output_table()*, considering the operations, builds a pandas DataFrame with the installation plan;
- *vessel_consumption()*, returns the vessel consumption for installation phase;
- *cost_metric()*, returns the maintenance costs per kW per year;
- *get_downtime()*, taking into account operations ending and failure dates, the downtime is assessed.

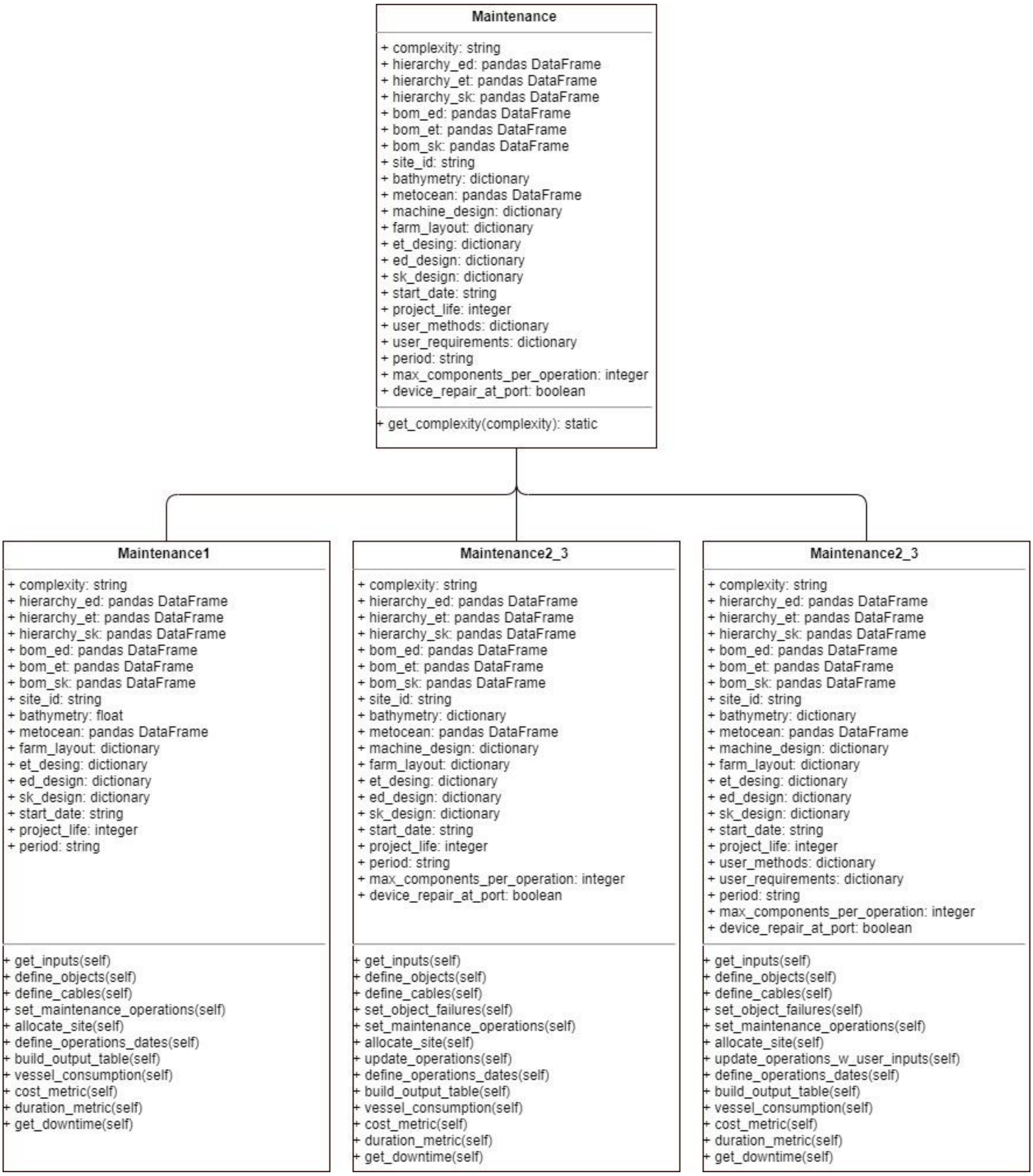


FIGURE 4.3 THE MAINTENANCE CLASS AND METHODS FOR THE TWO LEVELS OF COMPLEXITY

- Class Decommissioning (see Figure 4.4):
  - *define_objects()*, considering hierarchies and design inputs from other modules, a list of all components to installed is created (devices, foundations, moorings, etc.);
  - *allocate_site()*, allocate a *Site* (with coordinates and met-ocean time series) to the operations;
  - *update_operations_w_user_inputs()*, updates operations methods and requirements considering user inputs;
  - *define_operations_dates()*, considering *start_date* input and the operation sequence, operations dates are defined;
  - *build_output_table()*, considering the operations, builds a pandas DataFrame with the installation plan;
  - *vessel_consumption()*, returns the vessel consumption for installation phase.

