Deliverable 6.2: Evaluation according to costs, downtimes, etc. of different maintenance strategies

Fraunhofer IWES and WP6 Partners

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D6.2: Evaluation according to costs, downtimes, etc. of different maintenance strategies
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Abstract

This report presents the Deliverable D6.2 "Evaluation according to costs, downtimes, etc. of different maintenance strategies" as the result of the work in the DTOcean work package 6 "System operation and control" under task T6.2 "Maintenance strategies". The document describes in chapter 1 detailed objective of this work and the methodology to achieve these objectives. In the second chapter the selection process for the components of a wave or tidal energy device to be considered to calculate the costs and downtimes during the life cycle is discussed. For each device type, which is in scope of the DTOcean optimisation tool, a list of proposed components is given with respect to maintenance cost estimation. The third chapter gives a definition of the required parameters for the detailed description of the maintenance costs. An indexing scheme for those parameters is proposed to allow their identification within the global data base. Chapter 4 describes the approach for the software implementation for the development of the maintenance cost estimation algorithm. A conclusion of the definitions made and the obtained results are given in chapter 5.

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1 INTRODUCTION

1.1 OBJECTIVES

The objectives of D6.2 are to define the scope for the maintenance cost estimation with respect to:

- the components in scope, based on a hierarchic structure as defined in section 2.1 of this report.
- the degree of detail related to the parameters of those components, which are required to estimate the O&M costs as can be found in the section 3 of this report.
- the indexing, meaning and format of those parameters to be stored in the global data base; a proposal for such an indexing scheme is described in section 3.
- the description of the programming approach for the O&M cost estimation algorithms as given in section 4; in this approach, the automated setup of a maintenance model for the entire life cycle of an ocean energy generation array will be introduced.

1.2 METHODOLOGY

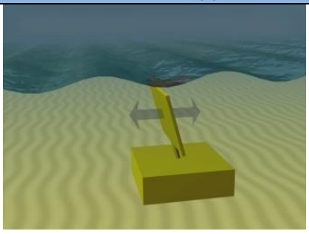
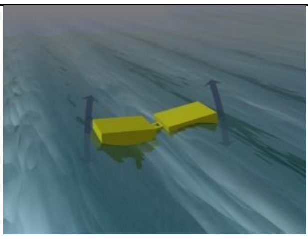
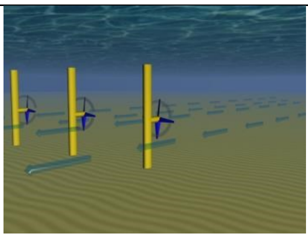
To obtain the above mentioned objectives, the following methodology will be applied:

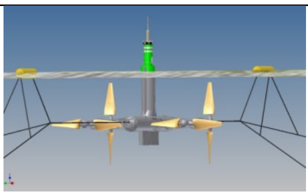
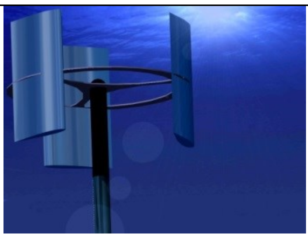
Step 1: for each ocean energy generation unit type as described in the deployment scenarios (defined in the DTOcean deliverable D1.1 “Detailed deployment scenarios for wave and tidal energy converters” [3]) the main components to be considered in the maintenance cost estimation will be selected. This selection process is based on the device classification approach as described in the deliverable “D5.2 Device classification template” of the Equimar project [4]. The approach chosen there divides an ocean energy generation unit into four subsystems:

- hydrodynamic subsystem,
- power-take-off subsystem,
- control subsystem and
- reaction subsystem.

Table 1-1 gives an overview about the considered device types and the related sites (corresponding to the scenarios as defined in D1.1).

Table 1-1: Summary of device types in scope

Type No.	Device type description	Example image (sources: [3] for type 1-5 devices and [8] for type 6 device)
1	Seabed fixed wave surge devices	
2	Floating wave point absorber devices	
3	Floating wave attenuator devices	
4	Seabed fixed horizontal axis tidal turbine devices	

5	Floating tidal turbine devices	
6	Seabed fixed vertical axis tidal turbine devices	

Step 2: Within the subsystems as defined in step 1, the most critical components will be selected. This ranking will be made by use of information from existing fault statistics data base analysis publications, e. g. as from Faulstich et al. in [1] (see section 2.1 for details). The results of the steps 1 and 2 will be described in section 2 of this report.

Step 3: A reference to the maintenance cost parameters of each individual component will be made by an indexing system. A proposal for the methodology of such an indexing system is described in Section 3 of the report, however it is clear that this indexing system must be discussed and synchronised with the specific parameter indexing systems of the other DTOcean WPs within the course of the algorithm development work.

Step 4: With the defined component parameters and additional parameters describing the maintenance action processing, a life cycle maintenance model will be defined for the ocean energy generation array. The maintenance action processing parameters and the approach for the model implementation is described in Section 4.

The collection of the required parameter values will be an ongoing process during the work of WP6 in the upcoming year. An initial set of parameters will be compiled to start with the testing of the developed algorithms and of the information exchange with tools/algorithms developed by the other WPs, mainly with logistics optimization algorithm, which will be developed in WP5.

2 SELECTION OF COMPONENTS IN SCOPE FOR MAINTENANCE COST OPTIMISATION

2.1 DEFINITION OF THE HIERARCHY OF THE COMPONENTS

Main subsystems as defined in the Equimar-D5.2 [4] are:

1. Hydrodynamic subsystem
2. Power-take-off subsystem
3. Control subsystem
4. Reaction subsystem

The following figureFigure 2-1 (from [4]) shows the graphical representation and the limitations of the subsystem for an example of a fixed foundation tidal turbine device in the left part. The right part of Figure 2-1 shows an example of a floating wave concentrator device. Even this device type is not mentioned explicatively in the scope of this report, the technical concept is very similar to such of the wave energy devices mentioned, since they all use a hydraulic system with a compressing unit (pistons and cylinders), an accumulator with a pressurized medium and a turbine to convert to rotational energy.

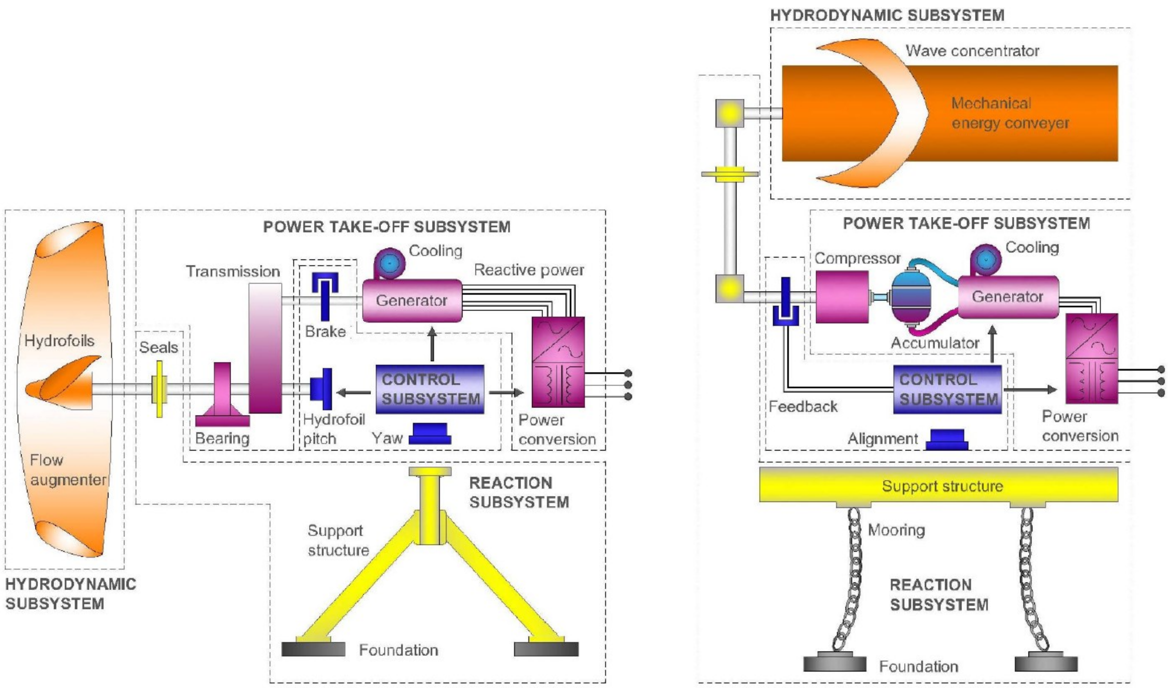


Figure 2-1: Example for subsystems of ocean energy devices (from [4])

Within the above defined subsystems, the scope must be refined to the main subsystem components. An approach to identify those components will be to look at other sectors of renewable energy generation. As a sector with a broad and long term experiences with respect to fault statistics and the calculation of annual failure rates, the wind energy has been identified. Wind turbine technology is quite similar to the technology of tidal turbines, using the same main components as rotating aero-/hydrodynamic subsystem, transmission element, pitching system, etc. The power take- off and control system for tidal turbines are mostly directly taken from wind energy suppliers. The connection to the electrical grid is more or less identical. Even between wind turbines and wave energy devices there is a large congruence in the main components used (rotational part of the power take off system, control system, grid connection, etc.).

