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Advanced monitoring, simulation and control of tidal devices in unsteady, highly turbulent realistic tide environments

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Project Title: Advanced monitoring, simulation and control of tidal devices in unsteady, highly turbulent realistic tide environments

Deliverable 1.2
RAM Assessment Report

WP 1
Increased Reliability of Tidal Rotors

WP Leader: Bureau Veritas **Task Leader:** Bureau Veritas

Dissemination level: Public

Summary: This report forms Deliverable 1.2 and details the work of Task 1.2 within WP1 of RealTide. It provides the description of the work carried out on the RAM (Reliability, Availability and Maintainability) analysis that have been developed on 2 generic tidal turbines. It covers the description of the scope of the study, the RAM methodology, process, tool and definitions, all the assumptions defined to build the RAM model including the reliability data, the results in term of tidal turbine availability, the critical components, the results of alternative cases that assesses the implementation of design modifications and condition monitoring on the critical components and results of sensitivity analysis to assess model robustness and key driven factors to turbine unavailability..

Objectives: RAM analysis will highlight the critical systems and components contributing to production losses, leading to design improvement recommendations in WP5 for future developments. The Criticality Analysis will allow prioritizing the components to monitor during WP4 and WP5, as the complexity (number of inputs) of the system will have a strong impact on the cost of the CMS. The outcomes of the RAM study will also provide valuable information to the cost model (WP5) about CAPEX, OPEX, and revenues. Based on scenarios suggested, alternative and sensitivity analyses will be conducted to assess the impact of key choices such as: component selection, electrical architecture and maintenance strategies. Results from these studies will provide guidance to the technology developers to achieve a better design, not only more reliable but also much easier to maintain, and an optimized O&M strategy.

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Abbreviations & Definitions

AC	Alternative Case
BC	Base Case
BV	Bureau Veritas
BV M&O	Bureau Veritas Marine & Offshore
CAPEX	Capital Expenditure
CBM	Condition Based Maintenance
CMS	Condition Monitoring System
CTV	Crew Transport Vessel
D	Deliverable
DFIG	Doubly-Fed Induction Generator
DM	Direct Measurement
DTA	Detail Analysis
EO	EnerOcean
FMECA	Failure Mode, Effect and Criticality Analysis
FMEA	Failure Mode and Effect Analysis
GA	General Assembly
HV	High Voltage
IDE	Indirect Detection
IEEE	Institute of Electrical and Electronics Engineers
IFR	Ifremer (Institut Français pour la Recherche et l'Exploitation de la Mer)
IFREMER	Institut français de recherche pour l'exploitation de la mer
ISSA	Ingeteam Power Technology
IVT	Inspection Visit Tools
kW	Kilo Watt
LV	Low Voltage
MBE	Model Based Estimation
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
MUID	Multiple Integrated Detection
MW	Mega Watt
O&G	Oil and Gas
O&M	Operations & maintenance
OPEX	Operational Expenditure
OREDA	Offshore Reliability Database
OSV	Offshore Supply Vessel
PARLOC	Pipeline and Riser Loss of Containment
P-F	Potential to Functional Failure
PMP	Project Management Plan
RBD	Reliability Bock Diagram
ROV	Remote Operated Vehicule
SAB	Sabella
SC	Sensitivity Case
SL	Surface Level
SCADA	Supervisory Control and Data Acquisition
T	Task
TT	Tidal turbine
UEDIN	The University of Edinburgh
UKCS	United Kingdom Continental Shelf
UPS	Uninterruptible Power Supply

WP	Work Package
WT	Wind Turbine
1-T	1-Tech
3D	Three Dimensional

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Distribution List

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EXECUTIVE SUMMARY

At present, there is a great energy demand in the whole planet. This demand has led to important technological advances in all branches of the energy sector in recent decades and of course a huge boom in renewable energy. This boom has led to the study and research of new methods for the extraction of energy through natural resources, promoting alternatives such as tidal energy technology.
Governments and Industry are making efforts to move towards a form of tidal energy device that will harness the free-flowing tidal stream and ocean current. Tidal stream power technology has gained prominence because of its simplicity, the ability to harvest energy directly from tidal currents, and the ecologically non-intrusive nature of the system. Obviously, this emergent technology is all under development and consequently there is no bank of information about their operating reliability.

There are three important factors that limit the development of maintenance and monitoring plans for tidal turbines:

- The fact that this technology is at an early development threshold makes it necessary to use data from the accumulated experience in similar technologies such as wind turbines [7].
- Small number of research and development of different types of Tidal Turbines (horizontal axis, vertical axis, floating tethered, seabed fixed, etc.) [8].
- The harsh marine environment and problems with accessibility for maintenance [7].

The Task 1.2 aims at conducting a Reliability, Availability and Maintainability (RAM) assessment to understand and increase the reliability of tidal energy devices using the inputs from the FMEA developed in task 1.1. This study will help refining:

- The recommendations in terms of design and monitoring enhancements;
- The cost model development in WP5 considering revenues and OPEX.

The generic tidal turbine concepts “complex bottom fixed tidal turbine” and “floating multirotor tidal turbine” (herewith called concept 1 and concept 3 respectively) were selected from previous D1.1 FMEA study [31] for having their designs and monitoring performances assessed. For each concept the design specification, equipment reliability and maintainability have been taken into account within its operational environment. The two concepts were modelled by means of Monte-Carlo based software in order to study the impact of their failures to the system performance, i.e. its operational availability, and to determine the most critical components, i.e. those that contribute the most to unavailability.

Due to lack of public data bases related to Tidal Turbine, the reliability data describing unplanned failures and subsequent repair of equipment’s has been collected from different sources related to Wind Turbines which provides similarities with tidal turbines in term of functionalities, components types and operability. Thus, the data utilized in this study has been taken from sources such as:

- Ingeteam Historical Data (on extended wind turbine farms);
- Generic Wind Turbine Reliability data sources open for the public;
- Industrial databases such as I-EEE [5], the Generic Tidal Turbine FMEA [31]; and
- Partner’s discussions and experience.

Design and monitoring recommendations have been proposed in Alternative cases in order to assess their effectiveness to increase system availability. Sensitivity cases were performed to assess the model robustness due to the reliability data uncertainties.

The RAM analysis presented the following results for each concept:

a) Concept 1

The availability of the base case over 20 years of operation is 71.82%. The Offshore Supply Vessel mobilisation was required 2.45 times per year for turbine's components repair.
The most critical components are in the following order:

- Gearbox and High Speed Shaft,
- Power Electronic Converter,
- Pitch System,
- Yaw system,
- Control System,
- Blade, and
- Generator.

The alternative case 1 has been defined to maximise the turbine availability. A full set of implementations were proposed as the simplification of the tidal turbine design (removal of Gearbox and High Speed Shaft, Pitch System, Yaw system), redundancy of the Power Electronic Converter and Control System, and monitoring of Blades and Generator as detailed in section 7.2.1. Consequently the resulting availability of the tidal turbine is increased to 86.03% (+14.21% of availability comparing with the base case) reducing the OSV mobilisation to 1.54 time per year.

The alternative case 2 proposed the implementation of condition monitoring on critical components according to section 7.2.2 and demonstrated this is an effective way to prevent failure in order to increase availability. However, the Condition Monitoring strategy requires the OSV to be mobilised more frequently. The turbine availability increases 5.30% (from 71.82% in the base case to 77.13% in AC 2) requiring an additional OSV mobilisation of 1.3 time per year, in average.

However, in reality a better knowledge about the turbine condition acquired with time and the number of visits/outages can be optimized when combining condition monitoring with a proper maintenance strategy leading to cost reductions. This factor has not been considered in this RAM analysis limiting in the results the effectiveness of implementing condition monitoring and also the optimisation of maintenance interventions.

Alternative case 3 assesses the turbine availability in case condition monitoring is implemented to one individual critical component at a time. According to section 7.2.3, Condition Monitoring is the most efficient when applied to the most critical components witch are Pitch and Gearbox (i.e. +2.01% availability for Pitch monitoring, +1.86% availability for Gearbox monitoring).
However, OSV will be mobilised more frequently if Condition Monitoring is applied: 1 extra OSV mobilisation every 3 years in the case of Pitch monitoring.

For that reason, it is very important to define the most convenient monitoring strategy according to the criticality of the component and also to combine with optimized maintenance strategies and redesign in order to increase availability and reduce OSV mobilization.

The sensitivity case 1 described in section 7.3.1 was carried out focusing on the impact of the weather conditions for OSV operations. The weather conditions causes up to 6.72% of unavailability, i.e. equivalent to 24.5 days/year of downtime. This is a considerable impact on the tidal turbine performance.

The sensitivity case 2 described in section 0 has been carried to assess the variation of availability in case the OSV is triggered when production rate is 50% or lower. The availability increased 1.60% in comparison with the base case while 1 additional OSV mobilisation every 10 years is required.

The sensitivity cases 3 and 4 from section 0 focused on the OSV logistic time. The logistic time has important influence on availability and also great uncertainty. The availability range varies from 61.92% to 77.50% comparing the worst scenario (SC 3 - OSV logistic time is multiplies by 2) and the best one (SC 4 - OSV logistic time is divided by 2). This difference (15.58%) confirms the high influence of the OSV logistic time in the availability.

The remaining sensitivity cases (SC 5 to 8) described in section 7.3.4 were carried out focusing on the Potential to Functional Failure (P-F) intervals of critical components. Different scenarios with P-F intervals ranging from 0 to 6 months resulted in different availability from 56.66% to 76.55%. The availability increases with greater P-F interval. It was further verified that the P-F time interval caused a “mask effect” on components’ contribution to unavailability. The real impact on unavailability were so distorted that while some components had their contribution over estimated, others were under estimated. As a consequence the top critical equipment should be set up based on the scenario where the P-F interval is equal to 0.

b) Concept 3:

The availability of the base case over 20 years of operation is 80.09%. The OSV mobilisation was required 1.87 time per year and the Crew Transport Vessel mobilisation 1.43 time per year.
The most critical components are in the following order:

- Pitch system,
- Blades;
- Gearbox and High Speed Shaft,
- Power Electronic Converter,
- Control System,
- Generator,
- Low speed shaft bearings, and
- Couplings.