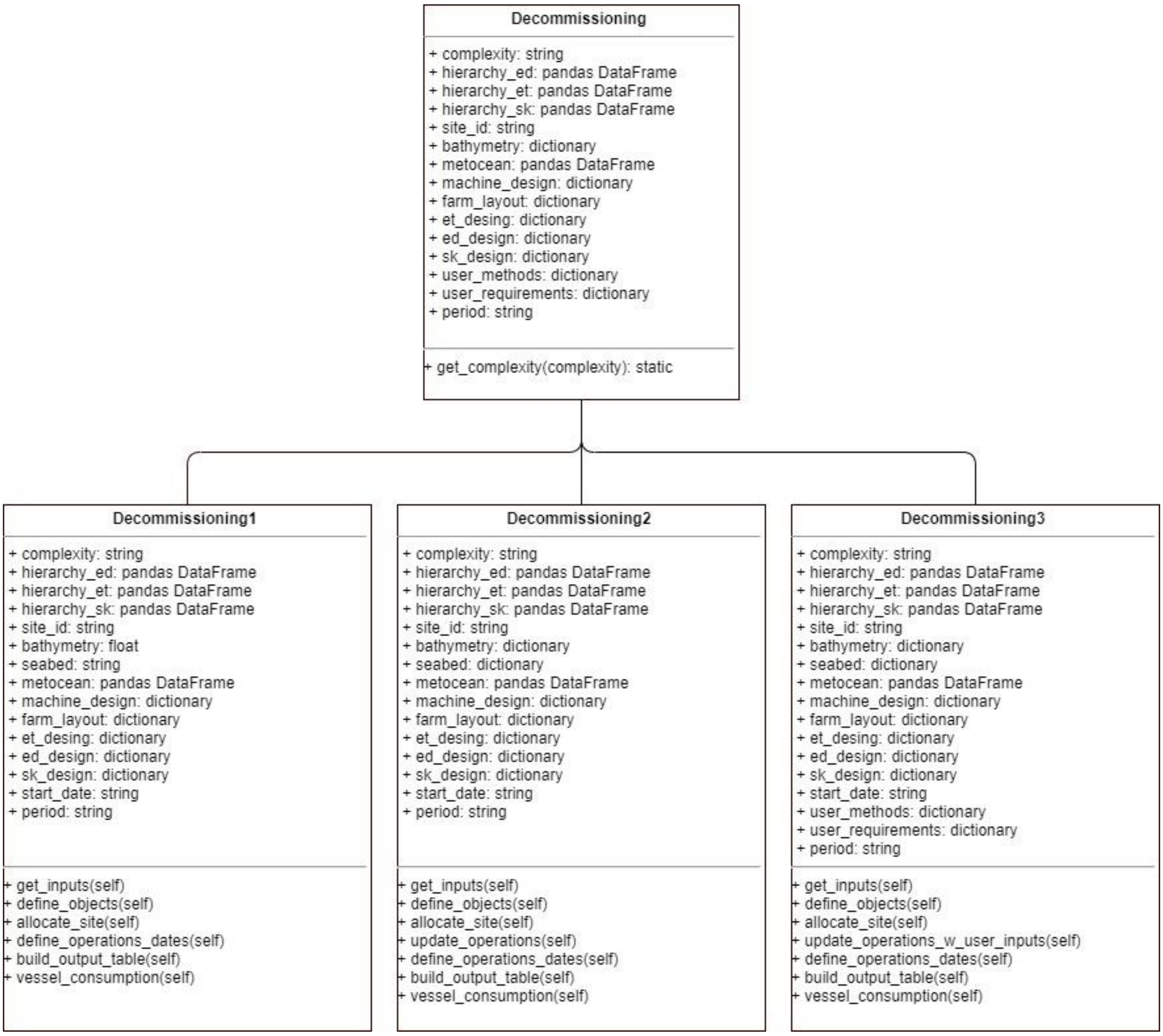


FIGURE 4.4 THE DECOMMISSIONING CLASS AND METHODS FOR THE TWO LEVELS OF COMPLEXITY

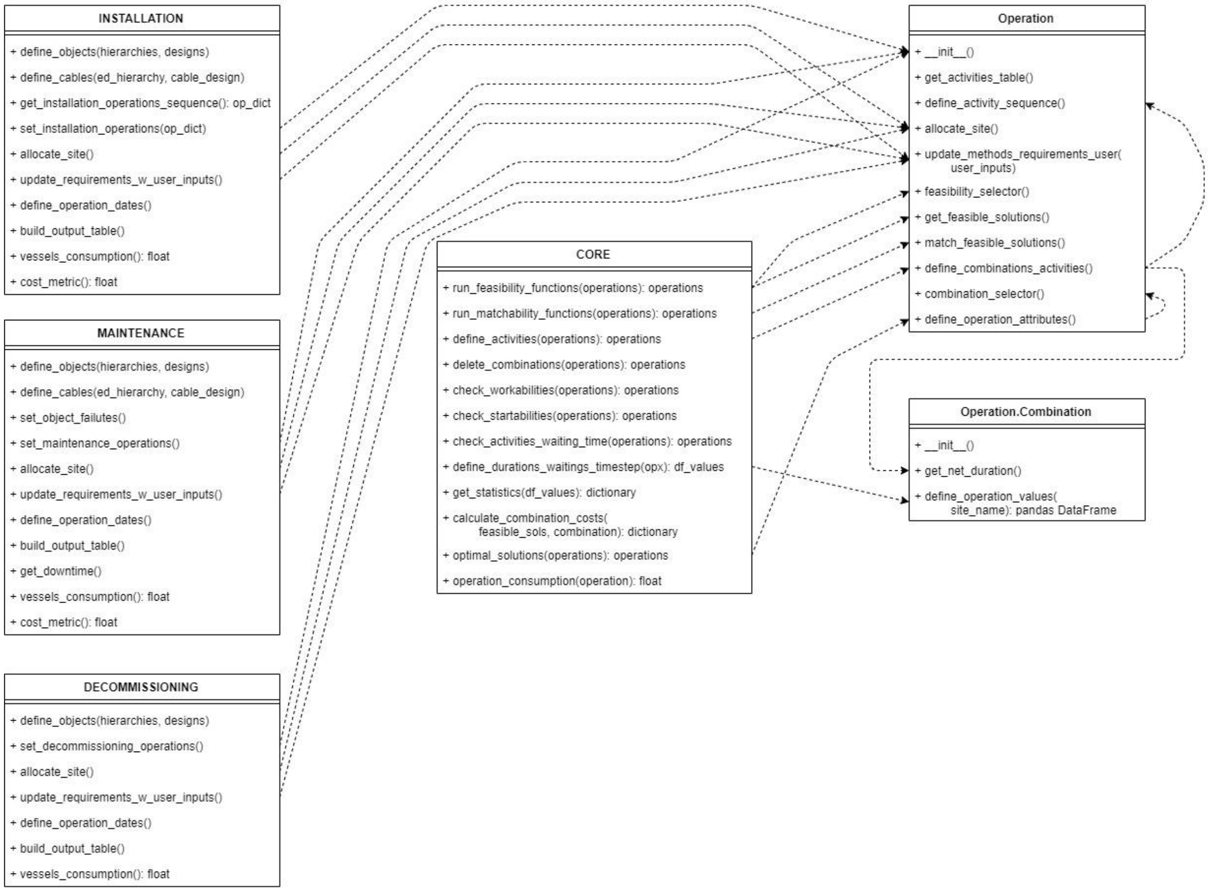


FIGURE 4.5 SUMMARY OF THE INTERACTION BETWEEN BUSINESS LOGIC CLASSES AND METHODS

4.1.2 API

Within the DTOceanPlus software, the API follows a representational state transfer (REST) approach and it uses HyperText Transfer Protocol (HTTP) as the transport protocol. Its robustness is due to strict design principles whose development it has been based on.

Similar to other DTOceanPlus modules, the LMO API follows the same principles and the OpenAPI specifications are adopted. An OpenAPI file was created, in json format, describing in detail all the paths, the services, and schemas that the LMO module will consume and supply for the other modules to consume.

The backend of the module will receive the services from the other modules, running the Business Logic and then preparing the outputs for the other modules and the users. This has been coded in Python, using Flask Blueprints.

4.1.3 GUI

The GUI of the modules of DTOceanPlus is being developed based on the same libraries to guarantee a consistent visual look.

The GUI of the LMO module, as represented in Figure 4.6, will be embedded into DTOceanPlus main module, and it generally consists of two parts. On the left, a tree is divided into inputs and outputs, which can be further expanded into the three project phases: Installation, O&M and Decommissioning.

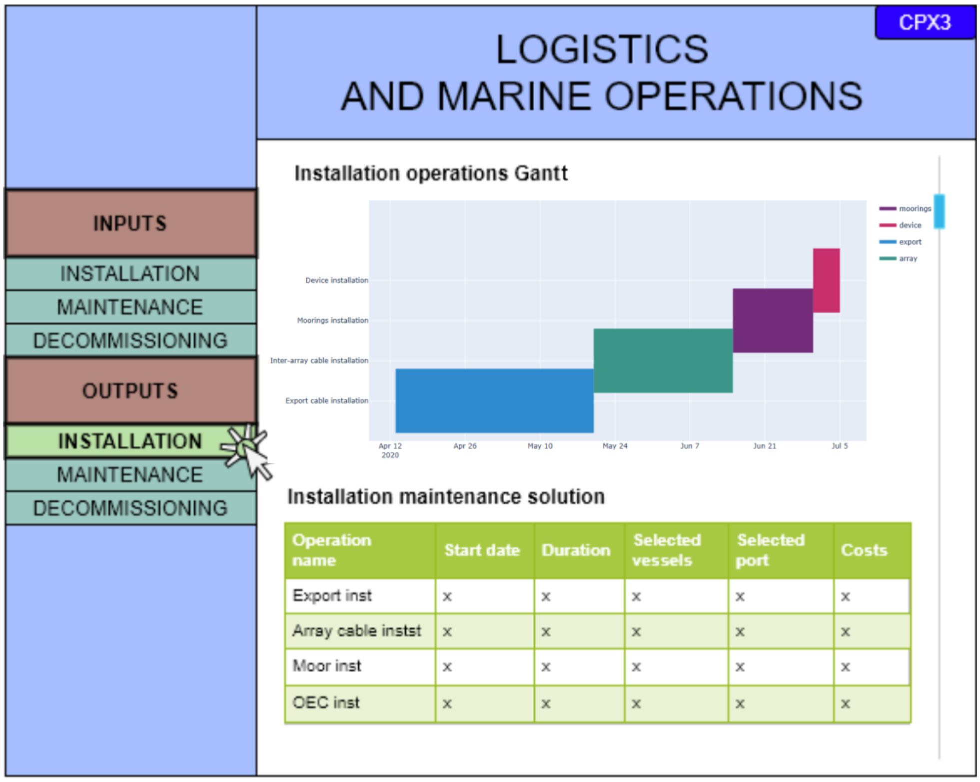


FIGURE 4.6 MOCK-UP OF THE LOGISTICS AND MARINE OPERATIONS MODULE, INSTALLATION OUTPUTS VIEW

4.1.4 THE TECHNOLOGIES

The Business Logic and the API of LMO were coded in Python version 3.7. The installation of the module requires the following packages:

- NumPy
- Matplotlib
- Pandas
- json
- Flask
- flask-babel
- flask-cors
- flask-url_for
- flask-requests
- flask-Blueprint
- flask-jsonify

- Pytest
- SciPy
- Sklearn
- GeoPy
- NetworkX
- utm
- datetime

The API will rely on OpenAPI specification v3.0.2.

The GUI of the module is being developed in Vue.js, using the library Element-UI.

4.2 TESTING AND VERIFICATION

The Business Logic implemented a validation of the data inputs, checking whether the required inputs for each method are set to "None" values. Similarly, in the Business Logic, the situations in which some values are zero, ultimately leading to numerical errors due to divisions by zero, were tested.

In total, a set of 3432 statements were developed, out of which 3383 are attributed to the Business Logic. A comprehensive set of "unit test" were implemented to test the code, and the coverage of said tests was measure using the py-cov extension of the py-test library. As presented Figure 4.7, the business logic of the LMO module was 76% tested.

```
/usr/local/lib/python3.8/site-packages/dtop_lmo/business/cpx3/__init__.py                3      0   100%
/usr/local/lib/python3.8/site-packages/dtop_lmo/business/cpx3/core_functionalities.py  545    238    56%
/usr/local/lib/python3.8/site-packages/dtop_lmo/business/cpx3/installation.py          295     95    68%
/usr/local/lib/python3.8/site-packages/dtop_lmo/business/cpx3/maintenance.py           199     52    74%
/usr/local/lib/python3.8/site-packages/dtop_lmo/business/cpx3/sim_failure_event.py      30      4    87%
/usr/local/lib/python3.8/site-packages/dtop_lmo/business/cpx3/travel/__init__.py         0      0   100%
/usr/local/lib/python3.8/site-packages/dtop_lmo/business/cpx3/travel/graph.py           19      5    74%
/usr/local/lib/python3.8/site-packages/dtop_lmo/business/feasibility.py                456     78    83%
/usr/local/lib/python3.8/site-packages/dtop_lmo/business/foo.py                          2      0   100%
/usr/local/lib/python3.8/site-packages/dtop_lmo/business/operations.py                  60     60     0%
/usr/local/lib/python3.8/site-packages/dtop_lmo/business/startability.py               114      3    97%
/usr/local/lib/python3.8/site-packages/dtop_lmo/business/waiting.py                     86      8    91%
/usr/local/lib/python3.8/site-packages/dtop_lmo/business/workability.py                 88      2    98%
/usr/local/lib/python3.8/site-packages/dtop_lmo/service/__init__.py                     22      0   100%
/usr/local/lib/python3.8/site-packages/dtop_lmo/service/api/__init__.py                  0      0   100%
/usr/local/lib/python3.8/site-packages/dtop_lmo/service/api/api/__init__.py              6      2    67%
/usr/local/lib/python3.8/site-packages/dtop_lmo/service/api/foo/__init__.py              6      0   100%
/usr/local/lib/python3.8/site-packages/dtop_lmo/service/gui/__init__.py                  0      0   100%
/usr/local/lib/python3.8/site-packages/dtop_lmo/service/gui/foo/__init__.py              9      0   100%
/usr/local/lib/python3.8/site-packages/dtop_lmo/service/gui/main/__init__.py             6      1    83%
-----------------------------------------------------------------------------------------------------------
TOTAL                                                                                 3432    830    76%
================ 53 passed, 544 warnings in 901.69s (0:15:01) ================
```

