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ENFAIT
ENABLING FUTURE ARRAYS IN TIDAL

D 9.3 – Reliability Availability Maintainability (RAM) models

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Contents

1 Introduction

A Funding Grant was awarded from the European Union's Horizon 2020 research and innovation programme in January 2017 to demonstrate a grid-connected tidal energy array at a real-world tidal energy site, propelling tidal energy towards competing on a commercial basis with alternative renewable sources of energy generation – Enabling Future Arrays in Tidal (EnFAIT). This was in response to the call LCE-15-2016: Scaling up in the ocean energy sector to arrays to generate significant learning through demonstration of cost-effective tidal arrays.

This document is produced to set out the Reliability Availability Maintainability (RAM) models to be used for EnFAIT turbines and infrastructure. It is to be submitted to satisfy deliverable D9.3 of the EnFAIT project and to be also made available for public dissemination.

1.1 Deliverables for Work Package 9 Optimise array reliability, maintainability & availability

The objective of EnFAIT Work Package 9 (WP9) "Optimise array reliability, maintainability & availability" is to design-in reliability and best-practice maintenance regimes to maximise tidal array availability through:

1) Delivering a Design Failure Mode Effect & Criticality Analysis (DFMECA) system (EnFAIT project document D9.2);
2) Conducting a Maintenance Strategy Review (MSR) to mitigate risk and minimise LCoE (EnFAIT project document D9.4);
3) Validation by Reliability Availability Maintainability (RAM) modelling & simulation (EnFAIT project document D9.3 – which is this document);
4) Designing, delivering & demonstrating cost-effective state-of-the-art Condition Monitoring System for tidal arrays (EnFAIT project document D9.5 which is for EnFAIT consortium members only).

See Figure 1 below for a graphical representation of the sequence and relationships between these documents.

Note: during the project it was decided to perform T9.3 RAM modelling after T9.4 MSR. The MSR analysis delivers the requirements for reliability, availability and maintainability. These are then to be validated through RAM modelling, therefore the sequence should be T9.4 and then T9.3.

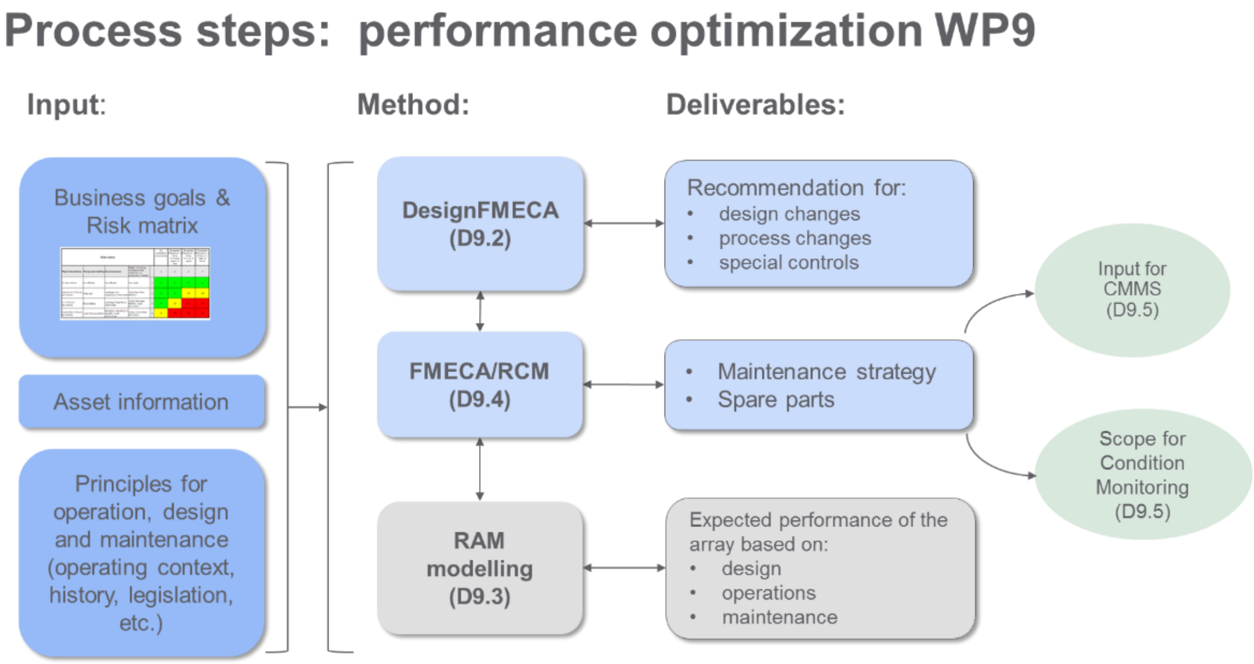

Figure 1: Process steps WP9

1.2 Scope of deliverable D9.3 Reliability Availability Maintainability (RAM) models

This deliverable describes the general RAM methodology and its application within the EnFAIT project. The actual data used for, and derived from, this methodology is only shared within the EnFAIT project consortium and European Commission stakeholders, where needed. That data is not published publicly as it contains commercial and technical confidential information.

