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

Deliverable D5.5

Energy Delivery Tools – Alpha version

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EXECUTIVE SUMMARY

The Energy Delivery (ED) tools will form part of the DTOceanPlus suite of second-generation open-source design tools for ocean energy. The ED module will design the electrical infrastructure to transmit power from ocean energy convertors to the onshore electrical grid.

Deliverable D5.5 "Energy Delivery Tools – alpha version" of the DTOceanPlus project includes the details of the Deployment Design Tools module: "Energy Delivery", and it presents the result of the work developed during the tasks T5.2 and T5.6 of the project. This document serves as the technical manual of the alpha version of the ED module, including all the data requirements, main functions, interfaces and all pertinent technical details.

This document describes the use cases and the functionalities, as well as the more technical aspects of the code implemented for the alpha version of this module. The ED module is built to be used as a standalone tool or within the framework of design tools of the DTOceanPlus project. It will offer two main design modes, a simplified design mode to give an estimate of costs and performance at an early stage, and a full design mode for later in the device/project development path.

The main outputs of the ED module are: optimised electrical network layouts and components for the electrical infrastructure, electrical losses within the network, and the power and energy delivered to the grid connection point.

The Business Logic, i.e. the core functions of the ED module, has been implemented in Python 3, based on the Electrical Sub-Systems design module from DTOcean 2.0. The code is provided with an Application Programming Interface (API), developed following the Open API specifications. The Business Logic of the new code was verified through the implementation of unit tests, guaranteeing easy maintainability for future developments of the module. The preliminary tests and verifications performed are also presented.

A section of this report is dedicated to examples, showing the capabilities of the module for the design of electrical infrastructure at various levels of complexity and array configurations.

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ABBREVIATIONS AND ACRONYMS

API	Application Programming Interface
BLP	Boundary-Layer Point
BOM	Bill of Materials
CP	Collection Point
CPX	Complexity (level of)
DP	Decline Point
EC	Energy Capture (DTOceanPlus module)
ED	Energy Delivery (DTOceanPlus module)
ESA	Environmental and Social Acceptance (DTOceanPlus module)
ET	Energy Transformation (DTOceanPlus module)
GCP	Grid Connection Point
GUI	Graphic User Interface
HOP	Hang-Off Point
HTTP	HyperText Transfer Protocol
LCOE	Levelised Cost of Energy
LMO	Logistics and Marine Operations (DTOceanPlus module)
LP	Lift Point
MC	Machine Characterisation (DTOceanPlus module)
ND	Number of devices
O&M	Operation and Maintenance
OEC	Ocean Energy Converter
OLP	Onshore Landing Point
PTO	Power Take-Off
RAMS	Reliability, Availability, Maintainability, Survivability (DTOceanPlus module)
REST	REpresentational State Transfer
SC	Site Characterisation (DTOceanPlus module)
SG	Stage Gate (DTOceanPlus module)
SI	Structured Innovation (DTOceanPlus module)
SK	Station Keeping (DTOceanPlus module)
SLC	System Lifetime Costs (DTOceanPlus module)
SPEY	System Performance and Energy Yield (DTOceanPlus module)
TDP	TouchDown Point
TEC	Tidal Energy Converter
TRL	Technology Readiness Level
TT	Technology Type (Tidal or Wave Energy Device)
WEC	Wave Energy Converter

GLOSSARY OF TERMS

Onshore Landing Point (OLP)	The point at which the subsea power cables cross the coast, which is also the limit of scope for the DTOceanPlus tools.
Grid Connection Point (GCP)	The point at which the OEC array is connected to the electrical grid, which often includes an onshore substation.
Transmission Collection Point (Trans CP)	Offshore collection point connecting an array to the OLP – could be a substation or hub. When devices in arrays act as CPs, they are not called Trans CP
Array Collection Point (Array CP)	Offshore collection points, within star networks, to which OECs are connected – could be a substation or hub
Transmission (or export) cable	Static subsea cable between OLP and collection point or device(s)
Array (or intra-array) cable	Static subsea cable between collection point(s) and/or device(s)
Umbilical cable	Dynamic cable between floating OEC and the static subsea network
Dry mate connector	A device used to connect electrical and data cables, to each other and to other equipment, where the connection must be made above water before being immersed
Wet mate connector	A device used to connect electrical and data cables, to each other and to other equipment, where the connection can be made underwater
Power factor	Defined as the ratio between real power P (kW) to apparent power S (kVA), where $S = \sqrt{(P^2 + Q^2)}$ and Q is the reactive power.

1. INTRODUCTION

1.1 SCOPE AND OUTLINE OF THE REPORT

This report is deliverable D5.5 of the DTOceanPlus project, which provides details of the Deployment Design Tools module "Energy Delivery" (ED), and it presents the result of the work developed during tasks T5.2 and T5.6 of the project. This document serves as the technical manual of the alpha version of the ED module, including the data requirements, main functions, interfaces and all the pertinent technical details. The alpha version of this tool is a fully functional version of the tool in terms of implementation of the calculations covered by the ED module (Business Logic). However, it has limited functionality in terms of Application Programming Interface (API), since the other modules are still under development. The alpha version has limited functionality in terms of Graphic User Interface (GUI), and this will be further developed during the integration phase.

The remainder of this report is structured as follows:

- Background on **electrical networks** within ocean energy converter (OEC) arrays/farms and **installation & protection methods** for subsea cables is given in Chapter 2.
- **User groups**, **use cases** within the suite of tools, and **functionalities** of the Energy Delivery tool are covered in Chapter 3, both for the simplified (CPX1) and full complexity (CPX2/3) design modes.
- The **implementation** is described in Chapter 4, covering the architecture, business logic, API, GUI, and technologies and packages used.
- **Examples** of the inputs and outputs are given in Chapter 5.
- Finally, **future work** is discussed in Chapter 6.

The Electrical Sub-Systems design module "dtocean-electrical module" from DTOcean 2.0 [1] was used as the starting point of code development. All existing functionalities of the Electrical Sub-Systems module in DTOcean 2.0 have been ported and improved within the ED module in DTOceanPlus.

1.2 SUMMARY OF THE DTOCEANPLUS PROJECT

The Energy Delivery module belongs to the suite of tools "DTOceanPlus" developed within the EU-funded project DTOceanPlus [2]. 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 sub-systems, energy capture devices and arrays) and at various levels of complexity (Early/Mid/Late stage).

At a high level, the suite of tools developed 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 metocean, 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 and 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.

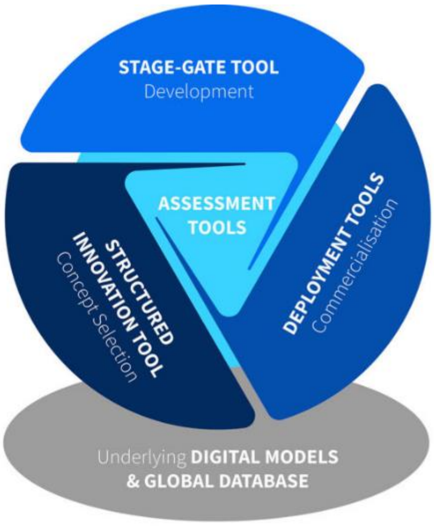

FIGURE 1.1: REPRESENTATION OF DTOCEANPLUS TOOLS

2. BACKGROUND

2.1 ELECTRICAL NETWORKS FOR OCEAN ENERGY ARRAYS

An electrical network, energy delivery or power transmission system is required to transmit energy generated by ocean energy converters (OECs) offshore to the onshore landing point (OLP) where it will be connected to the main electrical grid at the grid connection point (GCP), usually via an onshore substation. The OEC may be grouped around one or more collection points (CPs) to reduce the required number of cables to shore.

2.1.1 SCOPE OF DTOCEANPLUS ENERGY DELIVERY TOOL

The Energy Delivery module designs and assembles optimal solutions for the electrical infrastructure, which delivers electrical power to the onshore distribution network, for a given sub-system, device, array and site. The design objective of the module is to maximise the level and quality of the delivered power considering the cost and value of the solution proposed, as well as to ensure overall grid compliance. The term 'electrical infrastructure' includes all the key electrical components such as the umbilical cable for floating devices, static subsea array cables, electrical connectors, offshore collection points, and the transmission cables to the onshore grid. These components serve the following purposes:

- Transmission (or export) cable(s) – connecting to the onshore landing point.
- Connector(s) – linking cables to each device or collection point.
- Collection point(s) – acting as a hub or a substation or both. Each collection point (CP) contains connectors and optionally switchgear, transformer, power quality/conditioning equipment. They may be surface or seabed mounted. These may be:
  - Array collection points – CPs, within star networks, to which OECs are connected.
  - Transmission collection point – CP connecting an array to the OLP.
- Array (or intra-array) cable(s) – static subsea cables between collection point(s) and/or device(s)
- Umbilical cable(s) – between floating OEC and the static subsea network.

Note that not all these components would necessarily be a part of a network design. Some of these components are optional and are not found in certain network topologies.

A simplified schematic of the main three connected sub-systems (shown in blue) that constitute the electrical infrastructure is shown in Figure 2.1. The onshore connection (shown in the dashed grey box) between the OLP and GCP normally includes cables or overhead lines, and a substation close to the GCP. The design of, or assessment of the power flow through, the onshore network is beyond the DTOceanPlus scope.

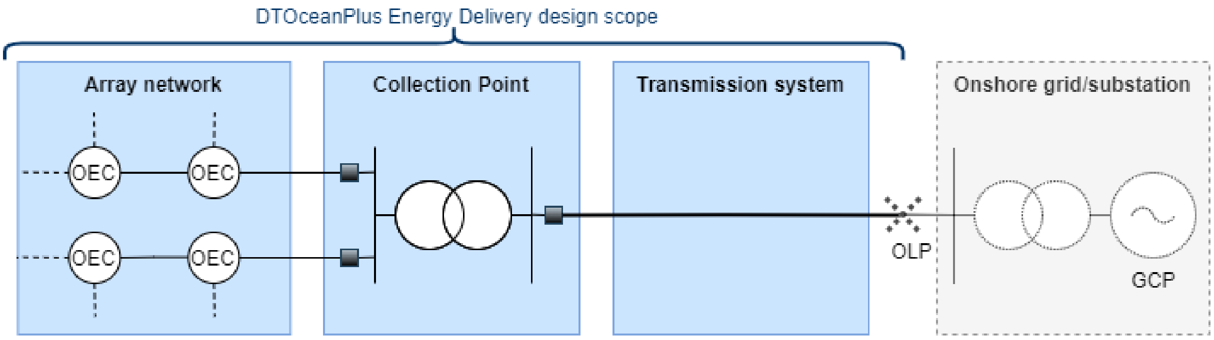

FIGURE 2.1: SIMPLIFIED GENERIC OFFSHORE ELECTRICAL NETWORK FOR OCEAN ENERGY ARRAYS

2.1.2 KEY EXCLUSIONS

The following items/subsystems are not presently included within the scope of the Energy Delivery module; however, it may be possible to add in these functionalities in future versions of DTOceanPlus.

- **Design of the onshore network or substation** is not included, as the design of these items is considered outside of the scope of the DTOceanPlus tools. However, the user can enter estimated losses and costs associated with these items. To assist with this, suggested cost values are provided by the module.
- **Battery storage** is not included, either as part of the device, or located at the onshore or offshore substations.
- **High Voltage Direct Current (HVDC) transmission** from the collection point(s) to the onshore network or within the array network will not be considered in this project and is considered to be an enabling technology. HVDC transmission may be required for bigger wave and tidal energy farms further away from the shore than those that would be seen in wave and tidal sector in the medium term. The Wave Energy Scotland landscaping study on Electrical Connections [2] suggested HVDC transmission would not likely be cost effective for small wave farms that are not a great distance from shore. For these reasons, HVDC transmission was excluded from the scope of the Energy Delivery module in the Functional Requirements (D2.2) [3].
- **Redundancy in the network**, in the form of either radials with ring redundancy or multiple parallel cables, are not included in the ED module. Any redundancy in the offshore transmission and array networks for offshore wind farms was found to be economical only above 90 MW capacity [4]. Redundancy has been excluded from the module since wave and tidal farms of such capacity will not be seen in the short-to-medium term.

2.1.3 NETWORK TOPOLOGIES CONSIDERED

At full complexity, there are multiple network topologies considered in the Energy Delivery module, which can be summarised as:

- **Direct connection to shore:** individual cable per device.
- **Radial networks:** multiple devices connected in series, with a collection point, which may be a substation, a hub or a device.

- **Star networks:** multiple devices connected in clusters to array collection point(s), with or without a transmission collection point.

These are implemented in six types as defined in Table 2.1. The original versions of DTOcean (1.0 and 2.0) only implemented two of these, the radial network topology with transmission CP and multi-cluster star with transmission CP, simply called radial and star respectively in the DTOcean deliverables and manuals. The four additional network topologies in DTOceanPlus are derived from these as shown in Table 2.1, and detailed in Section 4.1. For the full complexity version of the tool, the user can select which of these topologies to consider for their project, as discussed in Section 3.5.

Graphical examples of these network topologies are given below in Figure 2.3 to Figure 2.9, with a key to symbols in Figure 2.2. "Connection" in the figures represents either: a connector in the case of a fixed device or an umbilical and its connectors for floating devices. Note that not all topologies included in these figures will have the same likelihood of being used in real array deployments.

TABLE 2.1: NETWORK TOPOLOGIES IMPLEMENTED IN DTOCEANPLUS ENERGY DELIVERY

Network topology	DTO1/2 name	Derived from	Array CP	Trans. CP	Example(s)
Direct to shore	—	Radial with transmission CP	No	No	Figure 2.3
Radial	—	Radial with transmission CP	No	No	Figure 2.4, Figure 2.5
Radial with transmission CP	"Radial"	—	No	Yes	Figure 2.6
Single cluster star	—	Radial with transmission CP	No	Yes	Figure 2.7
Multi-cluster star	—	Multi-cluster star with trans. CP	Yes	Yes	Figure 2.8
Multi-cluster star with trans. CP	"Star"	—	Yes	Yes	Figure 2.9

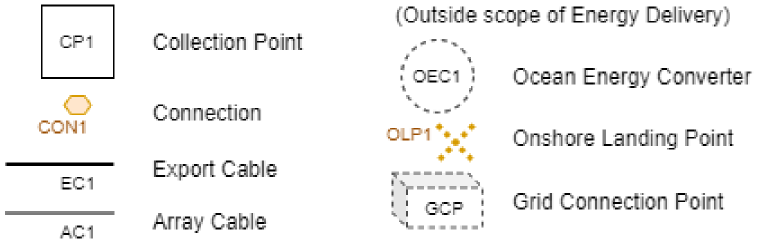

FIGURE 2.2 KEY TO SYMBOLS USED IN THE FOLLOWING NETWORK TOPOLOGY DIAGRAMS

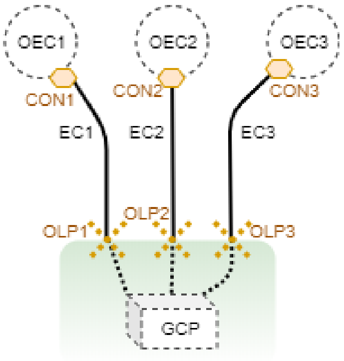

FIGURE 2.3 DIRECT TO SHORE NETWORK

RADIAL NETWORKS

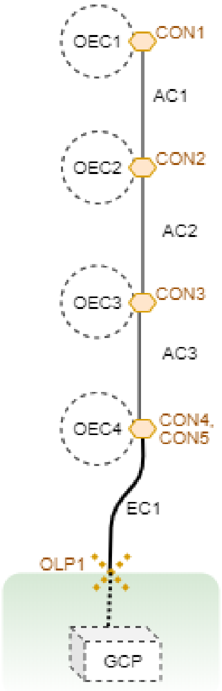

FIGURE 2.4: RADIAL NETWORK WITH SINGLE STRING CONNECTED TO A DEVICE AS A COLLECTION POINT

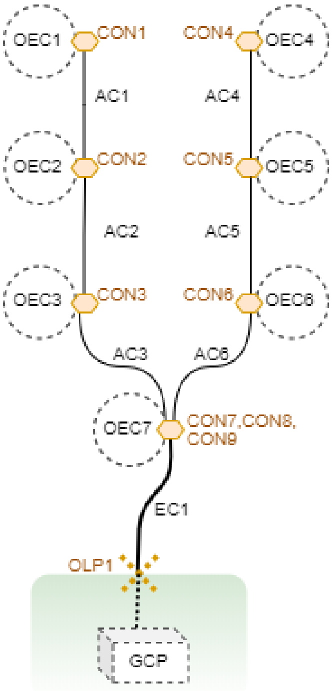

FIGURE 2.5: RADIAL NETWORK WITH MULTIPLE STRINGS CONNECTED TO A DEVICE AS A COLLECTION POINT

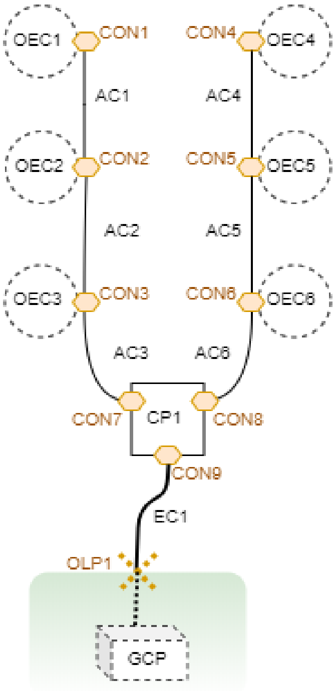

FIGURE 2.6: RADIAL NETWORK WITH ONE OR MORE STRINGS CONNECTED TO A TRANSMISSION COLLECTION POINT

STAR NETWORKS

Connector numbers omitted for clarity in the following diagrams

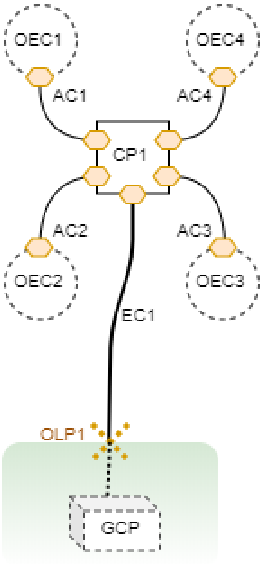

FIGURE 2.7: SINGLE CLUSTER STAR NETWORK WITH ONE COLLECTION POINT

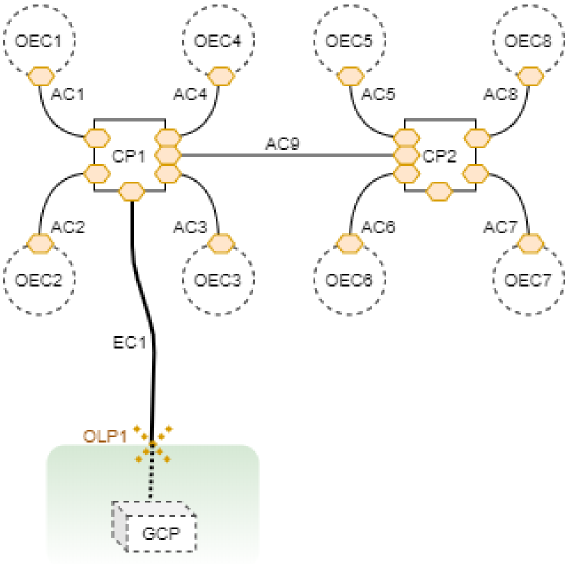

FIGURE 2.8: STAR NETWORK WITH MULTIPLE COLLECTION POINTS CONNECTED

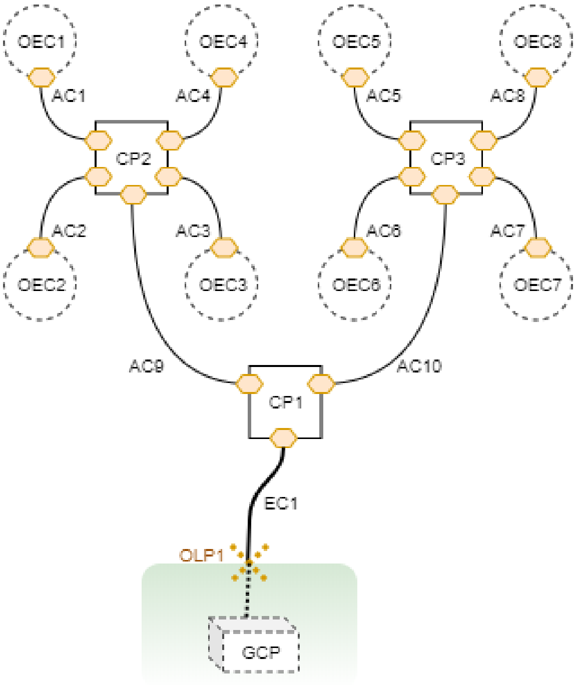

FIGURE 2.9: STAR NETWORK WITH MULTIPLE COLLECTION POINTS CONNECTED TO A TRANSMISSION COLLECTION POINT

2.2 INSTALLATION AND PROTECTION METHODS FOR SUBSEA ELECTRICAL CABLES

There are multiple methods of installing and protecting subsea cables. The optimum solution for a given project will depend on the seabed type amongst other factors. The installation and protection methods considered by the ED module in DTOceanPlus are detailed in Table 2.2 and Table 2.3, and are shown graphically in Figure 2.10 and Figure 2.11. Details of the technique selection are discussed in section 3.5.2.2.

TABLE 2.2: CABLE INSTALLATION METHODS IN DTOCEANPLUS

Method	Description/definition (adapted from [5], [7])
Jetting (or fluidisation)	Burial method employs water jets to break and/or fluidise the sedimentary layer of the seabed and sinks the cable into the soil.
Ploughing	Cable ploughs are towed from a host vessel with the cable being simultaneously buried as part of the lay process. The plough lifts a wedge of soil and places the cable at the base of the trench before the wedge of soil then naturally (via gravity) backfills over the cable.
Cutting	Mechanical cutting of hard and rocky seabed is typically via a rock wheel cutter, consisting of a rotating wheel disc fitted with replaceable rock cutting teeth, to cut a narrow trench. Progress is typically sow, and the cutting teeth may need to be replaced frequently.
Dredging	A trench can be dredged in soft/loose seabed with relatively shallow sides, the cable laid, and then material backfilled on top. This method may specifically be used where shell beds held together by fine sands are encountered. Due to the imprecise nature of their operation and significant environmental impact, they may be less likely be used for offshore renewable cables.
Surface lay	Cables are laid on the seabed surface, and typically protected via one of the following methods, detailed in Table 2.3.