FIGURE 4.7 COVERAGE OF THE TESTING ON THE BUSINESS LOGIC BY MEANS OF UNIT TESTS

5. EXAMPLES

In this section, a few logistic solutions examples generated by the LMO module at complexity level CPX3 are presented. The inputs that were used to generate the logistic outputs are presented as they will be integrated in the DTOceanPlus suite of tools when released.

It is important to stress that specified inputs were generated for illustration purposes only and do not correspond to any specific project or technology. Consequently, the obtained outputs do not hold any meaning and are not necessarily realistic. These were chosen as merely representative values to be used as a demonstration of the computational capabilities of the LMO module.

5.1 INSTALLATION

5.1.1 INPUTS

Considering an array of two wave energy converters, the input data could be collected as in Table 5.1.

TABLE 5.1 INPUT TABLE EXAMPLE FOR THE INSTALLATION SOLUTION

Quantity	Sub-Quantity	Source	Value	Unit
Level of complexity	—	SG/User	3	—
Number of devices	—	EC	3	—
Device topology	—	EC	Floating wave	—
Hierarchy_ET	—	ET	(See Table 5.2)	—
Hierarchy_ED	—	ED	(See Table 5.3)	—
Hierarchy_SK	—	SK	**(SEE** Table 5.4)	—
Cable_design	—	ED	(See Table 5.5Table 5.13)	—
Cp_design	—	ED	(See Table 5.6)	—
SK_design	—	SK	(See Table 5.7)	—
Device dry mass	—	MC	1000 000	kg
Device dimensions	*(L,W,H)*	User	(480,3.5,3.5)	[m,m,m]
Farm layout	—	EC	(See Table 5.8)	—
Met-ocean timeseries	*Hs, Tp, Ws, Cs*	SC	(See Table 5.9)	[m, s, m/s, m/s]
Soil type	—	SC	(See Table 5.10)	—
Lease area bathymetry	—	SC	(See Table 5.11)	—
Filter terminals according to area	—	User	False	—
Filter terminals according to crane	—	User	False	—
Filter terminals according to previous MRE projects experience	—	User	False	—
Filter terminals according to quay load	—	User	False	—
Filter terminals according to radial distance to site	—	User	200000	[km]
Piling method	—	User	Hammering	—

Quantity	Sub-Quantity	Source	Value	Unit
Cable burial method	—	ED	Ploughing	—
Device transport method	—	User	Wet	—
Device load-out method	—	User	Lift away	—
Collection point transport method	—	User	Dry	—
Collection point load-out method	—	User	Lift away	—
Install cable external protections	—	User	False	
Export cable landfall method	—	User	OCT	—
Post-lay cable burial	—	User	False	—
Installation start date	—	User	05/04/2020	*DD/MM/YYYY*
Project lifetime (years)	—	User	25	[years]
Port terminals database	—	Catalogue	—	—
ROV Equipment database	—	Catalogue	—	—
Piling Equipment database	—	Catalogue	—	—
Burial Equipment database	—	Catalogue	—	—
Vessel combinations database	—	Catalogue	—	—
Vessel cluster database	—	Catalogue	—	—

TABLE 5.2 HIERARCHY_ET INPUT EXAMPLE

Sys tem	Name	Design ID	Type	Sub type	Cate gory	Parent	Child	Gate	Failure Rate Replace ment
ET	ET1	ET_01	System	NA	Level 2	NA	[PTO1_1, PTO1_2]	OR	NA
ET	ET2	ET_01	System	NA	Level 2	NA	[PTO2_1, PTO2_2]	OR	NA
ET	ET3	ET_01	System	NA	Level 2	NA	[PTO3_1, PTO3_2]	OR	NA
ET	PTO1_1	ET_01	PTO	NA	Level 1	ET1	[MechT_1_1, ElecT_1_1, GridC_1_1]	AND	NA
ET	PTO1_2	ET_01	PTO	NA	Level 1	ET1	[MechT_1_2, ElecT_1_2, GridC_1_2]	AND	NA
ET	PTO2_1	ET_01	PTO	NA	Level 1	ET2	[MechT_2_1, ElecT_2_1, GridC_2_1]	AND	NA
ET	PTO2_2	ET_01	PTO	NA	Level 1	ET2	[MechT_2_2, ElecT_2_2, GridC_2_2]	AND	NA
ET	PTO3_1	ET_01	PTO	NA	Level 1	ET3	[MechT_3_1, ElecT_3_1, GridC_3_1]	AND	NA
ET	PTO3_2	ET_01	PTO	NA	Level 1	ET3	[MechT_3_2, ElecT_3_2, GridC_3_2]	AND	NA
ET	MechT_1_1	ET_01	Component	NA	Level 0	PTO1_1	NA	NA	0.0792
ET	MechT_1_2	ET_01	Component	NA	Level 0	PTO1_2	NA	NA	0.0792
ET	MechT_2_1	ET_01	Component	NA	Level 0	PTO2_1	NA	NA	0.0792
ET	MechT_2_2	ET_01	Component	NA	Level 0	PTO2_2	NA	NA	0.0792
ET	MechT_3_1	ET_01	Component	NA	Level 0	PTO3_1	NA	NA	0.0792
ET	MechT_3_2	ET_01	Component	NA	Level 0	PTO3_2	NA	NA	0.0792
ET	ElecT_1_1	ET_01	Component	NA	Level 0	PTO1_1	NA	NA	0.0635
ET	ElecT_1_2	ET_01	Component	NA	Level 0	PTO1_2	NA	NA	0.0635

Sys tem	Name	Design ID	Type	Sub type	Cate gory	Parent	Child	Gate	Failure Rate Replace ment
ET	ElecT_2_1	ET_01	Component	NA	Level 0	PTO2_1	NA	NA	0.0635
ET	ElecT_2_2	ET_01	Component	NA	Level 0	PTO2_2	NA	NA	0.0635
ET	ElecT_3_1	ET_01	Component	NA	Level 0	PTO3_1	NA	NA	0.0635
ET	ElecT_3_2	ET_01	Component	NA	Level 0	PTO3_2	NA	NA	0.0635
ET	GridC_1_1	ET_01	Component	NA	Level 0	PTO1_1	NA	NA	0.0414
ET	GridC_1_2	ET_01	Component	NA	Level 0	PTO1_2	NA	NA	0.0414
ET	GridC_2_1	ET_01	Component	NA	Level 0	PTO2_1	NA	NA	0.0414
ET	GridC_2_2	ET_01	Component	NA	Level 0	PTO2_2	NA	NA	0.0414
ET	GridC_3_1	ET_01	Component	NA	Level 0	PTO3_1	NA	NA	0.0414
ET	GridC_3_2	ET_01	Component	NA	Level 0	PTO3_2	NA	NA	0.0414

TABLE 5.3 HIERARCHY_ED INPUT EXAMPLE

Sys tem	Name	Design ID	Type	Sub type	Cate gory	Parent	Child	Gate	Failure Rate Replace ment [1/10^6hrs]
ED	ED Subsystem	NA	System	NA	Level 3	NA	[ED1, ED2, ED3]	OR	NA
ED	ED1	NA	System	NA	Level 2	NA	[Route1_1]	OR	NA
ED	ED2	NA	System	NA	Level 2	NA	[Route2_1]	OR	NA
ED	ED3	NA	System	NA	Level 2	NA	[Route3_1]	OR	NA
ED	Route1_1	NA	Energy route	NA	Level 1	ED1	[AC1, AC2, AC3, CP1, EC1, DM1, WM1_1, WM1_2, WM2_1, WM2_2, WM3_1, WM3_2]	AND	NA
ED	Route2_1	NA	Energy route	NA	Level 1	ED2	[AC2, AC3, CP1, EC1, DM1, WM2_1, WM2_2, WM3_1, WM3_2]	AND	NA
ED	Route3_1	NA	Energy route	NA	Level 1	ED3	[AC3, CP1, EC1, DM1, WM3_1, WM3_2]	AND	NA
ED	AC1	AC1	Component	array	Level 0	[Route1_1]	NA	NA	0.0146
ED	AC2	AC2	Component	array	Level 0	[Route1_1, Route2_1]	NA	NA	0.0146
ED	AC3	AC3	Component	array	Level 0	[Route1_1, Route2_1, Route3_1]	NA	NA	0.0146
ED	CP1	CP1	Component	hub	Level 0	[Route1_1, Route2_1, Route3_1]	NA	NA	0.0087