2 Challenges of RAM studies in the Marine Sector

2.1 Context

The marine energy sector is an emerging industry which is still in the early stages of development. Tidal stream systems and ocean waves systems are the two sources of marine energy identified as having significant potential to contribute to the European energy system.

The main problem facing marine energy is the high Levelized Cost of Electricity (LCoE) compared to other electricity generating systems including offshore wind energy [1]. This shows the importance of driving down the marine energy LCoE to a comparable level with offshore wind energy and beyond that in order to compete the LCoE of conventional energy sources and, therefore, securing a foothold as a part of the world energy future.

The EnFAIT project is carrying out a demonstration of a grid-connected tidal energy array with the aim to provide a step change in Levelized Cost of Electricity (LCoE) for tidal power.

To lower cost per MWh, it is instrumental to optimise the design of the array to the highest reliability and availability levels possible. The reasoning behind this, is that a highly reliable system suffers less breakdowns, resulting in lower maintenance and repair costs. Also, a lower number of breakdowns plus shorter repair times, results in a larger net operating time (i.e. higher availability). These performance indicators affect LCoE.

To increase reliability, a fundamental approach to root out failures is firstly put into practice, a Maintenance Strategy Review (applying FMECA and RCM analysis) delivering the requirements for reliability, availability and maintainability. These are then validated through RAM modelling.

Past history from wind energy shows that the drivetrain typically exhibits the most failures in arrays, and that this is linked to device interaction. The main purpose of this document is to define a RAM model that facilitates a process to create models at the design stage for optimum life cycle cost management of the array. The RAM methodology provides an integrated analysis of expected system performance based on system, operations and maintenance engineering. Included in this document is detail of the drivetrain model.

The University of Edinburgh is running this drivetrain model in parallel with the DTOCEAN (www.dtocean.eu) reliability tool and feeding in results to the RAM process of EnFAIT through the design stage. The drivetrain model may also be used to determine the impact of array loading effects due to turbulence and wake effects on drivetrain component wear and lifetimes.

2.2 RAM modelling

Due to the lack of operational experience in the tidal sector there is very little, long term data available for reliability, availability and maintainability (RAM) analysis. Where RAM studies have been undertaken in the wave and tidal sector, the data has been based on onshore and offshore wind. At such an early stage in the tidal industrial development, those developers who have marine energy experience keep any such data confidential for commercial reasons. Failure rate data for some components can be estimated from wind, such as umbilical, cables, transformers, gearbox, generator, blades, and power converter, but the loadings are very different in ocean energy converters.

Thies et al [2] estimated the failure rates of systems within a wave energy device using standard failure rate tables, and applied environmental factors for offshore according to Wolfram [3]. Delorm et al [4] performed a failure rate analysis of tidal current generators based on wind data and standard reliability tables (Oreda) and applied environmental factors based on [Table 2, Table 3]. Val [5] used probabilistic techniques to assess reliability for the drivetrain in a tidal current turbine.

Previous EU and UK research council projects of interest, in which RAM modelling has been undertaken, include:

- Dutch Offshore Wind Energy Converter (DOWEC) project (1999-2003)
- FP7: ReliaWind project (2008 – 2011)
- EPSRC: Supergen Marine (2003 – 2018)
- EU FP7: Marina Platform (2010 – 2014)
- H2020: INFRALERT (2015 – 2018)
- EU FP: DTOCEAN (2013 – 2016)

The methodology outlined in this report is based upon outcomes from all of the above, and specifically Supergen Marine [4 & 5], Marina Platform [6] and DTOCEAN [7], in which Edinburgh University has been partner.

3 Reliability Availability Maintainability (RAM)

The European Standard for Maintenance terminology [8] defines **reliability** as the ability of an asset to perform a required function under given conditions for a given time interval.
Availability is defined as the ability of an asset to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided.
Maintainability is defined as the ability of an asset under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources.

