OPTIMISING OPERATION AND MAINTENANCE STRATEGIES FOR MARINE RENEWABLE ENERGY CONVERTERS

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1 INTRODUCTION

Optimising maintenance strategies and reducing related Operation & Maintenance (O&M) costs is a significant challenge for the Marine Renewable Energy (MRE) sector. Selecting an appropriate maintenance approach can be particularly difficult for multiple devices at sea, such as MRE arrays or MRE platforms combining distinct devices. This paper will simulate O&M activities and compare strategies for a MRE platform, presenting a methodology, developed in the EU FP7 project -MARINA Platform- [1], combining an economic assessment and a Reliability, Availability and Maintainability (RAM) assessment.

In the methodology presented in section 2, all the costs involved over the lifespan of the platform i.e. manufacturing, installation, operation, maintenance and decommissioning, are identified and evaluated in the economic model. In addition, an optional O&M module has been developed in the MARINA project and integrated into the economic model to enable a detailed assessment of O&M costs. This O&M module is based on outputs of the RAM assessment, such as the number of spare parts purchased, frequency of maintenance vessels or crew mobilization.

The strength of this approach is to facilitate the detailed calculation of O&M costs, which are traditionally modelled through a simplified approach, in particular for emerging technologies when there is a lack of operational experience. For instance, O&M costs are frequently calculated as a percentage of capital expenditures (CAPEX) in the MRE sector. The combined RAM and economic assessment quantifies the impact of downtime due to failures and maintenance activities on energy production and subsequent revenue. This allows the user to compare and contrast the benefits of different maintenance strategies.

The Delta-E Mk2 platform, described in section 3, will be used as a case study. The concept is a floating platform combining one wind turbine with twenty Wave Energy Converters (WECs), exploiting synergies through the sharing of moorings, electrical components, maintenance utilities, etc. Through the combined economic and reliability assessment, a comparison between several preventive maintenance strategies and spare parts management policies will be made for the Delta-E Mk2 case study, with respect to availability and revenue.

While this methodology has been applied to a MRE combined platform in the framework of the MARINA project, the reliability/economic model would be also fully applicable to MRE arrays of offshore wind turbines (fixed or floating), tidal turbines or wave energy converters.

2 COMBINED RAM AND ECONOMIC MODEL

The methodology developed in the MARINA Platform project combines a RAM assessment undertaken by Bureau Veritas, followed by a lifecycle cost analysis developed by the University College Cork. Both are described in the corresponding MARINA deliverables [2] and [3].

2.1 RAM model description

The RAM model uses the following inputs:

- List of components for the Delta-E Mk2 platform,
- Mean annual electrical production,
- Preventive maintenance (PM) scenario, to preserve the system by replacing components before they actually fail: frequency and duration of maintenance activities, maintenance vessels, dispatch time, etc.
- Corrective maintenance (CM) scenario, to restore a failed component to its operational conditions: failure rates, failure modes, repair duration, etc.

The RAM model is created using Bureau Veritas proprietary software Optimise©, a continuous time, Monte Carlo (probabilistic) simulator. First, an "asset register" is created for the considered system, where each component is associated with its main reliability data such as the failure rate (λ) or Mean Time To Failure (MTTF), Mean Time To Repair (MTTR) and dispatch time of the maintenance vessel (see Table 1). Then, the components are ordered and connected in parallel or series configuration to show potential redundancies of the system.

TABLE 1: EXAMPLE OF ASSET REGISTER

Component	Maintenance vessel	Dispatch time (hrs)	MTTF (yrs)	MTTR (hrs)
A	workboat	72	12	10
B	...	...	...	...

The RAM model provides the availability of the considered system to produce electricity, accounting for the production loss due to planned and unplanned outages within the system life. The production availability can be expressed as the ratio of Actual Energy Production (AEP), considering downtime due to failures or preventive and corrective maintenance activities, and the potential energy production that system would have without outages.

$$Availability\ (\%) = \frac{Actual\ production}{Potential\ production} * 100$$

Additional outputs of the model are summarized in Table 2.