System	Name	Design ID	Type	Sub type	Category	Parent	Child	Gate	Failure Rate Replacement [1/10^6hrs]
ED	EC1	EC1	Component	export	Level 0	[Route1_1, Route2_1, Route3_1]	NA	NA	0.0061
ED	DM1	DM1	Component	dry-mate	Level 0	[Route1_1, Route2_1, Route3_1]	NA	NA	0.0124
ED	WM1_1	WM1_1	Component	wet-mate	Level 0	[Route1_1]	NA	NA	0.0243
ED	WM1_2	WM1_2	Component	wet-mate	Level 0	[Route1_1]	NA	NA	0.0243
ED	WM2_1	WM2_1	Component	wet-mate	Level 0	[Route1_1, Route2_1]	NA	NA	0.0243
ED	WM2_2	WM2_2	Component	wet-mate	Level 0	[Route1_1, Route2_1]	NA	NA	0.0243
ED	WM3_1	WM3_1	Component	wet-mate	Level 0	[Route1_1, Route2_1, Route3_1]	NA	NA	0.0243
ED	WM3_2	WM3_2	Component	wet-mate	Level 0	[Route1_1, Route2_1, Route3_1]	NA	NA	0.0243

TABLE 5.4 HIERARCHY_SK INPUT EXAMPLE

System	Name	Design ID	Type	Sub type	Category	Parent	Child	Gate	Failure Rate Replacement [1/10^6hours]
SK	ML11_seg	SK_ml_0	Component	line_segment	Level 0	ML11	NA	NA	0.00722
SK	ML11_anchor	SK_anchor_2	Component	anchor	Level 0	ML11	NA	NA	0.000278
SK	ML11	NA	System	mooring_line	Level 1	SK1	[ML11_seg, ML11_anchor]	AND	NA
SK	ML12_seg	SK_ml_0	Component	line_segment	Level 0	ML12	NA	NA	0.00722
SK	ML12_anchor	SK_anchor_2	Component	anchor	Level 0	ML12	NA	NA	0.000278
SK	ML12	NA	System	mooring_line	Level 1	SK1	[ML12_seg, ML12_anchor]	AND	NA
SK	ML13_seg	SK_ml_0	Component	line_segment	Level 0	ML12	NA	NA	0.00722
SK	ML13_anchor	SK_anchor_2	Component	anchor	Level 0	ML12	NA	NA	0.000278
SK	ML13	NA	System	mooring_line	Level 1	SK1	[ML13_seg, ML13_anchor]	AND	NA
SK	ML21_seg	SK_ml_0	Component	line_segment	Level 0	ML21	NA	NA	0.00722
SK	ML21_anchor	SK_anchor_2	Component	anchor	Level 0	ML21	NA	NA	0.000278
SK	ML21	NA	System	mooring_line	Level 1	SK2	[ML21_seg, ML21_anchor]	AND	NA
SK	ML22_seg	SK_ml_0	Component	line_segment	Level 0	ML22	NA	NA	0.00722
SK	ML22_anchor	SK_anchor_2	Component	anchor	Level 0	ML22	NA	NA	0.000278

Sys tem	Name	Design ID	Type	Sub type	Cate gory	Parent	Child	Gate	Failure Rate Replacement [1/10^6hours]
SK	ML22	NA	System	mooring_line	Level 1	SK2	[ML22_seg, ML22_anchor]	AND	NA
SK	ML23_seg	SK_ml_0	Component	line_segment	Level 0	ML22	NA	NA	0.00722
SK	ML23_anchor	SK_anchor_2	Component	anchor	Level 0	ML22	NA	NA	0.000278
SK	ML23	NA	System	mooring_line	Level 1	SK2	[ML23_seg, ML23_anchor]	AND	NA
SK	ML31_seg	SK_ml_0	Component	line_segment	Level 0	ML31	NA	NA	0.00722
SK	ML31_anchor	SK_anchor_2	Component	anchor	Level 0	ML31	NA	NA	0.000278
SK	ML31	NA	System	mooring_line	Level 1	SK3	[ML31_seg, ML31_anchor]	AND	NA
SK	ML32_seg	SK_ml_0	Component	line_segment	Level 0	ML32	NA	NA	0.00722
SK	ML32_anchor	SK_anchor_2	Component	anchor	Level 0	ML32	NA	NA	0.000278
SK	ML32	NA	System	mooring_line	Level 1	SK3	[ML32_seg, ML32_anchor]	AND	NA
SK	ML33_seg	SK_ml_0	Component	line_segment	Level 0	ML32	NA	NA	0.00722
SK	ML33_anchor	SK_anchor_2	Component	anchor	Level 0	ML32	NA	NA	0.000278
SK	ML33	NA	System	mooring_line	Level 1	SK3	[ML33_seg, ML33_anchor]	AND	NA
SK	SK1_x	NA	System	stationkeeping	Level 2	SK	[ML11, ML12, ML13]	AND	NA
SK	SK2_x	NA	System	stationkeeping	Level 2	SK	[ML21, ML22, ML23]	AND	NA
SK	SK3_x	NA	System	stationkeeping	Level 2	SK	[ML31, ML32, ML33]	AND	NA
SK	SK	NA	System	stationkeeping	Level 3	NA	[SK1_x, SK2_x, SK3_x]	AND	NA

TABLE 5.5 CABLE DESIGN EXAMPLE

Attribute	Description	Value	Units
marker	ED internal reference	1	[-]
db ref	Cables Catalogue reference	3	[-]
type	Cable type	array	[-]
burial_depth	Cable routes burial depth	[1.0, 1.0, 1.5, ..., 0.5, 0.0]	m
split_pipe	Cable routes split pipe protection requirement	[False, True, ..., True]	bool
c_matress	Cable routes concrete mattress protection requirement	[False, False, ..., False]	bool
current_rating	Cable rated current	180.0	A
voltage_rating	Cable rated voltage	6600.0	V
cable_x	Cable routes x UTM coordinates	[1000, 1010, 1020, ..., 1020]	m
cable_y	Cable routes y UTM coordinates	[200, 200, 200, ..., 210]	m
layer 1 start	Cable routes first seabed layer	[-50, -50, -50, ..., -50]	m
layer 1 type	Cable routes seabed type of layer 1	[sands, sands, ..., rocks]	[-]

TABLE 5.6 COLLECTION POINT DESIGN EXAMPLE

Attribute	Description	Value	Units
marker	ED internal reference	1	[-]
db ref	Collection point Catalogue reference	3	[-]
type	Collection point type	hub	[-]
location	Collection point UTM location	[1000, 200, -50]	[m,m,m]
output_connectors	Output electrical interfaces	Dry-mate	[-]
intput_connectors	Output electrical interface	Wet-mate	[-]
v1	Transformer primary rated voltage	6600.0	V
v2	Transformer secondary rated voltage	6600.0	V

TABLE 5.7 STATION KEEPING DRAG ANCHOR DESIGN EXAMPLE

Attribute	Description	Value	Units
type	Anchor type	Drag-anchor	[-]
id	Anchor ID in the Catalogue	anchor_0	[-]
drymass	Anchor drymass	1500.0	kg
dimensions	Anchor dimensions [*length* x *width* x *height*]	[1.5, 1.2, 1.0]	[m,m,m]

TABLE 5.8 FARM LAYOUT VARIABLE

Attribute	Description	Value	Units
farm			[-]
deviceID	Device ID	[0, 1, 2]	[-]
easting	Devices easting UTM coordinates	[0, 100, 200]	m
northing	Devices northing UTM coordinates	[0, 100, 200]	m
number_devices	Number of devices in the farm	3	[-]

TABLE 5.9 EXAMPLE OF THE MET-OCEAN CONDITIONS VARIABLE

Year	Month	Day	Hour	Hs	Tp	Ws	Cs
...	...	...	...	...	...	...	...
1992	1	15	5	1.5	7.5	5.5	0.1
1992	1	15	6	1.8	8.0	5.2	0.2
1992	1	15	7	1.9	8.0	5.3	0.1
1992	1	15	8	2.1	8.1	5.7	0.1
1992	1	15	9	1.9	7.9	6.0	0.2
1992	1	15	10	1.8	7.9	6.5	0.2
1992	1	15	11	1.9	8.0	7.0	0.2
1992	1	15	12	2.1	8.0	7.1	0.1
1992	1	15	13	1.9	8.0	7.1	0.1
1992	1	15	14	2.1	8.1	6.8	0.1
1992	1	15	15	2.2	8.2	6.5	0.1
1992	1	15	16	2.1	8.2	5.2	0.1
1992	1	15	17	1.9	8.0	3.1	0.1
...	...	...	...	...	...	...	...