RAM studies are usually used as a way of evaluating system capabilities, both in operation and design phases. As a system is being used for longer period of time, a RAM study is able to provide an assessment into the life time capabilities and enable maximising the return on investment. RAM techniques allow forecasting failures from the observation of operations & maintenance field data. The aim is to predict potential failure modes in the tidal array as well as to optimize decision making.

A RAM study benefits include [9]:

- Optimisation on capital investment by reducing the LCoE.
- Reduction in the maintenance and spares costs, while maintaining and / or increasing production levels.
- Decreasing the duration of any unplanned and planned outages.
- Optimisation of capital improvement options.
- Accurate forecasts of equipment lifecycle costs that reflect the equipment age, duty cycle and maintenance effectiveness.
- Alignment of maintenance resources based on the criticality of equipment to production revenue.

The RAM study can be divided into two stages after the Maintenance Strategy Review: RAM Modelling and RAM Analysis and Reporting as shown in Figure 2.

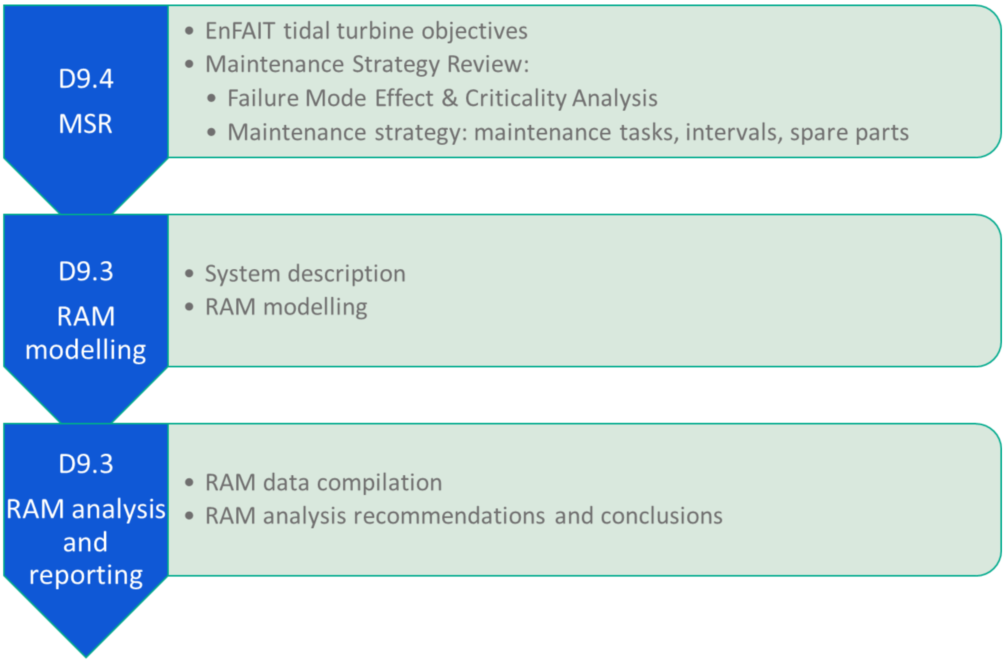

Figure 2: RAM analysis stages

3.1 Maintenance Strategy Review (MSR)

A Maintenance Strategy Review is a proven methodology to engineer an actionable full lifecycle maintenance plan for the array systems and components. Given the lack of long term reliability history in the tidal sector use is made of SKF's Asset Management Support Tool (AMST), which facilitates and documents a thorough Failure Mode Effect & Criticality Analysis (FMECA) and Reliability Centre Maintenance (RCM) analysis.

Through FMECA, failure modes & causes are identified, their effects and associated risk levels (or: criticality ranking) related to the array business drivers/plant economics. Through RCM analysis, specific maintenance & condition monitoring tasks are identified to prevent critical failure modes. Thus, the greatest risks from a commercial, health, safety, environmental and cost perspective are mitigated. The MSR delivers a comprehensive data set, including an asset inventory including tag hierarchy, the specification and design of a value adding maintenance and condition monitoring programme for the array that delivers tangible cost benefits and advises on spares strategy.

Please refer to the EnFAIT D9.4 Maintenance Strategy Review (MSR) document for further clarification on this methodology.

3.2 RAM modelling

A RAM model facilitates case studies, sensitivity analysis and optimization of equipment design, operations and maintenance. The model will take input data like the functional breakdown structure of the turbine asset, it's components and the effect of their potential failures. It will also use data from the maintenance program, like maintenance task interval and shutdown duration. From this data the model will calculate the reliability data for the turbine asset.