In this sector of wind turbines, there are several manufacturer independent fault statistics data bases existing, of which the German national funded research project “Wind Measurement and Evaluation Program (WMEP)”, which has been hosted by Fraunhofer IWES, covers more than 20 years of operational experience of onshore based wind turbines. Other fault statistics data base projects show quite similar results. In an intensive scientific discussion with the different research groups at different research entities over the recent years, the methodology of the data evaluations out of these data bases has been proven and optimized.

An aggregated analysis of the annual failure rates of different components of wind turbines is shown in Figure 2-2 below. The following section 2.2 describes the relevant components for the maintenance cost estimation. The failure rates given in Figure 2-2 will be used as a starting point for the required input data for the maintenance cost estimation algorithms for the respective components.

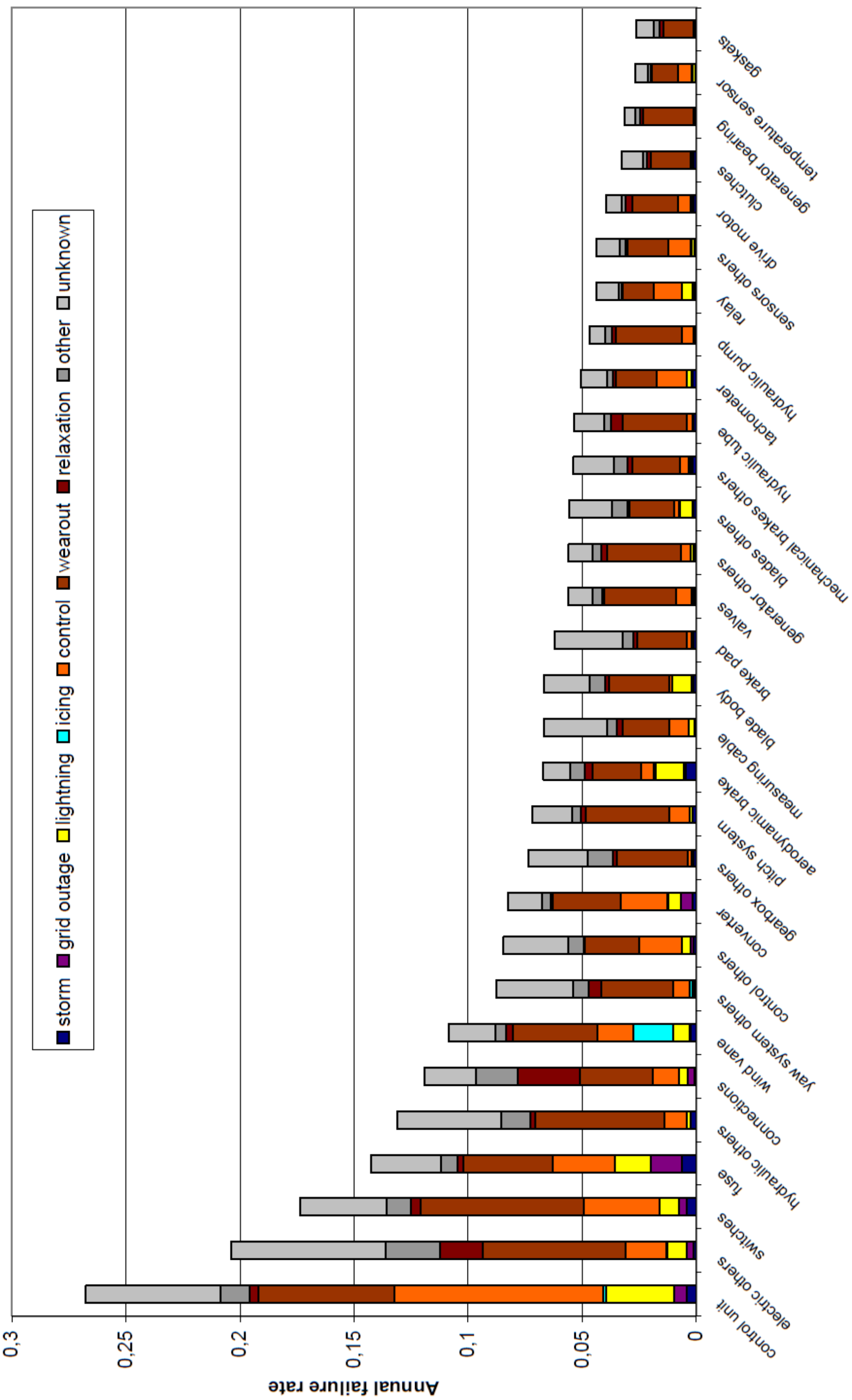

storm
grid outage
lightning
icing
control
wearout
relaxation
other
unknown
Annual failure rate
0,3
0,25
0,2
0,15
0,1
0,05
0
control unit
electric others
switches
fuse
hydraulic others
connections
wind vane
yaw system others
control others
converter
gearbox others
pitch system
aerodynamic brake
measuring cable
blade body
brake pad
valves
generator others
blades others
mechanical brakes others
hydraulic tube
tachometer
hydraulic pump
relay
sensors others
drive motor
clutches
generator bearing
temperature sensor
gaskets

Figure 2-2: Annual failure rates of the main components of wind turbines (from [1])

2.2 COMPONENTS IN SCOPE FOR MAINTENANCE COST ESTIMATION

The following sections will compile the main components within the subsystems, which will be considered for the maintenance cost calculations. For each individual device type as listed in Table 1-1, the selected components are listed. The selection was made on the basis of the technological requirements. This means that if a component is essential for the operability of the device, it has been considered.

The listed components should be understood as a proposal and might require revision based on discussion between the other WPs and the "reliability theme" work group of DTOcean. Such discussion will be made during the algorithm development work over the next project year. The list is also a compromise between the required degree of detail and the limited degree of complexity of the cost estimation algorithm, which will mainly influence the calculation time of the overall optimization process. Therefore, some of the main components, for example those of the electrical system, have been grouped together.

The first experiences from test runs with the overall optimization process as performed by the global optimisation tool, including all algorithms developed by the DTOcean WPs, will show if the chosen degree of component detail and the complexity of the algorithms leads to reasonable calculation time requirements of the overall optimization process. Required revisions to the detail / complexity will be made during the algorithm development process.

2.2.1 COMPONENTS FOR SEABED FIXED WAVE SURGE DEVICES

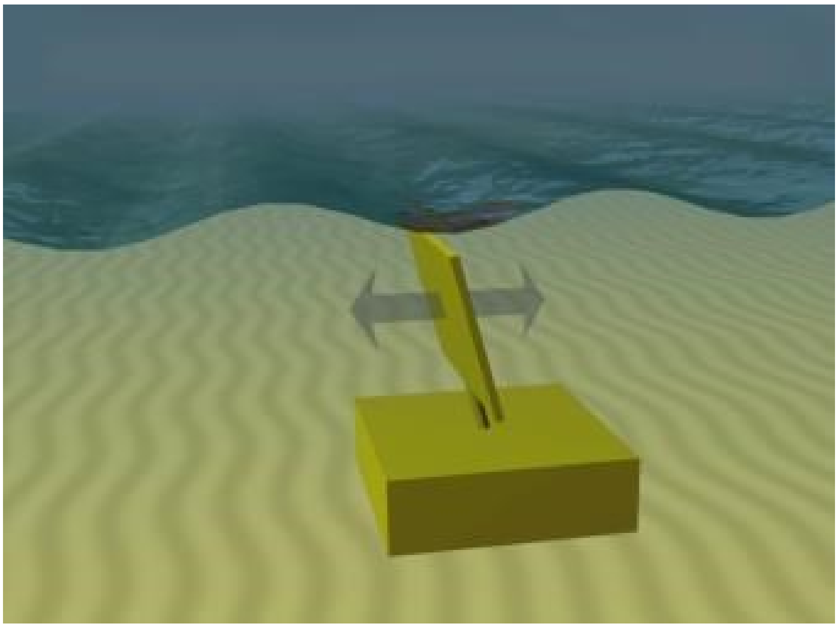


Figure 2-3: Example image of a seabed fixed wave surge device (from [3])

2.2.1.1 Hydrodynamic subsystem

Proposed components to be considered for maintenance cost estimation:

1. Flap body (coating, bio fouling, leakage)
2. Bearings/Joints on flap body (lubrication, increased friction, leakage)
3. Cathodic protection (sacrificial anodes)

2.2.1.2 Power-take-off subsystem

Proposed components to be considered for maintenance cost estimation:

1. Pistons and cylinders including joints(leakage, blocking)
2. Pipes and pressure tanks including oil filter system and release valves (leakage, blocking)
3. Linear to rotation converter (oil engine / airflow turbine performance)
4. Hydraulic/Pneumatic heat sink (overheating)
5. Generator and Frequency converter
6. Power cabling and (Subsea-)connectors including main switch at unit

2.2.1.3 Control subsystem

Proposed components to be considered for maintenance cost estimation:

1. Sensors
2. Actuators
3. Controller hardware including PLC and SCADA system
4. Communication system

2.2.1.4 Reaction subsystem

Proposed components to be considered for maintenance cost estimation:

1. Foundation
2. Coating
3. Scour protection
4. Cathodic protection (sacrificial anodes)

2.2.2 COMPONENTS FOR FLOATING WAVE POINT ABSORBER DEVICES

Figure 2-4: Example image of a floating wave point absorber device (from [3])

2.2.2.1 Hydrodynamic subsystem

Proposed components to be considered for maintenance cost estimation:

1. Buoyancy and ballast body (coating, bio fouling, leakage)
2. Linear moving connection element(sealing, lubrication, increased friction)
3. Cathodic protection (sacrificial anodes)

2.2.2.2 Power-take-off subsystem

Proposed components to be considered for maintenance cost estimation:

1. High pressure system (Pipes , pressure tanks, filters, Release valves)
2. Linear to rotation converter (Airflow/Hydraulic turbine) including gearings
3. Hydraulic/Pneumatic heat sink (overheating)
4. Generator and Frequency converter

5. Cabling and (Subsea-)connectors

2.2.2.3 Control subsystem

Proposed components to be considered for maintenance cost estimation:

1. Sensors
2. Actuators
3. Controller hardware including PLC and SCADA system
4. Communication system

2.2.2.4 Reaction subsystem

Proposed components to be considered for maintenance cost estimation:

1. Mooring system including anchors
2. Scour protection at mooring points

2.2.3 COMPONENTS FOR WAVE ATTENUATOR DEVICES

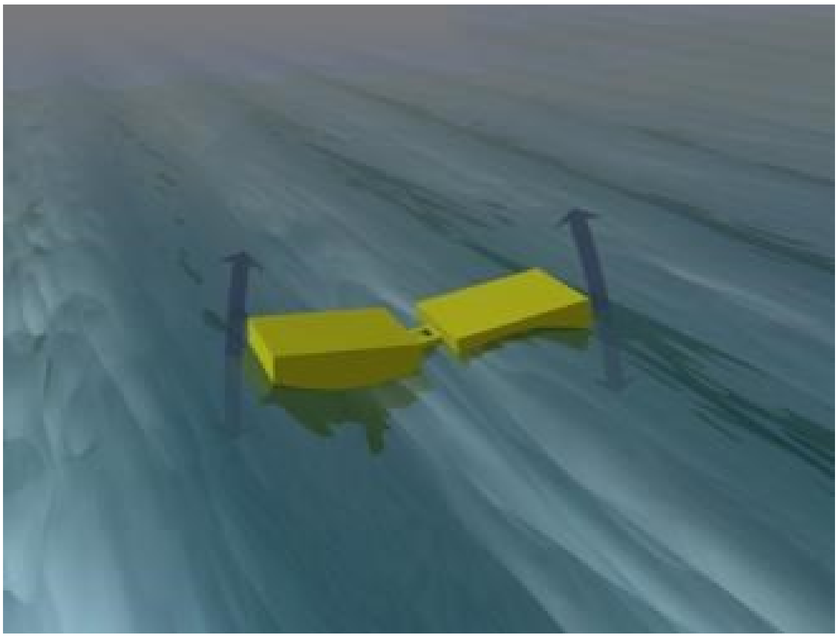


Figure 2-5: Example image of a wave attenuator device (from [3])

2.2.3.1 Hydrodynamic subsystem

Proposed components to be considered for maintenance cost estimation:

1. Floating bodies (coating, bio fouling, leakage)
2. Bearings/Joints on floating bodies (lubrication, increased friction, leakage)
3. Cathodic protection (sacrificial anodes)

2.2.3.2 Power-take-off subsystem

Proposed components to be considered for maintenance cost estimation:

1. Pistons and cylinders including joints(leakage, blocking)
2. Pipes and pressure tanks including oil filter system and release valves (leakage, blocking)
3. Linear to rotation converter (oil engine / airflow turbine performance)
4. Hydraulic/Pneumatic heat sink (overheating)

5. Generator and Frequency converter
6. Power cabling and (Subsea-)connectors including main switch at unit

2.2.3.3 Control subsystem

Proposed components to be considered for maintenance cost estimation:

1. Sensors
2. Actuators
3. Controller hardware including PLC and SCADA system
4. Communication system

2.2.3.4 Reaction subsystem

Proposed components to be considered for maintenance cost estimation:

1. Mooring system including anchors
2. Scour protection at mooring points
3. Cathodic protection (sacrificial anodes) of floating body

2.2.4 COMPONENTS FOR SEABED FIXED HORIZONTAL AXIS TIDAL TURBINE DEVICES

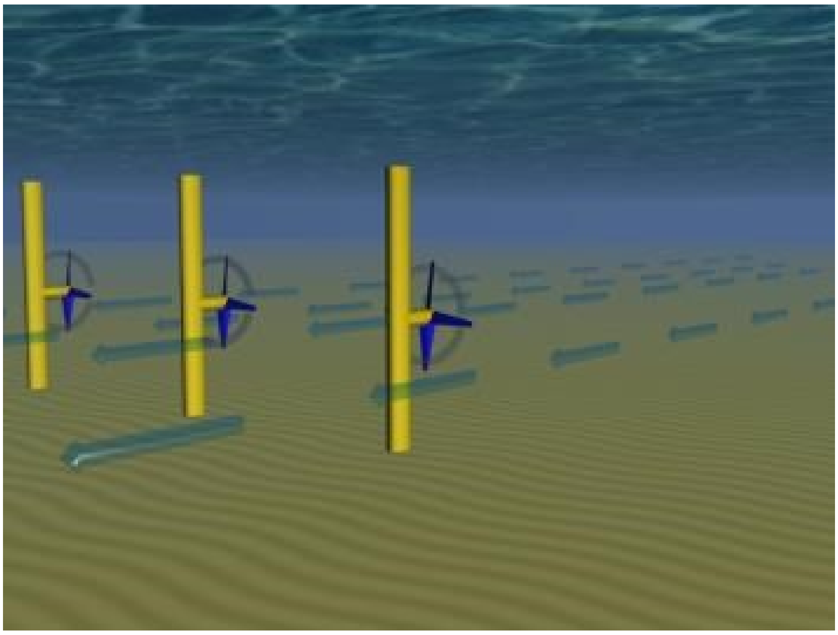


Figure 2-6: Example image of a seabed fixed horizontal axis tidal turbine device (from [3])

2.2.4.1 Hydrodynamic subsystem

Proposed components to be considered for maintenance cost estimation:

1. Rotor blades including pitch system

2.2.4.2 Power-take-off subsystem

Proposed components to be considered for maintenance cost estimation:

1. Main bearing, shafts and gearbox/transmission
2. Generator and Frequency converter
3. Power cabling and (Subsea-)connectors including main switch at unit

2.2.4.3 Control subsystem

Proposed components to be considered for maintenance cost estimation:

1. Sensors
2. Actuators
3. Controller hardware including PLC and SCADA system
4. Communication system

2.2.4.4 Reaction subsystem

Proposed components to be considered for maintenance cost estimation:

1. Foundation
2. Coating
3. Scour protection
4. Cathodic protection (sacrificial anodes)

2.2.5 COMPONENTS FOR FLOATING TIDAL TURBINE DEVICES

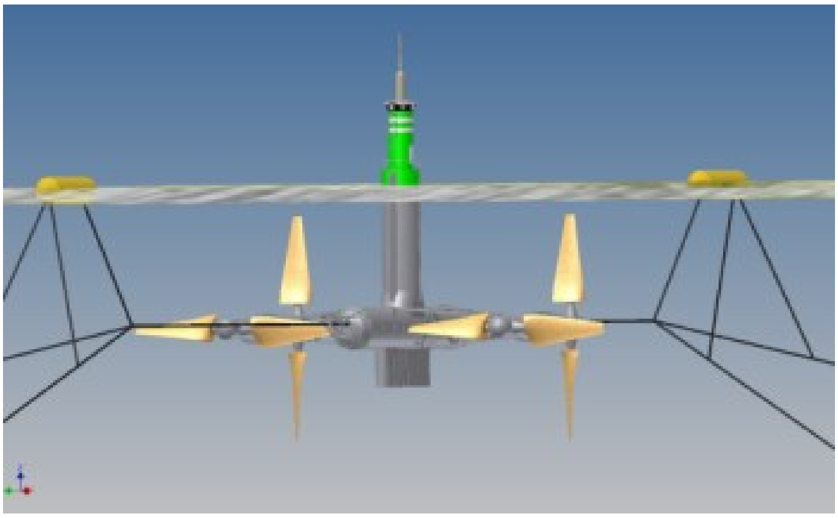


Figure 2-7: Example image of a floating tidal turbine device (from [3])

2.2.5.1 Hydrodynamic subsystem

Proposed components to be considered for maintenance cost estimation:

1. Rotor blades including pitch system

2.2.5.2 Power-take-off subsystem

Proposed components to be considered for maintenance cost estimation:

1. Main bearing, shafts and gearbox/transmission
2. Generator and Frequency converter
3. Power cabling and (Subsea-)connectors including main switch at unit

2.2.5.3 Control subsystem

Proposed components to be considered for maintenance cost estimation:

1. Sensors

2. Actuators
3. Controller hardware including PLC and SCADA system
4. Communication system

2.2.5.4 Reaction subsystem

Proposed components to be considered for maintenance cost estimation:

1. Mooring system including anchors
2. Scour protection at mooring points
3. Cathodic protection (sacrificial anodes) of floating body