TABLE 5.10 SEABED TYPE VARIABLE

Attribute	Description	Value	Units
latitude	UTM coordinate: latitude	[0, 0, 0, 0, …, 1000]	m
longitude	UTM coordinate: longitude	[0, 1, 2, 3, …, 1000]	m
value	Seabed soil type	[sands, sands, finesands, …]	[-]

TABLE 5.11 LEASE AREA BATHYMETRY

Attribute	Description	Value	Units
latitude	UTM coordinate: latitude	[0, 0, 0, 0, …, 1000]	m
longitude	UTM coordinate: longitude	[0, 1, 2, 3, …, 1000]	m
value	Water depth	[50.0, 50.3, 51.2, 74.3]	m

5.1.2 RESULTS

After running the LMO functionalities for the defined inputs, an installation solution is generated as presented in Table 5.12. The installation Gantt is represented in Figure 5.1.

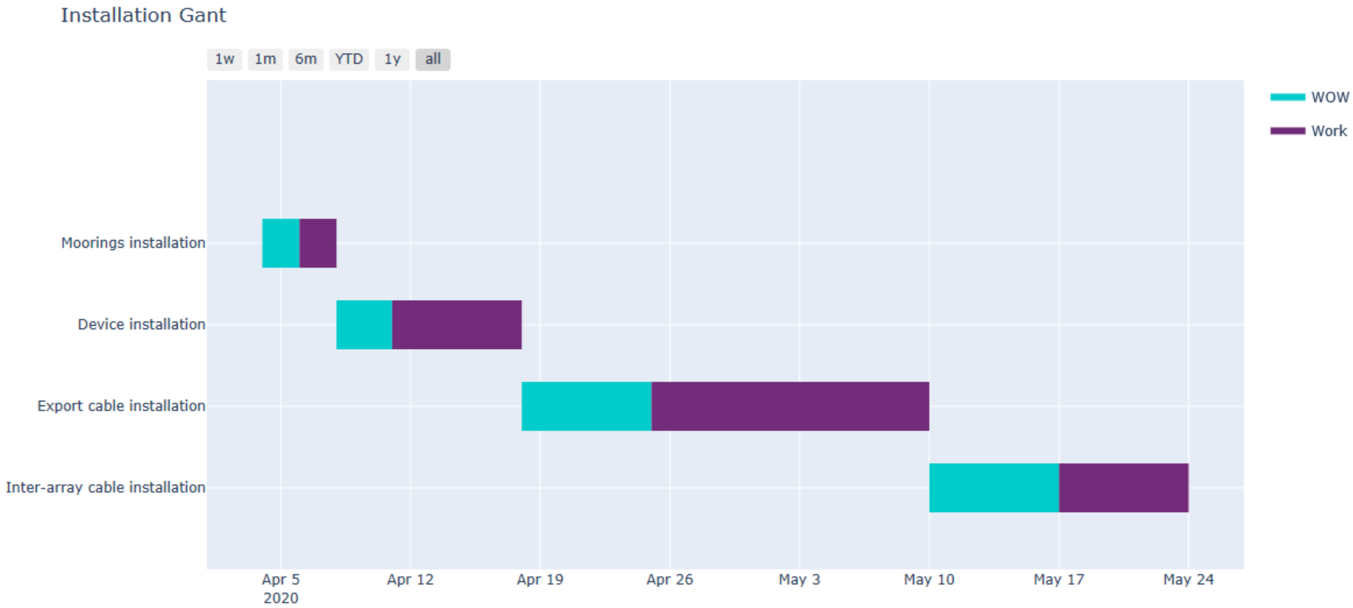


FIGURE 5.1 INSTALLATION GANTT EXAMPLE

TABLE 5.12 INSTALLATION SOLUTION

operation_id	name	tech_group	operation_type	technologies	date start	date end	duration_total	waiting_start	vessel_consumption	VC	operation_cost	Terminal id	port_cost	cost_label
[-]	[-]	[-]	[-]	[-]	[-]	[-]	[h]	[h]	[ton]	[-]	[€]	[-]	[€]	[-]
OP02_1	Mooring installation	Station Keeping	Drag-embedment	[SK1, SK2, SK3]	06/04/2020	08/04/2020	85.5	39.5	15.5	VEC_052	137210.0	P103	683.6	CAPEX
OP05_1	Device installation	Energy Transformation	Device	[OEC1, OEC2, OEC3]	11/04/2020	18/04/2020	229.0	65.5	247.2	VEC_007	2612751.6	P103	12999.8	CAPEX
OP06_1	Cable installation	Energy Delivery	Simultaneous	[EC1, CP1]	25/04/2020	10/05/2020	537.2	168.5	488.3	VEC_042	4880807.3	P103	24283.6	CAPEX
OP07_1	Cable installation	Energy Delivery	Simultaneous	[AC1, AC2, AC3]	17/05/2020	24/05/2020	323.7	160.3	368.9	VEC_042	7628584.9	P103	37953.2	CAPEX

5.2 MAINTENANCE

Considering an array of three wave energy converters, the input data could be collected as in the following sections. In order to calculate the replacement part costs, the bill of materials is also needed.

5.2.1 INPUTS

TABLE 5.13 EXAMPLE INPUTS FOR TESTING THE ECONOMIC ASSESSMENT FUNCTIONALITY

Quantity	Sub-Quantity	Source	Value	Unit
Level of complexity	—	SG/User	3	—
Number of devices	—	EC	3	—
Device topology	—	EC	Floating wave	—
Hierarchy_ET	—	ET	(See Table 5.2)	—
Hierarchy_ED	—	ED	(See Table 5.3)	—
Hierarchy_SK	—	SK	(See Table 5.4)	—
BOM ET	—	ET	(See Table 5.14)	—
BOM ED	—	ED	(See Table 5.15)	—
BOM SK	—	SK	(See Table 5.16)	—
Cable_design	—	ED	(See Table 5.5Table 5.13)	—
Cp_design	—	ED	(See Table 5.6)	—
SK_design	—	SK	(See Table 5.7)	—
Device_mass	—	MC	1,000,000	kg
Farm layout	—	EC	(See Table 5.8)	—
Metocean timeseries	*Hs, Tp, Ws, Cs*	SC	(See Table 5.9)	[m, s, m/s, m/s]
Soil type		SC	(See Table 5.10)	—
Lease area bathymetry		SC	(See Table 5.11)	—
Piling method	—	User	Hammering	—
Cable burial method	—	ED	Ploughing	—
Device transport method	—	User	Dry	—
Device load-out method	—	User	Lift away	—
Export cable landfall method	—	User	OCT	—
Installation start date	—	User	05/05/2020	DD/MM/YYYY
Project lifetime	—	User	25	years
Topside maintenance	—	User	True	—
Tow-to-port maintenance	—	User	True	—
Port terminals database	—	Catalogue	—	—
ROV Equipment database	—	Catalogue	—	—
Piling Equipment database	—	Catalogue	—	—
Burial Equipment database	—	Catalogue	—	—
Vessel combinations database	—	Catalogue	—	—
Vessel cluster database	—	Catalogue	—	—
Maintenance operations database	—	Catalogue	(See Table 3.5, Table 3.7)	—

Quantity	Sub-Quantity	Source	Value	Unit
Maintenance activities database	—	Catalogue	—	—

TABLE 5.14 ENERGY TRANSFORMATION BILL OF MATERIALS EXAMPLE

Design id	Id_catalogue	Size	Component name	Units	Unit costs [€[	Total cost [€]
ET_01	H2M_01	1.2	Airturbine	6	2000	12000
ET_01	M2E_01	1.00E+05	SCIG	6	2000	12000
ET_01	E2G_01	1.00E+05	B2B	6	2000	12000

TABLE 5.15 ENERGY DELIVERY BILL OF MATERIALS EXAMPLE

Design id	Id_catalogue	Size	Component name	Units	Unit costs [€[	Total cost [€]
CAT_Cable001	*CAT_Cable001*	–	Cable AC	3000	2300	6900000
CAT_Cable062	*CAT_Cable062*	–	Export cable	9000	5000	45000000
CAT_colpoint	*CAT_colpoint*	–	Subsea hub	1	1000000	1000000
CAT_con001	*CAT_con001*	–	Connector wet-mate	3	1000000	3000000
Tot_onshoreinf	–	–	***Total onshore infrastructure***	–	–	500000
Tot_transm	–	–	***Total Transmission network***	–	–	46000000
Tot_network	–	–	***Total Array network***	–	–	9900000
Tot_colpoint	–	–	***Total Collection point***	–	–	1000000

TABLE 5.16 STATION KEEPING BILL OF MATERIALS EXAMPLE

Design id	Id_catalogue	Size	Component name	Units	Unit costs [€[	Total cost [€]
CAT_Anchor001	Anchor	–	Anchor	9	5000	45000
CAT_ML001	Mooring line	–	Mooring line	2700	300	810000
Tot_SK		-	***Total costs of SK system***		-	**855000**

5.2.2 RESULTS

For the previously described inputs, the Logistics and Marine Operations module produces a maintenance solution (comprised of preventive and corrective maintenance interventions), compiled into two different tables for simplicity. For brevity, only five years of preventive maintenance interventions were included in Table 5.17, while Table 5.19 corresponds to twenty years of project. A list of failure events as shown in Table 5.18. For each device, a downtime table will be produced as the one in Table 5.20.