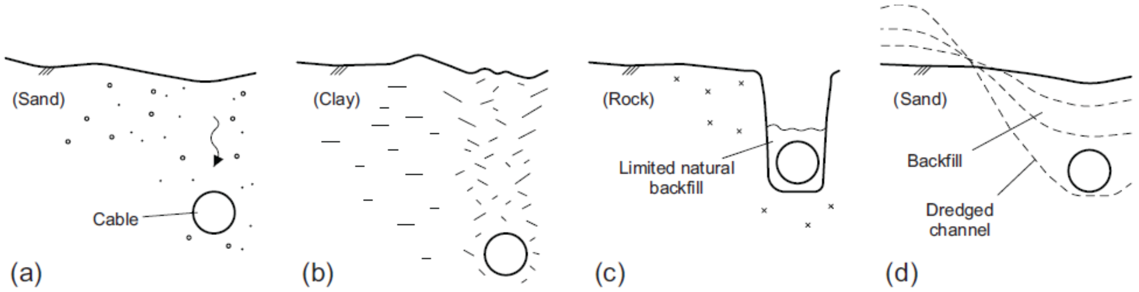

FIGURE 2.10: INSTALLATION AND PROTECTION OF SUBSEA CABLE THROUGH BURIAL. (A) JETTING / FLUIDISATION, (B) PLOUGHING, (C) MECHANICAL CUTTING, (D) OPEN TRENCH DREDGING [5]. NOTE SURFACE LAY NOT SHOWN AS IT IS NOT A PROTECTION METHOD

TABLE 2.3: CABLE PROTECTION METHODS FOR SURFACE LAY IN DTOCEANPLUS

Method	Description/definition (adapted from [5], [7])
Split-pipes	Tubular protection includes protective sleeves consisting of sections made of polyurethane or ductile iron. The segments typically comprise of cylindrical half-shells ('split pipe') that overlap, interlock and fit around the cable. They are often used in combination with mattresses or rock placement.
Mattress	Mattresses are lattices of segmented, mould-produced blocks of concrete or bitumen connected by polypropylene ropes which can be laid over a cable to stabilise and shield it, often at cable crossings. Small sections of the cable or gaps between mattresses may also be protected by pre-filled grout bags or gabion (rock filled) bags.
Rock Placement	Rock placement is the subsea installation of crushed stones of varying size to form a protective barrier over the cable. Rock placement is used for scour protection, at infrastructure crossings or where not reaching minimum burial depth left the cable insufficiently protected. Rock berms are relatively resistant against trawling and anchoring activities.

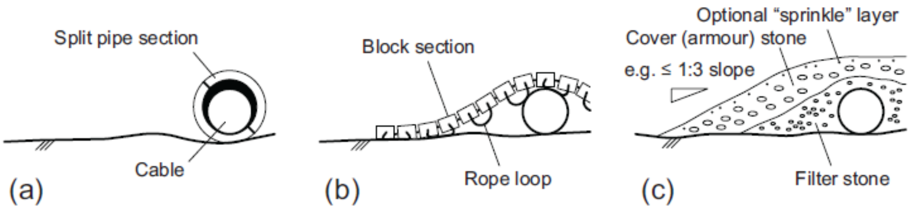

FIGURE 2.11 : NON-BURIAL CABLE PROTECTION.
(A) TUBULAR PRODUCT (SPLIT PIPES), (B) MATTRESS, (C) ROCK PLACEMENT [5]

3. USE CASES AND FUNCTIONALITIES

The Energy Delivery module designs the array and the power transmission networks for ocean energy devices and arrays. This section describes the main use cases of, and the functionalities implemented in, the tool. This section also discusses the two design modes provided by the ED module: simple (CPX1) and full (CPX2/3) complexity.

3.1 USER GROUPS

The overarching use case for the ED module is to design the array network and the power transmission system, either for a single device or an array of multiple devices. This can be to:

1. Develop a design of the electrical infrastructure, either at an outline/preliminary level or a detailed/optimised level, and/or
2. Improve cost/performance estimates for an array of devices by adding the context of the electrical infrastructure required.

Three key user groups were identified as part of the development of the functional requirements [3], these are Technology Developers, Project Developers, and Public or Private Investors. In Deliverable D5.1 [7], the Technical Requirements of the ED module were presented, and the use cases were listed for the different types of users identified. A simplified version of this is shown as Figure 3.1. The levels of complexity (CPX1/2/3) and the simple/full design modes are discussed further in Section 3.3.

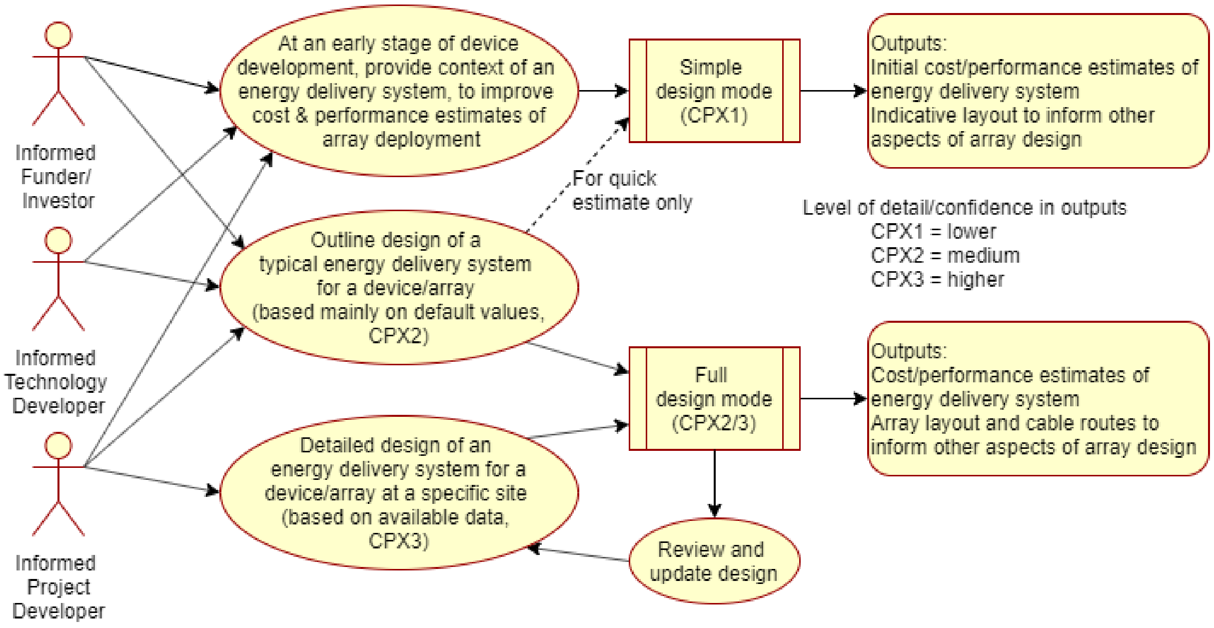

FIGURE 3.1: THREE MAIN USE CASES FOR THE ENERGY DELIVERY TOOL

3.2 USE CASES

In this section, the use cases are described from an operational perspective, with respect to what the user decides to do and which modules the user runs. The user is able to:

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

3.2.1 USE CASE WITHIN THE OTHER DEPLOYMENT TOOLS

In this case, the User will run one or more Deployment Design Tools. ED sits in the middle of the "Energy chain" and requires inputs from and provides inputs to other modules, as shown in Figure 3.2. ED requires SC, MC, EC, and ET to be run a priori. Outputs are provided to SK, LMO, and the assessment tools: SPEY, RAMS, SLC, and ESA.

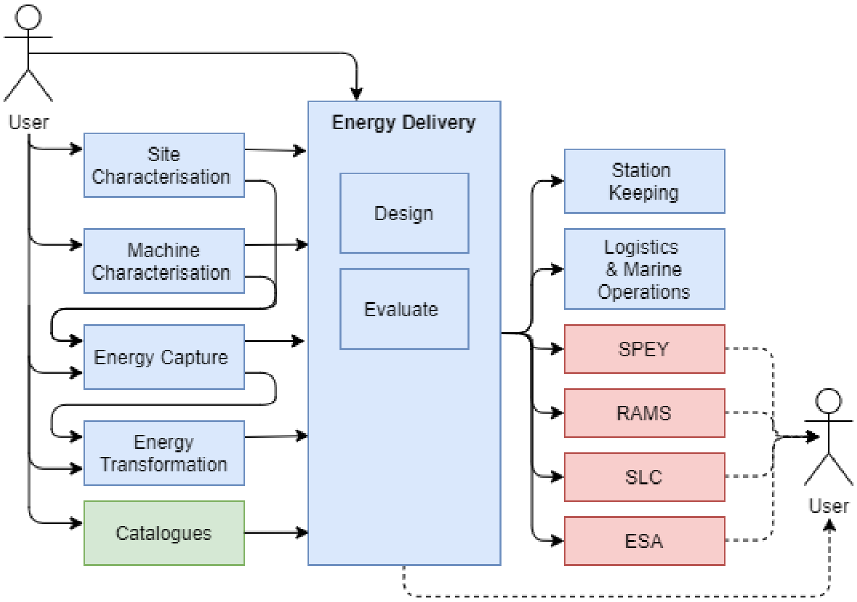

FIGURE 3.2: USE CASES FOR THE ENERGY DELIVERY TOOL WITHIN THE OTHER DEPLOYMENT TOOLS

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

In this case, the ED tool will be run within the framework of the Stage Gate or Structured Innovation design tools, as seen in Figure 3.3. 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 may require information from the Assessment modules.
3. The ED module will provide the required design parameters, if available, or
4. The user will be prompted to provide information and run the ED module, then
5. ED will provide the 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 show the outcome to the user.

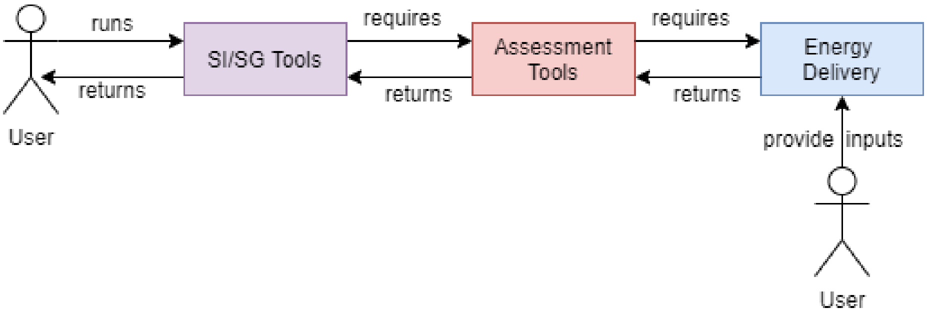

FIGURE 3.3: USE CASES FOR THE ENERGY DELIVERY TOOL WITHIN THE FRAMEWORKS OF THE SI/SG TOOLS

3.2.3 USE CASE IN STANDALONE MODE

In this case, the user would like only to consider the array and the power transmission networks, separate from the design of other items of an array requirement. The user will provide all the required inputs in this case, both for the design of the network, and also of the array and deployment site. They will be provided with one or more design solutions, providing details of the components plus costs and efficiencies. This is shown graphically in Figure 3.4.

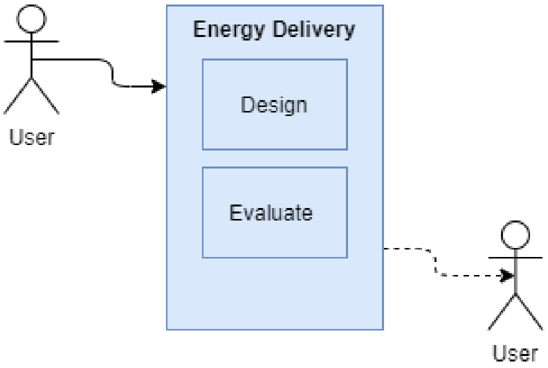

FIGURE 3.4: USE CASES FOR THE ENERGY DELIVERY TOOL IN STANDALONE MODE

3.3 FUNCTIONALITIES AT DIFFERENT LEVELS OF COMPLEXITY

The functionality of the Energy Delivery module is different for early versus later stage technology development, as a consequence of data availability, however there is no exact boundary between these stages.

To be consistent with the other tools, three levels of complexity (CPX1, CPX2, & CPX3) have been developed for the Energy Delivery module, as shown in Table 3.1. These offer increased certainty in the outputs, but with increasing level of input detail required from the user to run. The level of complexity will be set at the module level, with the implementation of this still to be determined.

The Energy Delivery module will have two design modes, low complexity (CPX1) and full complexity (CPX3). For an intermediate (CPX2) stage, the user can input default values or simplified/surrogate data to the full complexity algorithm, which will result in lower certainty in the outputs. An example of this would be flat bathymetry or example bathymetry from another reference site, rather than a detailed representation of the seabed slopes at the specific site.

Note that there is significant overlap between complexity levels CPX2 and CPX3, and the boundary between these is not fixed. The input and output parameters for these levels are of the same form, and the calculation is the same, as detailed in Table 3.2 below. The user may be able to provide some, but not all, of the additional detail depending on how advanced their project/deployment is. The full complexity process will make a calculation based on the data available. Thus, increasing the detail of any parameter will increase the confidence in the outputs.

The simplified mode (complexity level CPX1) can be used for early stage technologies or where little information is available about the deployment site. This nominally corresponds to Technology Readiness Level (TRL) 1-3, but could also be used to give a quick estimate at later stages of development. This will provide an estimation of electrical network parameters (cost, losses), with the process discussed in Section 3.4

The full mode (CPX2 & CPX3) is for mid-late stage technology development, where basic or detailed information is available regarding the proposed deployment. This will include the following functionalities, described further in Section 3.5.

1. Design of transmission system
2. Design of array network
    a. Clustering of devices around collection point(s)
    b. Connections within array network
    c. Routing of array cables, including design of umbilical cables for floating devices
3. Selection of suitable components
4. Evaluation of network designs

TABLE 3.1: CALCULATIONS AT THREE LEVELS OF COMPLEXITY FOR ENERGY DELIVERY MODULE

Input/output	Simplified process	Full complexity calculation process	
	CPX1 Simple	CPX2 Medium	CPX3 Complex
Bathymetry/ seabed	▫ Ignored	▫ Grid of average water depth (or detailed bathymetry) ▫ Main seabed type	▫ Grid of detailed bathymetry (or average water depth) ▫ Grid of seabed types
Array cable layout	▫ No specific design undertaken of the array cable layout ▫ Type of converter and fixed/floating ignored ▫ Total cable length estimated from number of devices & separation (either typical spacing or user input) ▫ Requirement for an offshore substation based on the number of devices, farm size and distance to shore	▫ Array cable layout and routes designed based on device positions, for user specified type(s) ▫ For floating devices, umbilical cable length calculated ▫ Default assumption of a fixed surface-piercing collection point foundation	▫ Array cable layout and routes designed based on device positions, for user specified type(s) ▫ For floating devices, umbilical cable length calculated ▫ User adjustable collection point type
Export cable route	▫ Length based on array distance to shore	▫ Route calculated	▫ Route calculated
Exclusion zones	▫ Ignored	▫ Ignored/considered	▫ Considered
Installation/ protection	▫ Ignored	▫ Cable installation method based on main soil type	▫ Cable installation method based on site soil types and seabed gradients
Delivered energy & losses	▫ Losses in the network determined from simple power, current, resistance relationships (no power flow analysis) ▫ Device power level based on user input/default capacity factor value	▫ Array & export losses, for simplified design ▫ Device power level based on user input/default capacity factor value ▫ Calculated with power flow solver ▫ Default assumption of unity power factor ▫ Can include user specified onshore losses (if known)	▫ Array & export losses, for detailed design ▫ Based on device transformed active and reactive power per sea-state[1] ▫ Calculated with power flow solver ▫ Can include user specified power factor ▫ Can include user specified onshore losses ▫ Delivered power within user specified voltage limits

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[1] Note: "sea-state" refers to a specific combination of environmental conditions for that technology type, e.g. Hs, Tp, dir for WEC, or U/V velocities for TEC.

TABLE 3.2: EXAMPLE DIFFERENCES BETWEEN COMPLEXITY LEVELS 2 AND 3 FOR ENERGY DELIVERY MODULE

Parameter	Lower detail (CPX2)	Higher detail (CPX3)	Difference
Bathymetry	Grid of average water depth	Grid of detailed bathymetry	Route avoids steep slopes, more accurate cable length
Seabed soil type	Grid of main seabed type	Grid of different seabed types	Avoids obstructions, more accurate costing
Exclusion zones	Ignore	Consider	Routing/placement avoids exclusion zones
Device transformed power	Active power and power factor calculated from capacity factor and assumed unity power factor	Active and Reactive power from ET module	Reactive power not just calculated from single power factor

3.4 FUNCTIONALITIES OF SIMPLIFIED DESIGN PROCESS

The ED module comprises of two main functionalities, namely designing and evaluating electrical network options. For the lowest complexity level, CPX1, a simplified network design will be produced within the ED module. This does not depend on an array layout or any site parameters. At this early stage, the design does not consider the spatial layout of the array, only cable lengths. The main, high-level, network topology constraints made are as follows:

- Every network design has a collection point, which could either be a substation or a hub
- The devices in the array are always connected in a radial layout
- Floating devices are treated the same as fixed devices

In essence, all network designs output at CPX1 consider only the radial layout shown in Figure 2.6.

The following sections describe the inputs required to run the ED module, the process flow of the design and evaluate functionalities, and the outputs from the module at CPX1.

3.4.1 INPUTS

The device and array level inputs for the ED module at CPX1 are given in Table 3.3. It is assumed that the user will know the power rating of each device and the number of devices in the array, or can fill in appropriate numbers to get the total rated power of the array/farm. Typical values for the distances between devices and from the farm to shore may be given by the user, depending on technology type and size. Nominal values could be suggested in the GUI, e.g. 100 m & 1 km. Guidance on device voltage could also be offered based on typical designs, e.g. a 100 kW device could be rated at 690 V or a 2 MW device could be rated at 6.6 kV.

Table 3.4 lists the optional inputs to the module at CPX1. Depending on the user choice, the onshore infrastructure may be included in the cost analysis. The onshore infrastructure cost can be a user input or may be estimated based on the farm size and the distance between the onshore landing point (OLP) and the grid connection point (GCP).

Table 3.5 lists default values used for some of these input and optional parameters. The parameters fac_export, fac_dev_dev and fac_dev_cp, in Table 3.5, are parameters internal to the ED module, used to obtain the lengths of array and export cables at CPX1. These are the default values for these parameters at the time of writing, however these may be updated in future.

TABLE 3.3: DEVICE AND ARRAY LEVEL INPUT DATA AT CPX1

Parameter	Description	Origin of the Data	Data Model	Units
power	The rated active power output of the OEC	ET module or user input	float	W
voltage	The rated voltage of the OEC	ET module or user input	float	V
number_of_devices	The number of devices in the array	EC module or user input	integer	-
array_spacing	The separation between devices in the array, assumed to be equal in the x and in the y directions	EC module or user input	float	m
distance_to_shore	The distance between the deployment site and the OLP	SC module or user input	float	m
onshore_infrastructure_flag	Control flag to decide whether to include the onshore infrastructure cost in the cost analysis	User input	bool	-

TABLE 3.4: OPTIONAL INPUT DATA AT CPX1

Parameter	Description	Origin of the Data	Data Model	Units
onshore_infrastructure_cost	Cost of onshore distribution/transmission lines and any onshore substation	User input	float	€
onshore_distance	Distance between the onshore landing point and the nearest onshore substation	User input	float	m
AEP_in	The annual energy production for the whole array, measured at the generator terminals without any network losses considered	ET module or user input	float	Wh
cap_factor	Capacity factor of the array to be used in the analysis	User input	float	%

TABLE 3.5: DEFAULT PARAMETER VALUES AT CPX1

Parameter	Default value	Units
onshore_infrastructure_cost	0.0	€
onshore_losses	0.0	%
cap_factor	30	%
fac_export	1.2	–
fac_dev_dev	1.2	–
fac_dev_cp	2.0	–
max_devices_per_radial	10	–
transformer_efficiency	99.47	%

3.4.2 DESIGN AND EVALUATION PROCESS

This section describes the design constraints and the process flow used to produce a simplified network design by the ED module at CPX1. The overall design process is firstly to design the transmission system, then the simplified array network, and finally evaluate the network option produced as detailed in the following sections, and shown in Figure 3.5.

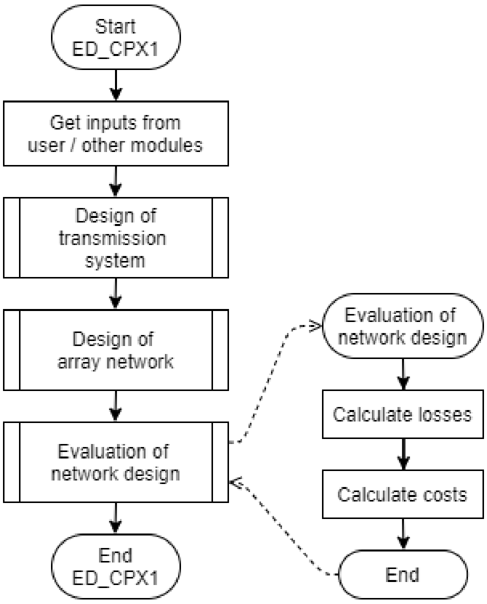


FIGURE 3.5: PROCESS FLOW OF THE DESIGN AND EVALUATE FUNCTIONALITIES AT CPX1

3.4.2.1 DESIGN OF TRANSMISSION SYSTEM

The process for the design of the transmission system at CPX1 is shown in Figure 3.6. The first step is the selection of an appropriate export voltage for the array. The export voltage is specified using the design limits guidance provided in Table 3.6, and is a function of the array rated power (i.e. $power \times number\_of\_devices$) and the distance to shore. These parameters corresponding to S_{max} and L_{max} respectively in Table 3.6. If the calculated export voltage is the same or lower than the device voltage, then the device voltage is selected. In this case, an offshore substation is not required, and the collection point will be a "hub". On the other hand, if the calculated export voltage is higher than the device voltage, then an offshore substation is required for the voltage transformation.