3.2.1 Step 1: Failure Mode Effect & Criticality Analysis (FMECA)

Applying RAM models to the Maintenance Strategy, it will be possible to study the effect of changes in the maintenance program. This will involve sensitivity analysis on parameters like task interval. A similar approach applies to input parameters like Mean Time Between Failures. The correct values of these parameters are not yet accurately known. Sensitivity analysis will show the relevance of such inaccuracies for the final result.

Applying the RAM model to engineering may reveal components that are critical to the reliability of the turbine. This may result in design modification and a revised maintenance plan. The model will confirm improvements made to components.

Planning RAM starts by setting the objectives of the model study. This involves identifying the output and input parameters that were suggested above. The components and the functional breakdown structure need to be documented first, since they are the input for the FMECA process.

After completion of FMECA detailed data is available on the effect, frequency and duration of potential failures, as well as a specification of the maintenance program. This includes maintenance tasks with interval, shutdown duration and mitigating effect on potential failures. FMECA also specifies which spare parts should be available to reduce repair time. This package of information is available as input for the RAM model.

For a detailed description of the FMECA process refer to the EnFAIT D9.4 Maintenance Strategy Review (MSR) document.

3.2.2 Step 2: Reliability Block Diagrams

The reliability model is developed using reliability block diagrams of the complete system in order to show the relationship between the various sub-assemblies in the system, and the components and sub-components within a subassembly. An initial estimate of failure rates can be made using surrogate data from various reliability databases. It should be noted that this data is meant to provide an indication of the components requiring more detailed design. More detail on this step is provided in chapter 4 of this document.

3.3 RAM analysis and reporting

RAM models report data on several levels of detail. At the top there will be a brief summary stating the MTBF and availability of a turbine. This data is the rolled-up result of the calculations that were executed by the model. The same data is used to produce so-called “bad actor” reports, both for performance killers and cost drivers. A performance killer is a component that contributes significantly to the overall downtime of the turbine, whereas a cost driver is a component that contributes significantly to the overall maintenance cost. Both reports provide basic information that helps understanding the turbine’s failure potential and facilitates generating proposals for improvement.

To validate the RAM model, it is also possible to check the sensitivity of results for uncertainties in parameters like downtime after a failure.

In addition, the data compiled by the model is available for any other form of data-analysis. This may be required to explain the data in the reports. It may also be used for other investigations, for example the identification of failure mechanisms that affect risk across several components.

The data complied is used to validate, and possibly improve, the operations and maintenance strategy which will be implemented for the tidal array.

4 The Reliability Block Diagram Methodology

The Reliability Block Diagram (RBD) represents each of the functional components in such a way that the reliability of the whole system can be understood by the interaction between the reliability of the sub-components, indicating which one must operate successfully for the system to operate. Each block (say 1, 2, or n) is considered in one of two states: either up or down. A RBD system can be represented by a serial and/or parallel configuration, depending on the functionality interaction (Figure 3). A serial connection means that if one or more of the elements are down, then the whole system is down; whereas a parallel connection represents redundancy (i.e. several elements should be down to put the whole system down).