TABLE 5.17 MAINTENANCE SOLUTION OUTPUTS (VIEW OF PREVENTIVE MAINTENANCE INTERVENTIONS ONLY)

operation_id	name	tech_group	operation_type	technologies	start_date	end_date	proj_year	duration_net	vessel_consumption	vec	operation_cost	base_port_id	port_cost	downtime	cost_label
[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[h]	[ton]	[-]	[€]	[-]	[€]	[h]	[-]
OP10_0	Topside inspection	ET	Preventive maintenance	[ET1, ET2, ET3]	01/05/2022	03/05/2022	1	63.4	8,000	VEC_067	700,000	P103	8,000	9	OPEX
OP10_1	Topside inspection	ET	Preventive maintenance	[ET1, ET2, ET3]	02/05/2023	04/05/2023	2	63.4	8,000	VEC_067	700,000	P103	8,000	9	OPEX
OP11_0	Underwater inspection	ET	Preventive maintenance	[ET1, ET2, ET3]	05/05/2023	07/05/2023	2	66.4	8,500	VEC_072	700,000	P103	8,000	12	OPEX
OP10_2	Topside inspection	ET	Preventive maintenance	[ET1, ET2, ET3]	02/05/2024	04/05/2024	3	63.4	8,000	VEC_067	700,000	P103	8,000	9	OPEX
OP12_0	Mooring inspection	SK	Preventive maintenance	[SK1, SK2, SK3]	05/05/2024	07/05/2024	3	66.4	8,500	VEC_075	700,000	P103	8,000	12	OPEX
OP13_0	Array cable inspection	ED	Preventive maintenance	[AC1, AC2, AC3]	09/05/2024	11/05/2024	3	66	8,400	VEC_078	700,000	P103	8,000	20	OPEX
OP10_3	Topside inspection	ET	Preventive maintenance	[ET1, ET2, ET3]	01/05/2025	03/05/2025	4	63.4	8,000	VEC_067	700,000	P103	8,000	9	OPEX
OP11_1	Underwater inspection	ET	Preventive maintenance	[ET1, ET2, ET3]	06/05/2025	08/05/2025	4	66.4	8,500	VEC_072	700,000	P103	8,000	12	OPEX
OP10_4	Topside inspection	ET	Preventive maintenance	[ET1, ET2, ET3]	02/05/2026	04/05/2026	5	63.4	8,000	VEC_067	700,000	P103	8,000	9	OPEX
OP14_0	Export cable inspection	ED	Preventive maintenance	[EC1]	06/05/2026	08/05/2026	5	63	7,900	VEC_079	700,000	P103	8,000	0	OPEX

TABLE 5.18 FAILURE EVENTS GENERATED USING RAMS'S TTF FUNCTION

Object ID	Failure rate [1/year]	TTF [h]	Failure dates counting from 01/05/2021
MechT_1_1	*0.0792*	82173	15/09/2030
ML1_seg_0	*0.00722*	144558	27/10/2037
AC1	*0.0146*	120972	17/02/2035
DM1	*0.0124*	88316	29/05/2031

TABLE 5.19 MAINTENANCE SOLUTION OUTPUTS (VIEW OF CORRECTIVE MAINTENANCE INTERVENTIONS ONLY)

operation_id	name	tech_group	operation_type	technologies	start_date	end_date	proj_year	duration_total	Vessel consumption	vec	operation_cost	base_port_id	port_cost	downtime	fail_date	replaced_parts	replaced_parts_cost	cost_label
[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[h]	[ton]	[-]	[€]	[-]	[€]	[h]	[-]	[-]	[€]	[-]
OP15_0	Device retrieval	ET	Corrective maintenance	MechT_1_1	17/09/2030	21/09/2030	10	157	25,000	VEC_083	820,000	P103	10,000	157	15/09/2030	NA	NA	OPEX
OP16_0	Device repair at port	ET	Corrective maintenance	MechT_1_1	22/09/2030	24/09/2030	10	72	NA	NA	60,000	P103	NA	72	NA	Air turbine	2,000	OPEX
OP17_0	Device redeployment	ET	Corrective maintenance	MechT_1_1	25/09/2030	02/10/2030	10	183	25,000	VEC_087	820,000	P103	10,000	183	NA	NA	NA	OPEX
OP19_0	Mooring line replacement	SK	Corrective maintenance	ML1_seg_0	01/11/2037	12/11/2037	17	267	35,000	VEC_092	1,020,000	P103	13,000	267	27/10/2037	Mooring line	2,700,000	OPEX
OP20_0	Cable replacement	ED	Corrective maintenance	AC1	25/02/2035	10/03/2035	14	315	120,000	VEC_094	1,050,000	P103	40,000	315	17/02/2035	Cable AC	2,300,000	OPEX
OP21_0	Cable repair	ED	Corrective maintenance	DM1	30/05/2031	07/06/2031	11	187	180,000	VEC_095	940,000	P103	40,000	561	29/05/2031	Connector	1,000,000	OPEX

TABLE 5.20 EXAMPLE DOWNTIME IN HOURS FOR OEC1

Year	January	February	March	April	May	June	July	August	September	October	November	December
1	475	256	386	153	369	193	134	77	3	97	205	249
2	385	475	487	91	225	336	2	10	84	256	165	241
3	325	368	418	262	298	184	122	15	64	93	284	151
4	380	379	461	329	238	81	60	121	30	196	123	151
5	289	263	328	263	203	243	137	133	36	100	197	255
6	330	287	313	85	349	147	124	67	129	238	118	145
7	452	470	471	145	256	177	47	39	42	145	102	175
8	302	451	441	306	346	245	35	124	112	220	261	296
9	448	385	349	80	124	211	45	18	58	181	253	167
10	516	214	457	278	326	113	139	24	15	133	92	153
11	327	231	417	179	217	159	86	63	108	280	226	118
12	273	230	271	203	273	307	106	70	41	113	116	279
13	287	243	505	187	178	165	83	105	78	211	202	85
14	450	414	261	260	100	253	50	43	77	153	232	75
15	453	475	344	266	98	196	56	39	109	238	183	130

6. FUTURE WORK

The present deliverable describes the framework and main functionalities of the Logistics and Marine Operations (LMO) module, implemented during tasks T5.2 and T5.8 of the DTOceanPlus project. At the time of writing, the module can be run in a standalone mode. However, in order to fully integrate it with the remaining modules of the DTOceanPlus suite of design tools, the following steps are required:

- The OpenAPI file should be "linked" to the other module's equivalent files, in order to guarantee a smooth, robust, and consistent data flow among the different pieces of the tool.
- The GUI will be developed to be consistent with the other tools and to provide the user with an easy access to the tool and its functionalities.
- The unit tests, including Pytest, Dredd and PACT, will be improved to fix any potential bugs.
- The verification in T5.9 will be started, when all the modules are fully developed.

The remaining work is part of the continuous development/integration methodology, as described in Deliverable D7.4 "Handbook of software implementation". These activities will be developed within T5.9 Verification of the code – beta version in order to extend the functionality of the LMO module from standalone to fully integrated in the DTOceanPlus toolset.

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ANNEX I: VESSEL COMBINATIONS

TABLE I.1 VESSEL COMBINATIONS CATALOGUE FOR EACH OPERATION

Fleet ID	Type	Item	Transportation	Qty	Main vessel	Qty	Tow vessel	Qty	Support vessel
VEC_001	Device Installation	Device	On deck Transportation	1	Propelled crane vessel				
VEC_002	Device Installation	Device	On deck Transportation	1	Jack-up Vessel				
VEC_003	Device Installation	Device	On deck Transportation	1	SOV Gangway / SOV Accommodation				
VEC_004	Device Installation	Device	Dry tow Transportation	1	Non propelled crane Vessel	1	Tug		
VEC_005	Device Installation	Device	Dry tow Transportation	1	Transport Barge	1	Tug		
VEC_006	Device Installation	Device	Dry tow Transportation	1	Semi-submersible	1	Tug		
VEC_007	Device Installation	Device	Wet tow Transportation			1	AHTS / Tug		
VEC_008	Device Installation	Device	Wet tow Transportation			1	AHTS / Tug	1	Multicat
VEC_009	Device Installation	Device	Wet tow Transportation			2	AHTS / Tug	1	Multicat
VEC_010	Device Installation	Device	Wet tow Transportation			3	AHTS / Tug	1	Multicat
VEC_011	Collection point Installation	Collection Point	On deck Transportation	1	Propelled crane vessel				
VEC_012	Collection point Installation	Collection Point	On deck Transportation	1	Jack-up Vessel				
VEC_013	Collection point Installation	Collection Point	On deck Transportation	1	SOV Gangway / SOV Accommodation				
VEC_014	Collection point Installation	Collection Point	Dry tow Transportation	1	Non propelled crane Vessel	1	Tug		
VEC_015	Collection point Installation	Collection Point	Dry tow Transportation	1	Transport Barge	1	Tug		
VEC_016	Collection point Installation	Collection Point	Dry tow Transportation	1	Semi-submersible	1	Tug		
VEC_017	Collection point Installation	Collection Point	Wet tow Transportation			1	AHTS / Tug		
VEC_018	Collection point Installation	Collection Point	Wet tow Transportation			1	AHTS / Tug	1	Multicat
VEC_019	Collection point Installation	Collection Point	Wet tow Transportation			2	AHTS / Tug	1	Multicat
VEC_020	Collection point Installation	Collection Point	Wet tow Transportation			3	AHTS / Tug	1	Multicat
VEC_021	Foundation Installation	Pile	On deck Transportation	1	AHTS / Tug				
VEC_022	Foundation Installation	Pile	On deck Transportation	1	Propelled Crane vessel				
VEC_023	Foundation Installation	Pile	Dry tow Transportation	1	Non propelled crane Vessel	1	AHTS / Tug		
VEC_024	Foundation Installation	Pile	Dry tow Transportation	1	Transport Barge	1	AHTS / Tug		