2.2.6 COMPONENTS FOR FIXED VERTICAL AXIS TIDAL TURBINE DEVICES

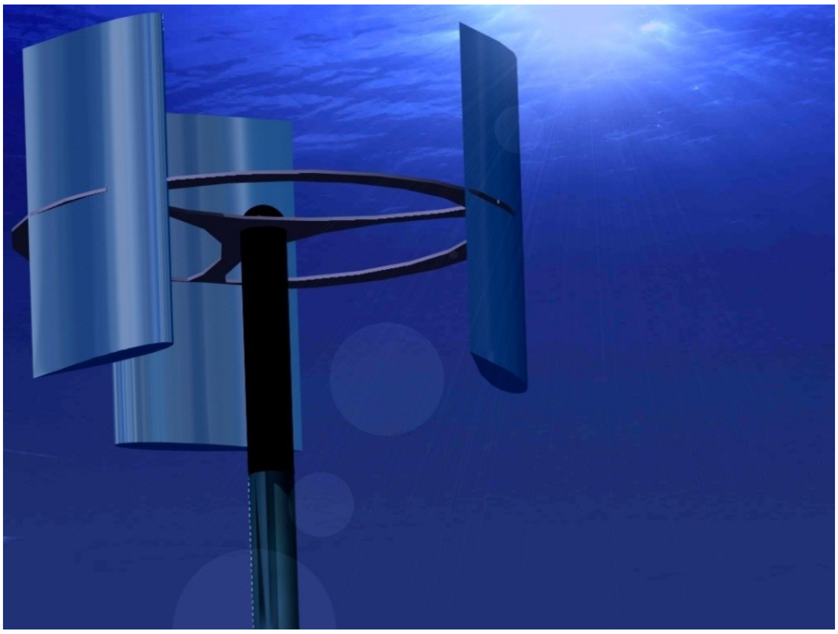


Figure 2-8: Example image of a seabed fixed vertical axis tidal turbine device (from [8])

2.2.6.1 Hydrodynamic subsystem

Proposed components to be considered for maintenance cost estimation:

1. Rotor blades including pitch system

2.2.6.2 Power-take-off subsystem

Proposed components to be considered for maintenance cost estimation:

4. Main bearing, shafts and gearbox/transmission
5. Generator and Frequency converter
6. Power cabling and (Subsea-)connectors including main switch at unit

2.2.6.3 Control subsystem

Proposed components to be considered for maintenance cost estimation:

1. Sensors
2. Actuators
3. Controller hardware including PLC and SCADA system
4. Communication system

2.2.6.4 Reaction subsystem

Proposed components to be considered for maintenance cost estimation:

1. Foundation
2. Coating
3. Scour protection
4. Cathodic protection (sacrificial anodes)

3 COMPONENT PARAMETERS FOR MAINTENANCE COST ESTIMATION

3.1 Methodology

To each of the components mentioned in section 0 an individual set of parameters needs to be allocated. Those parameters define the calculation of the maintenance cost by setting the required of information from the algorithms developed by the other WPs in DTOcean. For example, the mass and dimensions of a component defines the required transport capacity (lorry transport on land, deck space on ship, etc.), the lifting force defines the required crane capacity, the bollard pull and towing speed define the transportation for floating devices with respect to tug boat capacity and operation time, etc.

To clearly identify those parameters, an indexing scheme should be used as proposed below:

```
1  1  01  0001
|  |  |   └──────────────────────    parameter number (see Table 3-1)
|  |  └───────────────────────    main component number (see section 2.1 to 2.4)
|  └──────────────────────────    subsystem number (1 to 4 as listed in section 2.1)
└───────────────────────────────    Device type number (1 to 6 as defined in Table 1-1)
```

Example: the first maintenance parameter "mass" for the "coating" component of the foundation under the "reaction subsystem" of the wave surge device (type 1) will have the index 14020001.

This indexing scheme is meant to be a proposal to the other WPs in DTOcean and to the Technical Work Group (TWG), which is responsible for setting up the global data base. It seems to be beneficial when a consistent system of parameter indexing is defined for all parameters to be used in the DTOcean optimization tool. This indexing scheme should cover the indexing requirements of all the other WPs and should be worked out under the leadership of the TWG.

3.2 SPECIFIC PARAMETER DEFINITION PER COMPONENT

There will be parameters which are common for all the components mentioned in section 0. Those "basic" parameters should have the same parameter number in each component parameter data set definition. A preliminary selection of those parameters, as there will be required for the maintenance cost estimation algorithm, are listed in Table 3-1. It is quite likely that there are additional parameters required here to allow a proper data exchange with the algorithms of the other WPs. Therefore, the parameter compilation within the WPs should be coordinated in some way by the TWG to have an optimized parameter representation in the global data base.

Table 3-1: Basic parameter definition

Index	Parameter description	Unit	Remark
xxxx0001	mass	Kg	crane performance
xxxx0002	dimension x	M	deck space on transport vessel
xxxx0003	dimension y	M	deck space
xxxx0004	dimension z	M	deck space
xxxx0005	lifting force above sea surface	kN	crane performance
xxxx0006	lifting force below sea surface	kN	crane performance
xxxx0007	fixed maintenance interval (negative number when not applicable)	D	
xxxx0008	mean time between failure (MTBF) or annual failure rate	d or 1/year	
xxxx0009	spare part lead time (maximum of all possible spare parts)	d	
xxxx0010	time to detach/replace (incl. testing, reprogramming, etc.)	h	
xxxx0011	time to repair	h	
xxxx0012	cost for maintenance - inspection action	Euro	
xxxx0013	cost for maintenance - replacement action	Euro	incl. material, spare parts
xxxx0014	etc.		
xxxx0015			
xxxx0016			

For some of the components there may be individual parameters required. Those parameters should then be indexed with an offset, for example of 100. An example for such individual parameters is given in Table 3-2for the flap body of the wave surge device. With respect to the above proposed indexing scheme, the first two digits of the parameter indices for this component will be “11”, the component number in two digits is “01”. Parameter indices could then have an offset of 100 and therefore start at “0101”

Table 3-2: Specific parameter definition: example flap body of wave surge device (Type 1)

Index	Parameter description	unit	Remark
11010101	colour of coating	RAL-Number	
11010102	floating	yes/no	towing possible
11010103	etc.		

Furthermore, the review of the parameter definition will be an ongoing process over the coming year in the DTOcean project. Along with the programming work in all WPs, there may come up the demand for additional parameters, especially those for the data exchange between the WP algorithms. Other parameters might be found as not required for the maintenance cost estimation. Therefore, the above mentioned parameter selection and the proposed indexing scheme should be understood as an advanced proposal.

4 SOFTWARE IMPLEMENTATION

4.1 INTRODUCTION

The following sections in chapter 4 describe the approach for the realisation of a time domain lifecycle operation and maintenance (O&M) methodology tool for the integration into the global optimisation tool, of which to develop is the overall objective of the DTOcean project. This maintenance tool simulates the lifecycle operational phase of a Marine Renewable Energy Array (MREA) with all maintenance activities and costs. It can be used to understand and optimize the O&M of MREA in planning phase of a project due to changes in the maintenance strategy for a specific wave or tidal array. The estimation and minimisation of the maintenance cost will help the decision maker to choose cost-optimal solutions for the specific MREA.

4.2 METHODOLOGY FOR THE LIFECYCLE MAINTENANCE MODEL

4.2.1 TIME BASED MAINTENANCE MODEL

As a result of detailed discussions within the DTOcean Technical Work Group it was decided to use a time based approach for the weather windows analysis. This means that the necessary signals of weather time series as input of the DTOcean tool will be time based, using a daily time resolution. This decision opens the possibility to develop a more precise time series based maintenance strategy than the methods based on statistical approach.

The maintenance model is based on a defined time-sequential maintenance plan where the maintenance operations can be simulated over the complete life time of a MREA. The following three types of maintenance will be considered in the implementation:

- **Corrective maintenance** → based on an unexpected failure
- **Condition based maintenance** → based on the actual health of the system components
- **Calendar based maintenance** → based on fixed time intervals

The Schematic overview of a maintenance plan is depicted in Figure 4-1.