TABLE 2: RAM MODEL OUTPUTS - SUMMARY

Availability
Annual production availabilities
Average production availability over the platform lifetime
Equivalent number of days of total production loss
Failures
Number of failures over the platform lifetime
Critical components, ranked by number of failures and/or contributions to power production loss
Maintenance
Breakdown between PM and CM activities, expressed in % of total power production loss
Number of mobilisation of each maintenance vessel

2.2 Economic model description

As illustrated in Table 3, RAM study outputs are fed into the economic model including availability, failure frequency of components, number of spare parts purchased or frequency of maintenance vessels mobilization. The economic model calculates the Levelised Cost of Energy (LCoE) using outputs from the RAM model to show the impact of downtime due to failures and maintenance activities on the energy production and costs.

TABLE 3: COST MODEL INPUTS – SUMMARY

Site & Resource	
Water depth	Distance from shore
Potential Annual Energy Production	
Production availability at site *(from RAM model)*	
MRE farm details	
WT and WEC ratings	Device and project lifetime
N° of devices per platform	N° of platforms in farm
Platform specifications	
Structural materials	Mooring system
Installation vessels type and number	
O&M module *(from RAM model)*	
Maintenance vessels and crew available: travel time, shift crew categories (regular/specialist) and costs	
List of system/components: - associated vessel required for a repair/replacement - associated MTTR	
PM scenario including duration, resources required	
CM scenario including duration, number of failures per component over the lifetime and resources required such as vessels and number of mobilisations, spare parts.	

CAPEX costs are estimated considering the costs of platform structural materials, device (WEC and wind turbine type), mooring lines and anchors, installation, cabling, offshore and onshore substation, vessel fleet, project management and contingencies. The operational expenditure (OPEX) costs are estimated considering personnel, consumables/spare parts, vessels and other OPEX costs not currently considered by the RAM study e.g. mooring system maintenance, transmission system etc. as well as project level operational costs such as insurance, rental and utilities.

The LCoE is the cost of generating energy indicating the minimum price energy must be sold to break even. This is calculated by dividing the total lifetime costs in € (CAPEX and OPEX) by the total farm lifetime energy output in kWh. Both are discounted over the project lifetime to calculate the Net Present Value (NPV) as illustrated in the following equation:

$$LCoE\ (€/kWh) = NPV\left(\frac{total\ lifetime\ costs}{total\ lifetime\ energy\ production}\right)$$

To allow for some consideration of the uncertainty in cost figures as well as the stochastic nature of prices generally, the cost model runs a probabilistic study treating the majority of prices as random variables that are distributed across a normal distribution curve according to a standard deviation (SD). The cost model runs a number of iterations to determine the minimum, maximum and average LCoE as well as the distribution and cumulative probability of results.

2.3 Uncertainties and model validation

Results of the combined reliability and economic assessment are highly dependent on the model inputs and assumptions. However this data is extremely difficult to assess due to sparse field experience and confidentiality issues related to the MRE sector. Component failure rates may vary significantly depending on the source considered, and maintenance strategies are not MRE device specific but extrapolated from the wind industry sector. The level of concept detail available as well as the cost figure inputs would also significantly impact the accuracy of results.

Consequently, results of the present assessment shall be used with care. They should not be taken as an absolute figure, but only as a general guidance. Although generic inputs e.g. costs, MTTR etc. have been validated as much as possible based on published figures and through discussions with industry and suppliers, future accumulation of experience will help to bring these assumptions closer to the field reality and improve confidence in the absolute results. To deal with uncertainties, the problem was tackled at a variety of levels:

- both RAM and economic models undertake probabilistic studies, treating failure rates and costs as random variables to find average results for 1000 lifecycles using Monte Carlo simulation
- a number of sensitivity analyses have been run to assess the impacts of input data uncertainties into the model
- comparison with existing assessments has been conducted when possible, in particular with offshore wind turbines but also for WECs

The complementary studies detailed in [4] and [5], gave confidence in the order of magnitude of both the RAM model and the economic model outputs.

3 CASE STUDY

3.1 Delta-E Mk2 Platform

The Delta-E Mk2 concept, illustrated in Figure 1, is a large concrete floating platform in a triangular shaped arrangement combining one wind turbine with twenty WECs. The latter use the Oscillating Water Column (OWC) technology, where the rising and falling sea water surface produces an oscillating air current in each column which drives a bidirectional turbine directly coupled to a generator.