Fleet ID	Type	Item	Transportation	Qty	Main vessel	Qty	Tow vessel	Qty	Support vessel
VEC_025	Foundation Installation	Pile	On deck Transportation	1	Jack-up Vessel				
VEC_026	Foundation Installation	Pile	Wet tow Transportation			1	AHTS / Tug		
VEC_027	Foundation Installation	Suction caisson	On deck Transportation	1	AHTS				
VEC_028	Foundation Installation	Suction caisson	On deck Transportation	1	Propelled Crane vessel				
VEC_029	Foundation Installation	Suction caisson	Dry tow Transportation	1	Transport Barge	1	AHTS / Tug		
VEC_030	Foundation Installation	Suction caisson	Dry tow Transportation	1	Non propelled crane Vessel	1	AHTS / Tug		
VEC_031	Foundation Installation	Suction caisson	On deck Transportation	1	Jack-up Vessel				
VEC_032	Foundation Installation	Gravity based anchor	On deck Transportation	1	AHTS				
VEC_033	Foundation Installation	Gravity based anchor	On deck Transportation	1	Propelled Crane vessel				
VEC_034	Foundation Installation	Gravity based anchor	On deck Transportation	1	SOV Gangway / SOV Accommodation				
VEC_035	Foundation Installation	Gravity based anchor	Dry tow Transportation	1	Transport Barge	1	AHTS / Tug		
VEC_036	Foundation Installation	Gravity based anchor	Dry tow Transportation	1	Non propelled crane Vessel	1	AHTS / Tug		
VEC_037	Foundation Installation	Gravity based anchor	On deck Transportation	1	Jack-up Vessel				
VEC_038	Dredging	Sand	-	1	Dredger				
VEC_039	Trenching	Dredging / Ploughing / Cutting / Jetting	On deck Transportation	1	AHTS				
VEC_040	Trenching	Dredging / Ploughing / Cutting / Jetting	On deck Transportation	1	Dredger				
VEC_041	Trenching	Dredging / Ploughing / Cutting / Jetting	On deck Transportation	1	SOV Gangway / SOV Accommodation				
VEC_042	Cable installation	Simultaneous	On deck Transportation	1	Cable Laying Vessel (CLV)				
VEC_043	Cable installation	Post-burial	On deck Transportation	1	Cable Laying Vessel (CLV)				
VEC_044	Cable installation	With umbilicals	On deck Transportation	1	Cable Laying Vessel (CLV)				
VEC_045	Post-lay cable burial	Jetting / Cutting	On deck Transportation	1	AHTS				
VEC_046	Post-lay cable burial	Jetting / Cutting	On deck Transportation	1	SOV Gangway / SOV Accommodation				
VEC_047	External protection installation	Concrete Mattresses / Rock Filter Bags	On deck Transportation	1	Propelled Crane Vessel				
VEC_048	External protection installation	Concrete Mattresses / Rock Filter Bags	Dry tow Transportation	1	Non propelled crane Vessel	1	AHTS / Tug		
VEC_049	External protection installation	Concrete Mattresses / Rock Filter Bags	On deck Transportation	1	SOV Gangway / SOV Accommodation				
VEC_050	External protection installation	Concrete Mattresses / Rock Filter Bags	On deck Transportation	1	Transport Barge				
VEC_051	External protection installation	Rock dumping	On deck Transportation	1	Transport Barge				

Fleet ID	Type	Item	Transportation	Qty	Main vessel	Qty	Tow vessel	Qty	Support vessel
VEC_052	Mooring installation	Drag-embedment	On deck Transportation	1	AHTS				
VEC_053	Mooring installation	Drag-embedment	On deck Transportation	1	Tug				
VEC_054	Mooring installation	Drag-embedment	On deck Transportation	1	Multicat				
VEC_055	Mooring installation	Direct-embedment / Hydrojetting	On deck Transportation	1	AHTS				
VEC_056	Mooring installation	Direct-embedment / Hydrojetting	On deck Transportation	1	Multicat				
VEC_057	Mooring installation	Pre-installed	On deck Transportation	1	AHTS				
VEC_058	Mooring installation	Pre-installed	On deck Transportation	1	SOV Gangway / SOV Accommodation				
VEC_059	Mooring installation	Pre-installed	On deck Transportation	1	Multicat				
VEC_060	Support Structure Installation	Jacket / Tripod	Wet tow Transportation			1	AHTS / Tug		
VEC_061	Support Structure Installation	Jacket / Tripod	On deck Transportation	1	Propelled Crane vessel				
VEC_062	Support Structure Installation	Jacket / Tripod	Dry tow Transportation	1	Non propelled crane Vessel	1	AHTS / Tug		
VEC_063	Support Structure Installation	Jacket / Tripod	Dry tow Transportation	1	Transport Barge	1	AHTS / Tug		
VEC_064	Support Structure Installation	Jacket / Tripod	On deck Transportation	1	Jack-up Vessel				
VEC_065	Support Structure Installation	Jacket / Tripod	On deck Transportation	1	SOV Gangway / SOV Accommodation				
VEC_066	Survey	Survey	On deck Transportation	1	Survey vessel				
VEC_067	Preventive Maintenance	Topside Inspection	On deck Transportation	1	CTV				
VEC_068	Preventive Maintenance	Topside Inspection	On deck Transportation	1	Multicat				
VEC_069	Preventive Maintenance	Topside Inspection	On deck Transportation	1	DSV				
VEC_070	Preventive Maintenance	Underwater Inspection	On deck Transportation	1	CTV				
VEC_071	Preventive Maintenance	Underwater Inspection	On deck Transportation	1	Multicat				
VEC_072	Preventive Maintenance	Underwater Inspection	On deck Transportation	1	DSV				
VEC_073	Preventive Maintenance	Mooring Inspection	On deck Transportation	1	CTV				
VEC_074	Preventive Maintenance	Mooring Inspection	On deck Transportation	1	Multicat				
VEC_075	Preventive Maintenance	Mooring Inspection	On deck Transportation	1	DSV				
VEC_076	Preventive Maintenance	Array Cable Inspection	On deck Transportation	1	CTV				
VEC_077	Preventive Maintenance	Array Cable Inspection	On deck Transportation	1	Multicat				
VEC_078	Preventive Maintenance	Array Cable Inspection	On deck Transportation	1	DSV				

Fleet ID	Type	Item	Transportation	Qty	Main vessel	Qty	Tow vessel	Qty	Support vessel
VEC_079	Preventive Maintenance	Export Cable Inspection	On deck Transportation	1	CTV				
VEC_080	Corrective Maintenance	Device Retrieval	On deck Transportation	1	Propelled Crane vessel				
VEC_081	Corrective Maintenance	Device Retrieval	On deck Transportation	1	AHTS				
VEC_082	Corrective Maintenance	Device Retrieval	On deck Transportation	1	Multicat				
VEC_083	Corrective Maintenance	Device Retrieval	Wet tow Transportation			1	AHTS / Tug		
VEC_084	Corrective Maintenance	Device Redeployment	On deck Transportation	1	Propelled Crane vessel				
VEC_085	Corrective Maintenance	Device Redeployment	On deck Transportation	1	AHTS				
VEC_086	Corrective Maintenance	Device Redeployment	On deck Transportation	1	Multicat				
VEC_087	Corrective Maintenance	Device Redeployment	Wet tow Transportation			1	AHTS / Tug		
VEC_088	Corrective Maintenance	Device Repair On Site	On deck Transportation	1	Propelled Crane vessel				
VEC_089	Corrective Maintenance	Device Repair On Site	On deck Transportation	1	AHTS				
VEC_090	Corrective Maintenance	Device Repair On Site	On deck Transportation	1	Multicat				
VEC_091	Corrective Maintenance	Mooring Line Replacement	On deck Transportation	1	Propelled Crane vessel				
VEC_092	Corrective Maintenance	Mooring Line Replacement	On deck Transportation	1	AHTS				
VEC_093	Corrective Maintenance	Mooring Line Replacement	On deck Transportation	1	Multicat				
VEC_094	Corrective Maintenance	Cable Replacement	On deck Transportation	1	Cable Laying Vessel (CLV)				
VEC_095	Corrective Maintenance	Cable Repair	On deck Transportation	1	Cable Laying Vessel (CLV)				

ANNEX II: CLUSTER ANALYSIS

The database consists of a total number of 14,847 vessels and 46 technical parameters. Given the large number of samples, it is reasonable to assume that the data contained in the database is representative of the whole offshore industry fleet. The purpose of performing a statistical analysis to the database is to aggregate the large list of vessels into vessel groups, i.e. clusters with similar characteristics, that can be used as a reference for the vessel selection process of the Logistics module. A schematic representation of a two-dimensional vessel clustering process is presented in Figure II.1.