Alternative case 1. It was suggested the simplification of the tidal turbine design (removal of Pitch system, Gearbox and High Speed Shaft), redundancy of the Power Electronic Converter and Control System, and monitoring of Blades and Generator, Low speed shaft bearings, and Couplings as detailed in section 8.2.1. The resulting availability of the tidal turbine is increased to 89.39% (+9.30% of availability comparing with the base case) reducing the mobilisation of the OSV and the CTV to 1.15 and 0.86 time per year respectively.

Alternative case 2. The condition monitoring on critical components increases 2.44% the turbine availability (from 80.09% in the base case to 82.53% in AC2) as shown in section 8.2.2. However requires the OSV and the CTV to be mobilised additionally, in average, 1.1 and 1.05 time per year respectively.

However, in reality a better knowledge about the turbine condition acquired with time and the number of visits/outages can be optimized when combining condition monitoring with a proper maintenance strategy leading to cost reductions. This factor has not been considered in this RAM analysis limiting in the results the effectiveness of implementing condition monitoring and also the optimisation of maintenance interventions.

Alternative case 3 assesses the turbine availability in case condition monitoring is implemented to one individual critical component at a time. According to section 8.2.3, Condition Monitoring applied on Pitch is the most efficient to increase availability (i.e. +3.11% availability). This is because Pitch is the most critical component. However, additional OSV mobilisation are required (2 more mobilisations every 3 years) which could largely increase the OPEX. In other cases, such as for blades monitoring, while OSV mobilisation increases, the CTV mobilisation decreases.

As for concept 1, it is very important to define the most convenient monitoring strategy according to the criticality of the component and also to combine with optimized maintenance strategies and redesign in order to increase availability and reduce OSV mobilization.

Sensitivity case 1. The impact of the weather conditions for OSV and CTV operations is detailed in section 8.3.1. This factor causes up to 5.55% of unavailability, i.e. equivalent to 20.26 days/year of downtime. As for concept 1, this is a considerable impact on the tidal turbine performance.

Sensitivity cases 2 and 3 from section 8.3.2.2 focused on the OSV and CTV logistic times. The availability range varies from 72.24% to 84.62% comparing the worst scenario (SC2 - OSV and CTV logistic times are multiplies by 2) and the best one (SC3 - OSV and CTV logistic times divided by 2). This difference (12.38%) confirms the high influence of the OSV and CTV logistic times in the availability also for this concept.

Sensitivity cases 5 to 8 described in section 8.3.2.2 focused on the Potential to Functional Failure (P-F) intervals of critical components. Different scenarios with P-F intervals varying from 0 to 6 months resulted in different availability from 69.35% to 84.35%. Again, as for the concept 1, the availability increases with greater P-F interval. The same “mask effect” has been observed and so the top critical equipment should be set up based on the scenario where PF interval is equal to 0.

As a conclusion, the highlighted critical components of each concept are to be prioritized in WP4 for the development of the condition monitoring system.
Comparing the results from the 2 concepts, it can be also concluded that bottom fixed turbines will be more benefited of the Condition Monitoring implementation because it helps to reduce the impact of the complexity of repairing for this concept by anticipating critical failures

The design improvement recommendations suggested in the alternative cases are to be addressed in WP5 for future developments. The outcomes of the RAM study provides valuable information to the cost model about CAPEX (based on the Turbine Design structure), OPEX (based on components’ failure rates and on OSV/CTV mobilisations) and revenues (based on the turbine availability). The alternative and sensitivity cases assessed the impact of key choices such as: design structure architecture and maintenance strategies.

It is to be noted that this analysis does not take into account any preventive maintenance strategy associated with condition based maintenance that could not only enhance the tidal turbine availability but also optimise the OSV/CTV mobilisations and then OPEX.
Therefore, in the cost analysis to be implemented in WP5, it should be evaluated in economic terms the integration of the CMS in tidal turbines taking into account an effective CBM strategy based on the application of findings and developments from WP4.
It was also considered the weather conditions of a location with harsh climate location and difficult access. As the weather conditions has a significant impact on the tidal turbine availability, the results might change significantly for other locations.

Finally, one of the challenges of this study was the lack of data in the tidal turbine domain. Most of the data came from wind turbines specific databases what could lead to inconsistencies in the final result. A database specifically created for tidal turbines must be developed for further improvements (which will be treated in task 1.6). For this purpose it is also considered fundamental that tidal turbines have to be employed at real scale providing experience feedback and further developing tidal turbine technology. Finally, this study may be extended to a tidal turbine farm level in order to assess and develop global O&M strategy with an optimised CAPEX/OPEX trade-off.

1 INTRODUCTION

The RealTide project aims at developing the next generation of tidal devices in line with energy market and environmental policies expectations. This RAM report related to Work Package 1 “increased reliability of tidal rotors” provides a set of results oriented to understand and increase the reliability of tidal energy devices. A part of the work is related to generic tidal turbine designs, leading to a generic reliability database that will be further addressed to and developed in Task 1.6. To improve and really add value to this generic work, specific set of documents provided by the various partners directly involved in operational phases of tidal turbine development has been used.
The Reliability of tidal turbines is extremely difficult to assess due to the very limited field experience and confidentiality issues related to the emerging stage of development of the tidal sector. The lack of experience regarding tidal device failure rates in the harsh tidal environmental conditions induces high uncertainties on OPEX costs. It is expected that the output of this WP1 will lead to a reduction of uncertainties in the business models thanks to recommendations in design improvements that will be analysed and developed in WP5 and to an enhanced condition monitoring strategy which is being interactively developed in WP1 and WP4.
The Reliability, Availability and Maintainability (RAM) assessment that has been conducted in task T1.2 with the inputs from the FMEA developed in task T1.1 will help refining the recommendations in terms of design and monitoring enhancements and also refining cost model developed in WP5 taking in consideration CAPEX, revenues and OPEX.

During this task RealTide partners decided to implement Reliability, Availability and Maintainability (RAM) analysis for two selected generic tidal turbine concepts as part of the solution to assess the design and monitoring performances taking into account the design specifications, equipment reliability and maintainability in its operational environment. The concepts were modelled by means of Monte-Carlo based software in order to study the impact of their failures to the system performance, i.e. its operational availability, and determine the most critical components, i.e. those that contribute the most to unavailability. Due to data uncertainties, sensitivity cases were performed in order to assess the model robustness. Design and monitoring recommendations have been proposed and assessed in Alternative cases in order to assess their effectiveness to increase system availability. The results of the RAM analysis, i.e. system operational availability and maintenance requirements over the tidal turbine life cycle is part of the inputs to calculate the OPEX costs in the subsequent life cycle cost analysis in WP5 and to improve the monitoring plan to be developed in WP4.

The purpose of this document entitled “RAM Assessment Report” is to present assumptions, results and conclusion of RAM analysis developed by RealTide partners for two generic tidal turbines concepts – Complex Bottom Fixed and Floating Multirotor presented in document [31].

2 DESCRIPTION OF TASK 1.2

2.1 Overview

This deliverable includes the participation of partners Bureau Veritas, SABELLA SAS, Ingeteam, EnerOcean and 1-Tech. Deliverable 1.2 describes:

- how two generic tidal turbine concepts have been defined for the Reliability, Availability and Maintainability (RAM) assessment,
- the RAM methodology that have been applied to each concept,
- the assumptions, results, recommendations and the conclusions from the RAM to be addressed to other Tasks and Work Packages.

The objective of this task is to conduct a Reliability, Availability and Maintainability (RAM) assessment on a generic tidal turbine using a probabilistic model based on Monte Carlo simulations in order to refine recommendations from the Failure Mode and Effects Analysis developed in the task T1.1.

The critical components contributing to production losses will be highlighted leading to design improvement recommendations in WP5. This criticality analysis will allow prioritizing the components that must be monitored in WP4 and WP5 as the system complexity (number of inputs) has a strong impact on the cost of the CMS.

The outcomes of the RAM study will also provide valuable information to the cost model (WP5) on regards to revenues (availability for electrical production) and OPEX (frequency and duration of unplanned maintenance requirements).

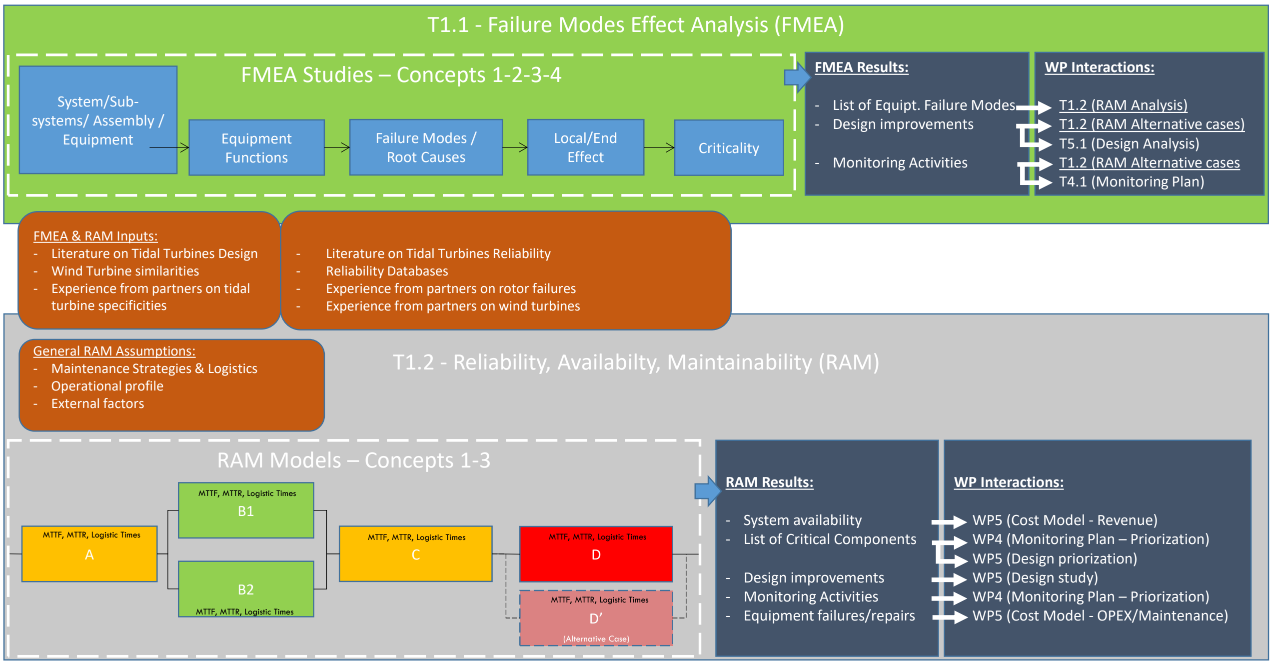


Figure 2-1 - WP1 - T1.2 RAM - Process and interactions with other tasks

Sensitivity analyses will be conducted to assess the model robustness. Alternative cases will be created based on the results of an initial base case to assess the benefits of implementing key choices such as: component selection, design/electrical architecture and maintenance strategies. The alternative studies will provide guidance for the technology developers to achieve a better design, not only more reliable but also easier to maintain, together with an optimized O&M strategy.