To account for an indirect cable route, the export cable length is assumed to be $= fac\_export \times distance\_to\_shore$, wherein fac_export was set at 1.2.

A catalogue of generic cables with their cross-section areas, resistances and current ratings is available in the module. The export cable is selected from the catalogue for the export cable voltage specified by the earlier step and the array power rating $(power \times number\_of\_devices)$.

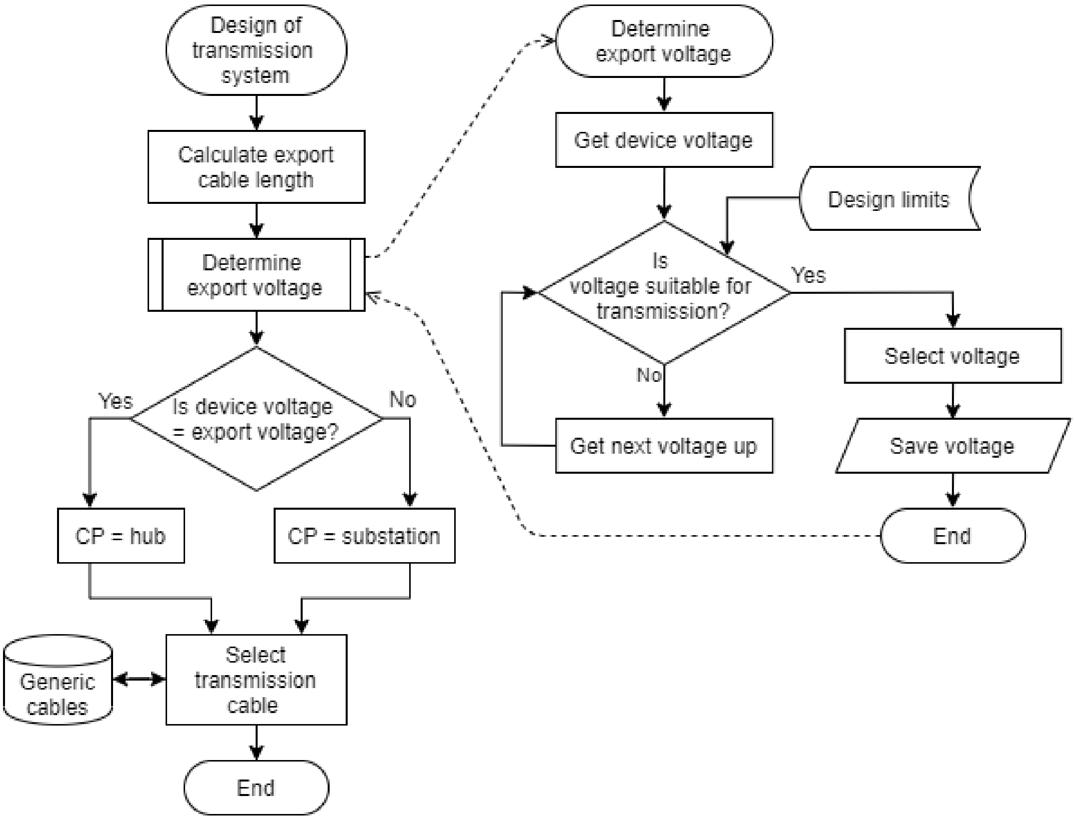


FIGURE 3.6: PROCESS FLOW OF THE TRANSMISSION SYSTEM DESIGN AT CPX1

TABLE 3.6: ESTIMATED MAXIMUM POWER AND DISTANCE CAPABILITY OF DIFFERENT VOLTAGE LEVELS (DESIGN LIMITS)

Transmission voltage (kV)	S_{max} (MVA)	L_{max} (km)
0.4	0.2–0.6	0.4–0.8
0.69	0.4–1.0	0.6–1.3
3.3	1.7–4.7	3.0–6.4
6.6	3.4–9.4	5.9–12.8
10	5.0–14	9–19
20	10–28	18–38
30	15–43	27–58
35	18–50	31–68
66	34–94	59–128
110	57–157	99–213

3.4.2.2 DESIGN OF ARRAY NETWORK

The array network at CPX1 is always connected in a radial layout. The division of devices between radials depends on the number of devices in the array. For arrays with up to 5 devices, all the devices are connected in a single radial. For arrays with between 6 and 10 devices, the devices are distributed between two radials. For arrays with greater than 10 devices, the devices are distributed between $(number\_of\_devices/10)$ radials, rounded up to the next integer (using the ceil() function). At present, a radial can have a maximum of 10 devices. The split of devices between radials in the network is stored in an internal list n_dev_str. The length of this list gives the number of radials, while each element of the list gives the number of devices in each radial.

The array cable length between devices $= fac\_dev\_dev \times array\_spacing$. The array cable length between the first device in a radial and the collection point $= fac\_dev\_cp \times array\_spacing$. The values fac_dev_dev and fac_dev_cp are constants, which at present have been set to 1.2 and 2 respectively.

Using these approximations, the total array cable length is evaluated for the array network design.

The array cable is selected from the catalogue of generic cables for the device voltage specified and the power rating required for the longest radial in the network $(\max(n\_dev\_str) \times power)$. The same array cable selected is used across the array network.

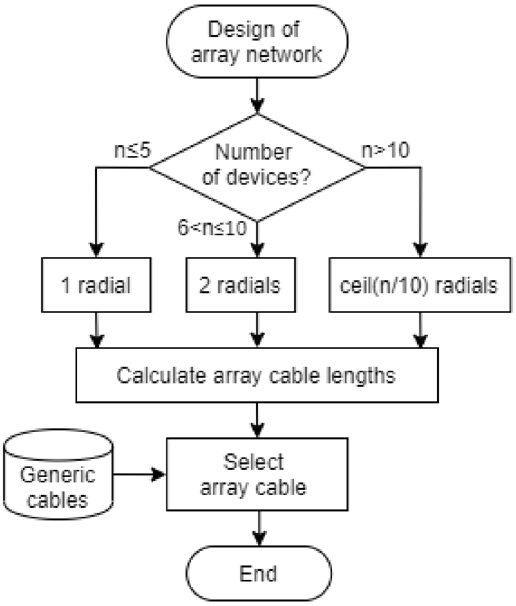


FIGURE 3.7: PROCESS FLOW OF THE ARRAY DESIGN AT CPX1

3.4.3 EVALUATION OF THE NETWORK DESIGN

The simplified network design is then evaluated technically in terms of the AEP and losses, and economically in terms of estimated costs, as shown in Figure 3.5.

TECHNICAL EVALUATION

To specify the power level of the devices in the array, which is required to evaluate the power losses, the capacity factor of the array needs to be determined. The capacity factor *cap_factor* and the AEP input AEP_{in} from the ET module or obtained as a user input, are optional inputs to the ED module. If they are not provided, then a typical capacity factor of 0.3 is assumed. If the ET module provides the AEP input, then the capacity factor of the array is calculated using (3.1). The power output of the devices in the array is then evaluated by $cap\_factor \times power$.

$$cap\_factor = \frac{AEP_{in} / (number\_of\_devices \times 8760)}{power} \tag{3.1}$$

The current through each section of the array network cable, connecting device/collection point a and b, is then calculated using (3.2). In this equation, n depends on the position of the device in the radial. For the last device in a radial $n = 1$, for the second to last $n = 2$ and so on, till the device connected to the collection point for which $n =$ number of devices in the radial.

$$i_{ab} = \frac{n \times power\_output}{\sqrt{3}\ voltage} \tag{3.2}$$

Based on the resistance per unit length r of the selected array cable, the cable length l_{ab} and the current i_{ab} through each array cable, the power loss in each array cable is evaluated using (3.3). The total power loss in the array network is obtained by summing the power loss seen in all the array cables.

$$power\_loss = 3 \times {i_{ab}}^{2} \times l_{ab} \times r. \tag{3.3}$$

At CPX1, devices are connected using array cables only, i.e. connectors and umbilical cables are excluded.

If a transformer is required on the collection point, its efficiency is used to calculate the power flow in the export cable. A transformer efficiency of 99.47%, which is approximately the average of the efficiencies of transformers seen in [8], has been used in the module.

The power output of the collection point transformer is taken to be the power flow through the export cable. The power loss in the export cable is calculated in the same fashion as array cables, which has been described above. The transformer power output minus the power loss in the export cable is the power delivered by the array at the OLP, *array_power_output*, which is calculated using (3.4). In the equation *power_loss_array*, *power_loss_transformer* and *power_loss_export* refer to the total power loss in the array network, CP transformer and the export cable as calculated before.

$$\begin{aligned} array\_power\_output \\ &= (cap\_factor \times power) \times number\_of\_devices \\ &- power\_loss\_array - power\_loss\_transformer \\ &- \ power\_loss\_export. \end{aligned} \tag{3.4}$$

The energy delivered to the shore (AEP) *annual_yield* is calculated from the power delivered at the OLP using (3.5). From all the calculations completed, the network efficiency *annual_efficiency* is evaluated using (3.6).

$$annual\_yield = array\_power\_output \ \times 8760. \tag{3.5}$$

$$annual\_efficiency \ = (annual\_yield / AEP_{in}) \times 100 \tag{3.6}$$

Typical failure rates for the cables and transformers in the network, obtained from [4], are also included for further analysis by subsequent modules.

ECONOMIC EVALUATION

Costs for components such as cables and CPs come from cost functions and not a catalogue. These cost functions were obtained from [10].

The onshore infrastructure costs, if not provided as a user input, are estimated based on just the array rated power and the length of the onshore line required, based on [10] [12] [12].

The total cost of the electrical system *total_cost* is calculated by adding the cost of the four main parts of the network design: the array network, the collection point, the export cable, and the onshore infrastructure. A simplified cost of energy *coe_elec* representing only the cost of the electrical infrastructure, is calculated using (3.7).

$$coe\_elec = total\_cost/annual\_yield \tag{3.7}$$

Users will be notified that power flow solutions may not be run at this stage (although this is still to be implemented in the GUI).

3.4.4 OUTPUTS

The ED module, at CPX1, outputs the results of the network design and evaluation. The user will be informed of the array layout assumptions used, cable lengths estimated, and the AEP and losses calculated in a simplified manner. They will not be able to see the array layout graphically as it is not based on device locations.

A simplified bill of materials (BOM) will be prepared with four subtotal costs:

- Total transmission network
- Total array network
- Total collection point
- Total onshore infrastructure

A simplified hierarchy will be produced. The energy routes for each device will comprise of one or more array cables, a collection point and an export cable.

An example of the inputs and outputs are given in Section 5.1.Table 3.7 shows a list of the outputs from the ED module at CPX1.

TABLE 3.7: OUTPUTS OF THE ENERGY DELIVERY MODULE AT CPX 1

Parameter	Description	Data Model	Units
annual_efficiency	Network efficiency over a year	float	%
annual_losses	Total electrical losses over a year	float	Wh
annual_yield	Array energy output over a year at the Grid Connection Point (GCP)	float	Wh
array_power_output	Real power delivered to the GCP for the capacity factor considered	float	MW
array_voltage	Array network voltage	float	V
array_cable_total_length	Total length of the array cables used in the design	float	m
b_o_m_new	Network bill of materials: includes cost estimates of the array network, collection point, export cable and the onshore infrastructure	pandas DataFrame	€
configuration	Network configuration	string	-
export_voltage	Export cable voltage	float	V
export_cable_total_length	Total length of the export cable used in the design	float	m
hierarchy_new	Component-to-component connection relationship for reliability analysis	pandas DataFrame	-
coe_elec	Simplified cost of energy for network design	float	€/kWh
n_array_cables	Number of array cables in the network	integer	-
n_cp	Number of collections points in the network	integer	-
n_export	Number of export cables in the network	integer	-
total_cost	Total cost of all components in the network	float	€

3.5 FUNCTIONALITIES OF FULL COMPLEXITY DESIGN PROCESS

This section describes the inputs required to run the ED module, the process flow of the design and evaluate functionalities and the outputs from the module at CPX 2 and 3.

3.5.1 INPUTS

At complexity levels CPX2 and CPX3 the ED module requires additional inputs than those at CPX1 presented in Table 3.3. The design and evaluation modes of the ED module are the same at CPX2 and CPX3, with either lower resolution input data or default values for certain parameters used at CPX2.

All inputs need to be provided by the user when operating in standalone mode (as defined in Section 3.2). However, when operating within the DTOceanPlus suite of tools, many of these inputs come from earlier modules.

3.5.1.1 ELECTRICAL COMPONENT AND CABLE INSTALLATION CATALOGUES

The ED module requires a catalogue of electrical components to choose equipment from during the design phase. This catalogue consists of six component tables listed in Table 3.8. The electrical component catalogue currently exists as an Excel file with individual sheets for these listed components. The number of components in the catalogue will dictate the possible range of network solutions that the ED module will propose.

In addition to the electrical component catalogue, the ED module also uses a cable installation catalogue. This catalogue exists as another Excel file and works as a simple look up table, showing cable installation rates for all installation technique and seabed type combinations.

TABLE 3.8: ELECTRICAL COMPONENT CATALOGUE INPUT DATA

Parameter	Description	Origin of the Data	Data Model	Units
static_cables	Electrical, mechanical and reliability specifications for static cables of different current and voltage ratings	Catalogue	pandas DataFrame	-
dynamic_cables	Electrical, mechanical and reliability specifications for dynamic cables of different current and voltage ratings	Catalogue	pandas DataFrame	-
wet_mate	Electrical, mechanical and reliability specifications for wet-mate connectors	Catalogue	pandas DataFrame	-
dry_mate	Electrical, mechanical and reliability specifications for dry-mate connectors	Catalogue	pandas DataFrame	-
transformer	Electrical, mechanical and reliability specifications for transformers of different power and voltage ratings	Catalogue	pandas DataFrame	-
collection_point	Electrical, mechanical and reliability specifications for collection points of different power and voltage ratings	Catalogue	pandas DataFrame	-

Parameter	Description	Origin of the Data	Data Model	Units
equipment_soil_compatibility	Installation rates matrix denoting ability of installation tools to function in different seabed types	Catalogue	pandas DataFrame	m/hour

3.5.1.2 SITE CHARACTERISTICS

As with the rest of the DTOceanPlus modules and tools, ED uses the Universal Transverse Mercator (UTM) coordinate system of eastings and northings, to represent longitude and latitude respectively, to define a point of the Earth's surface.

The ED module requires seabed information for both the lease and export cable corridor areas to identify feasible cable routes and protection options. The required site characteristics are listed in Table 3.9.

TABLE 3.9: SITE CHARACTERISTICS INPUT DATA

Parameter	Description	Origin of the Data	Data Model	Units
lease_bathymetry, export_bathymetry	The vertical profile of the sea bottom at each (given) UTM coordinate within the given area; expressed as [x,y,z,i,j,id,layer1 type] where: i and j are local indices, id is the unique point identifier and layer 1 type is the type of seabed	SC module or user input	pandas DataFrame	m
lease_exclusion_zones, export_exclusion_zones	List containing the UTM coordinates of the exclusion zone polygons within the given area; expressed as point id	SC module or user input	shapely Polygon	-

3.5.1.3 DEVICE CHARACTERISTICS

The device characteristics and specifications required by the ED module to design suitable networks for individual devices or arrays are shown in Table 3.10.

TABLE 3.10: DEVICE CHARACTERISTICS INPUT DATA

Parameter	Description	Origin of the Data	Data Model	Units
technology	The OEC technology: fixed/floating	MC module or user input	string	-
power	The rated active power output of the OEC	ET module or user input	float	W
voltage	The rated voltage of the OEC	ET module or user input	float	V
connection	The OEC connector type: wet-mate, dry-mate	MC module or user input	string	-
footprint_coords	The OEC footprint as a list of UTM [x,y,z] coordinates	EC module or user input	list	m

Parameter	Description	Origin of the Data	Data Model	Units
variable_power_factor	List of tuples for OEC power factor; val1 = power in per-unit, val2 = power factor	User input	list	-
constant_power_factor	A power factor value to be applied at every device power level	User input	float	-
connection_point	Location of electrical connection to device, as (x, y, z) coordinates in local device coordinate system	User input	tuple	m
equilibrium_draft	Device equilibrium draft without mooring system	User input	float	m

3.5.1.4 ARRAY CHARACTERISTICS

Table 3.11 shows the different parameters at the array/farm level that are required to run the ED module. An object of the Device Characteristics class is also passed to the array characteristics class for full information at the array/farm level.

TABLE 3.11: ARRAY CHARACTERISTICS INPUT DATA

Parameter	Description	Origin of the Data	Data Model	Units
landing_point	UTM coordinate reference of the onshore landing point, defining the end of the transmission cable	User input	tuple	m
layout	OEC layout, key = device id, value = UTM coordinates, as [x,y,z]	EC module or user input	dictionary	M
array_output	The total array power output at the different array power levels	ET module or user input	list	%
voltage_limit_min	The minimum voltage allowed in the offshore network	User input	float	per-unit
voltage_limit_max	The maximum voltage allowed in the offshore network	User input	float	per-unit
onshore_infrastructure_cost	Cost of the onshore infrastructure, for use in LCOE calculation	User input	float	€
onshore_losses	Electrical losses of the onshore infrastructure, entered as percentage of annual energy yield	User input	float	%

3.5.1.5 CONFIGURATION OPTIONS

For the device and array characteristics specified, the user is then given a number of configuration options, listed in Table 3.12, to constrain the optimisation solution. These options can be specified by the user in the GUI and allow the incorporation of constraints beyond the ED module.

TABLE 3.12: CONFIGURATION OPTIONS INPUT DATA

Parameter	Description	Origin of the Data	Data Model	Units
network_configuration	Predefined network topology to be used from: ▫ Direct to shore ▫ Radial ▫ Radial with transmission collection point ▫ Single cluster star ▫ Multi-cluster star ▫ Multi-cluster star with transmission collection point.	User input	string	-
export_voltage	Predefined export system voltage	User input	float	V
target_burial_depth_array	Predefined burial depth of the array cable(s)	User input	float	m
target_burial_depth_export	Predefined burial depth of the export cable	User input	float	m
collection_point_type	Predefined collection point type	User input	string	-
devices_per_string	Maximum number of devices per string in radial configuration	User input	integer	-
equipment_gradient_constraint	Maximum seabed gradient considered by the cable routing analysis	User input	float	degrees
installation_tool	Predefined installation tool	User input	string	-

3.5.1.6 DEFAULT PARAMETER VALUES

Default values are also provided for the full complexity mode of the ED module if the user does not know values of certain parameters, which would be mainly be expected at CPX2 but could also be used at CPX3. These parameters are shown in Table 3.13. At present, these parameters are hard-coded but during the integration phase these parameters will be saved as a configuration file or in a catalogue.

TABLE 3.13: DEFAULT PARAMETERS

Parameter	Default values	Units
constant_power_factor	1.0	-
connection_point	(0,0,0)	m
equilibrium_draft	0.0	m
onshore_infrastructure_cost	0.0	€
onshore_losses	0.0	%
voltage_limit_min	0.9	per-unit
voltage_limit_max	1.1	per-unit
target_burial_depth_array	1.0	m
target_burial_depth_export	2.0	m
equipment_gradient_constraint	14.0	degrees

3.5.2 DESIGN AND EVALUATION PROCESS

A high-level process flow diagram of the full complexity design and evaluate functionalities of the ED module is shown in Figure 3.8. For each of the network configurations selected by the user, the energy delivery system is designed, and components selected. This starts with the design of the transmission system to the shore and then proceeds to the array network. Multiple network design options are produced by the design functionalities of the module, which are then evaluated using a techno-economic analysis, as discussed below. After being evaluated, the user then selects the 'best' network option to be taken forward to the other modules for the remainder of the analysis. Some of the functionalities of the ED module depends on the network topology being considered (listed in Table 2.1).