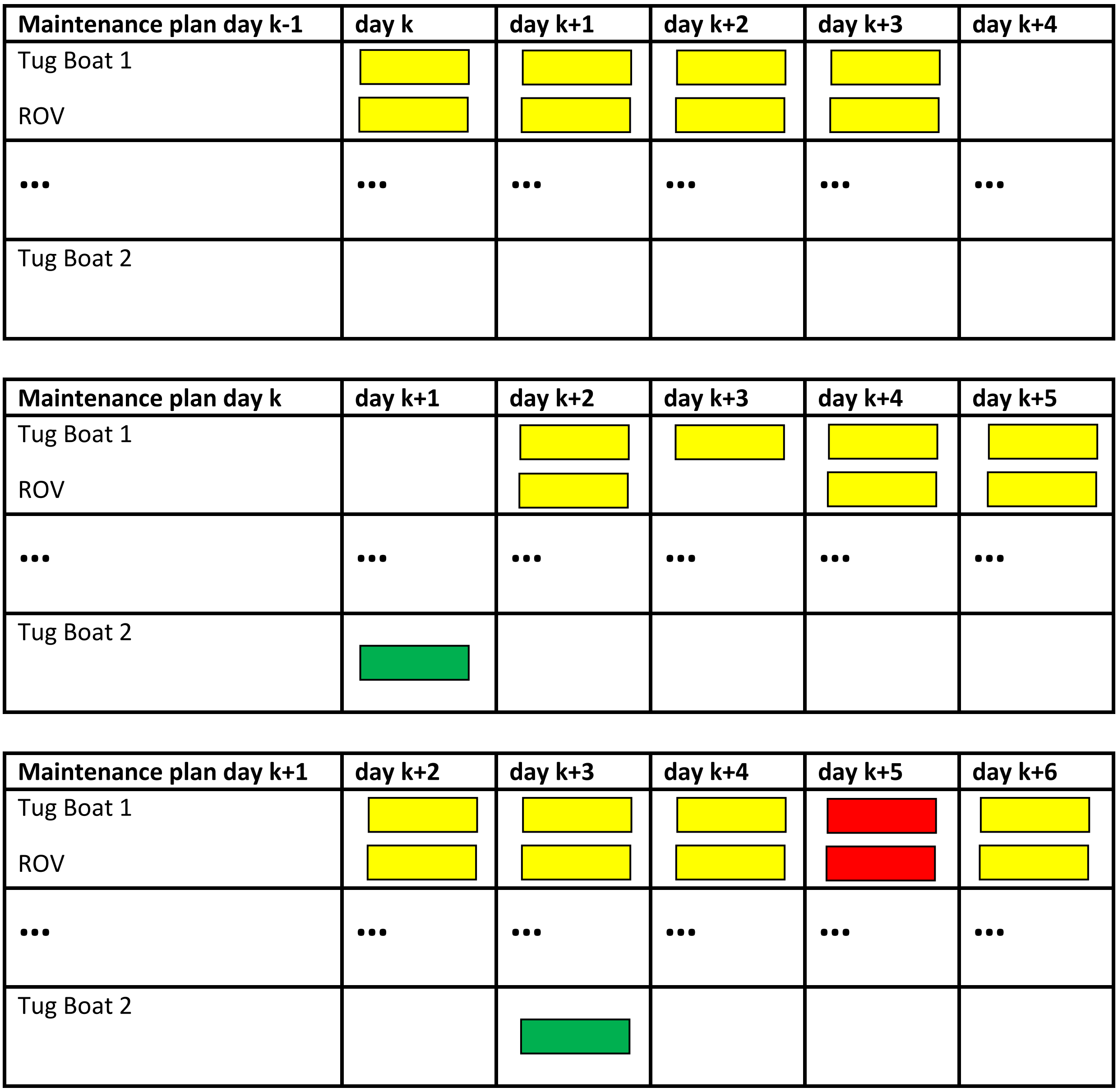
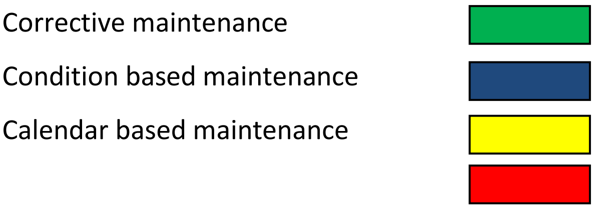


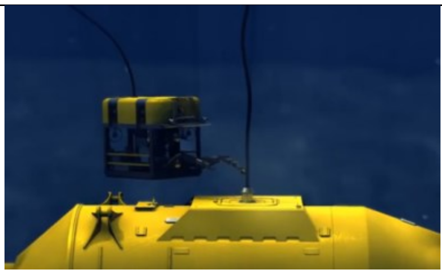
Figure 4-1: Schematic overview of a maintenance plan (based on [6])



Waiting due to the weather window

In the following the maintenance plan is described by the consideration of a simplified description of a calendar based maintenance to be carried out at the example of the DTOcean Scenario 5, i. e. a 10MW tidal turbine demonstration array at the Sound of Islay in Scotland (see [3] for details). The array will consist of 10 fully submerged, sea bed fixed horizontal axis tidal turbines with 1MW rated power each. The following Table 4-1 illustrates the maintenance process for this specific scenario. The images shown in the table are depicted from [9].

Table 4-1: Maintenance process for a submerged seabed fixed tidal device (Type 4)

Process step description	Illustrating image (from [9])
The maintenance concept for the submerged tidal turbines is to replace the turbine, which needs to be maintained, by a complete unit, which has seen a full revision, on site and take it back to the O&M base.	
The turbine unit is equipped with a buoyancy element and floats. Therefore, it can be tugged out to site.	
On site, an ROV is required to attach a guiding rope for the buoyancy element to the top of the turbine unit, which needs to be maintained	

Buoyancy element is lowered and attached to top of the nacelle.	
The turbine unit to be maintained is disconnected from supporting structure and is moving towards sea surface, but is still connected with a lower guiding rope When the turbine unit floats on sea surface, the ROV detaches the lower guiding rope from supporting structure.	 
ROV attaches lower guiding rope for the fully revised turbine unit to the supporting structure.	
The unit will be lowered and re-connected to the supporting structure. Then the buoyancy element is detached from nacelle and returns to sea surface. The upper guiding rope is detached by the ROV. The turbine unit at this array position now is fully operational again. The unit to be maintained will be towed back to the O&M base	

The generation of the maintenance plan will be illustrated by the following simplified example for the above described scenario. Assumed there shall be a calendar based maintenance carried out for four turbine units at day k (see upper part of Figure 4-1). Assumed that the tug boat can tow the turbine unit at a speed of 2.5 knots and that the O&M distance is 18.2 km (10 nautical miles). The time to travel will then be 4h to site and 4h back from site. The time to replace the unit shall be assumed with 3h. Therefore, with a maximum allowed working time for the crew per day of 12h, the replacement of one unit will require one full working day, i. e. 4 days in total for all four units. In a first step, the maintenance cost estimation algorithm will generate an initial maintenance plan as shown in the upper part of Figure 4-1. The algorithm passes a request to the logistics optimisation algorithm with the required specifications (e. g. the tug boat bollard pull to tow the turbine, the required towing speed, the ROV including operational staff, etc.).

The logistics optimisation algorithm feeds back that a a suitable tug boat and an ROV are available for the specific tasks of calendar based maintenance (yellow blocks in Figure 4-1) for four days from day k+2 onwards Therefore, the maintenance plan is revised accordingly.

At day k it appears that one device has failed and requires an immediate corrective maintenance at day k+1 (green blocks). This corrective maintenance requires an additional tug boat. The ROV can be used for both interventions. Therefore, the maintenance plan is updated by the maintenance cost algorithm (middle part of Figure 4-1) and a second request is passed to the logistics optimisation algorithm.

The feedback of the logistics optimisation algorithm is that the required second tug boat is available for day k+3 at the earliest. Furthermore, there is a weather constraint at day k+5. This requires the postponing of the last calendar based maintenance operation from day k+5 to day k+6.

The resulting final maintenance plan for the calendar based and corrective maintenance operation sequence is shown in the lower part of Figure 4-1. With this final maintenance plan, the maintenance cost estimation algorithm calculates the cost estimation. The required cost figures (daily rate for tug boats and ROV) will be provided by the logistics

In general, the following points will be integrated in the elaboration of the maintenance plan.

- The initial planning for calendar based maintenance and for condition based maintenance.
- The occurrence of random failures of different system components, requiring corrective maintenance. For each type of failure it will be defined how the repair has to be carried out and which resources are necessary.

- Checking of suitable weather windows and availability of different resources, for instance vessels, maintenance crews, etc.

A basic overview of the flow chart of the modelling process is depicted in the following Figure 4-2. On request of the global optimisation tool, loading and pre-processing all required parameters from the global data base into a temporarily storage, the initial maintenance plan will be generated by the algorithm (block “software initialisation…”) and a first request to the other optimisation algorithms will be done to derive the required input data for the maintenance plan initialisation. Then, the maintenance plan for the three possible strategies will be updated (as described in principle in the example given above), mainly due to logistics and wait time (weather windows, lead times, etc.) information coming from the logistics optimisation algorithm (three blocks “Update Maintenance plan…).

After updating and storing the intermediate results, the next request from the global optimisation tool is done with modified parameters. In the case of the example above, parameters for optimisation could be:

- Interval for calendar based maintenance: extending the interval decreases costs by having less interventions during the device life cycle, but leads to increase of cost by having more corrective maintenance cost and higher downtime related revenue losses.
- Vessel type: use of a large transport ship to carry all four turbines in one rush or to do the maintenance on deck; this will reduce the number of days (and therefore) of hiring the tug boat and ROV but will cause higher cost for the larger ship itself.

In the post processing block, the required information for output to the global optimisation tool is calculated and transferred. The information will be used by the global optimisation tool to prepare the report for the user.