The Figure 2-1 above summarises the Task 1.2 process, objectives and interactions with other Tasks and Work Packages.

2.2 Objectives

The objectives of this task are:

- to create a base case RAM model to reflect the current knowledge of power generation of two general tidal turbine concepts and their reliability performance;
- to evaluate the availability of the two generic tidal turbines in terms of power generation;
- to understand reliability bottleneck and advantage of different generic concepts;
- to provide sensitivity cases to search factors that contributes to variations of tidal turbine performance.
- to assist consortium in assessing opportunities to improve the performance tidal turbine through the analysis of alternative cases.
- to propose design alternatives and monitoring strategy to improve tidal turbine reliability for further analysis in WP4 and WP5 respectively;
- to compare power generation performance between different alternative cases for each generic tidal turbine concepts for further analysis in WP4 and WP5;
- to provide input data in term of system unavailability, equipment reliability and maintainability in view of the subsequent cost model calculations in WP5.

2.3 Subtasks

The Table 2-1 below presents the sub-tasks developed by the partners.

The detailed description of the sub-tasks is presented in section 4.2

Table 2-1. - List of sub-tasks for Tasks T1.2 RAM Assessment

SHORT NAME	SUB TASK DESCRIPTIONS
1. Information Gathering	**Information Gathering and Project Familiarisation** • Component List • Understanding of failure modes • Historical and estimated failure rates • Logistic • Failure impact on production, performance
2. Reliability Data Set	**Development of Reliability Data Set** • Public Reliability Databases • Historical and estimated failure rates consolidation • Engineering Judgment
3 Assumptions	**Assumptions definition** • Identification Of Equipment Critical To Production • Development Of RBDs • Operations And Maintenance • Asset register • Identification Of Sensitivity Analyses
4. Modelling & Simulation	**Model Construction and Simulation**. • Build RAM Model using RAM Software • Perform simulation with various model inputs
5. Results	**Results Generating and Sensitivity Analysis** • Quantify performance of the system in terms of overall availability • System criticalities • High component contributors to downtime • Perform sensitivity analysis for model robustness assessment
6. Recommendations	**Recommendations and Alternative Cases** • Understanding of production bottlenecks • Recommendations of changes in system design and monitoring • Perform alternative cases with the implementation of recommendations • Assess the benefits of implementing the recommendation on system performance

3 SCOPE

The scope of this study covers the main components included in the generic tidal turbine concept 1 (**Complex bottom fixed**) and concept 3 (**Floating multi rotor)** presented in the document “D1.1 – FMEA Report” [31] critical to power generation:

The **concept 1 – “complex bottom fixed”** (Figure 3-1) has horizontal axis rotors (i.e. axis of rotation parallel to the flow direction) with 3 blades and are fixed to the seabed via piling. In the complex fixed concept, the blades have pitch control, whereas the nacelle is completed with the yaw mechanism in order to maximize the produced energy. It also has a gearbox to represent indirect drive turbine. The selected type of generator for this concept is DFIG (Doubly-Fed Induction Generator). In order to capture various type of foundation, piling is included in this model. Overall, this model is selected to be analysed since it is one of the most common model developed by various turbine companies.

The **concept 3 – “Floating multi-rotor concept”** (Figure 3-2) has a horizontal axis rotor which is connected to two blades. It has pitch control and no active yaw mechanism although the floating structure can rotate around the turret which is moored to the seabed via mooring lines. A gearbox is connected to the drive. The generator type for concept 3 is induction generator.

Figure 3-1 - Complex bottom fixed tidal turbine concept - 3D Model

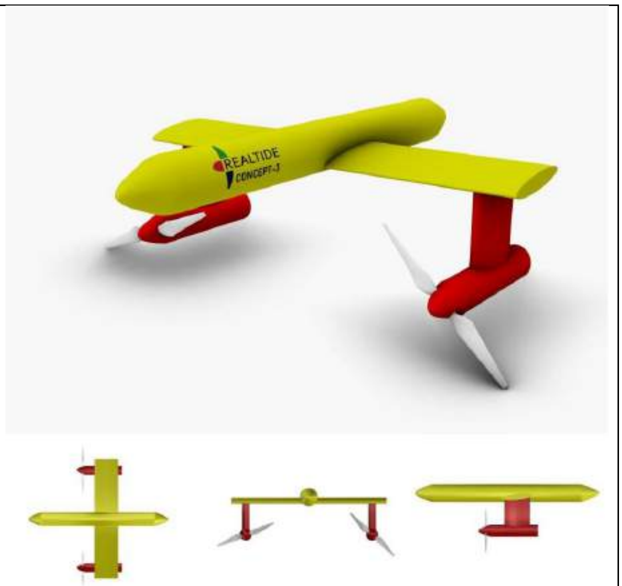


Figure 3-2 – Floating multi rotor - 3D Model

The technical boundary for each concept is the Tidal Turbine system and covers the same scope (i.e., sub-systems; assemblies, sub-assemblies, components and sub-components) presented in the document “D1.1 – FMEA Report” [31] – Appendix A and section 6.2.

Furthermore, The RAM analysis will simulate failures; repairs and maintenance logistics (described furtherer in the document) regarding the tidal turbines listed above and their respective impact on the capability to generate power.

4 RAM ANALYSIS

4.1 RAM methodology

4.1.1 RAM description

Asset systems are designed to perform a function in order to achieve a minimum production or service level. However assets failures reduce the capability of the system to meet these targets and, at the same time, increase the operational costs.
This is why assets failures should be considered at the design phase in order to assess the system design in view of optimizing its performance and Life Cycle Costs.

Reliability, Availability and Maintainability (RAM) is one of the most performing tools to assess systems design. Indeed, RAM modelling estimates the performance of a system, which is computed in terms of operational availability or production's capabilities. The results from a RAM modelling will identify possible causes of production losses and can examine possible system alternatives. The RAM study is thus a tool for decision-making allowing costs versus benefits analysis.

RAM modelling simulates the configuration, operation, failure, repair and maintenance of all assets included in a system. The inputs for a RAM modelling of a system include the physical components, equipment configuration, Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR), maintenance philosophy & logistics and operational profile. The outputs determine the resulting operational performance of the system over its life cycle.

In the RAM process, the systems to be analysed are modelled by means of a diagrammatic representation of its components and their interactions contributing to the system functionality.
Classical methods based on Boolean formalisms are Fault Trees, Event Trees and Reliability Block Diagrams [22][29].

Traditionally, the most used modelling method is the Reliability Block Diagram (RBD) which represents the components in a series of blocks connected in parallel or series configuration (see Figure 11.1). Each block represents a component of the system with a failure rate and a Mean Time To Repair. Parallel paths are redundant, meaning that all of the parallel paths must fail for the parallel network to fail. By contrast, any failure along a series path causes the entire series path to fail.

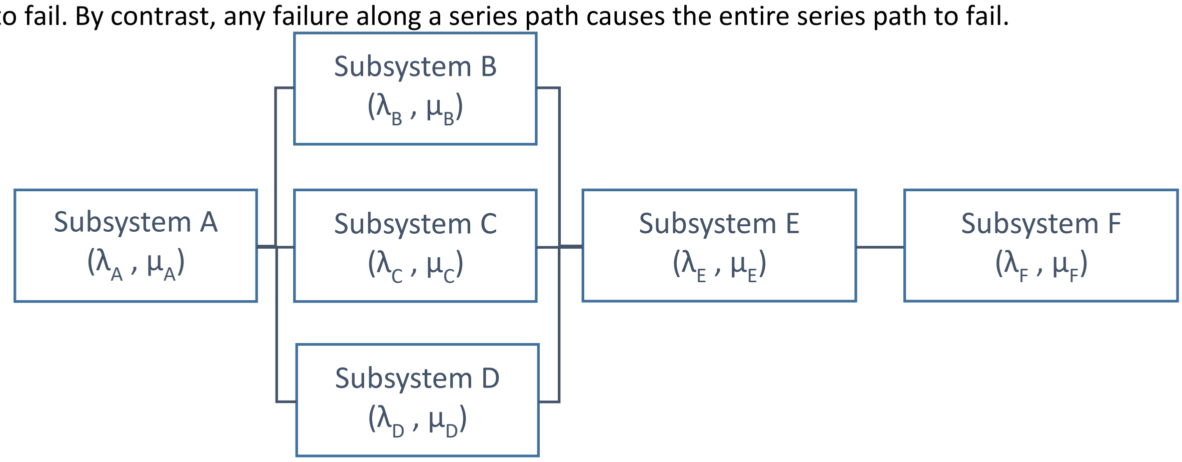


Figure 4-1 - Example of Reliability Block Diagram (RBD) representation of a system

4.1.2 Analytical calculation

The availability of an item is given by the simplified Equation 1.

$$A = \frac{\mu}{\lambda + \mu}$$

Equation 1

With:

- λ being the item failure rate (i.e. the ratio of the total number of failures to the total observation time, for a stated period in the life of an item); and
- µ being the item repair rate (i.e. the inverse of the average time required to repair a failed item).