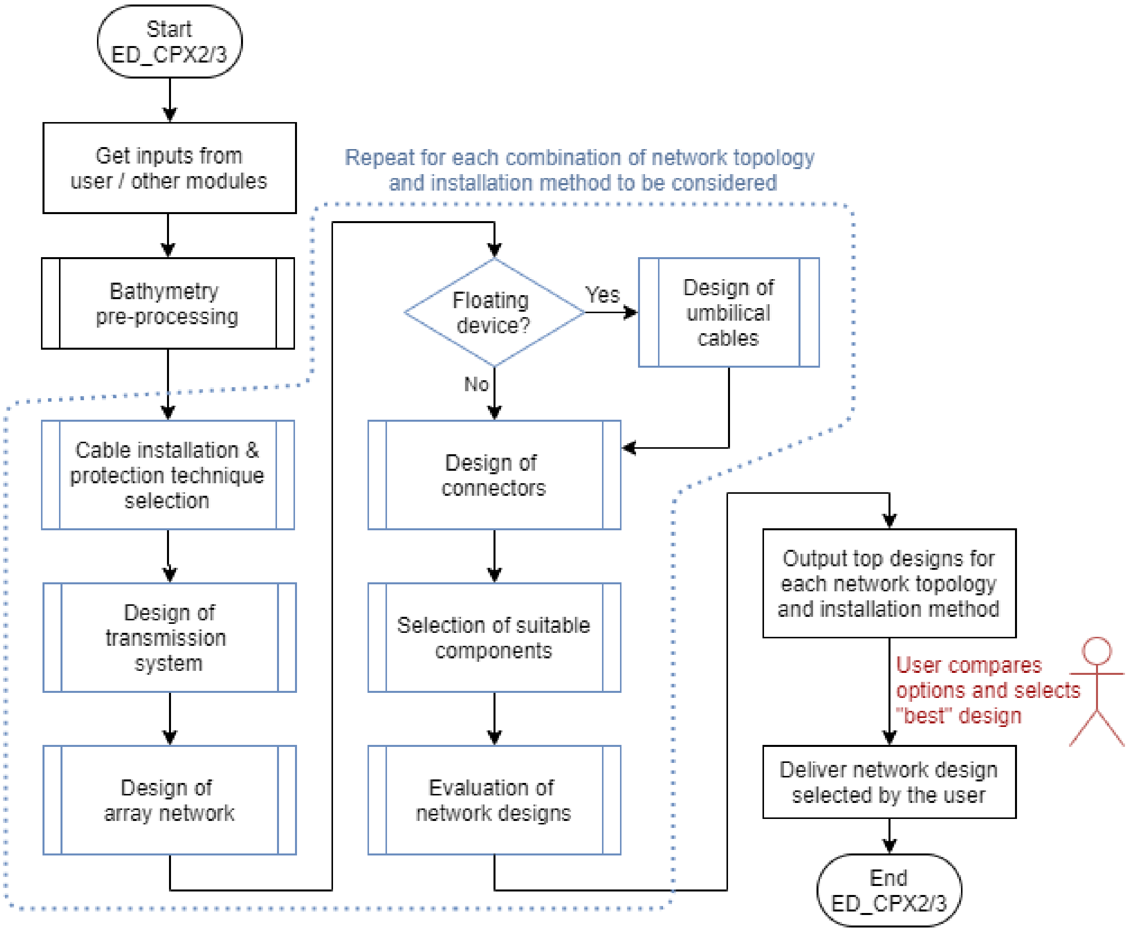


FIGURE 3.8: PROCESS FLOW OF THE DESIGN AND EVALUATE FUNCTIONALITIES AT CPX2 AND CPX3

3.5.2.1 BATHYMETRY PRE-PROCESSING

The site characteristics data, which include the lease area and the cable corridor bathymetry, need to be pre-processed for the cable routing optimisation routines used in the ED module. The pre-processing of the bathymetry data involves the following tasks:

- Merging the lease area and export corridor bathymetry data,

- Calculating the gradient and distance between all neighbouring points in the bathymetry data,
- Creating a NetworkX graph object for cable routing analysis,
- Removing points that lie within exclusion zones and lines that breach the gradient constraint specified as an input.

3.5.2.2 CABLE INSTALLATION AND PROTECTION TECHNIQUE SELECTION

Possible cable installation and protection techniques are briefly described in Section 2.2, with those considered in DTOceanPlus being jetting, ploughing, cutting, dredging and surface lay.

The cable installation and protection techniques that will be used on a project are largely defined by the seabed type, and within the ED module can either be user defined or can be selected by the module. Cable protection in offshore projects is an important aspect, as cable damage can be expensive, and may have a significant impact on the profitability of the project [13].

Cable burial is the most common protection method used in the offshore wind industry. All of the installation techniques included in the ED module with the exception of surface lay aim to do this in a range of different seabed types. Of the techniques being considered, the optimal technique is selected based on the cable length and installation rates (in metres/hour) in different soil types These are shown in Table 3.14, colour coded by tool suitability. This table exists as a catalogue that the ED module uses. The table entries of zero denotes incompatible installation technique and seabed type combinations.

TABLE 3.14 : CABLE INSTALLATION TECHNIQUE INSTALLATION RATES, COLOUR CODED BY TOOL SUITABILITY

Soil group	Seabed type	Installation rate [m/hr]			
		Jetting	Ploughing	Cutting	Dredging
Cohesionless	Loose sand	250	100	0	150
	Medium sand	200	350	275	87.5
	Dense sand	0	100	275	75
Cohesive	Very soft clay	475	0	0	150
	Soft clay	475	375	275	100
	Firm clay	250	500	275	75
	Stiff clay	0	550	75	50
Other	Hard glacial till	0	300	75	50
	Cemented	0	0	75	50
	Soft rock coral	0	0	50	50
	Hard rock	0	0	0	0
	Gravel cobble	0	350	0	75

Key:	Untrenchable	Not suitable	Suitable but not ideal	Suitable

The target cable burial depth in the array and the transmission networks are user inputs in the module. If these values are not provided, then default values for the burial depth based on the seabed type are selected. For all sandy seabed types (including loose, medium and dense sand), the burial depth target is 0.5 m, for clay seabed types (including very soft, soft, firm and stiff clay), it is 1.0 m, and for all the other seabed types (including hard glacial till, cemented, soft rock coral, hard rock and gravel cobble) the cable is surface laid.

Many of the early test facilities and array deployments have used surface lay as the option for cables, which is also an installation technique included in the module. Cables that are surface laid are susceptible to a number of risks and need to be protected. Surface laid cables are often protected using split pipes, concrete mattresses, or rock dumping, as illustrated in Figure 2.11. Within the ED module, whether or not to use any protection for surface laid cables and the protection option to be used is a user input. The design and costs of the protection method used and its equipment and installation costs are not included in ED module. The LMO tool includes the installation costs to the overall solution.

As a first step, in identifying the cable installation approach, all the seabed types present in the lease and cable corridor areas are identified during the bathymetry pre-processing. All installation techniques that are compatible with the soil types present in the bathymetry files are initially considered. For each of these cable installation techniques, areas in the lease and cable corridor areas compatible with the installation equipment are found. Separate NetworkX graph objects are then created for each cable installation technique individually.

In the use case where the cable installation technique is not specified by the user, the selected cable installation techniques are sorted in the descending order of installation rates and iteratively assessed, starting with the one with the highest installation rate. If an ED network design solution is obtained for a technique, the iterative search is stopped, and the cable installation technique used is saved as an output.

If the cable installation technique is user defined, the NetworkX graph of the particular installation tool is used to create network designs. In case this fails (e.g. if the chosen installation technique is not suitable for the seabed), the best tool based on installation rates is chosen and the user is informed of this.

3.5.2.3 DESIGN OF TRANSMISSION SYSTEM

The network design process starts with the design of the transmission system, which is often the most expensive part of the entire array's electrical infrastructure. Other than for very early array deployments, in which direct cables from every device to the shore are used, larger arrays will likely have one or more collection points. The collection point and the transmission system, as defined in Figure 2.1, are often designed together because they are interrelated.

For direct to shore connections, the transmission system is designed using the array design algorithm, but is referred to as a transmission system rather than an array network.

The transmission system design process is shown in Figure 3.9. This involves determining the transmission/export voltage required, which in turn determines whether some form of voltage transformation is required on the collection points. If collection points are required, their locations and the route of the export cable from the collection point to the onshore landing point need to be optimised.

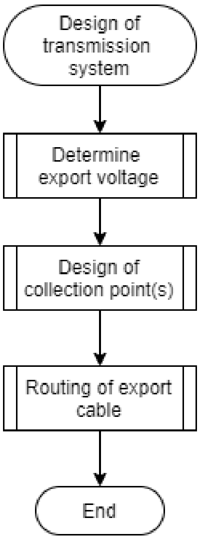


FIGURE 3.9: HIGH-LEVEL DESIGN PROCESS FOR TRANSMISSION SYSTEM

SELECTION OF EXPORT VOLTAGE

The first step of the transmission system design involves determining the transmission/export voltage to be used for the device/array in question. Technical and operational requirements place limits on the transmission of electrical energy for a given generation voltage, power magnitude and transmission distance. The export voltage required depends on the size of the device/array and the distance of the device/array to the onshore landing point. Determining the export voltage to be used is primarily based on the estimated maximum power and distance capability of a range of different voltage levels, available in the module as a lookup table, shown in Table 3.6. The algorithm, presented in Figure 3.10, then determines suitable voltage levels for analysis and, if necessary, proposes the use of step-up transformers on the collection point. The lowest voltage suitable for the device/array power and distance to the shore, starting from the device voltage, and the next higher voltage up are selected to be further assessed by the module. Choosing the next higher voltage up is important to examine if the savings due to the lower energy losses at the higher voltage is higher than the increase in equipment cost.

There are six network topologies included in the ED module and the selection of the export voltage occurs slightly differently for those that do not have a transmission collection point. In many planned and deployed small arrays, one of the devices in the array can also play the role of a collection point. In this case, the possibility of using the device voltage to transmit the power is assessed. If the device voltage is found to be insufficient, an error message informs the user of this constraint. This is the case with the direct connection to shore topology as well, wherein every device in a small array has a dedicated cable to the shore.

The export voltage can be user defined and the same check as shown in Figure 3.10 is applied. The next voltage up is not selected for assessment in that case.

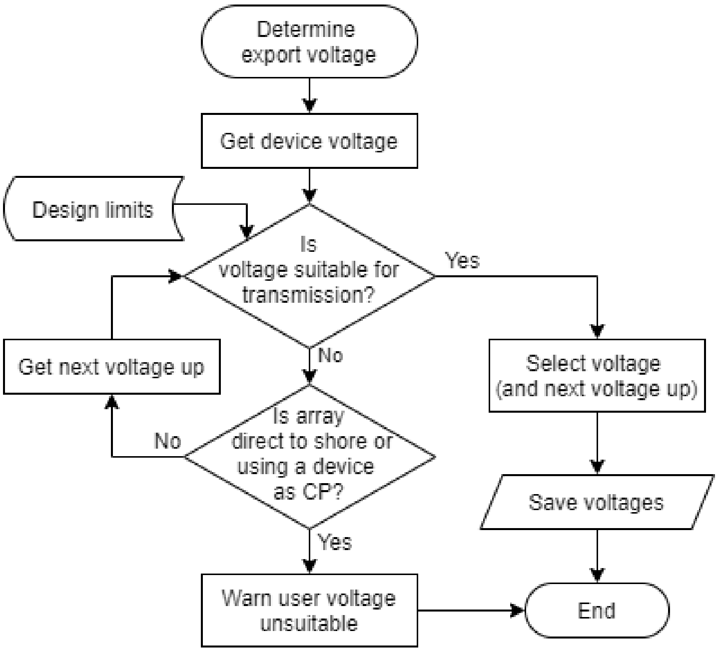


FIGURE 3.10: TRANSMISSION VOLTAGE SELECTION ALGORITHM

DESIGN OF COLLECTION POINT(S)

With larger deployments of devices further away from the shore, there often is a need for one or more collections points (CPs) in the array. The type of CP required also depends on the device voltage and on the export voltage, as determined by the assessment described in the preceding section. At a high level, CPs can be classified as:

1. **Transmission CPs** that connect the array to the OLP through the export cable.
2. **Array CPs**, to which OECs are directly connected, occur within star networks and collect the power generated by the clusters.
3. **Device CPs** are found in cases wherein a device in the array performs the role of a CP. The export cable to the shore originates from this CP. Device CPs are not referred to as transmission CP in this document.
4. **Virtual CPs** are used internally in the module for direct to shore networks. The onshore landing point acts as virtual CPs in such networks.

Transmission and array CPs can be further divided into the following sub-types:

1. **Passive offshore collection hubs**, wherein no voltage transformation is required between the array network and transmission system. These are expected to be seabed mounted.
2. **Offshore substations**, wherein voltage transformation is required between the array network and the transmission system. These will be fixed surface-piercing.

The first part of the CP design involves specifying the location of the collection point(s). Based on the network topology selected or being assessed, a network design can either have one CP (in radial networks and star networks with one cluster e.g. Figure 2.4 to Figure 2.7) or multiple CPs (in star networks with more than one cluster e.g. Figure 2.8 and Figure 2.9). The ED module only considers one transmission CP, which is where the export cable originates from and carries the array's power to the shore. Any other CP(s) in the network topology, collecting power generated by clusters of devices, will be called array CPs. Network topologies that use one of the devices as their CP, do not have either a transmission or an array CP (as shown in Table 2.1), to help differentiate these topologies from others that have a substation or hub as the CP.

The location of the transmission CP is defined in the module by a *k*-means clustering algorithm, a widely used algorithm for portioning data points into subsets [14], [15]. The layout of the devices in the array and the location of the onshore landing point are the main inputs to the function. In addition to these inputs, the grid of points, which is the output from the bathymetry pre-processing stage and includes exclusion zones, is also required. The *k*-means clustering algorithm attempts to minimise the Euclidian distance between observations (device/array CP location and OLP) and centroids (transmission CP location). For network topologies with only a transmission CP, the algorithm returns the centroid of the area defined by the device and OLP coordinates.

The output of the clustering algorithm is only an interim solution and is accepted as the final solution after further checks. The first check involves determining whether the interim transmission CP location lies within the lease area. If not, the transmission CP is moved from the interim location to the edge of the lease area closest to the interim location. The transmission CP location now becomes the intermediate location. The next check involves examining the proximity of the transmission CP to the devices. There is a threshold level set for this proximity and if there are breaches the transmission CP location is adjusted until no more threshold breaches are found. This now becomes the final transmission CP location. The algorithm used, which has been described here, is shown in Figure 3.11.

For network topologies in which a device acts as a CP, the device closest to the onshore landing point is selected as the CP.

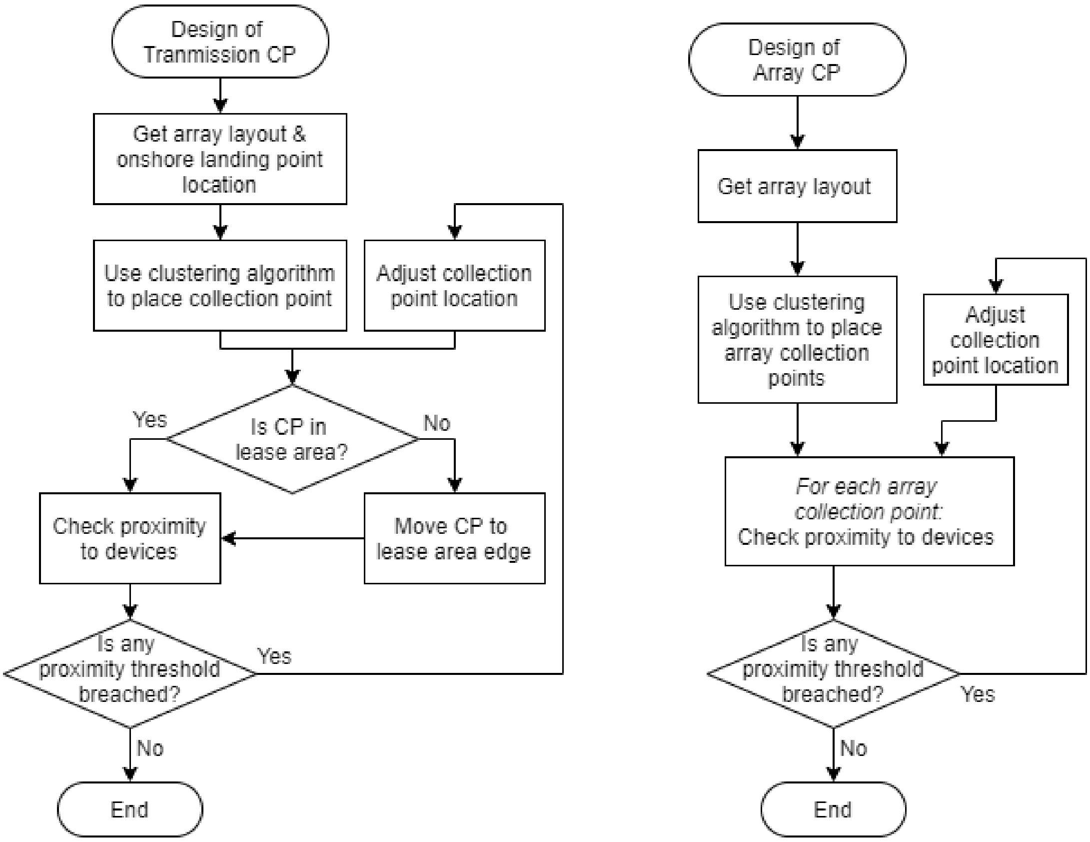


FIGURE 3.11: COLLECTION POINT LOCATING ALGORITHMS FOR TRANSMISSION CP AND ARRAY CP

ROUTING OF EXPORT CABLE

The next part of the design of the transmission system is specifying the export cable route between the transmission or device CP and the onshore landing point. The cable routing algorithm routes the cables along the seabed and evaluates the length of the cable. Exclusion zones and areas with steep gradients are avoided. The cable routing algorithm was implemented using a modified version of the Dijkstra's algorithm, a widely used algorithm for finding the shortest path between nodes in a graph [17]. The algorithm has the capability of removing constrained nodes, e.g. from exclusion zones or steep gradients, and works with NetworkX objects created in the bathymetry pre-processing stage (Section 3.5.2.1). The implementation requires the start and end points of the cable along with information of any constraints to be applied. The algorithm outputs the cable route, the length and the route path as a list of coordinates. Figure 3.12 shows the export cable routing algorithm implemented within the ED module.

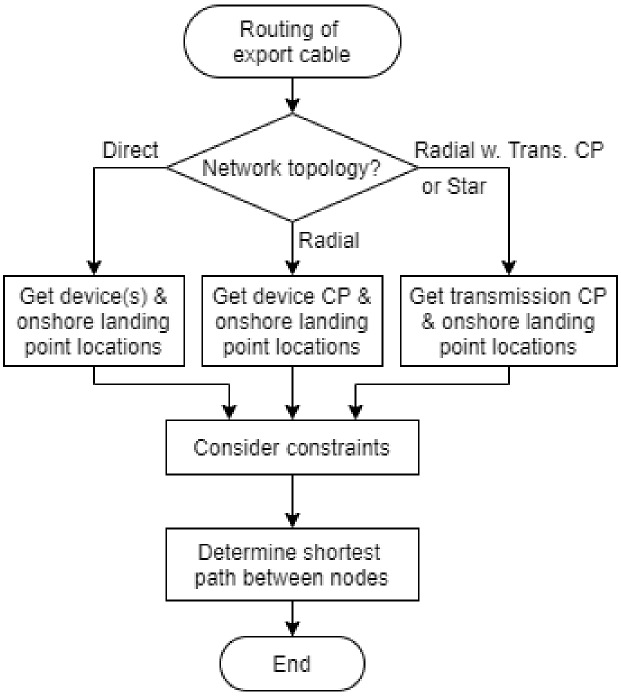


FIGURE 3.12: EXPORT CABLE ROUTING ALGORITHM

3.5.2.4 DESIGN OF ARRAY NETWORK

The design of the array network, which is the network that collects the power from the devices/array CPs to the transmission CP, is the next part of the energy delivery system design process.

At this stage in the sector development, there is no consensus on the best practice approach for array network layouts. Transfer of knowledge from the offshore wind sector is possible, but there are significant differences. Power and voltage ratings of wave and tidal device technologies are lower than of offshore wind turbines. The array layout in OEC farms is driven primarily by device hydrodynamics, with lower spacing between devices than those seen in wind farms. These will all have an overriding influence on the array network configuration. The network topologies considered in the ED module, which have been discussed briefly in Section 2.1.3, were selected keeping in mind this difference, and cater to both commonly used network topologies in offshore wind and planned/installed network topologies in wave and tidal arrays.

The array network design process depends on the network topology, as shown in Figure 3.13, and involves three main processes:

- Selection of array voltages,
- Clustering of the devices around CPs, and
- Routing of array cables between devices and between array CPs.

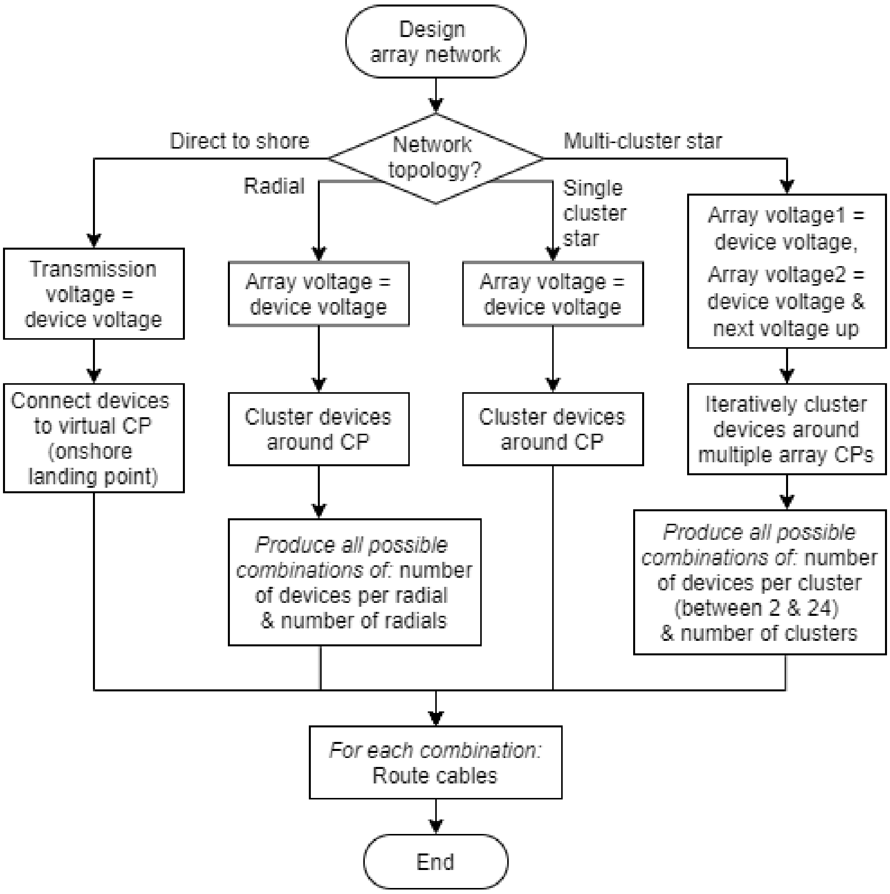


FIGURE 3.13: ARRAY NETWORK DESIGN PROCESS

SELECTION OF ARRAY VOLTAGES

Any part of the array network directly connected to a device operates at the device voltage. In the case of network topologies derived from the generic radial topology, this means that the entire array network operates at the device voltage. In network topologies derived from the generic star topology (i.e. multi-cluster star networks), the array network between the array CPs and the transmission CP can be at a different voltage to that of the device, denoted by Array voltage 2 in Figure 3.13. This decision is based on the power rating of the individual clusters and the distance/route between the array CPs and the transmission CP. The data in Table 3.6 is used for this purpose and two voltage levels, the minimum voltage required and the next one higher up, are chosen for evaluation.