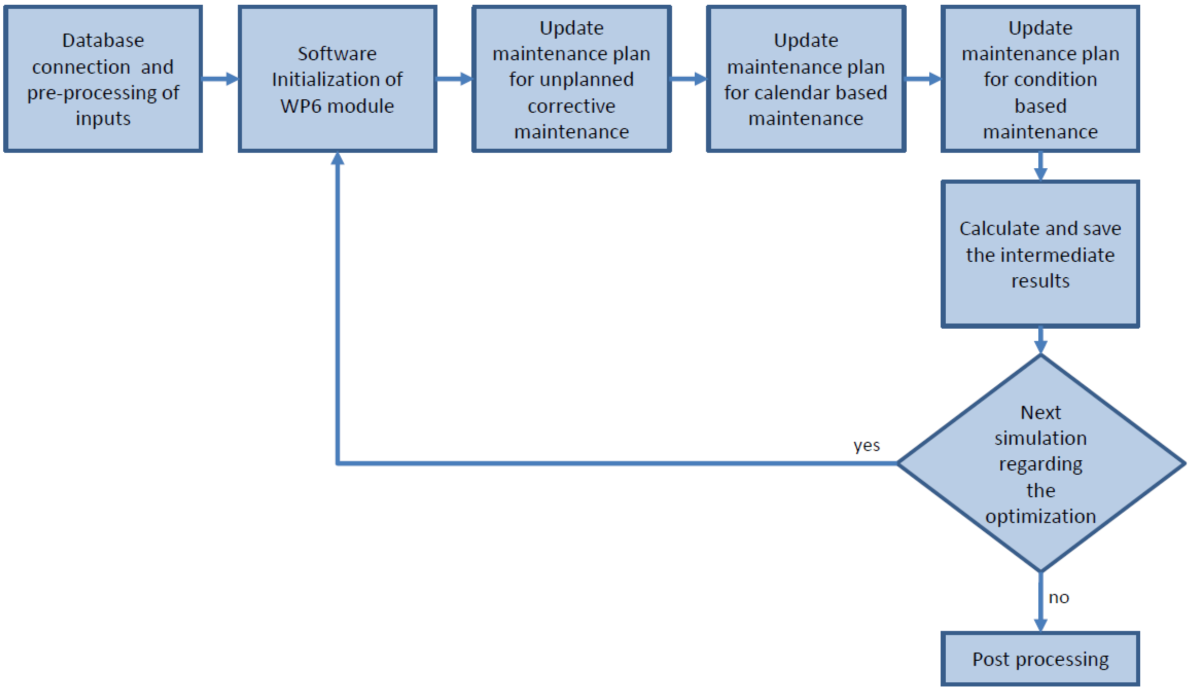


Figure 4-2: Basic overview of the flow chart of the modelling process (based on [6])

Due to the limited resources (equipment, personnel, materials, etc.), it is obvious that when several maintenance tasks have to be carried out, it is necessary to define a certain priority for each type of maintenance strategies in order to be able to structure the interaction between the different types of maintenance.

Priority definition for carrying out of the maintenance strategies:
1. Corrective maintenance
2. Condition based maintenance
3. Calendar based maintenance

Due to the above priority definition and the consideration of limitation of the resources a planned maintenance activities can be postponed. Please note that all maintenance tasks that are already started have highest priority and is excluded from the postponing process.

The advantage of time series development of maintenance strategy is that not only the long term average of maintenance cost in the planning phase but also an estimation of its distribution over the lifetime (depending on the accuracy of parameters) can be calculated (see Figure 4-3 as an example as discussed by Rademakers et. al. in [5]). With respect to the maintenance cost estimation algorithm outputs, this means that not only a long term average value for the maintenance effort (with respect to cost, personnel, equipment, etc.), e. g. over the entire life cycle of an ocean energy array as a long term average value for the required calculations during the planning phase. It can also be the effort calculated with a user defined time resolution (e. g. on a quarterly basis) to plan the OPEX cost distribution over the array life cycle.

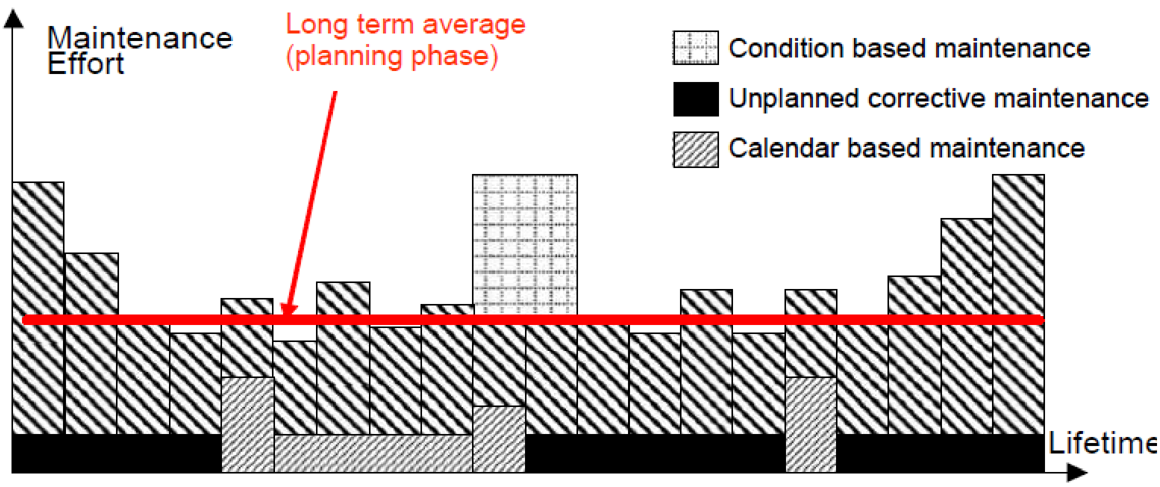


Figure 4-3: Maintenance effort over the lifetime of a renewable energy generating device [from 5]

4.2.2 GENERAL DESCRIPTION OF THE MAINTENANCE MODEL

The basic flow chart represented in Figure 4-4 gives the schematic overview of the maintenance model.

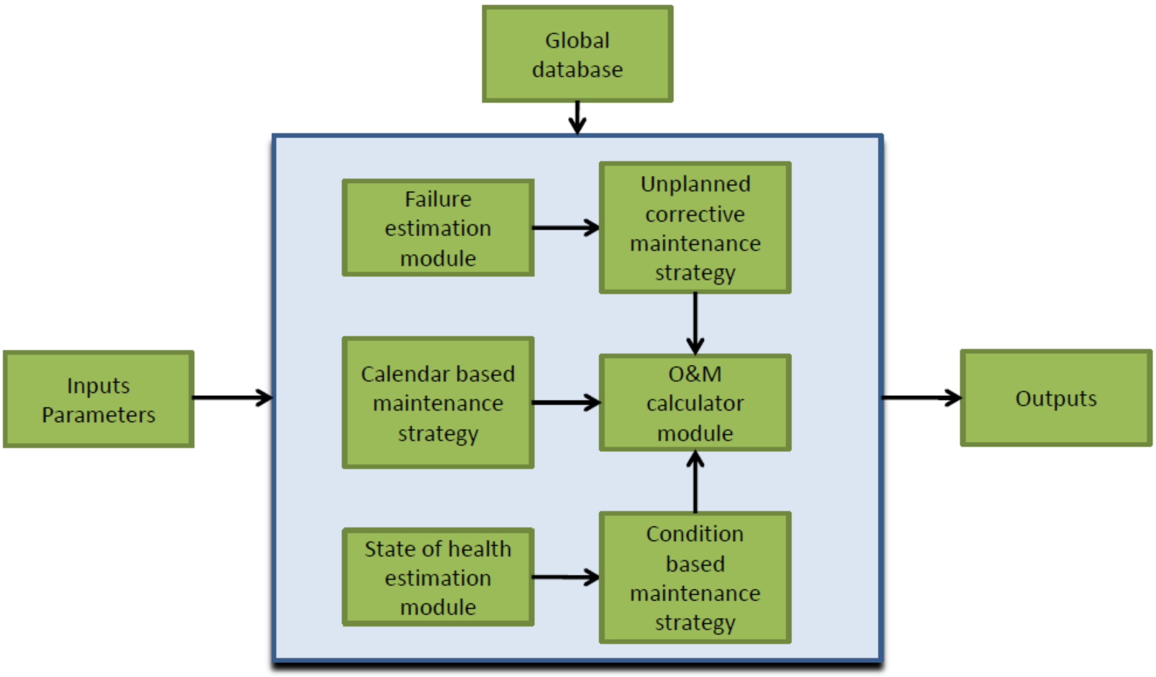


Figure 4-4: Overview top level flow chart of the maintenance model

The necessary values for the calculation of the outcomes of the maintenance model will be driven from the inputs and parameters of the model and global database of the DTOcean project. The three different maintenance strategies will be defined in a form of a maintenance plan as described in section 4.2.1.

The calculation modules of the maintenance model are described below:

<u>Failure estimation module in case of corrective maintenance:</u>

The occurrence of the random failures is a stochastic process, which will be modelled in failure estimation module by means of a Poisson process. A Poisson process is a known stochastic process for modelling of random events in time that occur independently from each other. The input for this calculation will be the component specific annual failure rate, which can be estimated out of the experiences present in other fields of the renewable industry (e. g. as described in section 2.1) or which will be defined as an input value by the user. Result of the Poisson process will be the specific points in time when the corrective maintenance actions occur in the maintenance plan of the component in scope.