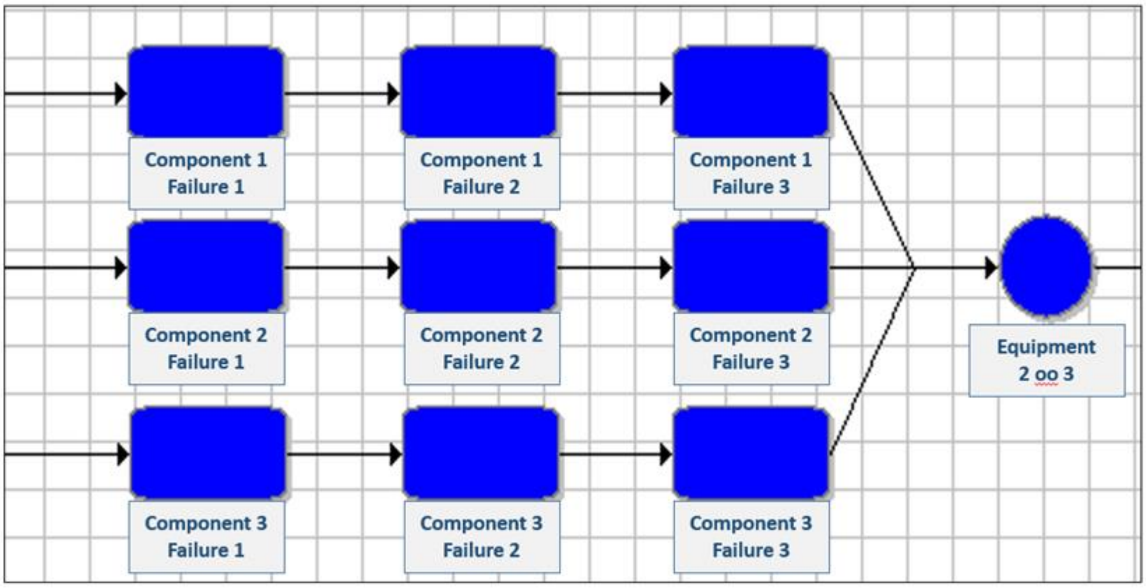

Figure 3: RBD example for n components in series and in parallel

The Reliability Function

For each element - and ultimately for the entire system - a reliability survival function R(t) can be calculated which represents the probability that the system or component will survive without any maintenance until a specified time t.

Therefore, $R(0) = 1$, $R(t) \geq 0$.

The Failure Rate Function

The failure rate function is obtained by dividing the probability that an item will fail in a determined time frame but knowing that the item has been working so far. Without going into the mathematical proofs, it can be demonstrated that the relationship between failure rate (λ) and the reliability function (R) is:

$$R(t) = \exp(-\int_0^t \lambda(u)du\ )$$

Typically, the failure rate follows a complex shape, but the bathtub curve is widely accepted (Figure 4). The curve shows that the probability of failure at the start of the operational life is higher as a result of mishandling, assembly or installation errors, or early defects. By the end of the component's or system's life the probability increases due to stress or wearing (wear out failure period). However, there is an intermediate region where the hazard rate tends to be a constant value (useful life period). In the tidal sector, current developments are most likely operating in the early failure (or: "burn-in") period.

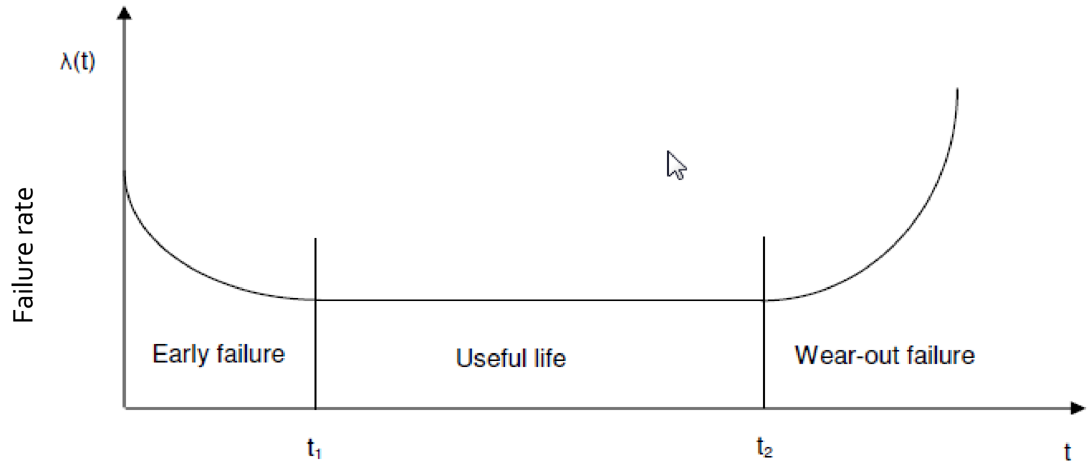

Figure 4: Theoretical bathtub curve

Hence, if the hazard rate becomes a constant, then the survival function is calculated as:

$$R(t) = \exp(-\lambda \cdot t)$$

where λ is the failure rate (number of failures per year).

Therefore, R(t = 1 year) is the probability that the system (or component) will survive for one calendar year without any maintenance.

4.1 Reliability Block Diagram Process

Using the Reliability Block Diagram Process as described in document *D7.2 TiPA Project Reliability Framework* [10],of the TiPA project also funded from the European Union's Horizon 2020 programme, tidal turbine reliability analysis considers a set of components as shown in Figure 5. For the EnFAIT project, the reliability block diagram is non-public information.