CLUSTERING OF DEVICES AROUND COLLECTION POINT(S)

The clustering requirements, and hence the algorithm used, for network topologies based on radial and star layouts are different. In variants of the generic radial topology there is only one CP, which is the transmission CP (or a device CP/virtual CP), and all the devices in the array need to be connected to it.

In variants of the generic star topology, there may be array CPs and devices need to be clustered and connected to them. Array CPs having from 2 to 24 devices connected to them are allowed, and all possible combinations of cluster sizes are assessed to obtain the best performing and the lowest cost solution. Designs made with clusters having only one device connected to every array CP are considered uneconomically and are ignored. The number of clusters to be considered for a particular array with a certain number of devices are determined and assessed iteratively.

For a specified number of clusters, the *k*-means algorithm, described earlier in Section 3.5.2.3 , is used to assign devices to array CPs. In addition to the layout of the devices in the array, the algorithm also requires the number of array CPs as an input and divides the array devices into the number of clusters required. The locations of the array CPs are also output. The clustering algorithm works to minimise the Euclidian distance between the devices in a cluster and their corresponding array CP.

CONNECTION OF DEVICES AND CPS

Connections need to be made for one or more cases:

- Devices to each other,
- Devices to CP(s), and
- Array CP(s) to transmission CP

To obtain the lowest cost array network solution, the objective is to use the shortest total array cable length within the allowable bathymetry points output from the pre-processing stage. This is achieved by using a travelling salesperson vehicle routing algorithm developed for cable routing in offshore wind farms [17]. At this stage, the cables are not routed but the connections between device(s) and CP(s) are optimised.

In variants of the generic radial topology there is only one CP and all the devices in the array need to be connected to it. The vehicle routing algorithm starts with defining a matrix of distances between all devices to each other and the CP. It then explores all possible topologies of radials from having just 1 device per string to having all the devices in a string and any combination in between. The maximum number of devices in a string is an optional user input, represented by *devices_per_string* in Table 3.12. If user defined, then radial topologies having a maximum of *devices_per_string* per string are considered. The next step involves using the vehicle routing algorithm to connect all the devices in the string(s) together to the CP. The algorithm does not allow crossing of array cables and the network solutions with cable crossings are ignored. All feasible radial network designs after this step are then evaluated. The maximum number of devices on a string can also be a user input as a constraint to the algorithm. Hence, iteratively, this process optimises the number of devices in the strings and the number of strings in a radial network with the objective of having the shortest array cable length.

In the case of network topologies derived from the star layout, the devices assigned to a particular array CP are directly connected to it. The vehicle routing algorithm is still used to connect the array CP(s) to the transmission CP using the shortest total intra-collection point cable length. Using this algorithm leads to hybrid network topologies with star clusters connected to each other and/or to the transmission CP either as radials or stars. The array CPs' locations become points on the route and the transmission CP becomes the target of the algorithm.

ROUTING OF ARRAY CABLES

Once the connections between the devices, between devices and the CP(s) and between CPs are finalised, the next step involves the actual routing of the cables on the seabed. The requirements of the cable routing algorithm for array networks are identical to that of the export cable. Therefore, the same cable routing algorithm based on the Dijkstra's algorithm, explained in Section 3.5.2.3, is used here.

3.5.2.5 DESIGN OF UMBILICAL CABLES FOR FLOATING DEVICES

Umbilical cables are used with floating devices to transfer their power generated to the subsea network. Umbilicals in floating wave and tidal devices are installed in highly energetic environments and are subject to dynamic and cyclical loading regimes. Double armouring is provided to umbilicals for hydrodynamic stability during the installation and operational phases, which is the main difference between them and static cables. The design of umbilicals in the ED module includes both their electrical and mechanical design and is as per DTOcean 1.0 and 2.0. The algorithm used for their design is shown in Figure 3.14.

An umbilical is selected from the catalogue based on the voltage rating of the floating device. The device location is taken to be the starting point of the umbilical. The first step in the design process involves setting the termination point of the umbilical on the seabed. The termination point is set along the projection of the static cable route between the device and its downstream device at approximately 1.5 times the minimum water depth from the device. This termination point of the umbilical is then used to reduce the virtual distance paths of the static cable between the device and the downstream component.

The lazy wave configuration of umbilicals, shown in Figure 3.15, is used for its mechanical design, which requires an iterative approach to solve for the cable forces at the main stress points. The approach used is based on the methodology presented in [18]. This approach had been shown to be comparable with commercially available finite-element software Orcaflex.

The set of equations to be solved to calculate the mechanical loading of an umbilical in the lazy wave configuration are included in Annex I. The outputs of the mechanical design, that are used for further processing by the ED module, are the umbilical cable length, and the x and z coordinates along the entire length of the umbilical. The length of the umbilical cable is used to evaluate its impedance from its impedance per unit length and the impedance matrices used for the power flow analysis are updated to reflect their inclusion.

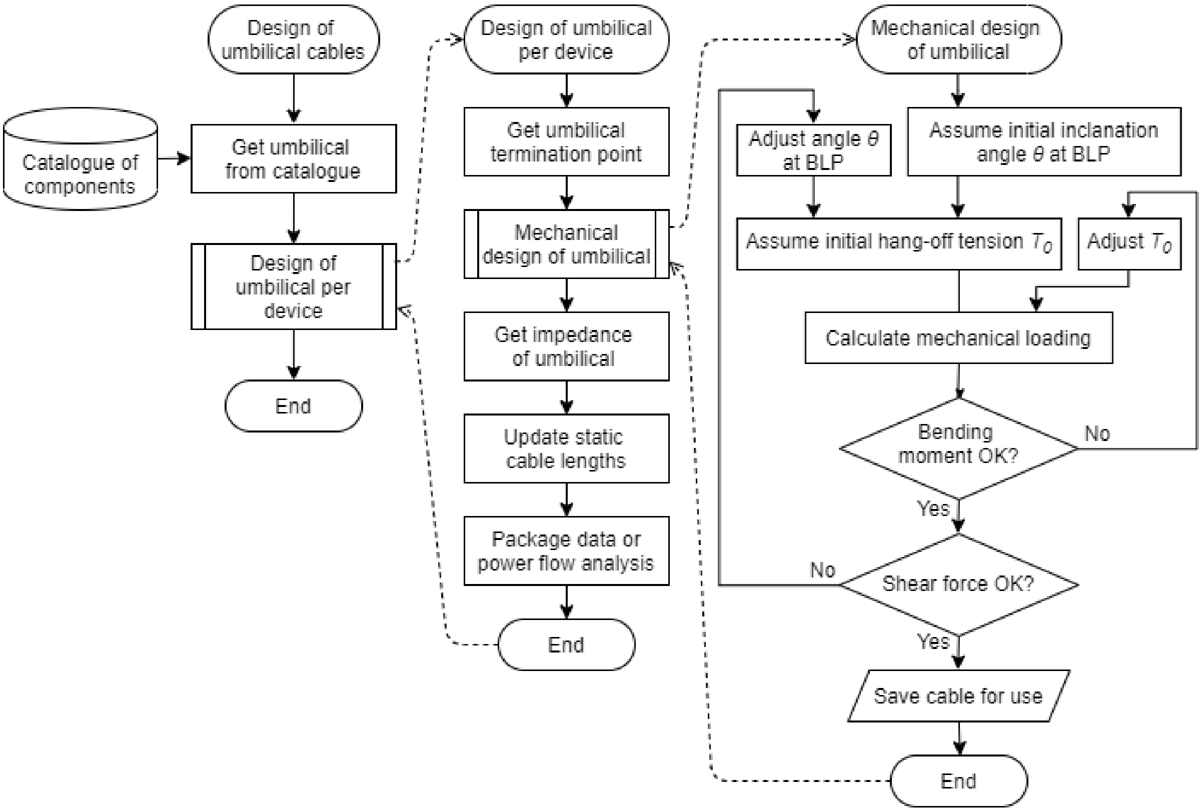
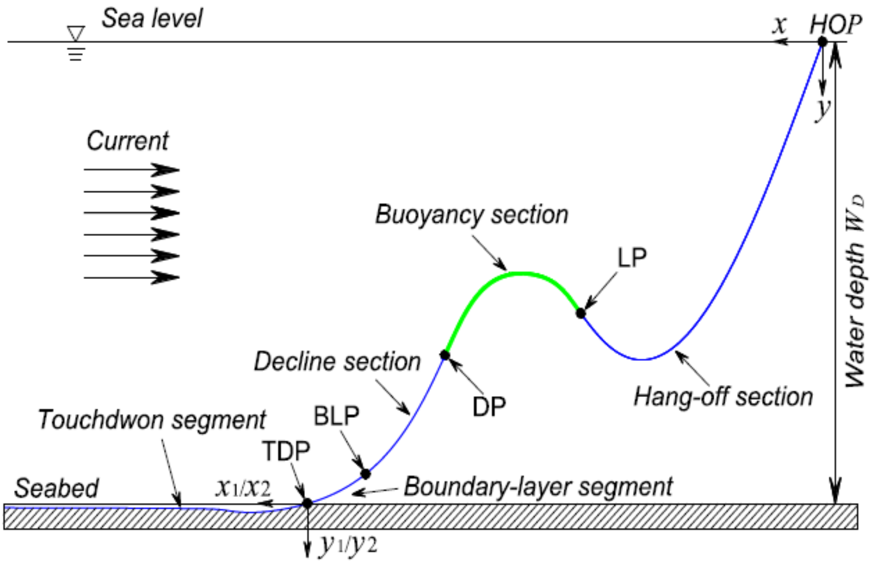


FIGURE 3.14: UMBILICAL DESIGN ALGORITHM



HOP	hang-off point
LP	lift point
DP	decline point
TDP	touchdown point
BLP	boundary-layer point

FIGURE 3.15: LAZY WAVE CONFIGURATION [18]

3.5.2.6 DESIGN OF CONNECTORS

Electrical connectors are used in wave and tidal arrays to allow for non-permanent connections of different parts of the electrical system, facilitating recovery of components for repair and maintenance. They are classified based on whether they are mated in the dry or wet environment, i.e. above or below the water surface, as dry and wet mate connectors. Connectors are used to form connections between cables and also between cables and other electrical equipment in the marine array. Within the ED module, both wet and dry mate connectors are included as options to make connections between cables and devices, to connect umbilical cables to static cable networks and to make connections of static cables to both surface piercing and subsea CPs. The connector type (wet or dry) on the device itself is a user input. The same connector type is used for the subsea connector that connects a floating device's umbilical to the static cable network. The input and output connector type for CPs are obtained from the electrical component catalogue.

In star network topologies, every device has only one connector to either a static or an umbilical cable. In radial network topologies, the device can have multiple connectors on itself. The number of these connectors on a device depends on the position of the device in the string - 1 if the device is at the end of a string, or 2 if the device is in the middle of a string or if the device is connected to a CP. If the device performs the role of a device CP, a connector for every string connected to the device will be required along with one for the export cable to the shore.

3.5.2.7 SELECTION OF SUITABLE COMPONENTS

After the array network and the transmission systems have been designed, the electrical components catalogue is accessed to select components for all the network designs generated. The components are selected using standard electrical parameters, i.e. total apparent power, current, and voltage.

There may be more than one network design options at this stage, and all these are carried on into the evaluation phase. For both radial and star network topologies with a separate transmission CP, (not one of the devices or array CPs) two export voltages are chosen to be assessed (as discussed in Section 3.5.2.3). In topologies derived from the generic radial topology, there will be network designs with varying number of strings and devices per string. In the case of topologies derived from the generic star topology, there will be network designs with different number of clusters and devices per cluster and also two intra-collection point network voltages (as discussed in Section 3.5.2.4). All possible combinations of network design options and export voltages are selected for evaluation. Components for all these combinations of network designs are selected from the catalogue and saved in a local catalogue file for use in the evaluation phase. The framework adopted for this process is shown in Figure 3.16.

In the case of radial topologies, at this stage, the selection of all components is based purely on the voltage level required (or voltage transformation required). Therefore, depending on the size of the electrical component catalogue available there might be multiple, replaceable components selected. For example, there might be 11 kV static cables of different current ratings in the catalogue, all of which are selected if the network design requires an 11 kV array network. In the case of star topologies, along with the voltage rating, the current rating of the component is also used to select components from the catalogue.

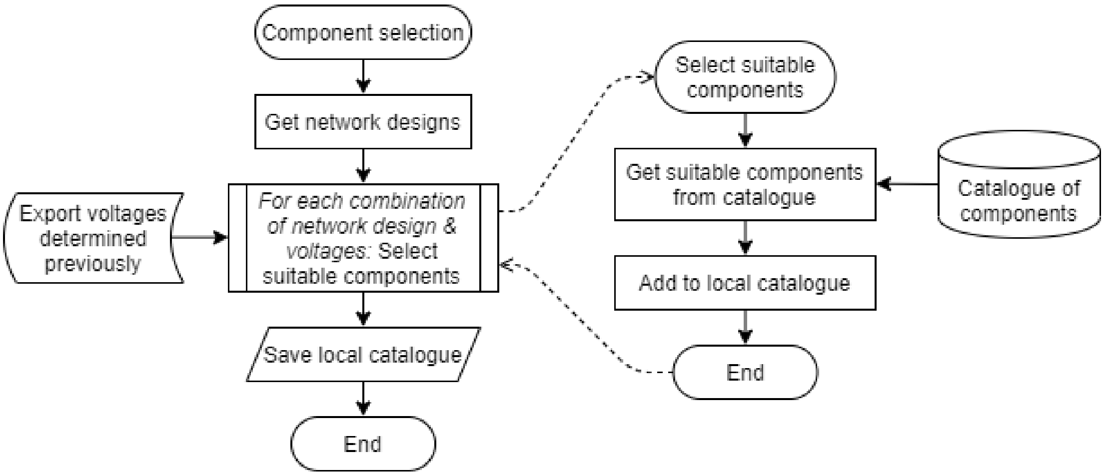


FIGURE 3.16: COMPONENTS SELECTION FRAMEWORK AND PROCESS FLOW

3.5.2.8 EVALUATION OF NETWORK DESIGNS

The other main functionality of the ED module is the techno-economic evaluation of network design-component combinations identified by the design functionality of the module. Figure 3.17 shows the algorithm used to evaluate the network design-component combinations.

This first deals with the technical evaluation of the network design-component combinations. All such combinations are iteratively assessed by running power flow analyses. The power flow is performed using PyPower [19], a Python port of MATPOWER [20]. This code allows for steady-state AC power flow or DC power flow analysis, however only AC power flow is implemented in the ED module. Power flow solutions are run for all output power levels of the device(s) and include both real and reactive power losses in the network. The power flow results include the branch power flows, voltage levels at all buses and the real and reactive power at the Grid Connection Point (GCP). The losses in the onshore network, that connects the OLP and the GCP, are implemented as a simple efficiency factor in the module. The power flow analyses results are examined to check if all the network design-components combinations are technically feasible. Technical feasibility is defined with respect to current rating or voltage limit breaches in the power flow results. Only those network design-component combinations that produce a technically feasible solution are selected for further evaluation.

Next, the frequency of occurrence f_i and the real power at the GCP P_i for the different array power levels are used to calculate $annual\_yield$, the Annual Energy Production (AEP), of the device/array using (3.8).

$$annual\_yield = \sum_{i=1}^{N} P_i \times f_i \tag{3.8}$$

The costs of all the components in the network designs are obtained from the electrical component catalogue. The AEP and the total equipment cost of the electrical infrastructure, *total_cost*, are used to calculate a simplified Cost of Energy *coe_elec* based on (3.7). The network design-component combinations are sorted in ascending order of the *coe_elec* and the top three designs, if they are available, are output. The network efficiency *annual_efficiency* is calculated as shown in (3.9).

$$annual\_efficiency = \left(\frac{annual\_yield}{annual\_yield + annual\_losses}\right) \times 100 \qquad (3.9)$$

The network topologies to be included in the optimisation are a user input. If not provided, all the network topologies available in the ED module are iteratively assessed and the top three network designs of each topology (based on *coe_elec*) are saved for the user. The user then chooses the network design for further analysis in the subsequent modules.

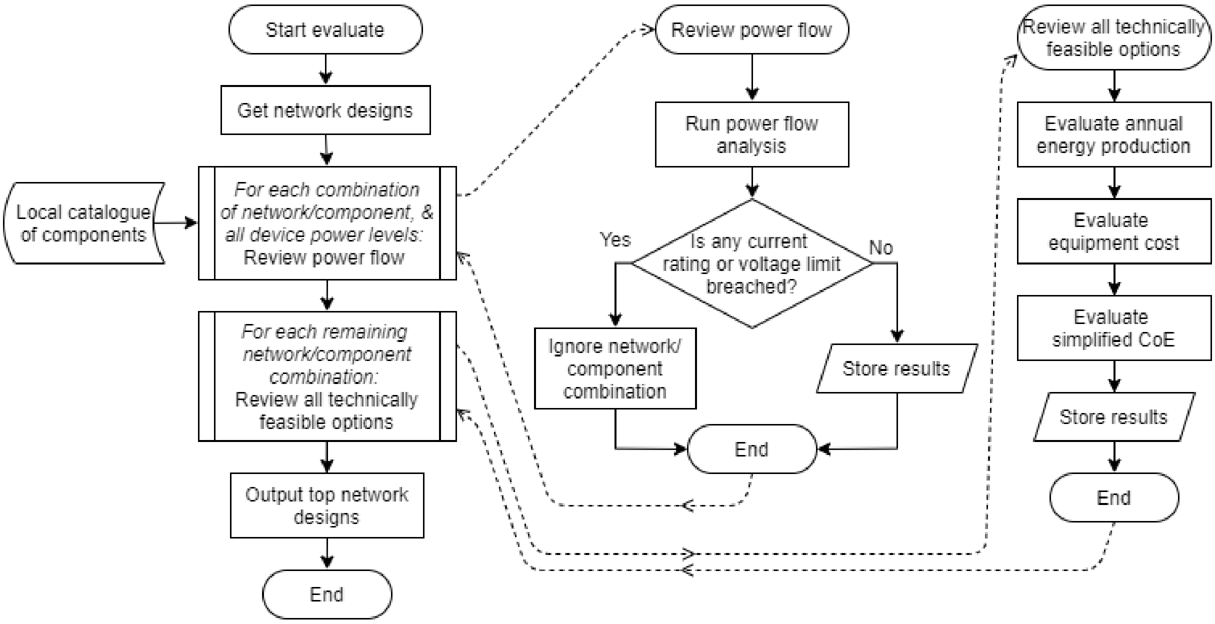


FIGURE 3.17: ALGORITHM OF THE EVALUATE FUNCTIONALITY

3.5.3 OUTPUTS

The ED module, at CPX2 and 3, outputs a list of network designs, including the top three designs for the network topologies selected by the user. Each network design object has the data fields given in Table 3.15. Example output files are shown in Section 5.2.

TABLE 3.15: OUTPUTS OF THE ENERGY DELIVERY MODULE AT CPX2 AND CPX3

Parameter	Description	Data Model	Units
annual_efficiency	Network efficiency over a year	float	%
annual_losses	Total electrical losses over a year	float	Wh
annual_yield	Array energy output over a year at the Grid Connection Point (GCP)	float	Wh
array_power_output	Real power delivered to the GCP for the different power generation levels	list	MW
array_reactive_output	Reactive power delivered to the GCP for the different power generation levels	list	MVAr
array_voltage	Array network voltage	float	V
array_cable_total_length	Total length of the array cables used in the design	float	m
b_o_m	Network bill of materials: includes component catalogue key, component type, design id, quantity, UTM coordinates	pandas DataFrame	-
b_o_m_dict	Structure which carries all the data in b_o_m described above	dictionary	-
b_o_m_new	Network bill of materials classified under the four cost centres: transmission system, array network, collection point and onshore infrastructure	pandas DataFrame	€
cable_routes	Cable route information as points for all cables in network design: includes cable catalogue key, design id, list of point objects traversed by cable, list of burial depth and protection for entire cable length	pandas DataFrame	-
cable_dict	Structure which carries all the data in cable_routes described above	dictionary	-
collection_points_design	CP specifications: includes mechanical specification required for LMO module	pandas DataFrame	-
collection_point_dict	Structure which carries all the data in collection_points_design described above	dictionary	-
configuration	Network configuration	string	-
dry_mate	List of dry mate connector objects with all design specifications	list	-
export_voltage	Export cable voltage	float	V
export_cable_total_length	Total length of the export cables used in the design	float	m
floating	Device type whether floating or not	bool	-

Parameter	Description	Data Model	Units
hierarchy_new	Component-to-component connection relationships for reliability analysis	pandas DataFrame	-
histogram_efficiency	Electrical efficiency at each power generation level	list	%
histogram_losses	Electrical energy losses at each power generation level	list	Wh
coe_elec	Simplified COE for comparison of electrical networks	float	€/kWh
power_histogram	The probability of occurrence of each power bin.	list	%
total_cost	Total cost of all components in the network	float	€
umbilical_cable_design	Umbilical cable specifications: includes the design id, catalogue key, device reference, seabed connection point and length	pandas DataFrame	-
umbilical_dict	Structure which carries all the data in umbilical_cable_design described above	dictionary	-
umbilical_cable_total_length	Total length of the array cables used in the design	float	m
wet_mate	List of wet mate connector objects with all design specifications	list	-

REPRESENTATION OF NETWORK HIERARCHY IN DTOCEANPLUS

To represent the component-to-component connection relationships and flow of electricity within the energy delivery network, a system hierarchy structure was agreed to by all DTOceanPlus partners. The network hierarchy comprises of a list of every component considered within the energy delivery system, including export and array cables, connectors, CPs etc., along with their failure rates from the catalogue. Every OEC in the array has one or more "energy routes", defined as the pathways to transmit energy from that OEC to the OLP. These energy routes are composed of a list of components, not including the OEC itself or the OLP, through which the energy generated by the OEC passed before reaching the OLP. If any item in an energy route fails, no energy can be transmitted by that OEC to the OLP – this relationship is represented by an AND gate. If there are multiple energy routes available for an OEC, it can transmit the energy to the OLP as long as a route is available – this relationship is represented by an OR gate. An example of the hierarchy for an array of seven devices at the lowest complexity is given in Table 5.3. This is a human-readable output that is used by the other modules, but is not designed as a user output.