State of health estimation module:

The state of health or degradation module is based on a simple model in order to simulate the alarm signal of a condition monitoring system. It is assumed that the degradation grade of a component is zero (%) at the installation and commissioning of the component and increases towards “1” (or 100%) during its maintenance cycle. A linear interpolation model simulates the degradation level of the considered component. The grade of degradation to trigger an alarm is a parameter of the component, which can be defined by the user. Figure 4-5 shows the degradation of the state of health (SoH) of a component under different load conditions, i. e. if it is built in devices on different positions in the array, with exposure to different load conditions. The different load conditions will be considered as different slopes of the degradation curves in the maintenance cost calculation algorithm.

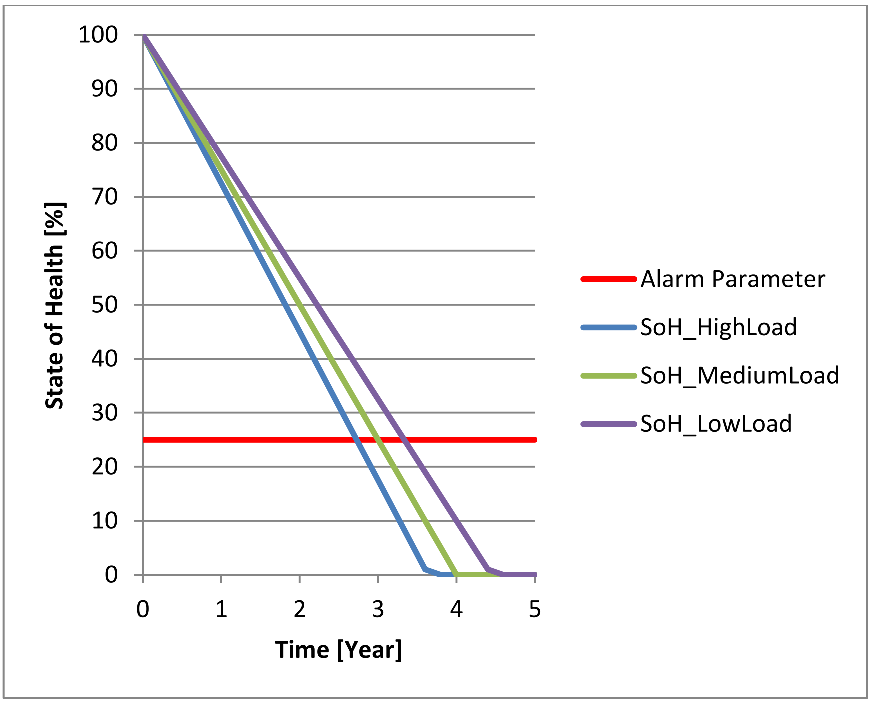


Figure 4-5: State of health degradation of a component under different load conditions

A major difference between corrective and condition based maintenance is the calculation of the array unit’s downtime. It is assumed that the downtime of the condition based maintenance activities is equal to the actual repair time. Downtime due to logistic time of spare parts, suitable vessels, maintenance crew and due to bad weather condition is not relevant. The maintenance model determines if the resources dedicated to a condition based maintenance activity with its required repair time are sufficient.

O&M calculator module:

In the following the modelling approach will be illustrated in the case of unplanned corrective maintenance. The other two maintenance strategies are the subsets of the approach for the calculation of unplanned corrective maintenance.

a) Unplanned corrective maintenance:
Unplanned corrective maintenance is carried out after a system component in a farm array fails, which causes the energy device to shut down. A typical maintenance activity of unplanned corrective maintenance is depicted schematically in Figure 4-6.

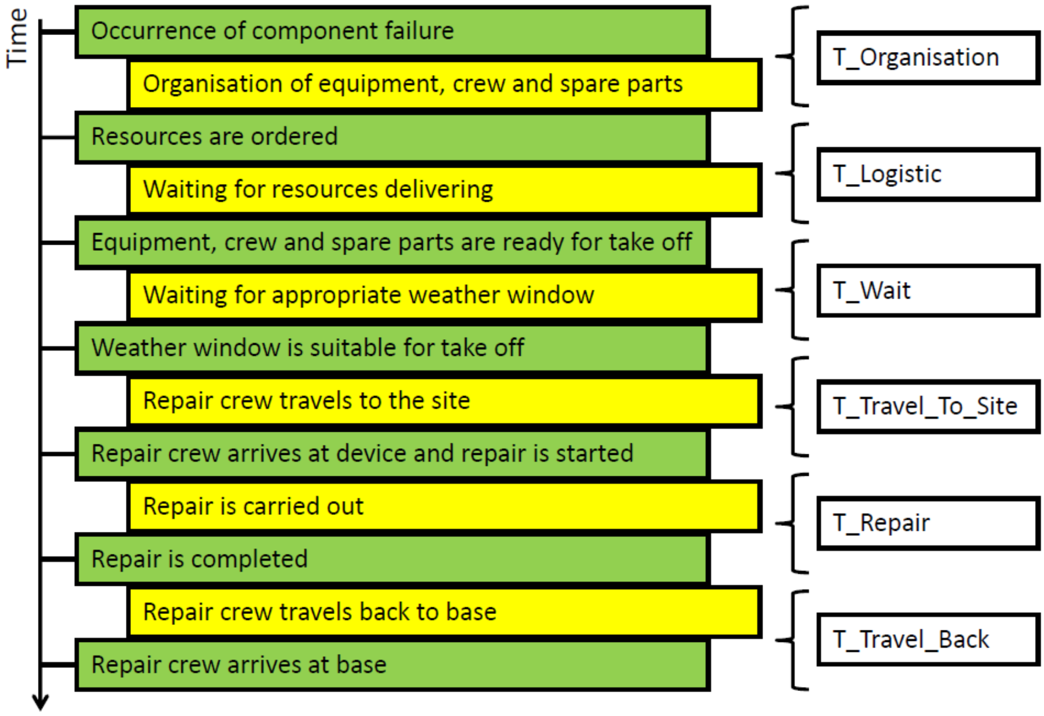


Figure 4-6: Maintenance process for a corrective maintenance (based on [7])

The description of the time parameter of corrective maintenance activity is depicted in Table 4-2

Table 4-2: Time parameter of maintenance process

Parameter	Description
T_Organisation	Time to organise logistic equipment, repair crew and spare parts
T_Logistic	Waiting time for all resources (logistic equipment, repair crew and delivery time of spare parts) to arrive to port and will be ready to travel to the offshore site for repair
T_Wait	T_Wait is calculated in weather window tool as a function of T_Travel_To_Site, T_Repair, T_Travel_Back and limiting variables such as wave height or wind velocity
T_Travel_To_Site	Time to travel to the edge of the MREA from the maintenance port
T_Travel_To_Device	Time to reach the desired device from the edge of MREA. In the first version of maintenance tool T_Travel_To_Device is neglected. IF the MREA area is big this time parameter should be considered.
T_Repair	Time to repair the device
T_Travel_Back	Time to travel back to the port

Depending on the defined parameter of the occurred error there will be different possibilities to carry out the maintenance:

- A maintenance team will be sent to the site to carry out the repair (Figure 4-6)
- First an inspection crew will be sent to the site to assess the occurred failure of the device (Figure 4-6 with T_Logistik = 0).

The process depicted in Figure 4-6 is only valid if the repair can be completed during one shift. In reality a repair action can be extended over a couple of days. In this situation the repair team will travel back to the harbour or hotel ship at the end of the working day and will travel back to the damaged device at the next morning. In this case, the calculation of an additional time T_Break is required and added to the overall time required for the maintenance action. T_Break will be placed between T_Travel_Back of day k and T_Travel of day k+1.

The process shown in Figure 4-6 is only valid if the repair can be completed in one dense period. If necessary the repair action can be split up in a number of separate actions.

b) Condition based maintenance:
Condition based maintenance will be initiated based on the observed status or degradation of a certain component. The process of condition based maintenance is similar as depicted in Figure 4-6. Three main differences can be distinguished:

- The occurred failure of a component is not the start of the maintenance process of the device but its grade of degradation.
- The condition based maintenance is planned in such a manner that the waiting time due to not suitable weather conditions is excluded (T_Wait = 0).
- The device is only shut down during the repair or replacement of the failed component (T_Downtime = T_Repair).

c) Calendar based maintenance:
Calendar based maintenance will be initiated based on the recommended maintenance planning by manufacturer of the component. The process of calendar based maintenance is similar as depicted in Figure 4-6. Three main differences can be distinguished:

- The occurred failure of a component is not the start of the maintenance process of the device but calendar indicating that preventive maintenance has to be carried out.
- The calendar based maintenance is planned in such a manner that the waiting time due to not suitable weather conditions is excluded (T_Wait = 0).
- The device is only shut down during the repair or replacement of the failed component (T_Downtime = T_Repair).

Annual failure rates of the components and their associated failure classification are two important parameters of the maintenance model which have to be defined in different templates.

In Figure 4-7 the grouping of system components is depicted, which should be considered in maintenance model, their subcomponents failure rates and their failure classification.