By establishing the failure and repair criteria of the system and its sub-systems, it is possible to represent the system in the form of reliability block diagram model that including the subsystems in series, in parallel, or a combination of both. In the Figure 4-1, the failure of one of the subsystems in series (A, E and F) will result in an immediate loss of the system function.

The failure of subsystems in parallel (or Redundant subsystems) do not cause the loss of the system function unless all of them have failed and are failed simultaneously.

Thanks to this representation, it is possible to calculate the system availability using availability equations for series and parallel configurations presented below:

The availability of Series configuration is given by Equation 2:

$$A_{series} = \prod_{i=1}^{n} Ai$$

Equation 2

And the reliability of Parallel configuration is given Equation 3:

$$A_{parallel} = 1 - \prod_{i=1}^{n} (1 - Ai)$$

Equation 3

Using Equation 1, Equation 2 and Equation 3, it is possible to calculate the system availability. However this method is difficult to apply for extremely complex models as it is often the case. Therefore simulations are used.

Depending on the selected tool, the system is represented by a model such as Fault tree, Reliability Block Diagrams (RBD), Petri nets or functional “Bricks and links” that recreates component behavioural modes (e.g. functioning, failed, repairing…) and the system functional architecture (e.g. redundancy between equipment). In a simpler way, each equipment is represented by an element called “event”, “block” or “brick” which is linked to other elements. The way elements are linked depends on their functionalities and the impact of their failures on the system performance.

Nowadays, innovative RAM tools are able to model other kinds of items which are not pieces of equipment but that can have an influence on the system performance, such as maintenance utilities, spare parts or even external factors such as weather.

For each equipment, reliability and maintainability data are entered in the model, together with other data defined in the RAM assumptions such as logistics times, production profile, etc.

Deterministic RAM tools will convert the RAM model into complex reliability, availability formulas. The formulas can calculate several performance indicators such as the average availability of each equipment and the system itself over the system life cycle.

A Monte-Carlo based tool will simulate cycles of operations over the system life cycle duration. The RAM tool will simulate equipment failures and repairing based on the probabilistic reliability data entered for each equipment.

As the tool performs the simulations, the impact of the sequence of failures and repairs on the system performance over its life cycle is progressively computed and measured.

4.1.3 Monte Carlo simulation

Monte Carlo simulations attempt to replicate or approximate real life occurrences by mathematically modelling projected events using random numbers. In practice, this means that although probabilistic distributions are being used to model the failure and repair characteristics of the components within a production system, each unique timing and sequence of events will yield different performance results.

By running a number of trial run simulations (usually called lifecycles) each based on a different random number seed and aggregating the results over all of these lifecycles, the Monte Carlo simulations can represent the overall performance of a model and the variability of that performance.
Each lifecycle has its own random number seed, which determines the timing of the events of that lifecycle. The lifecycle availabilities should be provided, together with a list of each lifecycle, its availability and the simulation seed for that lifecycle. Any given lifecycle could then be reproduced exactly by entering the random number seed, in order to analyse the series of event in this particular lifecycle.

4.2 Method process

The creation of RAM models for each tidal turbine concept defined in section 3 is part of the scope of this task. The Table 4-1 presents the various steps adopted to create each RAM Model.

Table 4-1 - RAM Process

1. Information Gathering and Project Familiarisation • Component List • Understanding of failure modes • Historical and estimated failure rates • Logistic • Failure impact on production, performance **2. Development of Reliability Data Set** • Public Reliability Databases • Historical and estimated failure rates consolidation • Engineering Judgment **3. Assumptions** • Identification Of Equipment Critical To Production • Development Of RBDs • Operations And Maintenance • Asset register • Identification Of Sensitivity Analyses	**4. Model Construction and Simulation** • Build RAM Model using RAM Software • Perform simulation with various model inputs **5. Results Generating and Sensitivity Analysis** • Quantify performance of the system in terms of overall availability • System criticalities • High component contributors to downtime • Perform sensitivity analysis for model robustness assessment **6. Recommendations and Alternative Cases** • Understanding of production bottlenecks • Recommendations of changes in system design and monitoring • Perform alternative cases with the implementation of recommendations • Assess the benefits of implementing the recommendation on system performance

4.2.1 Information gathering

The aim of this study is to perform a RAM analysis on a "Generic" Tidal Turbine, which is not a real case. Then most of the information required for the RAM modelling had to be assumed based on partner's experience in order to provide assumptions reflecting "typical" tidal turbine operational conditions and "typical" maintenance philosophy which should be valid for most of the tidal turbines currently on operation.
Information collection was carried out for each tidal turbine concept from different input sources as listed hereafter:

- Components list based on Design taxonomy of each concept defined in Task T1.1 [31];
- Generic Tidal Turbine FMEA defined in Task T1.1 [31];
- Weekly video conferences between BV and Sabella;
- Video conferences between BV, Sabella, Ingeteam and EnerOcean (09/08/2019, 24/10/2019,31/01/2019)
- Failure data (i.e.: Mean time To failure, Mean Time To Repair) from databases described in section 4.4.1, Ingeteam historic and partners experience;
- RAM workshop during GA meeting in Brest on the 18th of June 019.

Based on the above, overall assumptions were set up for each concept such as:

- Model structure and component level;
- Component failures and their consequence to production;
- Estimated failure rates and time to repair;
- Maintenance means and logistics required to repair tidal turbine;
- Weather windows for maintenance activities.

4.2.2 Reliability Data Set

One of the most important issues in the RAM analysis process is the data used to describe the unplanned failure and subsequent repair of equipment. It is fundamental that the data is reliable and appropriate otherwise the benefits from the study will be limited.
Furthermore, the data are normally not available at the same level as the components intended to be modelled. In such cases, model adaptations are required and/or new assumptions need to be defined. Thus, components and their failure modes are grouped according to their criticality, characteristics and the availability of data.
In the scope of this study, data from the following sources were incorporated into the RAM model.

- Generic industry sources (e.g. OREDA 2009 [3][4], I-EEE[5]);
- Wind Turbine data sources (e.g.Offshore Wind Turbine - Reliability, Availability, and Maintenance [9]);
- Ingeteam historical and maintenance records for Wind Turbines;
- FMEA report from D1.1 [31]; and
- Partners' experience.

It is important to highlight that due to the lack of available experience on Tidal Turbines most of the reliability data was collected from Wind Turbines reliability databases as the components and technologies are very similar.
Complementary to the reliability data, maintainability data together with the maintenance logistic and production data were collected during this step.
Model adaptations were introduced when required and/or new assumptions were defined when the data were not available at the level of detail initially defined. Thus, components and their failure modes were grouped according to their criticality, characteristics and the availability of data.

4.2.3 Assumptions

The assumptions and data used to construct and configure the model were structured and documented. Detailed assumptions are presented in section 6 and includes:

- Tidal turbine components to be included in the RAM model;
- Their Failure modes and effects;
- Reliability parameters;
- Specific system interactions as a result of the design or operation such as:
  - Component boundaries and quantities;
  - System architecture including components redundancy level;
  - Preparation time before repair;
  - Restart time after repair;
  - Logistic time;
  - Spares lead time;

- Logistics times such as:
    - Mobilisation Times (time to mobilise workers and maintenance utilities required to carry out a repair);
    - Preparation Time (time to adequately prepare for the repair prior to commencing);
    - Time to re-start the equipment / installation; and
    - Spare Lead time (time required to source equipment items).

Then, A Reliability Block Diagram (RBD) is carried out, The RBDs portray graphically the impact of equipment failure (whether in series or parallel), and any other interactions that can impact production. Figure 4-2 presents an example of an RBD.

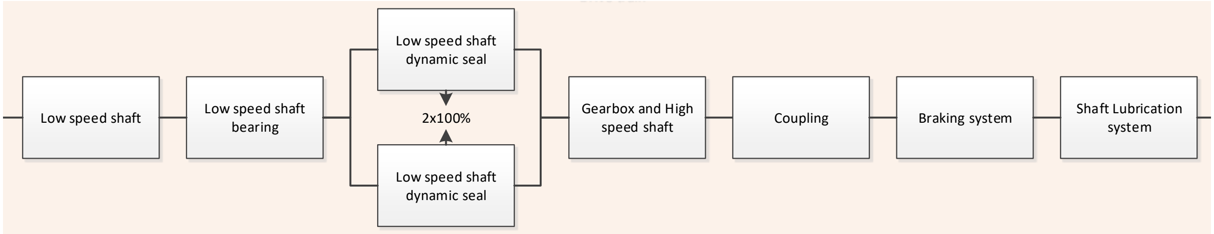


Figure 4-2 Example Reliability Block Diagrams

As explained in 4.1.2, any failure along a series path causes the entire series path to fail, whereas parallel paths are redundant, meaning that all of the parallel paths must fail for the parallel network to fail. Parallel path is described with a term such as “2 x 100%”. 2 x 100% path do not cause production losses unless both path have failed and are failed simultaneously. Failure of either one of 2 x 50% paths will cause normal production to reduce to 50%.

An **Asset Register** is also built in order to present the main reliability data such as MTTF, MTTR, and Production Losses. The asset register is a list of the components containing the different data used in the RAM model specifically for each component.

For some parameters to be considered in the model, it is not possible to define a “typical” or “generic” assumption, because several credible options can be defined for these parameters. An example is the time to mobilize an OSV: this time can vary from few days to several months depending on location of the tidal turbine, location of logistic facilities, contractual times, operator reaction time, etc... In such situation, a mean value is defined for the model and the other options are kept aside and modelled afterward in Sensitivity cases in order to understand how much these factors impact the results. In other words, the sensitivity cases consist in simulating the model with a variation of some assumptions and verify how much those variations influence the result. The sensitivity analyses will allow to determine the robustness of the model for each “tested” assumptions.

Finally, in the assumptions it should be justified why some the components are excluded from the scope. For example, as the purpose of the RAM analysis is not intended to assess safety issue, all component that are not required in normal operation such as safety systems (fire, bilge, ...) are not included in the RAM analysis. In contrary, catastrophic situations or failures (eg. Structural collapse) that could lead to complete loss of the turbine are not supposed to happen during turbine operation life and external failures (ex.: due to lake of maintenance, human error, dropped object...) that can not be controlled are also excluded from the scope but don’t need to be recorded. Indeed, all assumptions not recorded are supposed not considered in the RAM analysis.