4. IMPLEMENTATION

The ED module is based on the Electrical Sub-Systems module in DTOcean v2.0.0 [1], which has been ported from Python 2.7 to Python 3.6 and additional functionalities added.

4.1 ARCHITECTURE OF THE TOOL

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

- The **Business Logic**, including a set of modules, classes, libraries implementing all the functionalities of the modules
- The **Application Programming Interface** (API) that will constitute the gate of the module to the other modules. The ED module will consume services from earlier design modules (SC, MC, EC, ET) and provide services to design modules (LMO, SK), assessment modules (SPEY, RAMS, SLC, ESA) and the SG and SI tools.
- The **Graphic User Interface** (GUI), which provides the means for interacting with the user, with 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 the ED module is modular, with the bathymetry pre-processing occurring prior to any electrical network design. The network design stage is divided into two, with specific design processes defined for the two main classes of network topologies: radial and star. The other network topologies implemented in the module, which have been listed in Table 2.1, have been derived from one of these two main classes of network topologies.

4.1.1.1 COMPLEXITY LEVEL 1

At CPX1, the ED module architecture comprises of five main classes as shown in Figure 4.1. Note that the class diagram only shows the main methods available in the classes.

ElectricalLowCmplx: The ElectricalLowCmplx class is composed of one input class: ElectricalArrayDataLowCmplx, which contains all the input data required for computation at CPX1, as shown in Table 3.3. Upon initialisation of the ElectricalLowCmplx class, its run_module() method is called, which creates and executes an instance of the OptimiserLowCmplx class.

ElectricalArrayDataLowCmplx: This is a data container class that carries all the array level input data shown in Table 3.3. Upon initialisation of the class, input checks on the array level input data are executed. The ElectricalMachineDataLowCmplx object is included within this class.

ElectricalMachineDataLowCmplx: This is a data container class that carries all the device specifications. Upon initialisation of the class, input checks on the device level input data are executed.

OptimiserLowCmplx: This is the main design class, which has methods that design the network solution and evaluate it as described in Section 3.4.2. The array_cable_length() method designs the array network for a given number of devices and estimates the array cable length required. Appropriate cables for the array network and the export cable are picked using the calc_current_actual() and select_cable() methods. The array_losses(), get_cable_loss() and power_loss_transformer() methods are used to calculate the power losses in the array network, the export cable and the transformer on the transmission CP. The Annual Energy Production is calculated using the AEP_calc() method. The class also contains a set of methods that calculate the cost of the transmission CP, the cables and the onshore infrastructure, which are the main cost centres in the network design at CPX1. The make_bom() and the make_hierarchy() methods populate the bill of materials and the network hierarchy tables for other modules to access. The final role of the OptimiserLowCmplx class is to create NetworkLowCmplx objects that store information of the designed network.

NetworkLowCmplx: This is the data container class that carries all the data from the network design and its evaluation. It is created by the OptimiserLowCmplx class. The class has the write_results_to_json() method which outputs the network design information into a json data file.

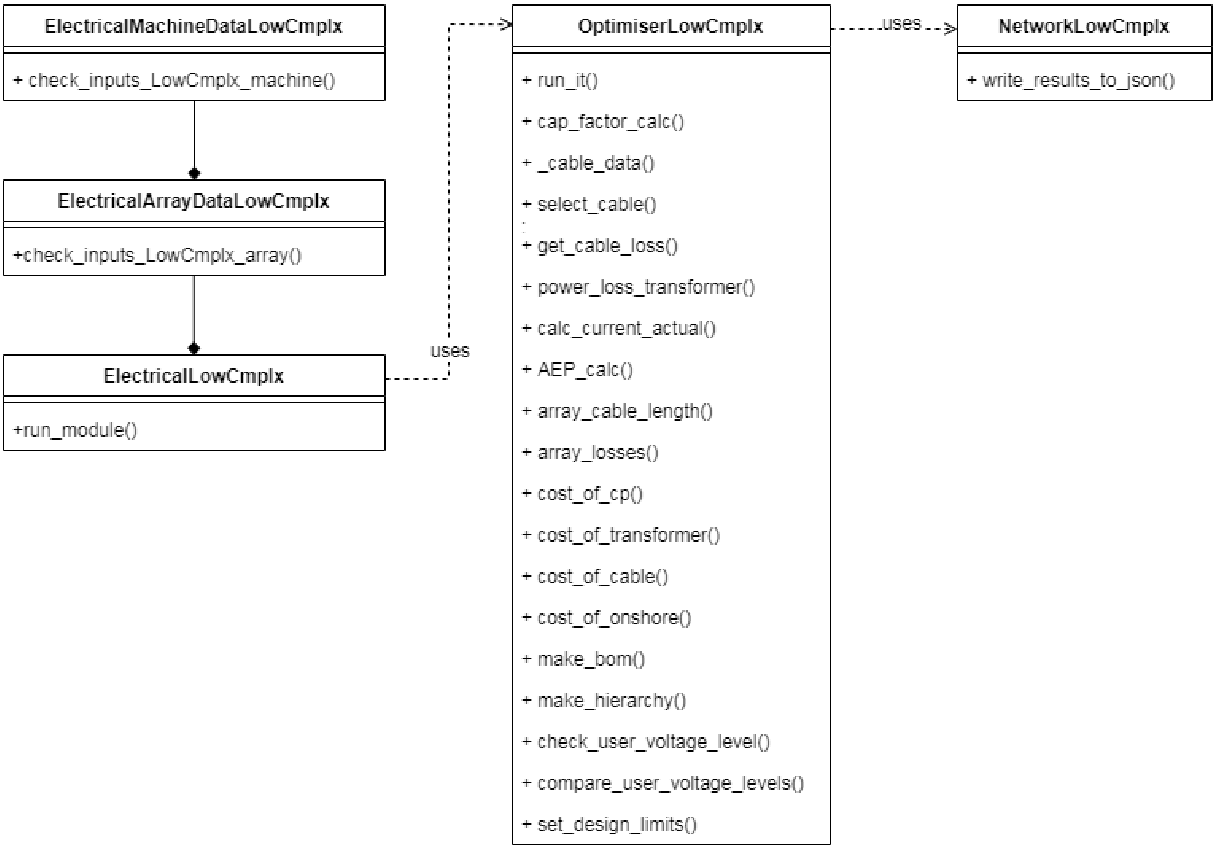


FIGURE 4.1: CLASS DIAGRAM AND METHODS AT CPX 1

4.1.1.2 COMPLEXITY LEVELS 2 AND 3

At CPX2 and CPX3, the ED module architecture comprises of the classes as shown in Figure 4.2. These classes and some of their main functions are discussed in this section. Note that the class diagram only shows the main methods available in the classes. The names of the classes representing the network topologies are listed in Table 4.1.

TABLE 4.1: CLASS NAMES FOR NETWORK TOPOLOGIES USED IN DTOCEAN 2.0 AND DTOCEANPLUS

Network topology	DTO1/2 class name	DTOceanPlus class name
Direct to shore	—	DirectNetwork
Radial	—	RadialNetwork_noCP
Radial with transmission CP	RadialNetwork	RadialNetwork
Single cluster star	—	StarNetwork_1cluster
Multi-cluster star	—	StarNetwork_noCP
Multi-cluster star with trans. CP	StarNetwork	StarNetwork

Electrical: The Electrical class is composed of six input classes: ElectricalComponentDatabase, ElectricalMachineData, ElectricalArrayData, ConfigurationOptions, ElectricalSiteData, and ElectricalExportData, which contains all the input data and processes required for computation at CPX2 and 3 (shown in Table 3.8 to Table 3.12). Upon initialisation of the Electrical class, a number of checks on the input data (contained in utility file input_tests) are performed. The Electrical class also initialises the Grid and the GridPoint classes. The methods in these classes along with the functions available in the grid_processing utlility file perform all the bathymetry-pre-processing described in Section 3.5.2.1. The iterate_multi_tools() method in the class performs the top-level iteration through installations techniques discussed in Section 3.5.2.2. The Electrical class creates and executes an instance of the Optimiser class, which is the controller class.

ElectricalComponentDatabase: This is a data container class that carries all the electrical component catalogue data. The class consists of six individual component tables as listed in Table 3.8.

ElectricalSiteData: This is a data container class that carries all the geotechnical and geophysical data from the lease area. The parameters of this class are listed in Table 3.9. The class includes methods to check the input data and to do preliminary data processing.

ElectricalExportData: This is a data container class that carries all the geotechnical and geophysical data from the export corridor. The parameters of this class are listed in Table 3.9. The class includes methods to check the input data and to do preliminary data processing.

ElectricalMachineData: This is a data container class that carries all the device specifications. Table 3.10 lists all the parameters of this class. The class includes methods to check the input data and to do preliminary data processing.

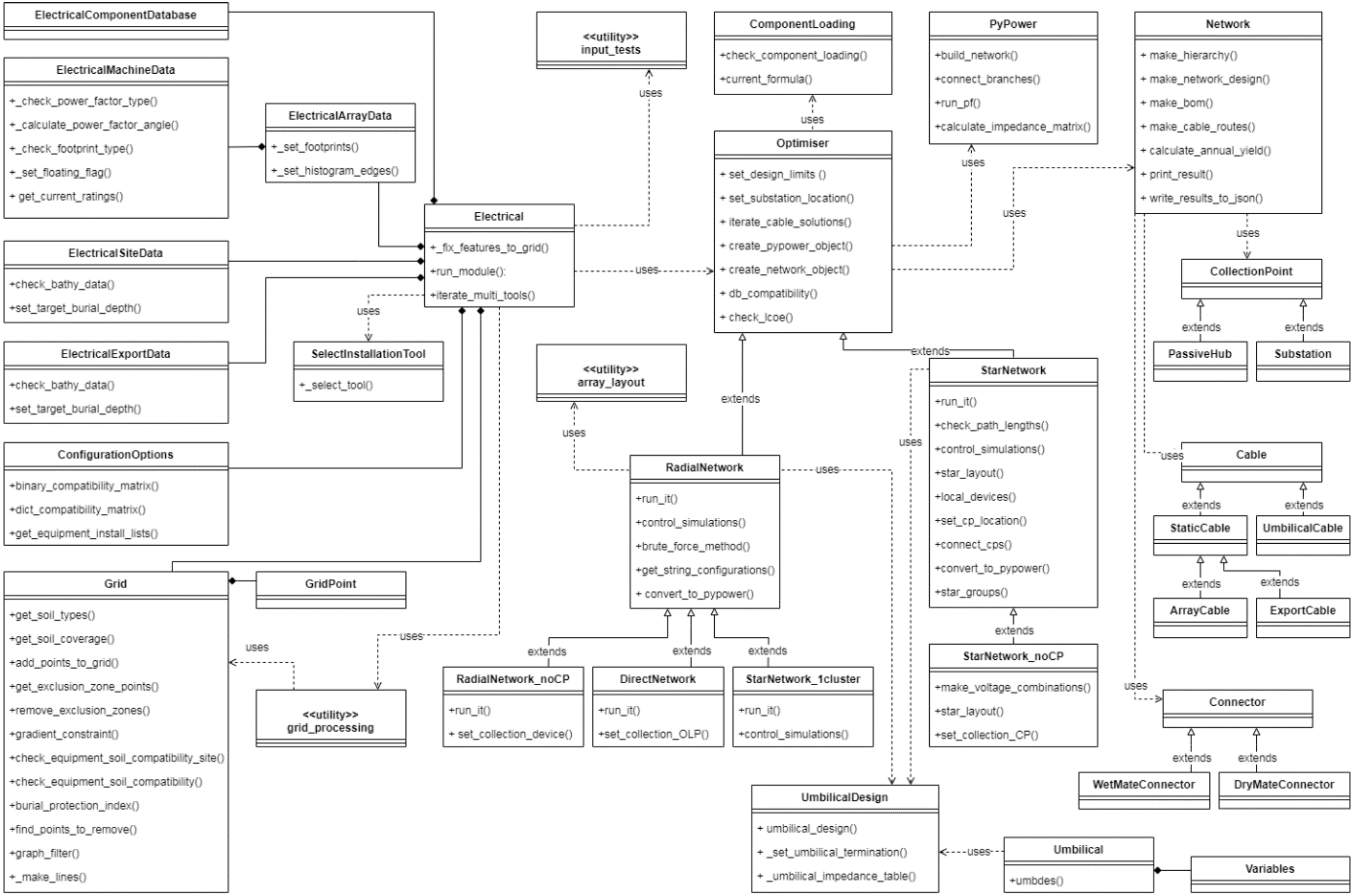


FIGURE 4.2: CLASS DIAGRAM AND METHODS AT CPX2 AND CPX3

ElectricalArrayData: This is a data container class that carries all the array level input data shown in Table 3.11. The ElectricalMachineData object is included within this class. The class includes methods to check the input data and to do preliminary data processing.

ConfigurationOptions: This is a data container class that carries all the user configuration options as listed in Table 3.12. The class includes methods to check the input data and to do preliminary data processing.

Grid: This class holds the data structure for the grid and is composed of a number of GridPoint objects. The Grid object contains useful information of the lease and cable corridor areas and has methods that filter seabed based on considered installation technique, as described in Sections 3.5.2.1 and 3.5.2.2.

GridPoint: This class holds the data structure for the grid point data, which carries information of every x-y coordinate point in the lease and cable corridor areas. All neighbouring points of an individual point are saved. The spatial distance and gradients between the point and all its neighbours are calculated. A series or edges and vertices are created for graph analysis.

grid_processing: This is a utility file with functions that work with both the GridPoint and Grid objects. The functions in this utility file along with the methods in the Grid class perform most of the bathymetry pre-processing discussed in Section 3.5.2.1. The set of functions in this utility file creates the Grid object and the NetworkX graph object, which is assigned to an attribute of the Grid class.

Optimiser: The Optimiser class is a controller class that defines the search space in the network design optimisation process and outputs the top three network designs. The search space in the optimisation is mainly defined by the voltage levels to be used in the array network and the transmission system. Using the processes described in Sections 3.5.2.3 and 3.5.2.4 technically feasible voltage levels are proposed for each part of the network. This class also has methods that extract data from the electrical component catalogue and create a number of network design-component combinations for evaluation as explained in Section 3.5.2.7. The Optimiser class aids the technical evaluation by creating and executing instances of the PyPower class. The Optimiser class also creates objects of the Network class to analyse and store detailed information of the designed networks.

RadialNetwork: This is a special instance of the Optimiser class. This class contains methods that design the connection of devices in radials, which is described in Section 3.5.2.4. The array network design methods in this class also use functionality from the array_layout utility file.

RadialNetwork_noCP: This is a special instance of the RadialNetwork class. This class contains methods that design the connection of devices in radials without a transmission CP. The CP is set to be the device closest to the onshore landing point.

DirectNetwork: This is a special instance of the RadialNetwork class. This class contains methods that design the direct connection of devices to the onshore landing point. The virtual CP is set to be the onshore landing point.

StarNetwork_1cluster: This is a special instance of the RadialNetwork class. This class contains methods that design a radial network with each string in the radial only having one device (hence named as a single cluster star).

StarNetwork: This is a special instance of the Optimiser class. This class contains methods that handle the clustering and connection of devices to array CPs and also the connection of these array CPs to the transmission CP. The functionalities of the methods in this class are described in Section 3.5.2.4.

StarNetwork_noCP: This is a special instance of the StarNetwork class. This class contains methods which handle the clustering and connection of devices to array CPs. The transmission CP is set to be the array CP closest to the onshore landing point.

UmbilicalDesign: This class holds the data structure for the Umbilical object, which is instantiated prior to the umbilical design. The class has methods that set the termination point for the umbilical cable and also evaluate the impedance of the umbilical based on the design.

array_layout: The array_layout utility file provides a number of functions to connect devices/CPs in the array network. The functionality of these function has been described in Section 3.5.2.4.

PyPower: This class packages the network configurations, made by the network topology classes, to a uniform format for the power flow analysis. This is accomplished using methods named convert_to_pypower() available in all the network topology classes. The PyPower data structures created, using the create_pypower_object() method of the Optimiser class, are used to generate bus and branch data for running the power flow analysis. The convert_to_pypower() method generates a set of connection matrices that carry information of all connections in the network. These connection matrices along with the distance matrix created by the network topology classes are used by the PyPower object to formulate the impedance matrix of the network, which is used to then run an AC power flow solution. Further details of the PyPower class methods and data structures is available in [21].

ComponentLoading: This class has methods to check the current flow through the branches in the network and also checks if any current rating breaches are seen in the results of the power flow analysis. It sets up flags if current rating breaches are seen, which makes that associated network design-component combination technically infeasible.

Network: This is the class that carries the data structure for the network design. The Network object is instantiated by the Optimiser class and its main role is to process and store the network design data to be easily used by the user either to examine results or for further analysis. The class has the write_results_to_json() method which outputs the network design information into a json data file.

Cable: The Cable class is the data structure for all the cable design data. A Cable object is instantiated by the Network class for every cable in the network design. StaticCable and UmbilicalCable are subclasses of the Cable class, while ArrayCable and ExportCable are instances of the StaticCable class.

CollectionPoint: The CollectionPoint class is the data structure for all the CP design data. A CollectionPoint object is instantiated by the Network class for every CP in the network design. PassiveHub and Substation are subclasses of the CollectionPoint class.

Connector: The Connector class is the data structure for all the connector design data. A Connector object is instantiated by the Network class for every connector in the network design. WetMateConnector and DryMateConnector are subclasses of the Connector class.

4.1.2 API

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

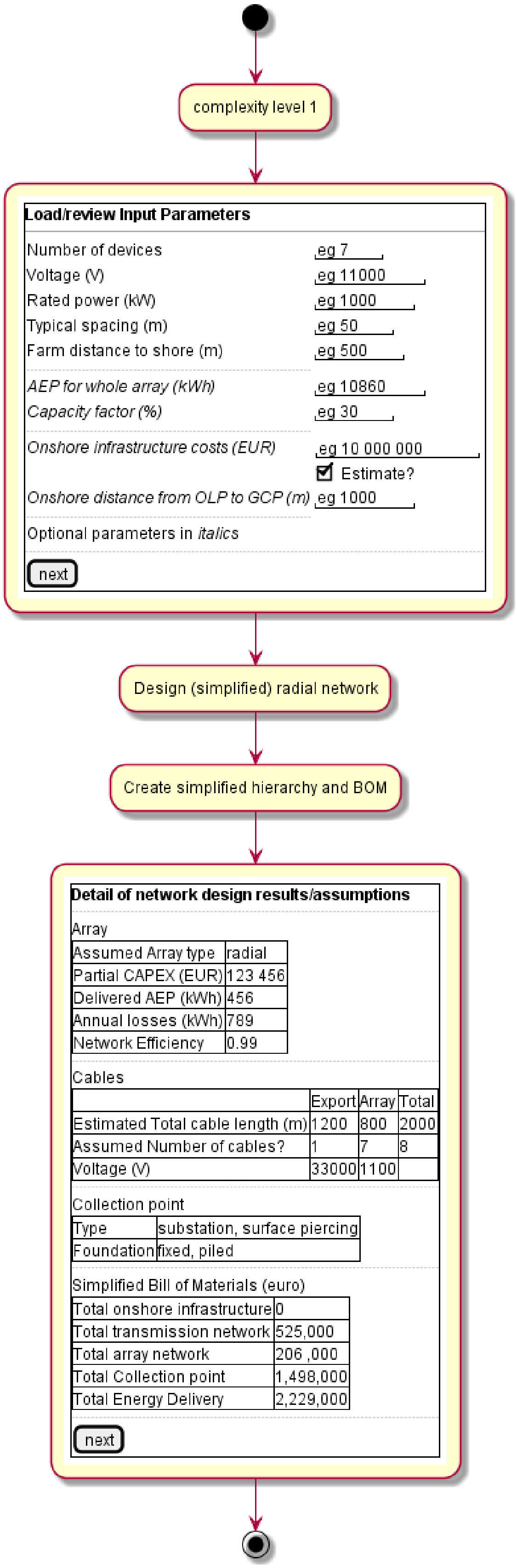
Similar to other DTOceanPlus modules, the ED module's API follows the same principles and the language OpenAPI is adopted. An OpenAPI file was created, in json format, describing in detail all the paths, services, and schemas that the ED module will consume and supply for the other modules to consume.

The backend of the module will receive the services from the other modules, run the Business Logic and then prepare the outputs for the other modules and users. This will be coded in Python, using Flask Blueprints.

4.1.3 GUI

The final GUI of the ED module is still under development. For all modules of DTOceanPlus, the GUI will be based on the same libraries to guarantee a consistent visual look.

Mock-ups of the main screens for the ED module at simple (CPX1) and full complexity modes (CPX2 and 3) are given in Figure 4.3 and Figure 4.4/Figure 4.5.