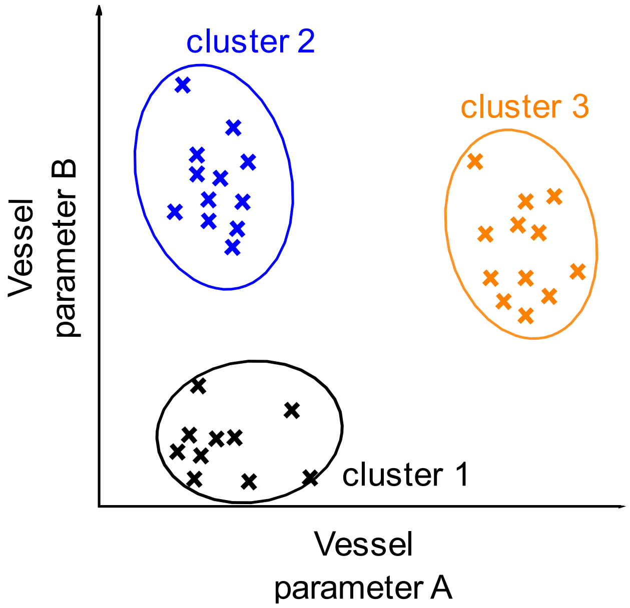

FIGURE II.1 SCHEMATIC REPRESENTATION OF THE VESSEL CLUSTERING PROCESS FOR TWO PARAMETERS

On some occasions, the raw information about a given vessel was not complete as some parameters were missing. For this reason, vessel data was firstly pre-processed and regressions between vessel parameters were unveiled. This allowed to increase the number of vessel samples to be considered in the analysis. In Figure II.2, the linear relationship between jack-up leg length and the vessel's maximum operating water depth is presented. This enabled to consider jack-up vessels that did not have one of the two technical parameters, which would otherwise be discarded.

For each vessel type, the core technical parameters were identified. Vessels were clustered according to these parameters using the K-Means data clustering method, an unsupervised machine learning algorithm [62]. Before feeding the vessel data into the algorithm, data was standardised, which consists of rescaling the values of the variables in the dataset so they share a common scale. This is particularly important since the database data comprised of variables with different units (e.g., kilograms, tons, meters, square meters), and with very different scales (e.g., 0-1 vs 0-1000).

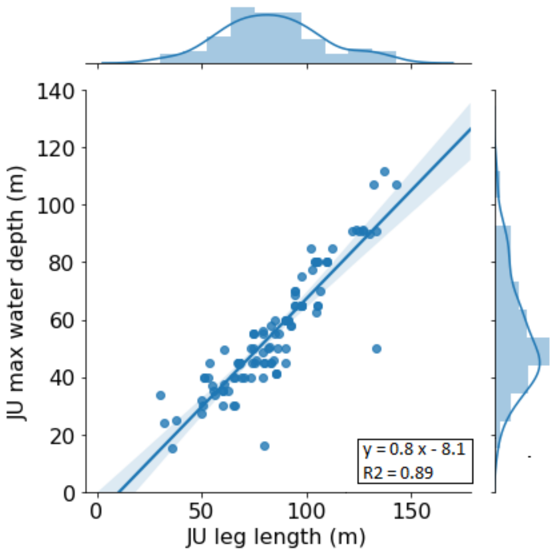

FIGURE II.2 RELATIONSHIP BETWEEN JACK-UP LEG LENGTH AND ITS MAXIMUM OPERATING DEPTH

Through an iterative process, the algorithm labels datapoints in accordance to the closest distance to a centroid, in other words assembling datapoints in families in function of the minimal distance to the closest centroid [63]. A graphical and numerical value output is provided for each cluster within each vessel type. The graphical output displays a maximum of three dimensions as for the numerical output, percentile values P25, P50 and P75 are provided for every cluster within a vessel type.

The output of the vessel clustering process for the AHTS vessel is represented in Table II.1. The clustering parameters used for the obtention of this table were bollard pull, total installed power, length overall and deadweight tonnage. A visual representation of the vessel clusters is presented in Figure II.3.

TABLE II.1 RESULTS OF THE CLUSTER ANALYSIS OF THE AHTS VESSEL TYPE

	Unit	Cluster 1			Cluster 2			Cluster 3			Cluster 4		
		P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75
LOA (m)	m	41.18	48	51.48	85.39	90.29	92	59.2	60	64.53	69.6	72.5	76
Beam	m	11005	11.8	12.8	20.06	22	22	13.8	14.95	15.8	16	16.6	17.4
Depth	m	4.6	4.91	5.3	9	9.5	9.6	5.5	6.02	6.5	7.2	7.5	8
No. Passengers	–	14	18	23.75	38	53.5	70	15.75	24	42	24	30	36
Berths	–	14	18	24	38.75	54.5	60.5	22	28	42	24	30	36
Top Speed	km/h	23.2	23.6	25.0	30.9	32.8	33.3	22.8	24.1	25.9	26.1	27.8	29.6
Service speed	km/h	20.4	22.2	24.1	21.3	22.2	27.8	20.4	22.2	24.1	22.2	24.1	25.9
MDO Fuel capacity	ton	260	341.5	500	883	1020	1322	433.5	530	650	761	895.88	1030
IFO Fuel capacity	ton	320	400	565	1223.75	1462	2010	510.22	530	599.75	775.42	850	1117.3
GT	ton	499	704	891.5	4602	6186	7137.5	1329	1676	1890	2325	2605	3070
Free deck area	m²	125	204	250	660	750	800	330	363	418	462	515	578
Helipad	–	0	0	0	0	0	0	0	0	0	0	0	0
DP[24]	–	-1	-1	-1	2	2	2	-1	1	1	1	2	2

[24] Vessels without DP systems were attributed a "-1" to facilitate data processing.

	Unit	Cluster 1			Cluster 2			Cluster 3			Cluster 4		
		P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75
Dead Weight Tonnage	ton	411.17	676.5	868	3866.5	4200	4547	1263.5	1440	1726	2241.5	2515	2947.3
Draft	meter	3.8	4.2	4.5	7.5	7765	7.94	4.75	4.95	5.1	5.9	6.1	6.6
Total Installed Power	kW	2354	2984	3750.03	13380	16000	17280	3839	4120	5280	7522	9000	10595
Number of Engines	–	2	2	2	2	4	4	2	2	2	2	2	4
Crane Lifting capacity	ton	3	5	10	10	15	82.5	3	4.1	10	5	5	10
Moonpool	–	0	0	0	0	0	0	0	0	0	0	0	0
Crane Outreach	meter	5	10	12	10	12	15.25	8	10	12.8	10	12	14
Deck strength	t/m²	5	5	6	10	10	10	5	5.25	7.5	5	5.75	10
Bollard Pull	ton	40	50.18	64.75	210.5	250	282	65	71	84	123	150	165
Construction year	–	1979	2005	2009	2006	2010	2014	1987	2009	2012	2003	2009	2012
ROV Ready	–	0	0	0	0	0	0	0	0	0	0	0	0

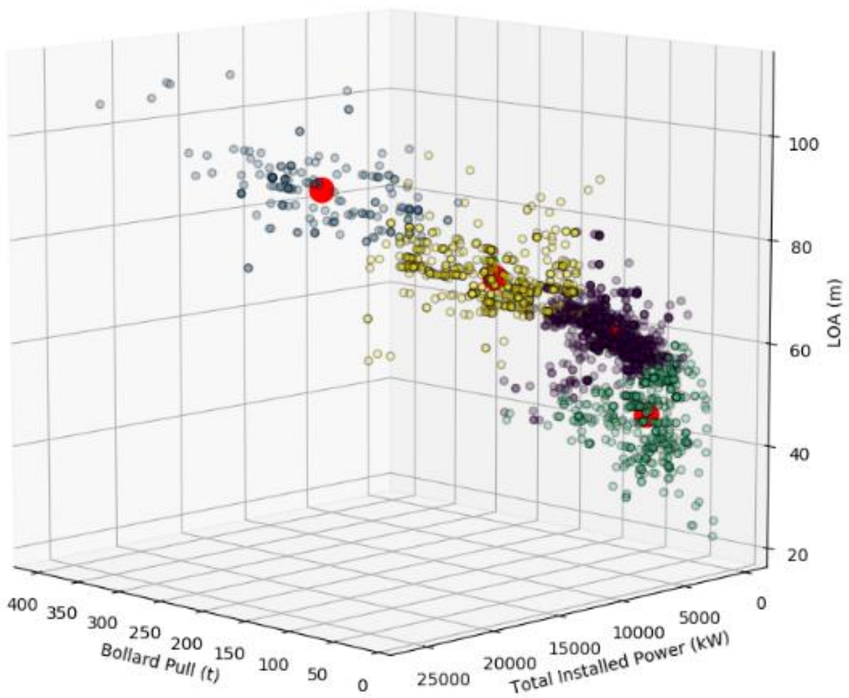

FIGURE II.3 THREE-DIMENSIONAL VIEW OF THE AHTS CLUSTERS

CONTACT DETAILS

Mr. Pablo Ruiz-Minguela

Project Coordinator, TECNALIA

www.dtoceanplus.eu

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EDF terminated its participation on 31st January 2019.

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