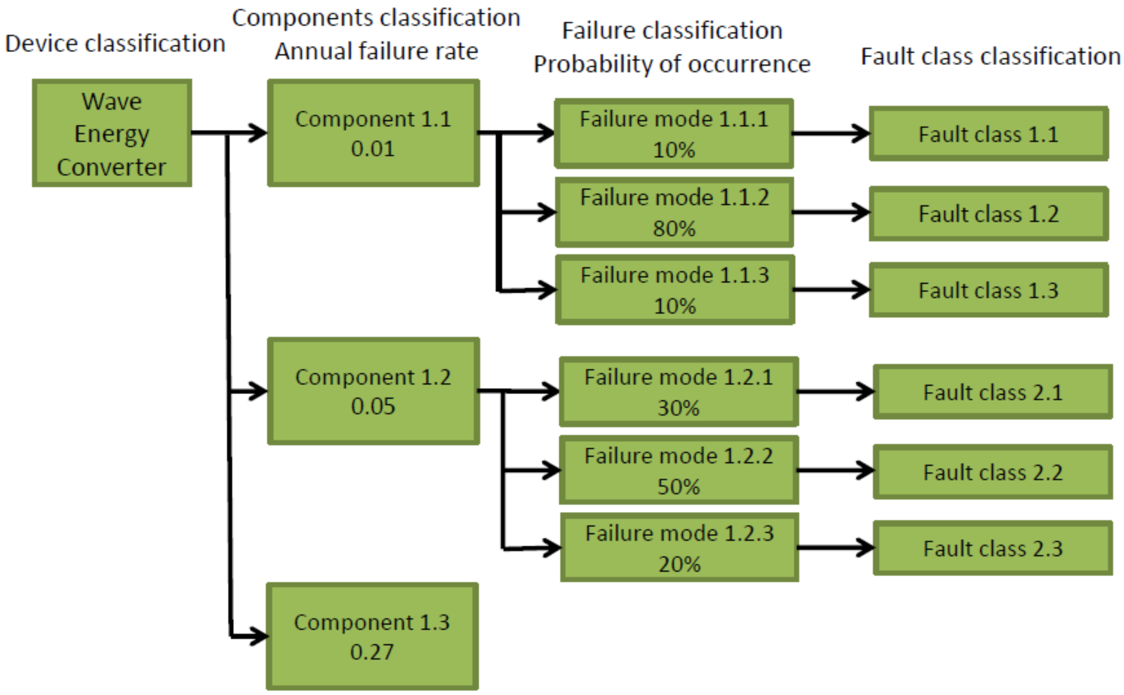


Figure 4-7: Grouping of the considered system components for corrective maintenance strategy (based on [6])

The annual failure rates of the components 1.1 to 1.3 will be divided into a number of failure modes with different probabilities of occurrence. The sum of the probabilities of occurrence of one component is 100%. The failure modes will be related to the failure of a sub-component, e. g. the failure main bearing of the gearbox of a tidal turbine device.

Each failure mode is connected to a fault class. In the fault class, there are the required actions defined to repair the fault and bring the device back to operation.

All maintenance actions associated with the fault classes will be categorised into different maintenance categories which defines the repair actions. A fault class will be linked with its defined repair strategy. In the case of the example given above (fully submerged tidal turbine with sealed housing), the action related to all fault classes will be to replace the complete turbine unit. In fault classes related to other device types, it will be the replacement of selected components or the repair of smaller components on site.

The specific parameters for the different fault classes will be the time for the maintenance action, the costs of spare parts required, etc. With this information, the costs for each maintenance event as defined in the maintenance plan for each component will be calculated and the total sum of all component maintenance costs will be calculated as the overall maintenance cost of the device during its life cycle with respect to the selected maintenance strategy mix and the selected maintenance parameters (calendar based maintenance interval length, vessel types to use, etc.).

d) Calculation of the loss of revenue

Scheduled or unscheduled downtimes of devices in an ocean energy array will cause loss of revenue with respect to the generated electrical energy and, therefore, need to be considered as additional indirect maintenance costs. Downtime of the devices due to the maintenance actions will be calculated according to the examples given in Table 4-3 (which may need extension during the algorithm development phase). In the maintenance cost estimation algorithms, revenue losses will be calculated in a first approach out of the annual energy yield of the device (as will be defined by the calculations of the array layout optimisation algorithm) and the actual calculated downtime value as a fracture of the yearly energy yield. Faults may occur which affect more than one device in an array, e. g. due to a damaged subsea cable. In this case, the revenue losses for all of the devices will be calculated and summed up.

Table 4-3: Calculation of downtime for different maintenance strategies

Maintenance	T_Downtime
Corrective maintenance	T_Logistics+ T_Wait+ T_Travel+ T_Repair+ T_Travel_Back
Condition based maintenance on site	T_Repair
Calendar based maintenance on site	T_Repair

4.2.3 INPUTS OF THE MAINTENANCE MODEL

The following inputs are required to define the maintenance actions. The listed parameters reflect the present stage of the discussion with the other algorithm developing WPs and surely will be modified and extended during the algorithm development process.

- T_Organisation, T_Logistic , T_Wait, T_Travel_To_Site, T_Repair, T_Travel_Back
- Material and labour cost
- Number of personnel
- Access vessels type for crew
- Access vessels types for materials
- Access vessels for crews and materials
- Internal or external hoisting equipment
- Array layout
- Performance curves of the devices
- Different tables which contain annual failure rates, probability of occurrence of fault class, etc. (see Annex)
- …

4.2.4 OUTPUTS OF THE MAINTENANCE MODEL

The results to be delivered by the maintenance cost estimation algorithm at the present stage of the discussion with the other WPs are:

- Optimal maintenance strategy which minimizes the sum of additional CapEx and OpEx
- Maintenance costs (split into CapEx, Opex, Loss of revenue)
- Time-based and production-based availability
- Downtimes
- …

There will be modifications and extensions to this list during the algorithm development work in the course of the DTOcean project. With the first experiences from simulations with simplified models of the algorithms to be developed, detailed analysis of the data exchange flow within the global optimisation tool will be possible and this will give the required information to identify required hand shake parameters.

5 CONCLUSIONS

The deliverable D6.2 “Evaluation according to costs, downtimes, etc. of different maintenance strategies” describes the results of the work undertaken in the DTOcean WP6 task T6.2 “Maintenance strategies” to estimate the maintenance costs of devices in wave and tidal ocean energy devices.

In the introduction chapter 1, the scope of T6.2 has been described. In the second chapter the selection process for the components of a wave or tidal energy device to be considered to calculate the costs and downtimes during the life cycle is discussed. A methodology for categorisation of the main subsystems of different device types has been found by using the definition as worked out in the Equimar project. For each device type, which is defined in the description of work and the deliverable D1.1 “Detailed deployment scenarios for wave and tidal energy converters” as to be in scope of the DTOcean optimisation tool, a list of components has been proposed with respect to maintenance cost estimation. This list should be understood as a preliminary compilation, which will need revision and extension during the algorithm development work in WP6 in the coming year.

The third chapter gives a definition of the required parameters for the detailed description of the maintenance costs. An indexing scheme for those parameters is proposed to allow their identification within the global data base. Again, this indexing scheme need further revision and extension and needs to be agreed with the other WPs of the DTOcean project and needs to be integrated in the data access procedures with the global data base as it is under the responsibility of the Technical Work Group.

Finally, Chapter 4 describes the approach for the software implementation for the development of the maintenance cost estimation algorithm. The first step to achieve this is the definition of a maintenance plan for each component of each device type, which represent all required maintenance actions and allows estimating the life cycle maintenance costs. Chapter 4 gives a first approach for the required definitions of the input and output relations to the user and to the algorithms to be developed by the other DTOcean WPs. This first approach must be understood as the basis for the start of the algorithm programming work. It will be subject to several revisions during the programming progress in WP6 and the other WPs. A major prerequisite to successfully finalise the programming work in DTOcean will be the development for a simulation environment for testing the interdependencies of the different algorithms under the DTOcean optimisation tool.

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7 ACRONYMS

WP	Work Package
DoW	Description of Work
O&M	Operation and maintenance
WMEP	Wind Measurement and Evaluation Programme
PLC	Programmable Logic Controller
SCADA	Supervisory Control and Data Acquisition
TWG	Technical Work group
MTBF	Mean Time Between Failure
MREA	Marine Renewable Energy Array
CapEx	Capital Expenditures
OpEx	Operational Expenditures
SoH	State of Health

ANNEX

Five different scenarios are defined in deliverable 1.1 for the consideration in DTOcean project. The following tables have to be defined for each of them. In the following the rough layout of these tables will be described. After discussion with project partners involved in WP6 and WP5 these tables will be probably extended. After this discussion an excel-file will be developed containing the tables which will be needed in maintenance model.

Annual failure rates of components:

The energy conversion device of each scenario has to be divided in an amount of components which should be considered in maintenance strategy.

Example:

Component	Annual failure rate	Fault class	Probability of occurrence of fault class	Repair action
Gearbox	0.35	Shaft failure Bearing failure Oil system failure	75% 20% 5%	RA1 RA2 RA3
…	…	…		…

The probability of occurrence of a fault class is the probability that the component is out of order caused by this fault class. The repair action is the description how the maintenance should be down.

Each fault class should be linked with different tables which define the material cost, labour cost and different times such as repair time, logistics time, etc.

The following table links the fault class with some attributes of component which should be replaced.

Fault class	Component	Weight (kg)	Dimensions (m)	Cost (€)	T_Delivery (h)	T_Repair (h)	Crew size and cost
FC1	-						

Fault class	Component	Weather condition				
FC1	-					