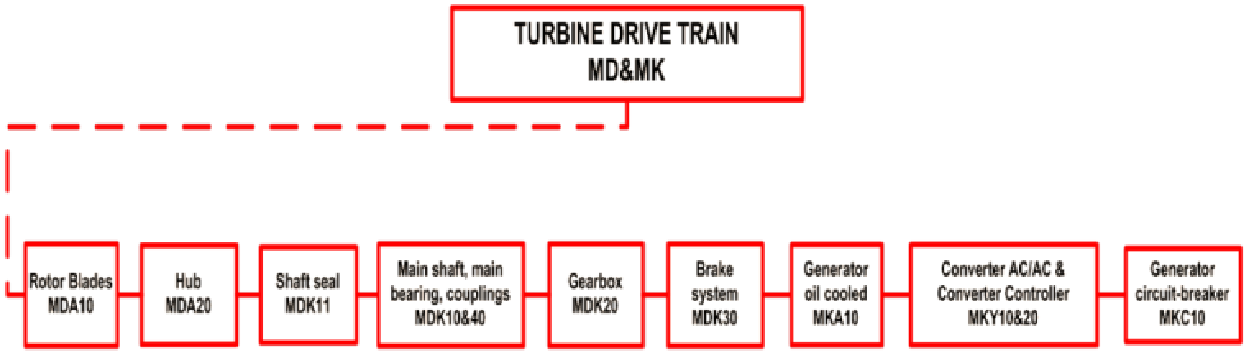

Figure 5: Generic turbine drive train & generator for a tidal energy converter proposed by Delorm [4]

4.2 Modelling and Assumptions

In the tidal energy sector, there is very limited published historical data. The main inputs for the modelling are based on [10]. Due to the lack of available data a number of assumptions have to be made in order to produce any meaningful output. Sensitivity analysis is used to assess the importance of critical parameters.

To develop a RAM model several assumptions are required. Paragraph "3.3.2. Establishing requirements" in the EnFAIT D9.4 Maintenance Strategy Review (MSR) document lists the known main requirements for design, operations and maintenance for EnFAIT tidal turbine array. This report includes requirements for e.g. annual energy production, planned service life, number of planned stops, which will be used as assumptions for the RAM modelling. EnFAIT document D9.4 also describes the method to derive critical components, failure modes and failure rates which will also be used as input.

4.3 Data selection

Due to the stochastic nature of the model, data quality and quantity are of fundamental importance in the study. In this sense, the more quality in data, the less biased the predictions are, and the more quantity, the less variance in the final results.

Figure 6 describes a typical failure episode in an individual component (asset). All parameters are explained in Table 1. Two cases are recognized: available and unavailable. A failure may occur at a given time, and the asset starts malfunctioning. After a reaction time, the failure is registered and a maintenance work order (WO) is opened with the aim of restoring the normal function of the component.