4.2.4 Model Construction and Simulation

In the RAM process, the systems to be analysed are modelled by means of a diagrammatic representation of its components and their interactions contributing to the system functionality.

In that RAM analysis, the tidal turbine configuration and maintenance operations are modelled in a petri net representation as explained in sections 4.1.2 and 4.3 using the RAM software GRIF-PETRI to construct the model based on the Reliability Block Diagram, and the general assumptions. The main Reliability Data inputs come from the Asset Register and other inputs such as operational profile and logistics come from the general assumptions. Then, the Monte Carlo simulation is performed by the RAM tool to simulate tidal turbine operation, failures, repairs and maintenance of all assets included in the model as described in section 4.1.3. The RAM simulation will assist in providing the tidal turbine production availability as per definition in section 5.4 and understanding into equipment configuration and others factors the major contributors to unavailability.

The first model is entitled the “Base Case model" and is used as a basis and reference for further Sensitivity cases and Alternative cases.

4.2.5 Results Generating and Sensitivity Analysis

The results from the simulation will represent the total power generated over the tidal turbine life; a system life being equivalent to the duration of continuous operation (20 years), not only accounting for the time achieving the maximum production capacity but all production throughput even at times spent delivering at a reduced production capacity.

The base case model for each concept will be analysed and the following information will be reported:

- Average Production Availability over System Life (20 years);
- Production loss contribution breakdown by individual components;
- Contribution to production loss from operational behaviours such as: maintenance delays, and metocean constraints;
- Maintenance intervention frequencies.

Then the model is simulated again for each sensitivity cases defined in previous steps and the results are compared to each other in order to identify the sensitivity or robustness of the model to the variation of certain assumptions. The more the result changes with a data variation, the less robust is the model this input data. When this case occurs, it indicates that the data need to be the as accurate as possible in order to reduce the uncertainty of the result.

4.2.6 Recommendations and Alternative Cases

The main purpose of the Alternative Cases of the RAM analysis is to consider different set of scenarios providing options in terms of design improvements and enhancement monitoring. The alternative cases must be analysed and the key points shall be compared with the Base Case in order to assist in determining the option that best meets the project’s objectives, i.e. the optimization of tidal turbines reliability and performance.

After gathering the results from the base case, the most critical elements to tidal turbine availability were highlighted and alternatives to the original design and monitoring were proposed. Each alternative was modelled and simulated as an “Alternative case”.

For each alternative case simulated, an output set containing the total power production, turbine availability, components contribution to downtime, maintenance mobilization during operating lifecycle has been produced in order to be used as input in the cost modelling that will be performed in the WP4 and WP5.

4.3 RAM Software

Several RAM softwares are available in the market. Bureau Veritas used the RAM software GRIF-PETRI developed by Satodev (Subsidiary of Total) to undertake the RAM analysis.
GRIF-PETRI software is a Monte Carlo based RAM modelling allowing simulating global behaviour of dynamic systems by using Petri-Net models and enables analysing systems with high level of complexity. GRIF-PETRI also allows a precise simulation of system behaviour with regards to the propagation of its equipment failure and to identify which failure combination leads to a particular situation.

As per [21], A Petri net is a mathematical modelling language for the description of systems with dynamic discrete events. It is also known as a place/transition (PT) net. A Petri net is basically a directed bipartite graph, in which the nodes represent transitions (i.e. events that may occur, represented by bars) and places (i.e. conditions, represented by circles) (see Figure 4-3).
In a RAM model using Petri net, the places represent the equipment states. States are basically “In operation” and “Failed”. Other states can be added, like “Partial failure” and “Total failure”, in order to differentiate failures that lead to degraded modes or critical failures. “Stand-by” state can be added for redundant equipment, and so on. The nodes represent basically failures and repairs (transition from “In operation” state to “Failed” state, and vice-versa). Extra nodes can be added according to the transition between states, like it is the case for redundant equipment which need a specific transition from the “Stand-by” state to “In operation” state.
Petri nets can also be used to model components other than equipment, for example: Maintenance Utilities and Spare Parts

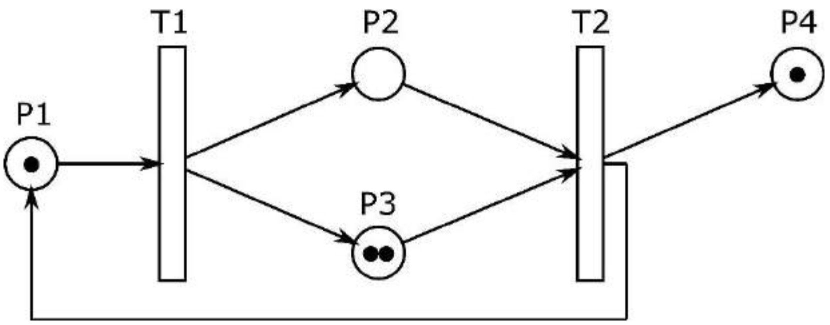


Figure 4-3 - Example of Petri net representation of a system

4.4 Reliability Data

4.4.1 Databases and sources

4.4.1.1 Overview

Due to lack of public databases regarding tidal turbines, reliability data was collected from different sources specially the ones related to Wind Turbines which provides similarities with tidal turbines in term of functionalities, components types and operability.

Thus, data for this study has been taken from the following sources:

- Ingeteam Historical Data:
  Reliability study on wind turbine farms performed by Ingeteam that resulted in a database as presented in section 4.4.1.2;
- Generic Wind Turbine Reliability data sources:
  There are various accessible wind turbine reliability studies which can be used as surrogate data for tidal turbine reliability assessment as presented in section 4.4.1.3 ;
- Industrial databases:
  Several reliability databases are commonly used in industrial RAM studies such as OREDA 2009 [3][4] and PARLOC [41], for Offshore Oil&Gas units or I-EEE [5] for power plants.
  A description of the main industrial database sources is presented in section 4.4.1.4.
- Generic Tidal Turbine FMEA [31]:
  A qualitative analysis of Tidal Turbine failures have been performed in task T1.1 - FMEA and can be used to estimate failure rates (section 4.4.1.5).
- Partner's discussions and experience (section 4.4.1.6)

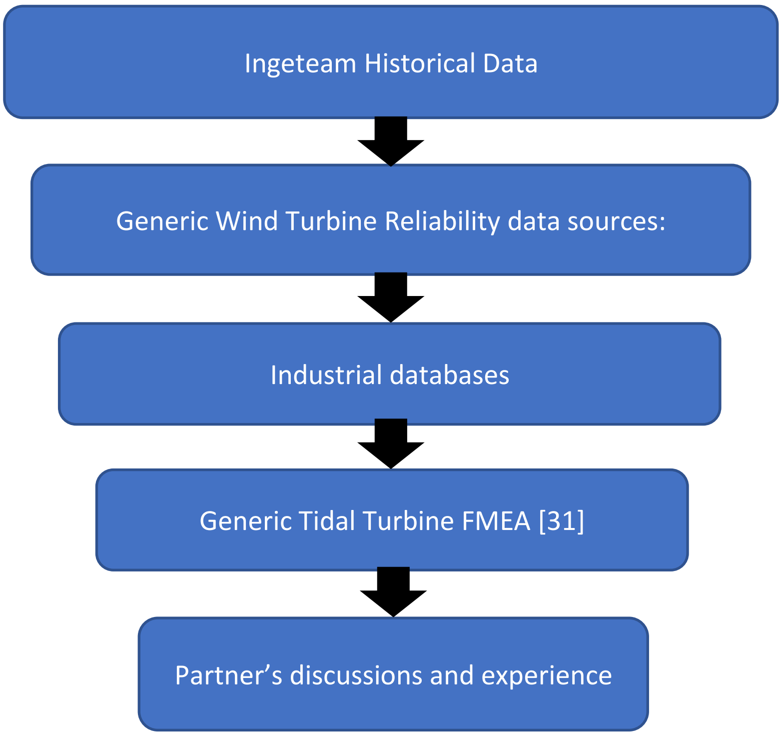


Figure 4-4 - Data sources hierarchy

Figure 4-4 above presents the data sources hierarchy. Therefore, the reliability data were firstly collected from the Ingeteam historical database. However, if the data was not available in this database, the data was taken from the generic wind turbine reliability database or from Industrial databases. In case of data unavailability, the necessary data was estimated, initially based on the Generic Tidal Turbine FMEA or ultimately considered by partners' experience.

The same reliability data set was applied to both tidal turbine concepts studied. Components with the same technology had the same reliability data applied in different design cases.

4.4.1.2Ingeteam historic data

Ingeteam provides O&M services for wind turbines up to 15 MW for onshore and offshore applications.

Today they have more than 5,600 maintained turbines throughout the world, with a Total Installed Wind Power of +8.6GW, and an extended experience on the installation and maintenance of multi-technology wind turbines of different manufacturers.

Ingeteam performed reliability / availability studies with the failure data collected during 3 years in a total of 34 wind farms, totalling 852,92 MW with 716 wind turbines from different manufacturers, models and power going from 600kW to 2300 kW (see Table 4-2), all of them using geared drive technology. The data has been collected for turbines with less than 1.5MW and then for more powerful ones to compare their results, in this case the wind turbine distribution is like follows:

Table 4-2 – Ingeteam reliability study - Wind turbine population

Wind Farms with Wind Turbines ≥1500kW	Nbr of Wind Turbines:	Total Power (MW) :
16	251	475,4
Wind Farms with Wind Turbines <1500kW	**Wind Turbines:**	**Total Power (MW) :**
18	465	377,52

Due to confidentiality issues, the data resulting from the Ingeteam reliability study are presented in this report with relative values in term of percentages.

The data showed in Figure 4-5 presents the yearly failure rates per fault element and the average of downtime generated by these failures based on the analysis of all wind turbines during 3 years. The Figure 4-6 presents the data of wind farms whose turbines have power lower than 1500kW while the Figure 4-7 presents the data for wind farms whose turbines have power greater or equal to 1500kW.