FIGURE 1: DELTA-E MK2 PLATFORM MODEL
(ECOLE CENTRALE DE NANTES)

The rated power of each OWC is 500 kW for a total rated wave power of 10 MW. The selected wind turbine is the 5 MW reference wind turbine defined by the National Renewable Energy Laboratory (NREL) [6]. Due to the motion constraints imposed by the inclusion of a wind turbine, a large concrete platform was envisaged, equipped with a turret mooring system. A model scale (1:50) of the Delta-E Mk2 concept was successfully tank tested at University College Cork and in Ecole Centrale de Nantes in 2013-2014.

3.2 Model assumptions

The model is based on a site location in the North sea. A 35 km distance from shore and from harbour has been selected to model respectively the grid connection and regular trips of the maintenance vessels.

To establish average results and confidence levels, both RAM and economic probabilistic models are run for 1000 individual lifecycles of 25 years. In the economic model, a normal distribution curve with a SD of 10% is applied across all variable costs. In the RAM model, exponential distributions with λ parameter (failure rate) are used to represent components probability of failure by a given time.

The electricity normal production rate, i.e. the actual production when there is no interruption, is presented in Table 4. The normal production rate has been assessed in the MARINA project on the basis of an average energy production using 10 years of data. Multiple WECs are assumed to produce the same amount of energy at a given time. It should be noted that the wind production has been assessed using wind resource data at a height of 10m.

TABLE 4: ELECTRICITY NORMAL PRODUCTION RATE OF THE DELTA-E MK2 PLATFORM

Number of WECs	20
Number of WT	1
Rated power / total WECs	10 MW
Rated power / total WT	5 MW
Annual energy production	**38,46 GWh**
WEC	49%
WT	51%

Other assumptions of the model are detailed in [4] and [5], including components failure rates, mean time to repair, spare parts management, maintenance strategies, crew and vessels specifications, associated costs, etc. Some of the model assumptions may be brought closer to field reality in the future thanks to the experience accumulated in the MRE sector.

3.3 Comparison with simplified O&M assessment

When comparing the results between simplified O&M costs represented by % of CAPEX costs or €/MWh extrapolated from the industry, and the advanced O&M module presented in this paper (see 2.2), there is an approximate increase of 40% in total OPEX costs for the Delta-E Mk2 platform. As the order of magnitude of the model results have been validated against wind and wave O&M costs (see 2.3), this gives confidence in the improvement offered by this methodology compared to traditional simplified models.

4 OPTIMISATION OF MAINTENANCE STRATEGIES

4.1 Preventive maintenance strategy

The aim of preventive maintenance is to preserve a system by replacing components before they actually fail. PM activities include partial or complete overhauls, oil changes, lubrication, etc. In the present study, the PM scenario is based on literature assumptions ([7], [8], [9]) and discussion with industry. A scheduled approach has been assumed (Figure 2), including:

- Annual scheduled visual inspections and general maintenance tasks e.g. tightening of bolts, replenishing consumables etc.
- An additional overhaul every 5 years, excluding the final year where decommissioning will occur.

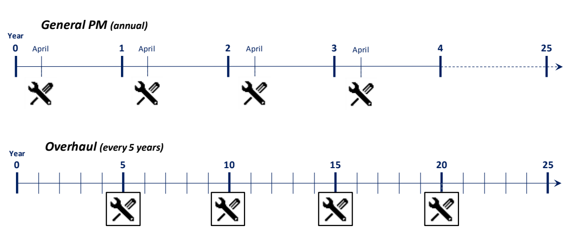

FIGURE 2: PREVENTIVE MAINTENANCE PLANNING

All PM activities are assumed to be conducted with a workboat. PM technicians are supposed to undertake shifts of 10 hours per day, only during daylight. Using a conservative estimate, 180 man hours (6 days / 3 people) for annual PM of the wind turbine and 300 man hours (10 days / 3 people) for overhauls every 5 years have been considered. As no real experience is available when it comes to WECs, a simplified scaling approach has been applied based on an assumed standard of 20 man hours maintenance per 250kW and a 20% increase per additional WEC. Based on [10], a cost of general maintenance consumables for PM is calculated with additional expenditure every five years for consumables used during overhauls, such as gearbox oil changes.