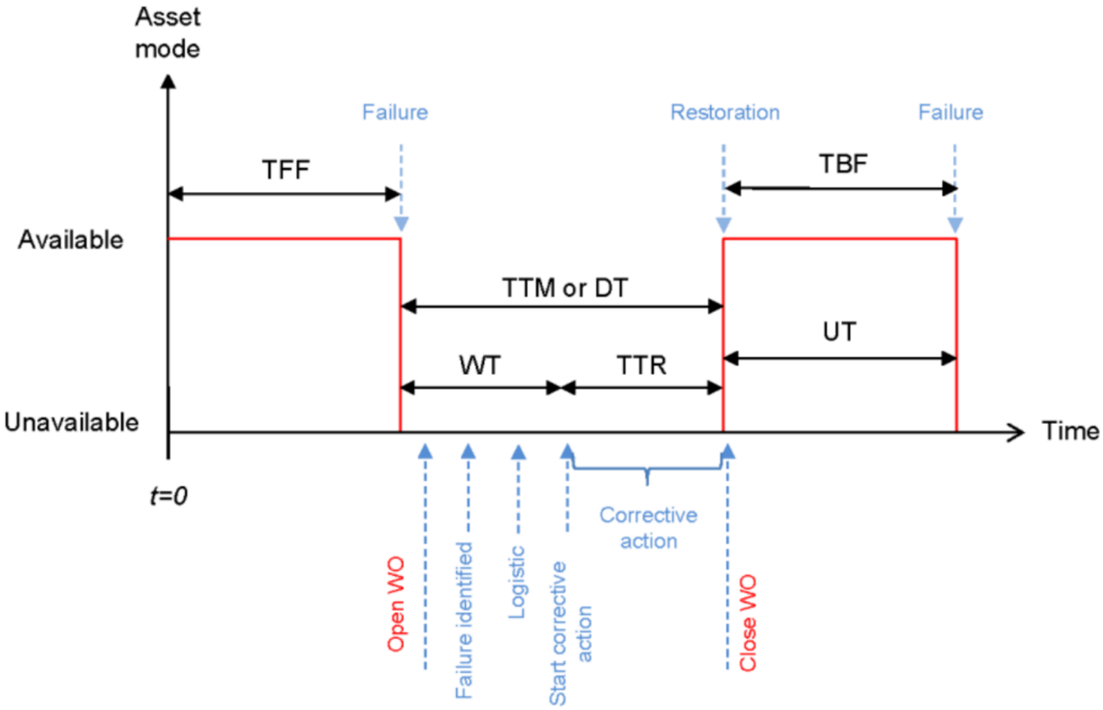

Figure 6: Failure episode and definition of times [09]

Assuming a reparable component and distinguishing between the Time to the First Failure (TTF) and the Time Between Failures (TBF) after repairing the component, then the state of the component at time t can be described by a state variable $s(t)$:

$$\boldsymbol{s(t)} = \begin{cases} \mathbf{1}, & \boldsymbol{if\ the\ component\ is\ functioning\ at\ time\ t} \\ \mathbf{0}, & \boldsymbol{if\ the\ component\ is\ failure\ state\ at\ time\ t} \end{cases}$$

Reliability
Mean Time Between Failure (MTBF) = $\frac{\text{Total Operative Time}}{\text{Total Number of Failures}}$
Probability Distribution Function (PDF) of failures f(t)
Reliability (probability of success) : R(t) = $\int_t^{\infty} f(s)ds$ [=P(T ≥ t)]
Unreliability (probability of failure) : Q(t) = 1 – R(t) = $\int_0^t f(s)ds$ [=P(T < t)]
Failure rate: λ = $\frac{f(t)}{R(t)}$ [=P(F at *t*|S until *t*)]. When λ is constant then λ=1/MTBF
Availability
Mean Up Time (MUT)
Mean Down Time (MDT)
Availability (A) = $\frac{\text{MUP}}{\text{MUP+MDT}}$, Unvailability ($\bar{A}$)
Operational Availability (A_O) = $\frac{\text{MTBF}}{\text{MTBF+MTTR}}$
Maintainability
Maintainability (probability of repair) M(t) = $\int_0^t g(s)ds$
Probability Distribution Function (PDF) of restoration times g(t)
Mean Time To Maintain (MTTM) = $\frac{\text{Total TTM}}{\text{Total Number of Failures}}$
Mean Time To Restore/Repair (MTTR) = $\frac{\text{Total TTR}}{\text{Total Number of Failures}}$
Restoration/repair rate (μ) = 1/MTTR (when constant)
Operational Restoration/repair rate (μ_O) = 1/MTTM (when constant)
Operational Availability (A_o) = $\frac{\text{MTBF}}{\text{MTBF+MTTR}}$
False Alarm Rate (FAR)
Safety
Mean Time Between Safety System Failure (MTBSF)
Hazard Rate H(t) and Tolerable Hazard Rate (THR)
Time To Return to Safety (TTRS)

Table 1: RAM(S) parameters according to IEC 61703, 2001

4.3.1 Failure Rates

A component failure rate database specifically for marine renewable energy systems has yet to be compiled. Therefore as with other projects, EnFAIT will make use of existing databases, and use correction factors as applied by Delorm and Thies to adapt the data to the marine environment, and take into account the operational loads of the tidal turbine. A list of databases that will be used in EnFAIT is given in Table 2.

The failure rate distribution is shown in Figure 4. In EnFAIT all failure rates are close to constant (4). Therefore, the model systematically incorporates exponential distributions with the λ parameter is used to represent the component probability of failure by a given time. In this case, it is considered that the component will not last until the end of its useful life but rather that a random failure will occur in the same proportions than other identical industrial components.

This based upon the application of similar components in very different applications, mainly offshore oil and gas, and military applications. Delorm adopts a methodology based on the use of such surrogate failure rate data and applies so-called "environmental factors" in order to take into account the marine environment, but these factors were developed by the US military, and for marine applications they specifically refer to naval environments. Reference [12] provides the rationale for these environmental factors, but they only apply to electronic components. Reference [13] does consider environmental aspects for mechanical components, but Delorm does not apply these in her analysis. Table 3 and Table 4 show some examples of environmental factors used by Delorm. The base data is referenced to GROUND FIXED (GF) systems, and factors describing a NAVAL SHELTERED (NS) or NAVAL UNSHELTERED (NU) environment are used to take marine into account. NS refers to components located below deck, and NU refers to components operating on deck, i.e. Exposed to the marine environment.