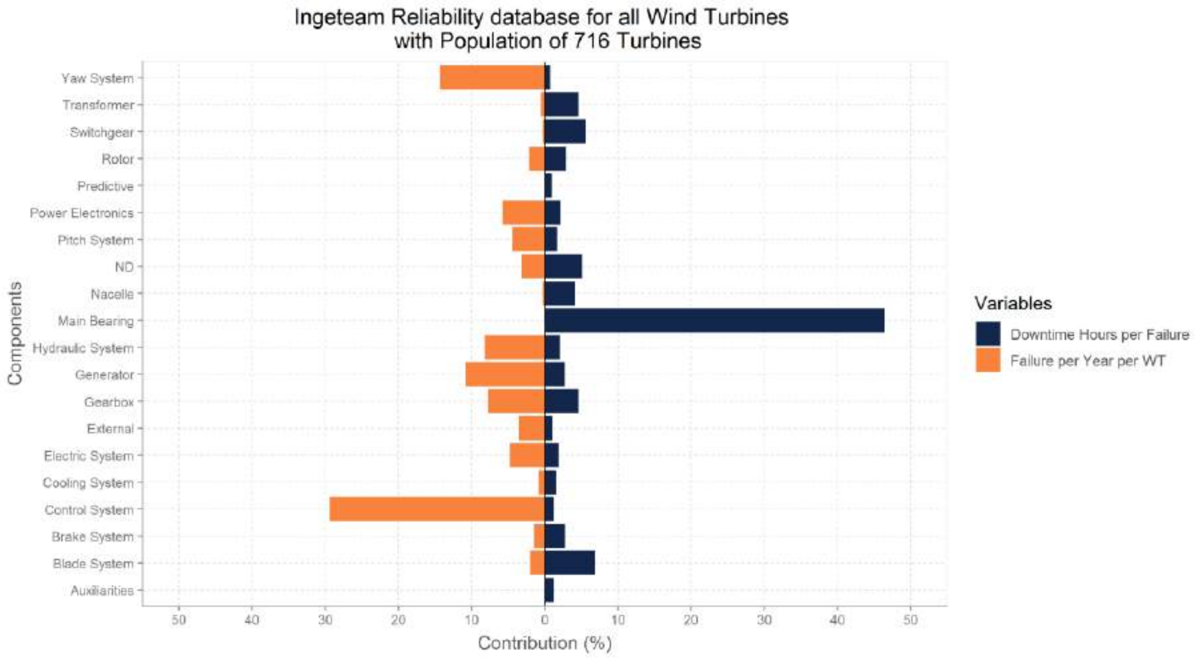


Figure 4-5– Ingeteam reliability database for all Wind Turbines (relative values)

"ND": Not Defined - failure where there is not enough info to determine the subsystem failing.

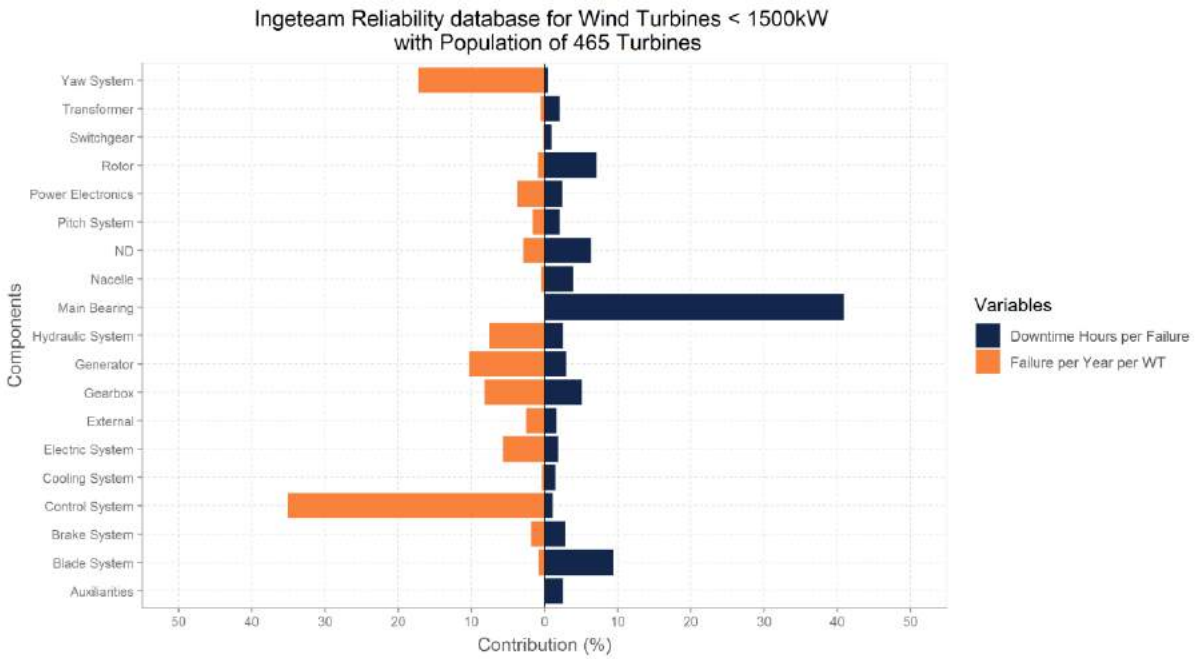


Figure 4-6– Ingeteam reliability database for Wind Turbines < 1500kW (relative values)

"ND": Not Defined - failure where there is not enough info to determine the subsystem failing.

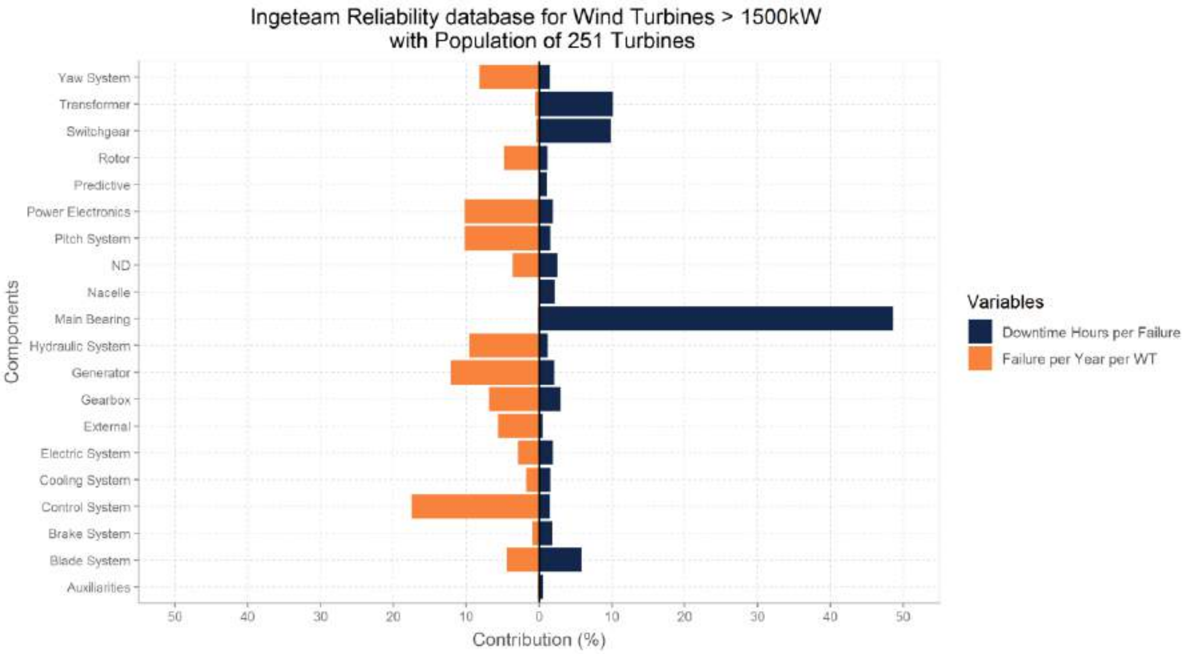


Figure 4-7 – Ingeteam reliability database for Wind Turbines ≥ 1500kW (relative values)

"ND": Not Defined - failure where there is not enough info to determine the subsystem failing.

It is to be noted that the number of failures presented in Ingeteam database is relatively high compared to other sources presented in section 4.4.1.3. This is explained mainly by two factors:

- Ingeteam data considers every situation that the machine stops as a failure even when the system is required to reboot; this is not necessary the case for other sources.
- Ingeteam data includes quite old turbine models (around 15 years); the age affects dramatically the reliability of the machines.

Furthermore, the range of power that current wind turbines and those that are under development in Europe goes from 0,5MW to almost 4MW, however most of tidal turbines are typically designed to produce between 1MW and 2MW [27].

Taking this into consideration, another reliability / availability study has been performed with a population of newer wind turbines (less than 10 years old) and with 1500 kW of power. The failure data were collected during 2 years in a total of 3 wind farms, totalling 145,5 MW with 97 wind turbines of the same model with 1500kW of power, all of them using geared drive technology.

Figure 4-8 presents the yearly failure rates per fault element and the average of downtime generated by these failures based on the analysis of these wind turbines during the 2 years period.