Load/review Input Parameters

Number of devices	eg 7
Voltage (V)	eg 11000
Rated power (kW)	eg 1000
Typical spacing (m)	eg 50
Farm distance to shore (m)	eg 500
AEP for whole array (kWh)	eg 10860
Capacity factor (%)	eg 30
Onshore infrastructure costs (EUR)	eg 10 000 000 ☑ Estimate?
Onshore distance from OLP to GCP (m)	eg 1000

Optional parameters in *italics*

Detail of network design results/assumptions

Array

Assumed Array type	radial
Partial CAPEX (EUR)	123 456
Delivered AEP (kWh)	456
Annual losses (kWh)	789
Network Efficiency	0.99

Cables

	Export	Array	Total
Estimated Total cable length (m)	1200	800	2000
Assumed Number of cables?	1	7	8
Voltage (V)	33000	1100	

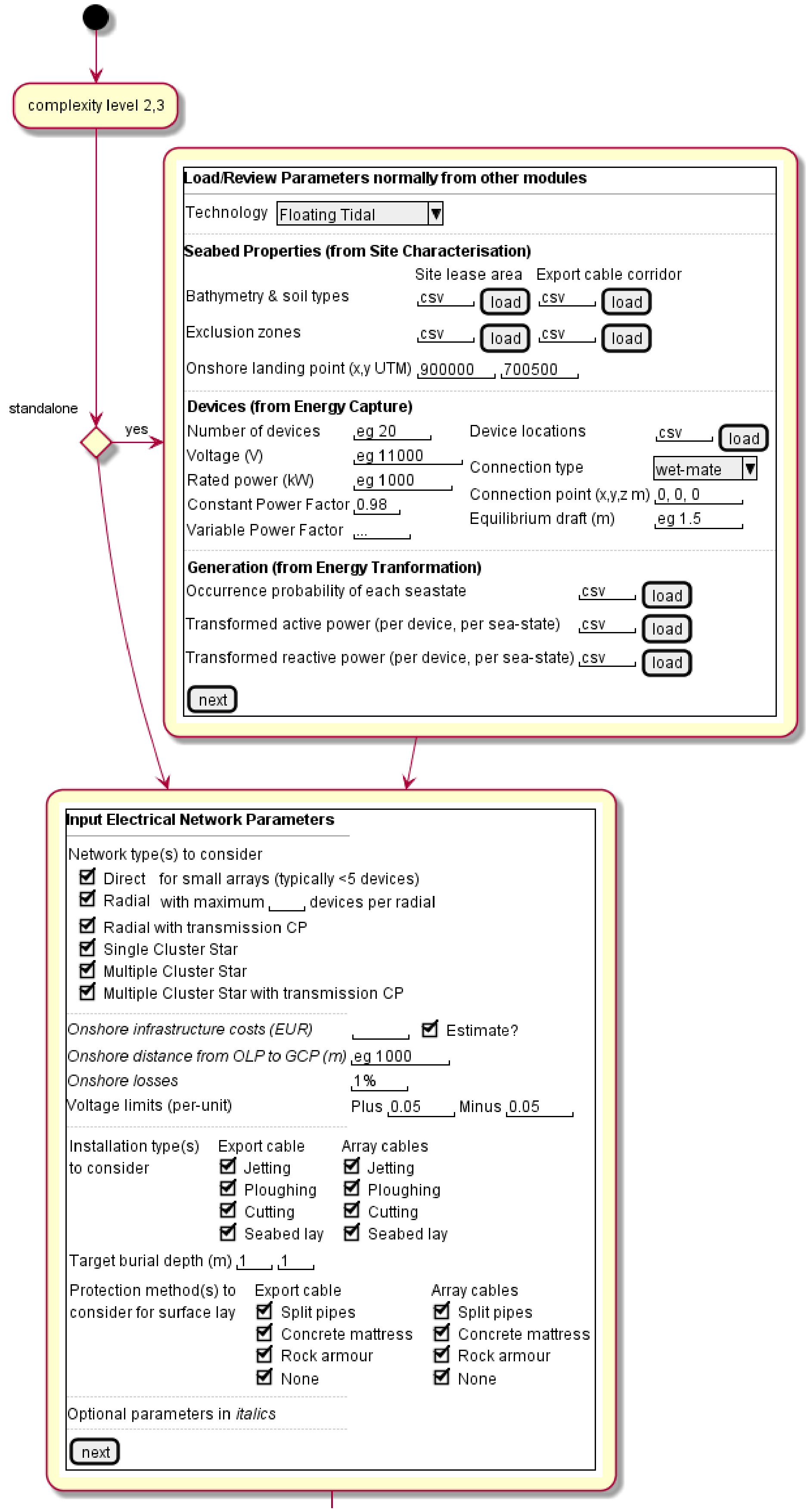
Collection point

Type	substation, surface piercing
Foundation	fixed, piled

Simplified Bill of Materials (euro)

Total onshore infrastructure	0
Total transmission network	525,000
Total array network	206 ,000
Total Collection point	1,498,000
Total Energy Delivery	2,229,000

FIGURE 4.3: PROCESS & GUI MOCK-UP FOR MAIN SCREENS AT CPX1



Load/Review Parameters normally from other modules

Technology: Floating Tidal ▼

Seabed Properties (from Site Characterisation)

	Site lease area		Export cable corridor	
Bathymetry & soil types	csv	load	csv	load
Exclusion zones	csv	load	csv	load

Onshore landing point (x,y UTM) 900000, 700500

Devices (from Energy Capture)

Number of devices: eg 20
Voltage (V): eg 11000
Rated power (kW): eg 1000
Constant Power Factor: 0.98
Variable Power Factor: ...
Device locations: csv load
Connection type: wet-mate ▼
Connection point (x,y,z m): 0, 0, 0
Equilibrium draft (m): eg 1.5

Generation (from Energy Tranformation)

Occurrence probability of each seastate: csv load
Transformed active power (per device, per sea-state): csv load
Transformed reactive power (per device, per sea-state): csv load

next

Input Electrical Network Parameters

Network type(s) to consider
- ☑ Direct for small arrays (typically <5 devices)
- ☑ Radial with maximum ____ devices per radial
- ☑ Radial with transmission CP
- ☑ Single Cluster Star
- ☑ Multiple Cluster Star
- ☑ Multiple Cluster Star with transmission CP

Onshore infrastructure costs (EUR) ____ ☑ Estimate?
Onshore distance from OLP to GCP (m) eg 1000
Onshore losses 1%
Voltage limits (per-unit) Plus 0.05 Minus 0.05

Installation type(s) to consider

Export cable	Array cables
☑ Jetting	☑ Jetting
☑ Ploughing	☑ Ploughing
☑ Cutting	☑ Cutting
☑ Seabed lay	☑ Seabed lay

Target burial depth (m) 1, 1

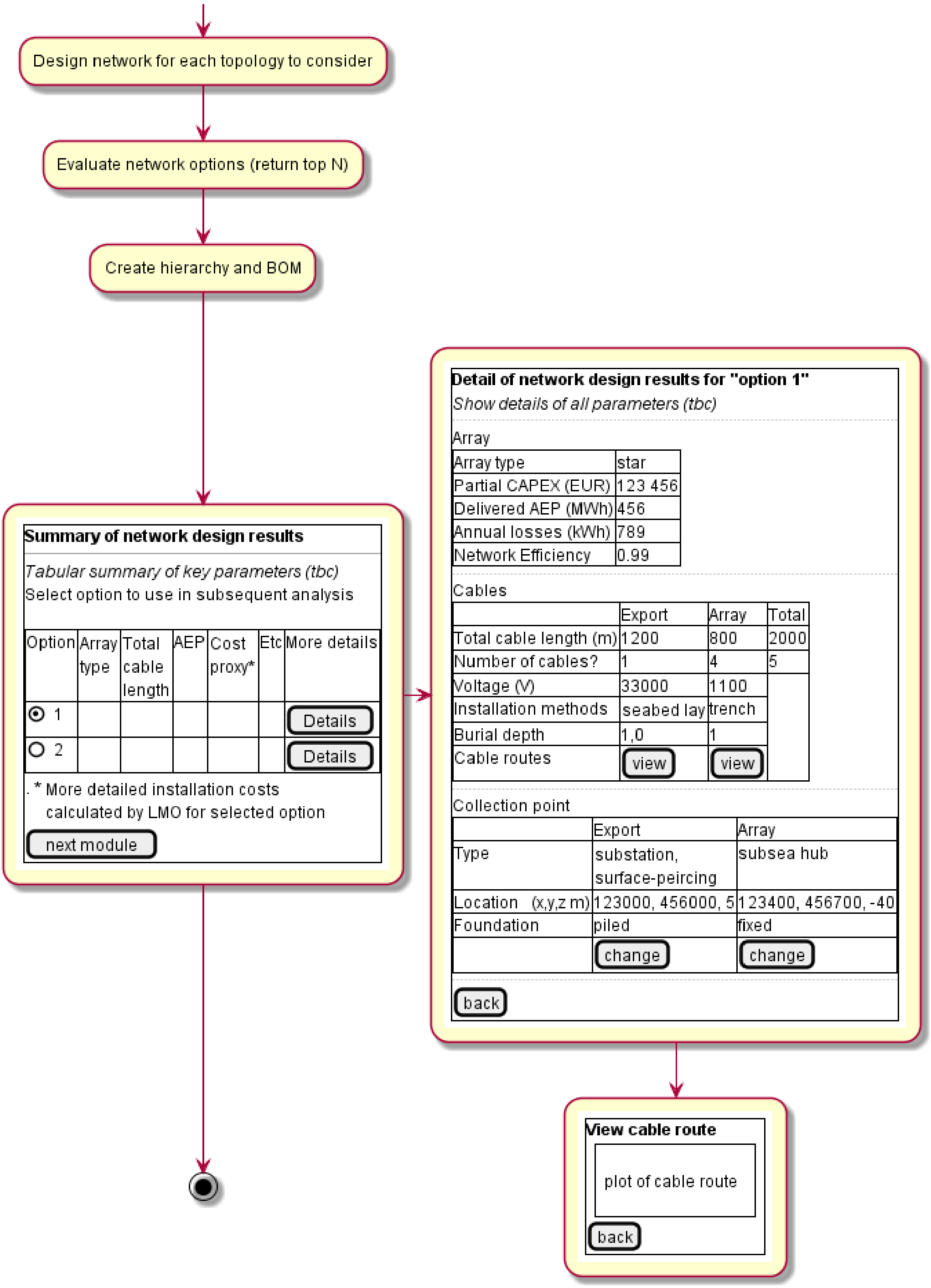
Protection method(s) to consider for surface lay

Export cable	Array cables
☑ Split pipes	☑ Split pipes
☑ Concrete mattress	☑ Concrete mattress
☑ Rock armour	☑ Rock armour
☑ None	☑ None

Optional parameters in *italics*

next

FIGURE 4.4: PROCESS & GUI MOCK-UP FOR MAIN SCREENS AT CPX2/3 (1/2)



Summary of network design results

Tabular summary of key parameters (tbc)
Select option to use in subsequent analysis

Option	Array type	Total cable length	AEP	Cost proxy*	Etc	More details
◉ 1						Details
○ 2						Details

. * More detailed installation costs calculated by LMO for selected option

Detail of network design results for "option 1"

Show details of all parameters (tbc)

Array

Array type	star
Partial CAPEX (EUR)	123 456
Delivered AEP (MWh)	456
Annual losses (kWh)	789
Network Efficiency	0.99

Cables

	Export	Array	Total
Total cable length (m)	1200	800	2000
Number of cables?	1	4	5
Voltage (V)	33000	1100	
Installation methods	seabed lay	trench	
Burial depth	1,0	1	
Cable routes	view	view	

Collection point

	Export	Array
Type	substation, surface-peircing	subsea hub
Location (x,y,z m)	123000, 456000, 5	123400, 456700, -40
Foundation	piled	fixed
	change	change

View cable route

FIGURE 4.5: PROCESS & GUI MOCK-UP FOR MAIN SCREENS AT CPX2/3 (2/2)

4.1.4 TECHNOLOGIES AND PACKAGES USED

The Business Logic and the API of ED have been coded in Python version 3.6.8. The installation of the module requires the following packages:

- PyPower
- NumPy
- Matplotlib
- Pandas
- descartes
- networkx
- scipy = 1.2.1
- shapely
- json
- Flask
- flask-babel
- flask-cors
- flask-url_for
- flask-requests
- flask-Blueprint
- flask-jsonify
- Pytest
- xlrd

The API will rely on OpenAPI specification v3.0.2.

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

4.2 TESTING AND VERIFICATION

The Business Logic implemented a validation of the data inputs, with appropriate warning and error messages. The input data validation ensures that the module process flow only starts if correct input data is provided.

For the new code in DTOceanPlus at CPX1, a comprehensive set of "unit tests" has been implemented covering the different functionalities of the Business Logic. Through these unit tests, individual units/components/functions of the code are tested. Coverage of these tests, measured by means of the py-cov extension of the py-test library, is 100%. The additional functionalities added at CPX2 and CPX3 was integrated into the DTOcean 2.0 code and have comprehensive set of "unit tests" as well. Overall, the unit test coverage has been improved from 22% in DTOcean 2.0 to 30% in DTOceanPlus. Further unit testing of code re-used from DTOcean 2.0 will be implemented prior to the integration phase. Details of the unit testing coverage is shown in Table 4.2.

TABLE 4.2: UNIT TEST COVERAGE REPORT

Module	Statements	Missing	Excluded	Coverage
dtocean_electrical__init__.py	6	1	0	83%
dtocean_electrical_build.py	1	1	0	0%
dtocean_electrical\grid__init__.py	0	0	0	100%
dtocean_electrical\grid\grid.py	131	41	0	69%
dtocean_electrical\grid\grid_processing.py	162	31	0	81%
dtocean_electrical\input_utils__init__.py	0	0	0	100%
dtocean_electrical\input_utils\input_tests.py	66	17	0	74%
dtocean_electrical\input_utils\utils.py	65	30	0	54%
dtocean_electrical\inputs.py	334	222	0	34%
dtocean_electrical\main.py	134	114	0	15%
dtocean_electrical\network__init__.py	0	0	0	100%
dtocean_electrical\network\cable.py	60	11	0	82%
dtocean_electrical\network\collection_point.py	88	73	0	17%
dtocean_electrical\network\connector.py	19	11	0	42%
dtocean_electrical\network\network.py	946	816	0	14%
dtocean_electrical\network\networkLowCmplx.py	75	37	0	51%
dtocean_electrical\network\switchgear.py	5	5	0	0%
dtocean_electrical\network\transformer.py	16	16	0	0%
dtocean_electrical\optim_codes__init__.py	0	0	0	100%
dtocean_electrical\optim_codes\array_layout.py	412	321	0	22%
dtocean_electrical\optim_codes\optimiser.py	1316	1093	0	17%
dtocean_electrical\optim_codes\optimiserLowCmplx.py	388	0	0	100%
dtocean_electrical\optim_codes\power_flow_v2.py	351	317	0	10%
dtocean_electrical\optim_codes\umbilical_ajc.py	162	150	0	7%
dtocean_electrical\output.py	34	29	0	15%
dtocean_electrical\utility.py	1	1	0	0%
Total	**4772**	**3337**	**0**	**30%**

5. EXAMPLES

This section presents a few example network design solutions generated by the ED module at CPX1 and CPX 3. The inputs that were used to generate the designs and the outputs are presented as they will be integrated in the DTOceanPlus suite of tools when released.

Note that these inputs were generated for illustration purposes only and do not correspond to any specific project or technology. Consequently, the obtained outputs may not necessarily be realistic, but demonstrate the computational capabilities of the ED module

5.1 SIMPLIFIED ENERGY DELIVERY NETWORK (CPX1)

This section shows the inputs and outputs from an example ED model CPX1 run.

5.1.1 INPUTS

The five input parameters to the simplified energy delivery network are given in Table 5.1.

TABLE 5.1: SIMPLIFIED ENERGY DELIVERY INPUTS

Input Parameter (unit)	Value
Number of devices	7
Device Rated power (kW)	500
Device Voltage (V)	11000
Device separation/spacing (m)	250
Distance to shore (m)	5000

5.1.2 OUTPUTS

The main outputs of the simplified energy delivery network are a summary BoM (Table 5.2), and a hierarchy of the network (Table 5.3) which is a human-readable output to other modules. A graphical representation of the designed network is shown in Figure 5.1, however this is not an output of the module, it is merely provided here for clarity.

TABLE 5.2: SIMPLIFIED ENERGY DELIVERY BILL OF MATERIALS

Item	Cost (€)
Total onshore infrastructure	0
Total transmission network	525,000
Total array network	206 ,000
Total Collection point	1,498,000
Total Energy Delivery	2,229,000

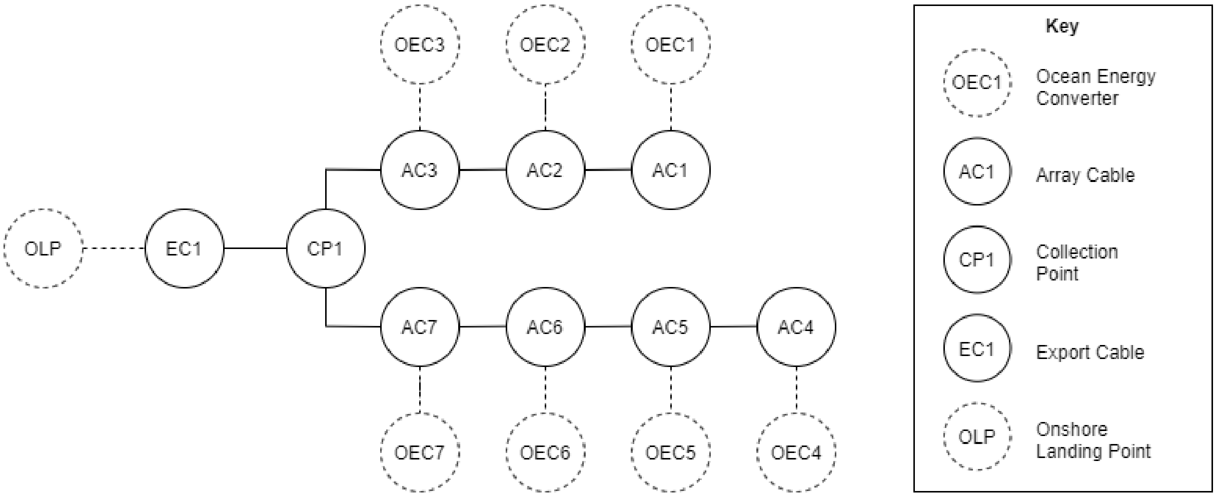


FIGURE 5.1: GRAPHICAL VISUALISATION OF NETWORK AT CPX1, DASHED ITEMS OUTSIDE SCOPE (NOTE THIS IS NOT A MODULE OUTPUT, PROVIDED HERE FOR CLARITY ONLY)

TABLE 5.3: SIMPLIFIED ENERGY DELIVERY HIERARCHY FOR SEVEN DEVICES

System	Name	Design ID	Type	Category	Parent	Child	Gate	FailureRate Minor	FailureRate Replacement
ED	ED_OEC1	NotAppl	System	Level 2	[]	['Route1_1']	OR	NotAppl	NotAppl
ED	ED_OEC2	NotAppl	System	Level 2	[]	['Route2_1']	OR	NotAppl	NotAppl
ED	ED_OEC3	NotAppl	System	Level 2	[]	['Route3_1']	OR	NotAppl	NotAppl
ED	ED_OEC4	NotAppl	System	Level 2	[]	['Route4_1']	OR	NotAppl	NotAppl
ED	ED_OEC5	NotAppl	System	Level 2	[]	['Route5_1']	OR	NotAppl	NotAppl
ED	ED_OEC6	NotAppl	System	Level 2	[]	['Route6_1']	OR	NotAppl	NotAppl
ED	ED_OEC7	NotAppl	System	Level 2	[]	['Route7_1']	OR	NotAppl	NotAppl
ED	Route1_1	NotAppl	Energy route	Level 1	['ED_OEC1']	['AC1', 'AC2', 'AC3', 'CP1', 'EC1']	AND	NotAppl	NotAppl
ED	Route2_1	NotAppl	Energy route	Level 1	['ED_OEC2']	['AC2', 'AC3', 'CP1', 'EC1']	AND	NotAppl	NotAppl
ED	Route3_1	NotAppl	Energy route	Level 1	['ED_OEC3']	['AC3', 'CP1', 'EC1']	AND	NotAppl	NotAppl
ED	Route4_1	NotAppl	Energy route	Level 1	['ED_OEC4']	['AC4', 'AC5', 'AC6', 'AC7', 'CP1', 'EC1']	AND	NotAppl	NotAppl
ED	Route5_1	NotAppl	Energy route	Level 1	['ED_OEC5']	['AC5', 'AC6', 'AC7', 'CP1', 'EC1']	AND	NotAppl	NotAppl
ED	Route6_1	NotAppl	Energy route	Level 1	['ED_OEC6']	['AC6', 'AC7', 'CP1', 'EC1']	AND	NotAppl	NotAppl
ED	Route7_1	NotAppl	Energy route	Level 1	['ED_OEC7']	['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
ED	AC4	AC4	Component	Level 0	['Route4_1']	[]	NA	0.00024	0.00024

System	Name	Design ID	Type	Category	Parent	Child	Gate	FailureRate Minor	FailureRate Replacement
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

5.2 FULL COMPLEXITY ENERGY DELIVERY NETWORK (CPX2 AND CPX3)

This section shows the inputs and outputs from three example ED model runs at full complexity (CPX3), representing the device sizes and the network topologies that have been used or considered in real wave and tidal deployments. For the three example runs the same lease and export corridor bathymetry (lease_area_0709.xlsx and export_area_0709.xlsx) and the electrical component catalogue (mock_db_v2.xlsx) were used, which can all be found in the GitLab repository [22]. Samples of the lease area bathymetry and the static cable catalogue are shown in Table 5.4 and Table 5.5 respectively. No exclusion zones were included for the lease area or cable corridor. The other inputs that have not been changed between the three example runs are shown in Table 5.4.