Using these databases, a failure rate asset register will be produced for the turbines in EnFAIT, which can then be applied to both single turbines and an array of turbines.

Database name	**Description & Source**
NPRD-1995	Non Electronics Parts Reliability Information and Analysis Centre (RAC) Utica, New York, USA
NPRD-2011	Non Electronics Parts Reliability Information and Analysis Centre (RAC) Utica, New York, USA
MIL-HDBK-338B, 1998	Electronic Design Reliability Handbook, US Dept. of Defence
MIL-HDBK-217F, 1991	Military Handbook. Reliability Prediction of Electronic Equipment – Revision F. US Dept. of Defence
MIL-HDBK-217F, Notes 2, 1995	Military Handbook. Reliability Prediction of Electronic Equipment – Notice 2. US Dept. of Defence
Journal of Reliability Information Analysis Centre	RIAC,https://acc.dau.mil/adl/en-US/31009/file/5573/Journal-updated-3-10%202.pdf
Offshore Reliability Data Handbook (OREDA) [11]	Det Norske Veritas, Edition 1 1984, Edition 3 1997, Edition 4 2002, Edition 5 2009.

Table 2: Databases to be used in this project

			To That Environment*				
	MIL-HDBK-217F (1991)		GB	GF	GM	NS	NU
		SD-18 (2006)	Protected	-	-	Normal	Severe
From This Environment	GB	Protected	-	2.0	5.0	3.3	10.0
	GF	-	0.5	-	2.5	1.7	3.3
	GM	-	0.2	0.4	-	0.7	1.4
	NS	Normal	0.3	0.6	1.4	-	2.0
	NU	Severe	0.1	0.3	0.6	0.5	-

*Environments defined in nomenclature

Table 3: Environmental Factors

Failure Rate Estimate	Method using surrogate data	Limitations
Conservative ***FRE**$_{con}$*	No environmental adjustment applied. $\lambda_i^{(b)} = \lambda_{Gi\ max}$	Represents a conservative failure rate for a branch, *b*, but neglects environmental conditions.
Environmentally Adjusted Conservative ***FRE**$_{env}$*	Multiplied by an environmental factor, π_{Ei}. $\lambda_i^{(b)} = \lambda_{Gi\ max}\ \pi_{Ei}$ For mechanical components: $\pi_{Ei} = 1$ For electrical/electronic components: π_{Ei} as defined in Table 4.3.	Represents a conservative failure rate for a branch, *b*, but takes account of environment.

Table 4: Failure Rate Estimates (Delorm)

4.4 Optional: detailed multi-physics modelling

Depending on the outcome of the above steps, detailed multi-physics models may also be used to further investigate failure modes. This detailed modelling work will focus mainly on the drivetrain, where there are a number of critical components, such as electrical windings and bearings. The methodology adopted to further investigate failure modes is outlined below.

4.4.1 Electro-mechanical tidal to wire system modelling

Typical and extreme operating conditions will be simulated from the tidal turbine prime mover through to connection to the grid, but with focus on the drivetrain components, namely the generator and power converter. Both electrical and mechanical models will be developed providing system level output for feeding into more detailed multi-physics sub-system models. The system model is dynamic, and can be driven to simulate extreme operating conditions enforced by both the marine environment or by events on the electrical grid.

4.4.2 Detailed electro-mechanical models of critical components

System level output from the previous step will be used to feed more detailed electromagnetic, thermal, structural and bearing models of the various components and their sub-components. This modelling will lead to a better understanding of component failure modes, and the design required to overcome such failures. Output from this step will be fed into component lifetime models.

4.4.3 Component Lifetime Models

Lifetime results from the previous step will be used to estimate component lifetime using component manufacturer's and material data. If the lifetime estimate falls outside accepted bounds, this information will be fed into the design process as part of the design for reliability guidelines.

A more detailed description of these types of modelling is provided in [10].

5 Conclusion

This report presents a RAM model design, enabling a process to create models at the design stage for optimum life cycle cost management of the tidal array of EnFAIT and future commercial tidal arrays.

Based on the Maintenance Strategy Review outcomes and relevant databases, RAM modelling and analysis provides an integrated analysis of expected system performance before data on years of actual operations and maintenance become available.

Because of the lack of historical failure rate data in the early-stage tidal energy sector, detailed multi-physics models may be used to investigate failure modes. This detailed modelling work will focus on critical component failure induced outages only. The methodology consists of integrated electromechanical modelling linked to component lifetime models.

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