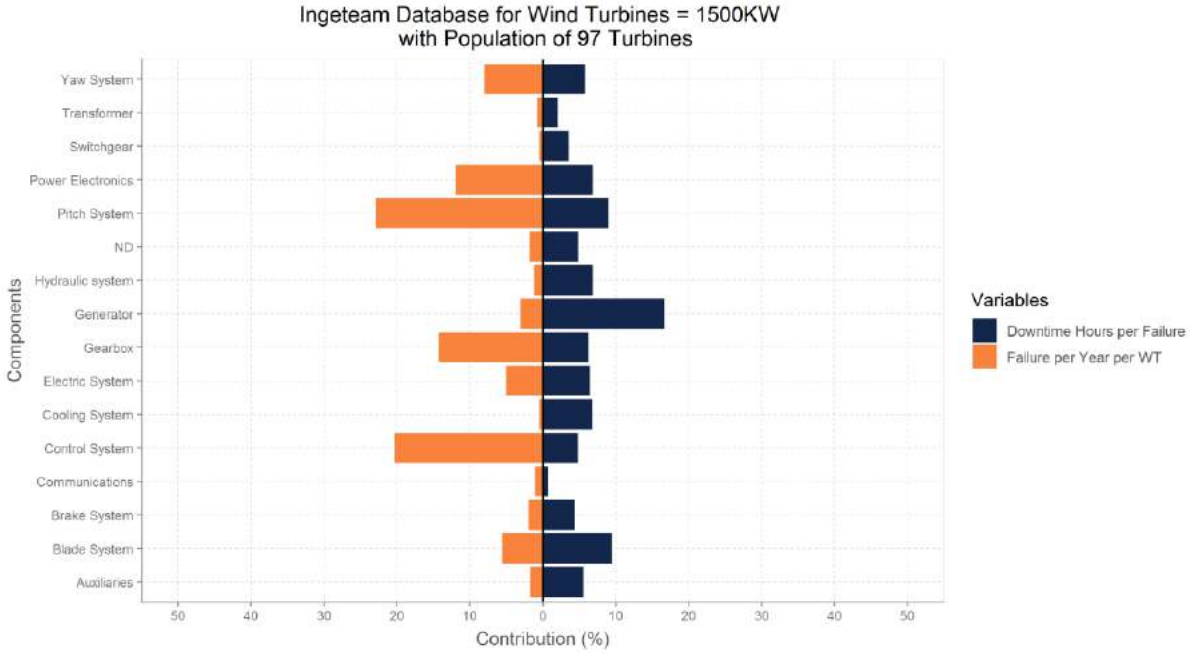


Figure 4-8 - Ingeteam reliability database for Wind Turbines = 1500KW (relative values)

"ND": Not Defined - failure where there is not enough info to determine the subsystem failing.

As explained in section 4.4.6.1, the failure must be divided into 4 types of failures according to their duration: Trivial failures including failures with local and remote failures, Trivial failures including failures with local and excluding remote failures, Minor Failures and Major Failures. The resulting failure rates for each type of failure are presented in the following figures:

- Figure 4-9 : Trivial stops with a duration of less than one hour, including failures with local and remote failures;
- Figure 4-10 : Trivial Failures (stops with a duration of less than one hour), including failures with local interventions only (remote interventions such as turbine reset has been removed from this table as per explained section 6.3.2);
- Figure 4-11 : Minor Failures (failure stops with a duration of less than one hour and more than twenty-four hours); and
- Figure 4-12 : Major Failures (failure stops with a duration of more than twenty-four hours).

Data from Figure 4-10, Figure 4-11 and Figure 4-12 were the ones that have been used for this present RAM study.

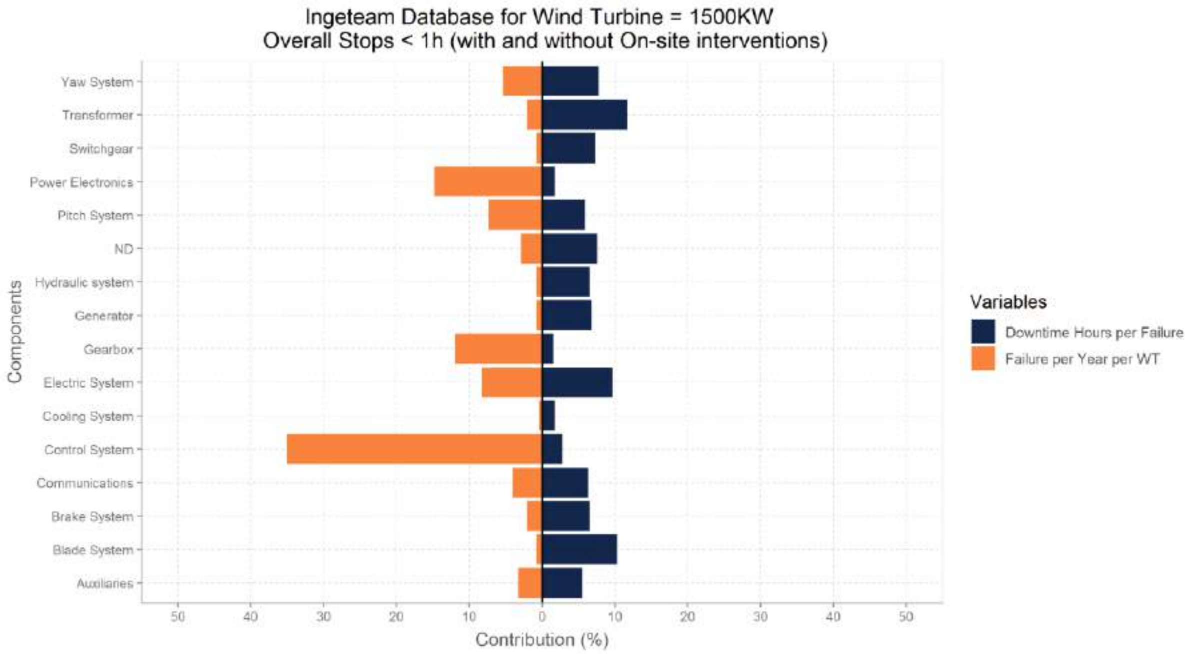


Figure 4-9 - Ingeteam reliability database for Wind Turbine = 1500KW – Trivial failures: Downtime < 1h (with and without interventions) (relative values)

"ND": Not Defined - failure where there is not enough info to determine the subsystem failing.

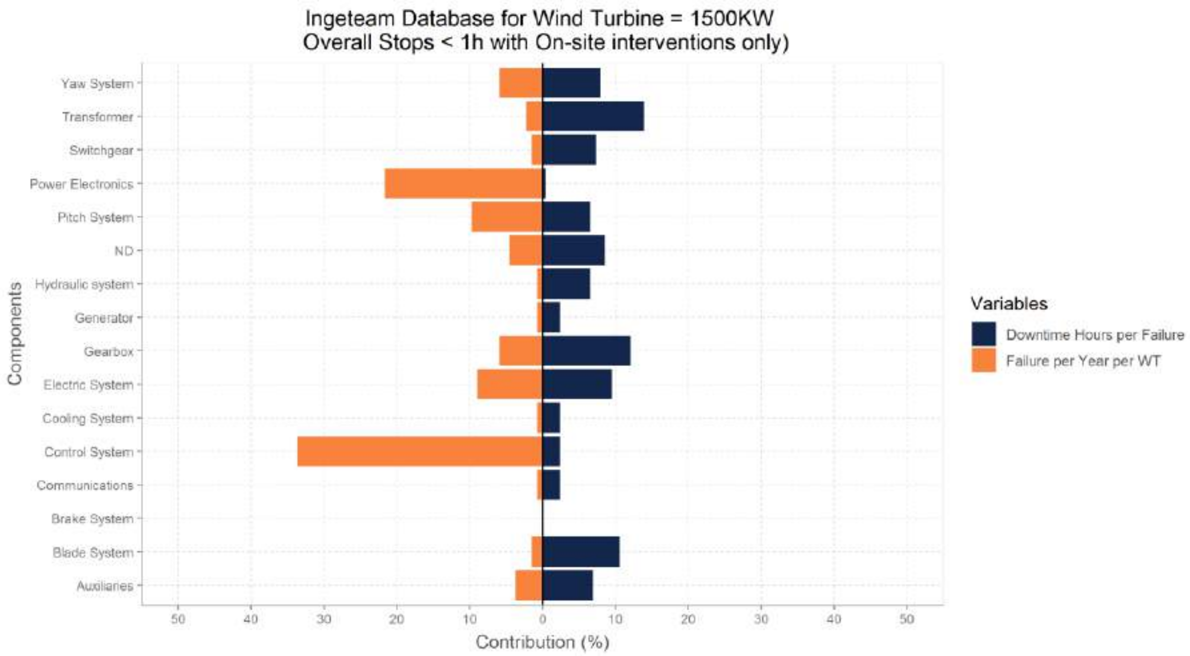


Figure 4-10 - Ingeteam reliability database for Wind Turbine = 1500KW - Trivial failures: Downtime < 1h with interventions only (relative values)

"ND": Not Defined - failure where there is not enough info to determine the subsystem failing.

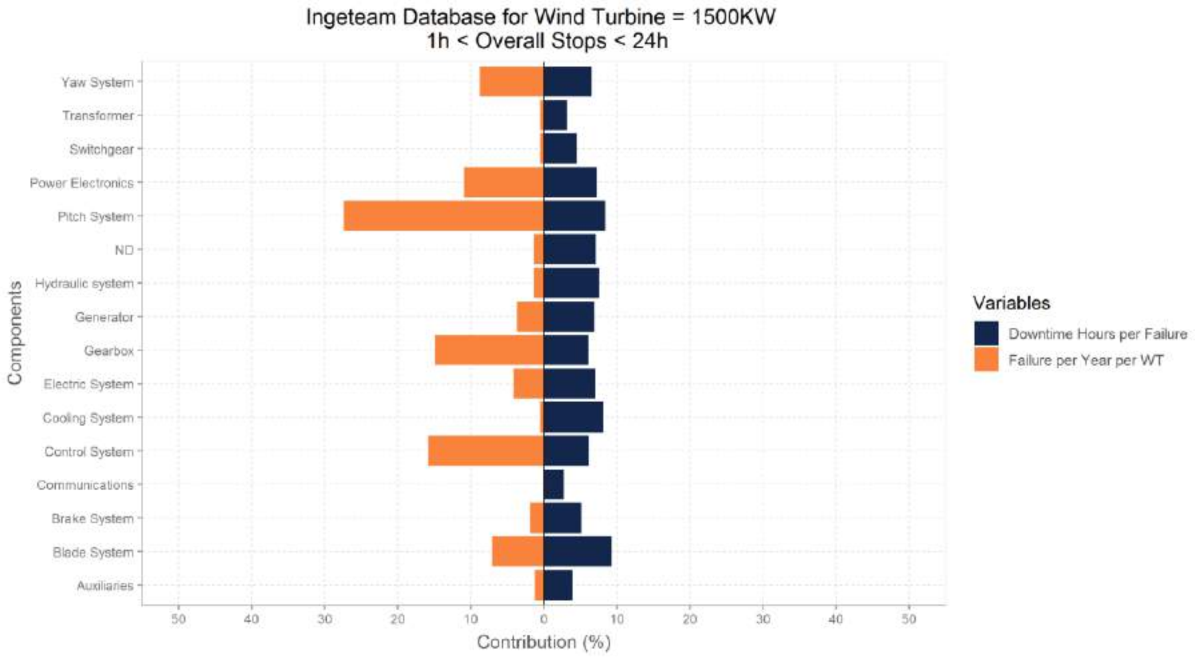


Figure 4-11 - Ingeteam reliability database for Wind Turbine = 1500KW – Minor failures: 1h < Downime < 24h (relative values)

"ND": Not Defined - failure where there is not enough info to determine the subsystem failing.