TABLE 5.4: SAMPLE OF THE LEASE AREA BATHYMETRY DATA USED FOR CPX3 EXAMPLES

id	i	j	x	y	Layer 1 start	Layer 1 type
5518	36	82	1360	1320	-50	loose sand
5519	36	83	1360	1330	-50	loose sand
5520	36	84	1360	1340	-50	loose sand
5521	36	85	1360	1350	-50	loose sand
5522	36	86	1360	1360	-50	loose sand
5523	36	87	1360	1370	-50	loose sand
5524	36	88	1360	1380	-50	loose sand
5525	36	89	1360	1390	-50	loose sand
5526	36	90	1360	1400	-50	loose sand
5527	36	91	1360	1410	-50	loose sand

TABLE 5.5: SAMPLE OF THE STATIC CABLES' CATALOGUE USED FOR CPX3 EXAMPLES

id	v_rate	a_air	r_ac	xl	c	dry_ mass	diameter	mbr	mbl	cost	max_ operating _temp
1	6600	180	0.67	0.46	0.17	8700	79.00	1.15	150000	600.00	90.00

TABLE 5.6: COMMON INPUTS USED FOR CPX3 EXAMPLES

Parameter	Value	Units
footprint_coords	[(0.0,25.0,0.), (-25.0, -25.0,0.0), (25.,-25.,0.0)]	m
variable_power_factor	[[0.5, 0.8], [1.0 , 1.0]]	per-unit
connection_point	(0,0,0)	m
equilibrium_draft	0.	m
landing_point	(0.0, 1250.0)	m
array_output	[0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 1.0]	per-unit
onshore_infrastructure_cost	0.0	€
onshore_losses	0.0	%
voltage_limit_min	0.9	per-unit
voltage_limit_max	1.1	per-unit
target_burial_depth_array	1.0	m
target_burial_depth_export	2.0	m
equipment_gradient_constraint	14.0	degree

5.2.1 EXAMPLE 1: ARRAY OF 3 FIXED TIDAL TURBINES

Example 1 of the CPX3 run is for a 3-device array of fixed tidal turbines, each rated at 100 kW and operating at 3.3 kV. The network topology selected is direct connection to shore.

5.2.1.1 INPUTS

Table 5.7 shows the inputs provided to the ED module for this example run.

TABLE 5.7: INPUTS USED FOR EXAMPLE 1 OF CPX3 RUN

Parameter	Value	Units
technology	fixed	-
power	100000	W
voltage	3300	V
connection	dry-mate	-
layout	{'Device003': (1280, 687), 'Device002': (1200.0, 1100.0), 'Device001': (1119, 1512)}	m
network_configuration	Direct	-

5.2.1.2 OUTPUTS

Table 5.8 shows a subset of high-level assessment outputs from the run. Figure 5.2 shows a schematic of the network design. Table 5.9 shows the data contained in a dry-mate connector object.

TABLE 5.8: OUTPUTS FROM EXAMPLE 1 OF CPX3 RUN

Parameter	Value	Units
annual_efficiency	0.94	%
annual_losses	150922404.27	W
annual_yield	2477077595.73	Wh
array_voltage	N/A	V
export_voltage	3300	V
histogram_efficiency	[0.5, 0.75, 0.83, 0.87, 0.89, 0.91, 0.92, 0.93, 0.94, 0.94]	%
histogram_losses	[15010.17, 15089.0, 15245.34, 15478.6, 15788.2, 15751.98, 16048.53, 16393.64, 16787.07, 17228.58]	W
coe_elec	1.09	€/kWh
total_cost	2692287.81	€

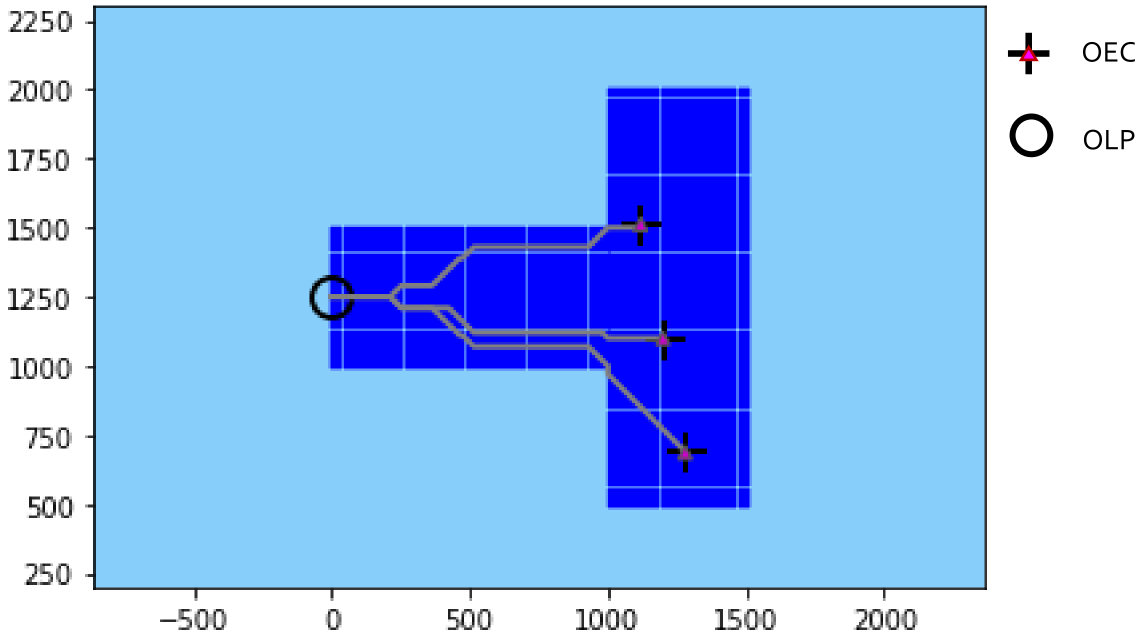


FIGURE 5.2: NETWORK DESIGN SCHEMATIC OF EXAMPLE 1 OF CPX3 RUN

TABLE 5.9: DRY-MATE CONNECTOR OUTPUT DATA

Parameter	Value	Units
db_key	126	-
marker	1	-
type_	dry-mate	-
utm_x	1120.0	m
utm_y	1510.0	m

5.2.2 EXAMPLE 2: ARRAY OF 5 FLOATING TIDAL TURBINES

Example 2 of the CPX3 run is for a 5-device array of floating tidal turbines, each rated at 2 MW and operating at 33 kV. The network topology selected is radial without a separate transmission CP.

5.2.2.1 INPUTS

Table 5.10 shows the inputs provided to the ED module for this example run.

TABLE 5.10: INPUTS USED FOR EXAMPLE 2 OF CPX3 RUN

Parameter	Value	Units
technology	floating	-
power	2e6	W
voltage	33e3	V
connection	wet-mate	-
layout	{'Device003': (1280, 687), 'Device002': (1200.0, 1100.0), 'Device001': (1119, 1512), 'Device005': (1038, 1924), 'Device004': (1498, 1694)}	m
network_configuration	Radial no CP	-

5.2.2.2 OUTPUTS

Table 5.11 shows a subset of high-level assessment outputs from the run. Figure 5.3 shows a schematic of the network design. Table 5.12 shows the data contained in a part of an array cable object.

TABLE 5.11: OUTPUTS FROM EXAMPLE 2 OF CPX3 RUN

Parameter	Value	Units
annual_efficiency	0.94	%
annual_losses	5031412177.24	W
annual_yield	82568587822.76	Wh
array_voltage	33000.0	V
export_voltage	33000.0	V
histogram_efficiency	[0.5, 0.75, 0.83, 0.87, 0.89, 0.91, 0.92, 0.93, 0.94, 0.94]	%
histogram_losses	[500376.09, 503071.15, 508352.07, 516199.27, 526593.41, 525091.19, 534986.35, 546501.4, 559629.27, 574362.12]	W
coe_elec	0.0658	€/kWh
total_cost	5436166.60	€

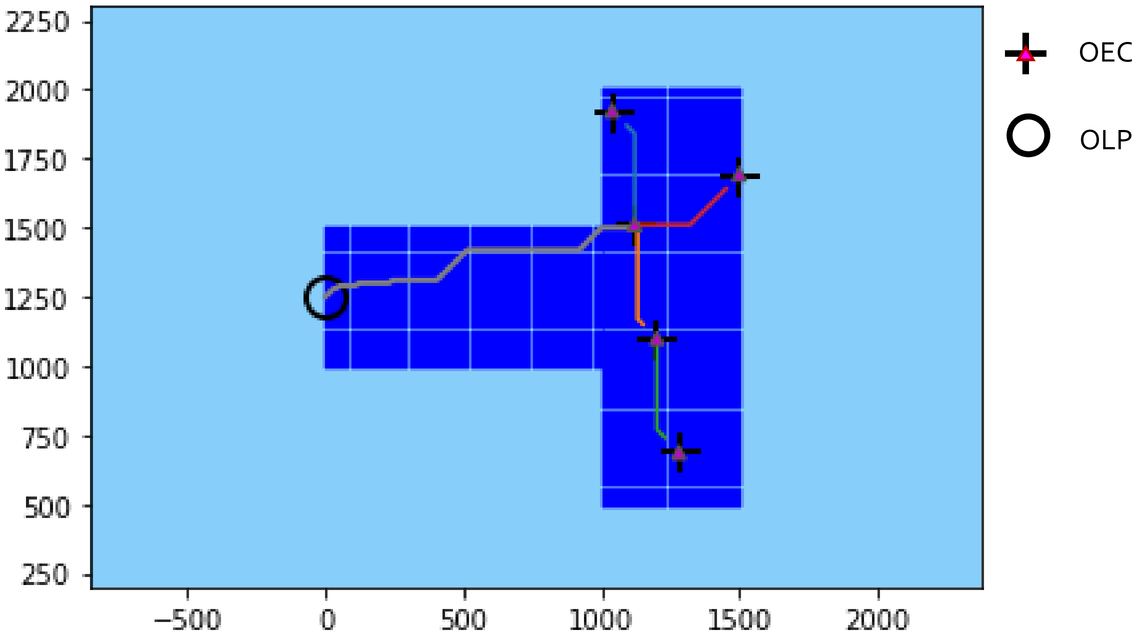


FIGURE 5.3: NETWORK DESIGN SCHEMATIC OF EXAMPLE 2 OF CPX3 RUN

TABLE 5.12: SAMPLE OF ARRAY CABLE OUTPUT DATA

marker	db-ref	burial _depth	split pipe	x	y	layer 1 start	layer 1 type
5	17	1.0	False	1120.0	1510	-50	loose sand
5	17	1.0	False	1120.0	1520	-50	loose sand
5	17	1.0	False	1120.0	1530	-50	loose sand
5	17	1.0	False	1120.0	1540	-50	loose sand
5	17	1.0	False	1120.0	1550	-50	loose sand
5	17	1.0	False	1120.0	1560	-50	loose sand
5	17	1.0	False	1120.0	1570	-50	loose sand
5	17	1.0	False	1120.0	1580	-50	loose sand
5	17	1.0	False	1120.0	1590	-50	loose sand

5.2.3 EXAMPLE 3: ARRAY OF 21 FLOATING WAVE DEVICES

Example 3 of the CPX3 run is for a 21-device array of floating wave devices, each rated at 200 kW and operating at 690 V. The network topology selected is star. In this example, the transmission voltage was set at 33 kV.

5.2.3.1 INPUTS

Table 5.13 shows the inputs provided to the Energy Delivery module for this example run.

TABLE 5.13: INPUTS USED FOR EXAMPLE 3 OF CPX3 RUN

Parameter	Value	Units
technology	floating	-
power	200000	W
voltage	690	V
export_voltage	33000	V
connection	wet-mate	-
layout	{'Device001': (1100, 600), 'Device002': (1100, 800), 'Device003': (1100, 1000), 'Device004': (1100, 1200), 'Device005': (1100, 1400), 'Device006': (1100, 1600), 'Device007': (1100, 1800), 'Device008': (1250, 600), 'Device009': (1250, 800), 'Device010': (1250, 1000), 'Device011': (1250, 1200), 'Device012': (1250, 1400), 'Device013': (1250, 1600), 'Device014': (1250, 1800), 'Device015': (1400, 600), 'Device016': (1400, 800), 'Device017': (1400, 1000), 'Device018': (1400, 1200), 'Device019': (1400, 1400), 'Device020': (1400, 1600), 'Device021': (1400, 1800)}	m
network_configuration	Star	-

5.2.3.2 OUTPUTS

Table 5.14 shows a subset of high-level assessment outputs from the run. Figure 5.4 shows a schematic of the network design. Table 5.15 and Table 5.16 show subsets of the data contained in a CP and in an umbilical object. Table 5.17 shows a part of the network bill of material.

TABLE 5.14: OUTPUTS FROM EXAMPLE 3 OF CPX3 RUN

Parameter	Value	Units
annual_efficiency	0.90	%
annual_losses	3536896777.32	W
annual_yield	33255103222.68	Wh
array_voltage	6600	V
export_voltage	33000	V
histogram_efficiency	[0.5, 0.74, 0.82, 0.85, 0.87, 0.89, 0.9, 0.9, 0.9, 0.9]	%
histogram_losses	[210924.06, 218147.7, 232245.4, 252880.77, 279749.5, 277622.85, 303472.81, 333183.65, 366645.77, 403755.34]	W
lcoe	0.52	€/kWh
total_cost	17387604.38	€

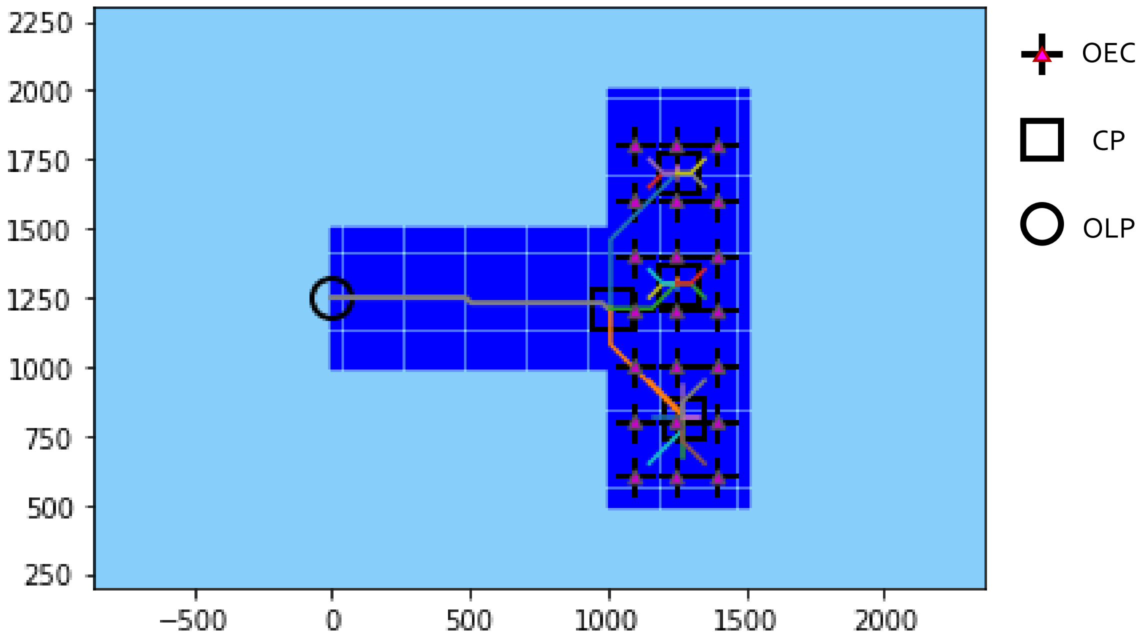


FIGURE 5.4: NETWORK DESIGN SCHEMATIC OF EXAMPLE 3 OF CPX3 RUN

TABLE 5.15: SAMPLE OF COLLECTION POINT OUTPUT DATA

Marker	Origin	Mass	Volume	Length	Width	Height	Profile
2	[1010.0, 1210.0]	100	1000	10	10	10	rectangular
14	[1250.0, 1300.0]	100	1000	10	10	10	rectangular
6	[1250.0, 1700.0]	100	1000	10	10	10	rectangular
10	[1270.0, 820.0]	100	1000	10	10	10	rectangular

TABLE 5.16: SAMPLE OF UMBILICAL OUTPUT DATA

Marker	db_ref	Device	seabed_connection_point	Length
18	33	Device006	[1150.0, 1650.0, -50.0]	99.59
23	33	Device007	[1150.0, 1750.0, -50.0]	99.59
28	33	Device013	[1250.0, 1680.0, -50.0]	108.49

TABLE 5.17: SAMPLE OF DETAILED NETWORK BILL OF MATERIALS

Marker	db_ref	install_type	utm_x	utm_y	quantity
34	30	wet-mate	1250.0	1800.0	1.0
37	30	wet-mate	1350.0	1650.0	1.0
115	126	dry-mate	1250.0	1300.0	1.0
0	17	export	None	None	1026.45
4	1	array	None	None	589.41
14	123	substation	1250.0	1300.0	1.0
18	33	umbilical	None	None	99.59

6. FUTURE WORK

This deliverable captures the main functional and technical aspects of the Energy Delivery module, implemented during the tasks T5.2 and T5.6 of the DTOceanPlus project. While the module can be run in standalone mode at the time of writing, some work is still required to be fully integrated in the suite of tools of DTOceanPlus:

- 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 API should be further developed in order, again, to integrate the module with the other tools;
- 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.

There are a number of other tasks to be undertaken to finalise the ED module prior to the final software release, including:

5. Improving the unit test coverage of functions and methods re-used from DTOcean 2.0
6. Implementing cost proxies for cable installation techniques collaborating with LMO
7. Expanding the catalogues of components
8. Defining/updating costs model parameters and parameter default values used at CPX1 and 2
9. Creating a configuration file/catalogue for all currently hard coded parameter values

The remaining work is part of the continuous development/integration methodology described in Deliverable D7.4 "Handbook of software implementation" [23]. These activities will be developed within T5.2 (ongoing task) and T5.8 Verification of the code – beta version (running once all the other modules have been developed), in order to extend the functionality of the ED module from standalone to fully integrated in the DTOceanPlus toolset.

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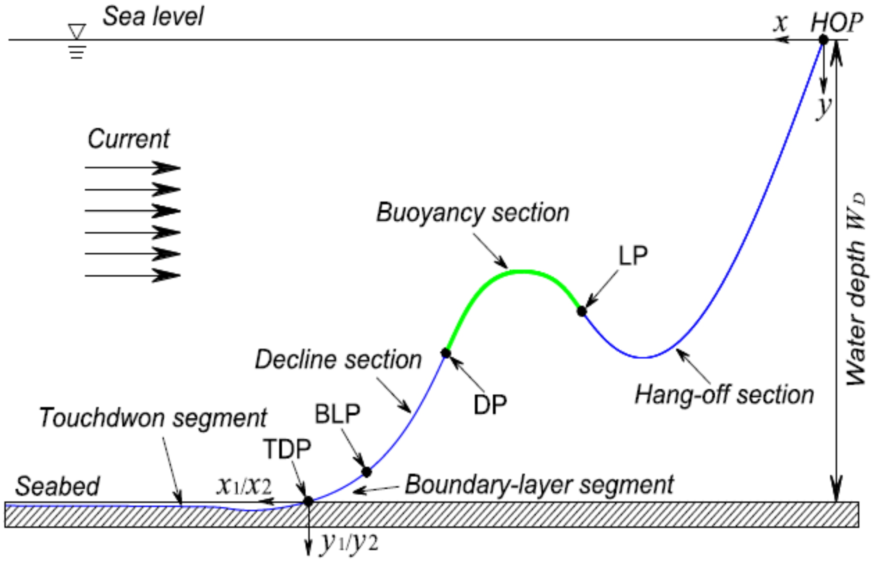
ANNEX I. UMBILICAL MECHANICAL DESIGN ALGORITHM

The equations used for the mechanical design of the umbilical, based on the methodology presented in [18] are given below.



HOP	hang-off point
LP	lift point
DP	decline point
TDP	touchdown point
BLP	boundary-layer point

TABLE I.1: UMBILICAL LAZY WAVE CONFIGURATION

$$V_i = V_{i-1} + F_\tau ds \sin\theta_{i-1} - F_n ds \cos\theta_{i-1} - wds \tag{I.1}$$

$$H_i = H_{i-1} + F_n ds \sin\theta_{i-1} - F_\tau ds \cos\theta_{i-1} \tag{I.2}$$

$$T_i = \sqrt{V_i^2 + H_i^2} \tag{I.3}$$

$$\theta_i = \tan^{-1}(V_i/H_i) \tag{I.4}$$

$$x_i = x_{i-1} + ds\cos\theta_{i-1} \tag{I.5}$$

$$y_i = y_{i-1} + ds\sin\theta_{i-1} \tag{I.6}$$

$$M_i = -EI\frac{d\theta_i}{ds} \tag{I.7}$$

$$S_i = -\frac{dM_i}{ds} \tag{I.8}$$

where: T, H, V represent the axial tension, horizontal and vertical force; F_n and F_τ represent the drag force in the normal and tangential direction per unit length; ϑ is the inclination angle of the cable, w is the submerged weight per unit length; ds is the length of the section, EI is the flexural stiffness; M is the bending moment, S is the shear force and x and y represent the local coordinate system of the touchdown point.

As the lazy wave cable configuration is divided into three segments, continuity conditions are necessary at the boundary-layer point (BLP) and the touchdown point (TDP). BLP continuity is calculated by (I.9)-(I.12), where: *D* is the cable outer diameter, with TDP continuity represented by (I.13)-(I.16).

$$y_1(L) = y_{BLP} - (W_D - D/2) \tag{I.9}$$

$$y_1'(L) = \tan(\theta_{BLP}) \tag{I.10}$$

$$-EIy_1''(L) = M_{BLP}(T_0, \theta_{BLP}) \tag{I.11}$$

$$EIy_1''(L) = S_{BLP}(T_0, \theta_{BLP}) \tag{I.12}$$

$$y_1(0) = y_2(0) = 0 \tag{I.13}$$

$$y_1'(0) = y_2'(0) \tag{I.14}$$

$$y_1''(0) = y_2''(0) \tag{I.15}$$

$$y_1'''(0) = y_2'''(0) \tag{I.16}$$

The conditions for passing the bending moment and shear force test are given in (I.17) and (I.18) where: ε_1 and ε_2 are specified tolerances.

$$|W_D - D/2 - y_{BLP} + y_1(L)| < \varepsilon_1 \tag{I.17}$$

$$|S_{BLP}^{+} - S_{BLP}^{-}|/S_{BLP}^{+} < \varepsilon_2 \tag{I.18}$$

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