4.2 Full shut-down versus partial shut-down

Optimisation of PM and CM strategies for MRE devices can be conducted in the near future with input from operational experience at sea. As a first step, a comparison is made in this paper between two different simple PM scenarios for the Delta-E Mk2 platform case study.

In the full shut-down strategy, the whole Delta-E Mk2 platform is down during the annual inspection and the additional overhaul every five years. However, the high independence and modularity of MRE devices in the Delta-E Mk2 platform, in particular considering the twenty OWCs, should be exploited to facilitate continuous energy production despite the maintenance of a single element. Maintenance activities should be tailored to fit with this modularity e.g. only the device being serviced stops, allowing power production to continue for other devices.

In the partial shut-down strategy, when an individual WEC is under repair, the other WECs and the wind turbine are still available for electricity generation. Conversely, the wind turbine PM activities include electrical equipment mutualized between wind and wave, therefore no electricity production is possible when the wind turbine is down.

The benefit of applying a partial shut-down maintenance strategy versus a full shut-down one is quite straightforward as illustrated in Table 5. The partial shut-down strategy improves the production availability and decrease the LCoE of the Delta-E Mk2 platform. Although the result was quite predictable, the impact is not negligible as a relative 6% difference can be observed between the two strategies[1].

[1] Due to the uncertainties in the model assumptions and inputs highlighted in section 2.3 ; and confidentiality issues ; results are presented only in a comparative way.

TABLE 5: FULL VS PARTIAL SHUT-DOWN STRATEGY

Shut-down	Full	Partial	Δ
Availability	1	1.06	+ 5.8 %
LCoE	1	0.94	- 6.1 %

4.3 Spare parts management policy

In the present case study, corrective maintenance activities can be carried out either with a workboat or a floating crane for heavier operations. The assumption is made that minor repairs with the workboat can be done directly, without any spare parts supply time, small elements being already stored in the harbour. Conversely, two weeks of wait time is assumed to get heavier spare parts that would be handled with the floating crane. One of these weeks is to be considered in parallel with the logistics time of mobilizing the floating crane.

An alternative scenario has been considered, assuming that any required spare part to be handled with the floating crane would be also available in the harbour. The resulting availability shows a quasi-null impact (+ 0.26%) of the spare parts management policy on the results. There is also no impact on the LCoE. In this case study few components were assigned for a repair with the floating crane, so the low number of mobilisations explains the low impact of changing the spare parts policy. However, this methodology would facilitate comparison of other scenarios including spare parts wait time for repairs conducted with the workboat, allowing the decision maker to determine the best stock management.

5 CONCLUSIONS

The main achievement of this study is the application of a combined reliability and economic model developed within the MARINA project to optimise maintenance strategies for MRE devices. Outputs of the reliability assessment are fed into the lifecycle cost analysis to facilitate a more detailed evaluation of O&M costs and actual energy production of the platform, including downtime due to failures and maintenance activities. This is a noticeable progress beyond the state of the art, while O&M costs of MRE projects are otherwise frequently simplified, for instance as a percentage of CAPEX costs. However, due to sparse field experience and confidentiality issues in the MRE sector, inputs data and model assumptions come with a significant part of uncertainties and should be further refined thanks to field experience.

In the present paper, the reliability/economic model has been used to compare several maintenance strategies. The case study was a platform combining one wind turbine and twenty WECs, developed within the MARINA Platform project. Benefits of independence and modularity of MRE devices during preventive maintenance activities were demonstrated. Although the result of this comparison was quite predictable, the model can be used in the future to investigate more sophisticated preventive maintenance strategies. In addition, two different spare parts management policies were investigated. Future refinements of the PM and CM scenarios can be considered, such as the impact of the mean time to repair or the impact of the maintenance vessel fleet size and type.

It should be noted that the combined reliability/economic model is not limited to MRE combined concepts. MRE arrays of offshore wind turbines (fixed or floating), tidal turbines or wave energy converters can also be addressed.

6 ACKNOWLEDGMENT

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