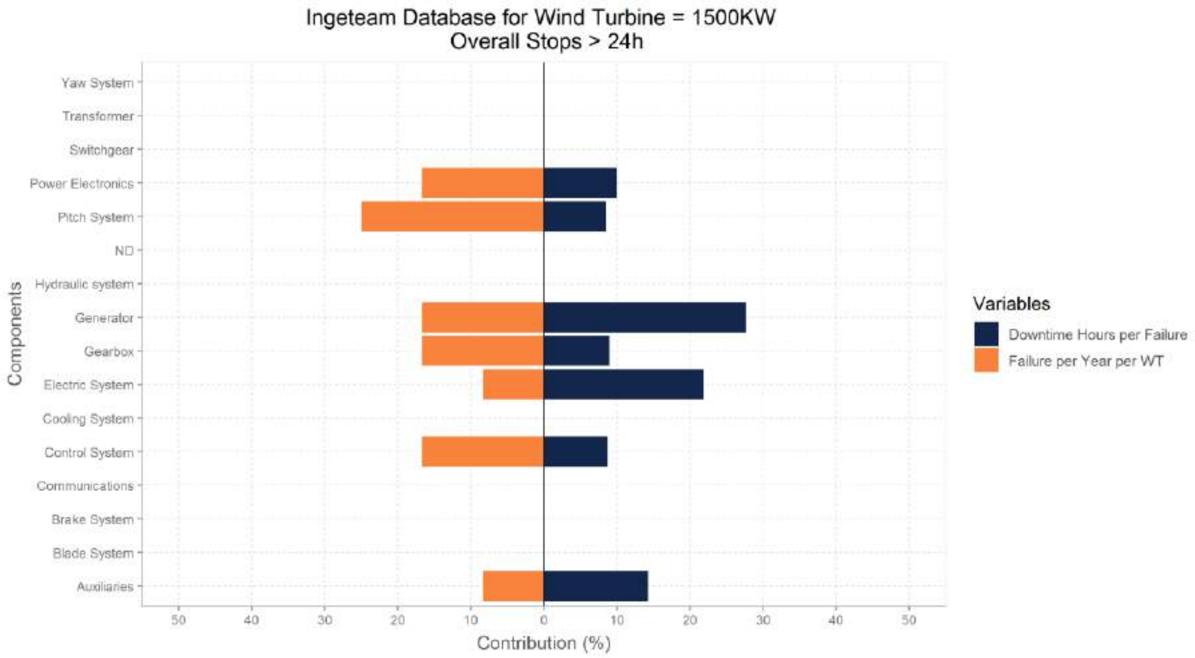


Figure 4-12 - Ingeteam reliability database for Wind Turbine = 1500KW - Major failures: Downtime > 24h (relative values)

"ND": Not Defined - failure where there is not enough info to determine the subsystem failing.

For a better representation of the magnitude of the 3 types of failures for each component, the Figure 4-13 below compiles the data from Figure 4-10, Figure 4-11 and Figure 4-12 :in one unique chart.

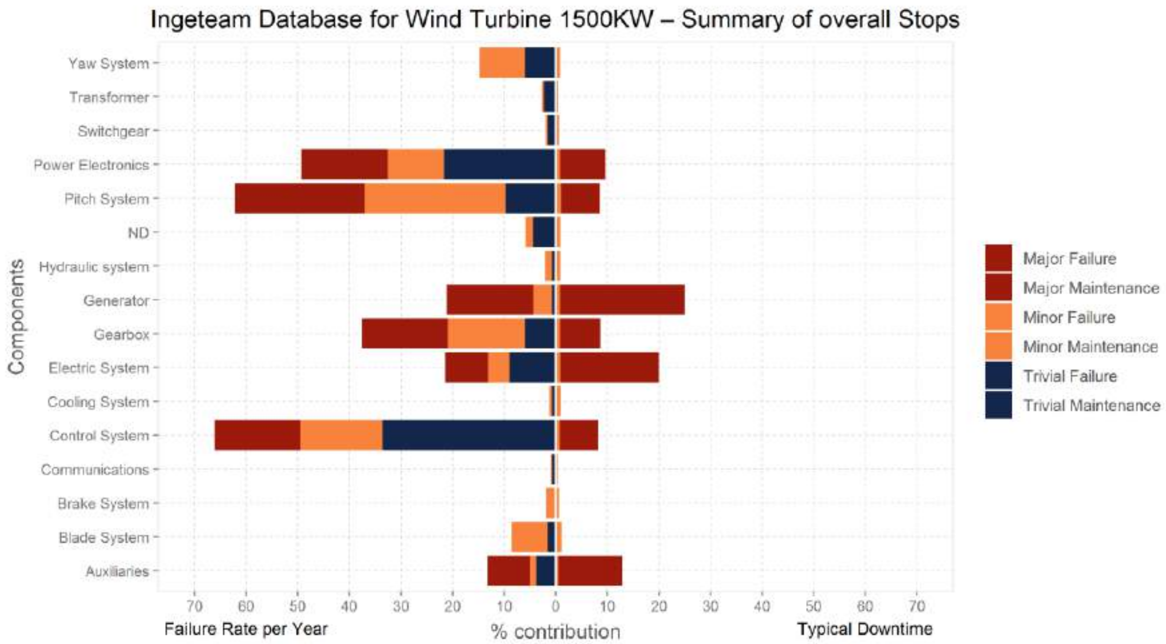


Figure 4-13 - Ingeteam reliability database for Wind Turbine 1500KW – Summary of all failure (relative values)

"ND": Not Defined - failure where there is not enough info to determine the subsystem failing.

4.4.1.3Generic Wind Turbine databases

Considering tidal turbine industry is still in early stage, its reliability database is not currently available. However, there are some references related to wind Turbines providing reliability data which can be used as a reference for tidal turbines. Hereafter, are presented a summary of the main data found in respect of failure rates of Wind Turbines.

a) Wind turbine failure data on turbine level

The Figure 4-14 shows overall trend of wind turbine failure rates over time. It provides general illustration of the reliability level of wind turbines. The data for this figure were taken from Windstats survey for Germany and Denmark, since the wind turbine populations in Windstats database from these two countries are large, LWK and WMEP survey in Germany, and EPRI survey in USA. The Windstats German survey population covers up to 4500 turbines and the Danish one covers up to 2500 turbines with overall investigated period of 10 years from 1994 to 2004, whereas the LWK survey in Germany covers both fixed and variable speed wind turbine with geared or direct drives over 15 years of operation from 5800 wind turbine-years. WMEP survey covers similar operation period of 15 years but with more turbine population resulting in 15400 wind turbine-year [32]. All these surveys indicate onshore wind turbine failure rate hovering around 0.8 – 5 failures per year with trend similarity of decreasing failure rate over time.

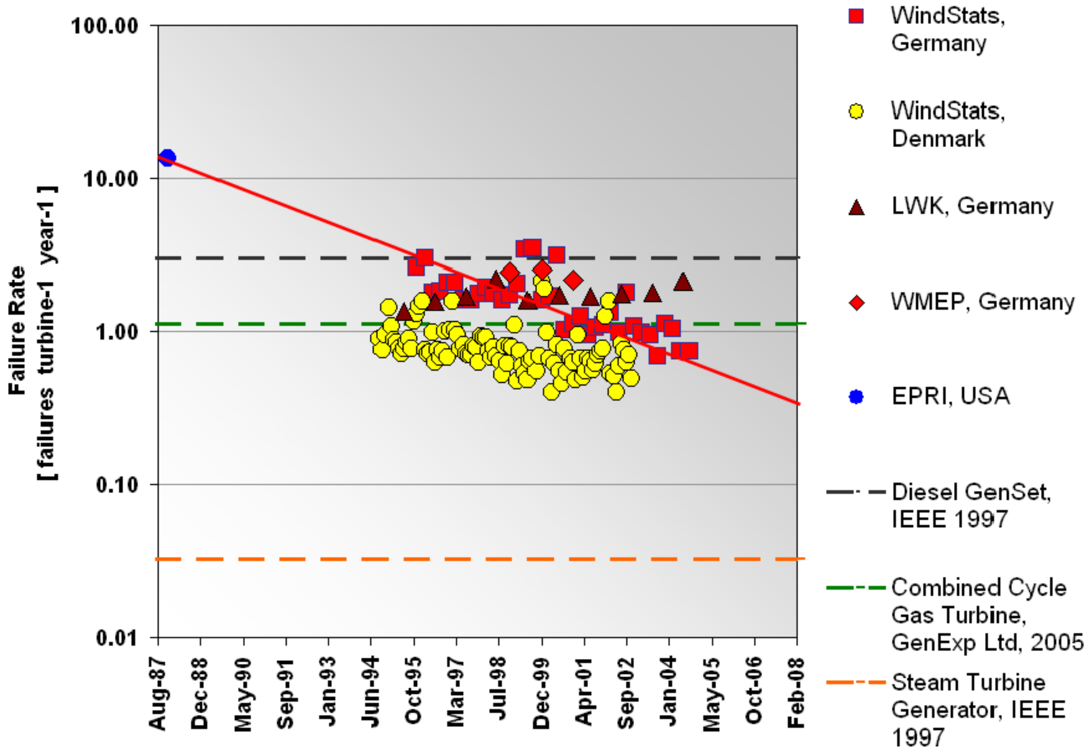


Figure 4-14 - Trend in turbine failure rate with time [32]

Figure 4-14 also compares wind turbine failure rates with those for diesel generators, combined cycle gas turbine, and steam turbine from in IEEE report [5]. This comparison provides a benchmark against other power generation technology.

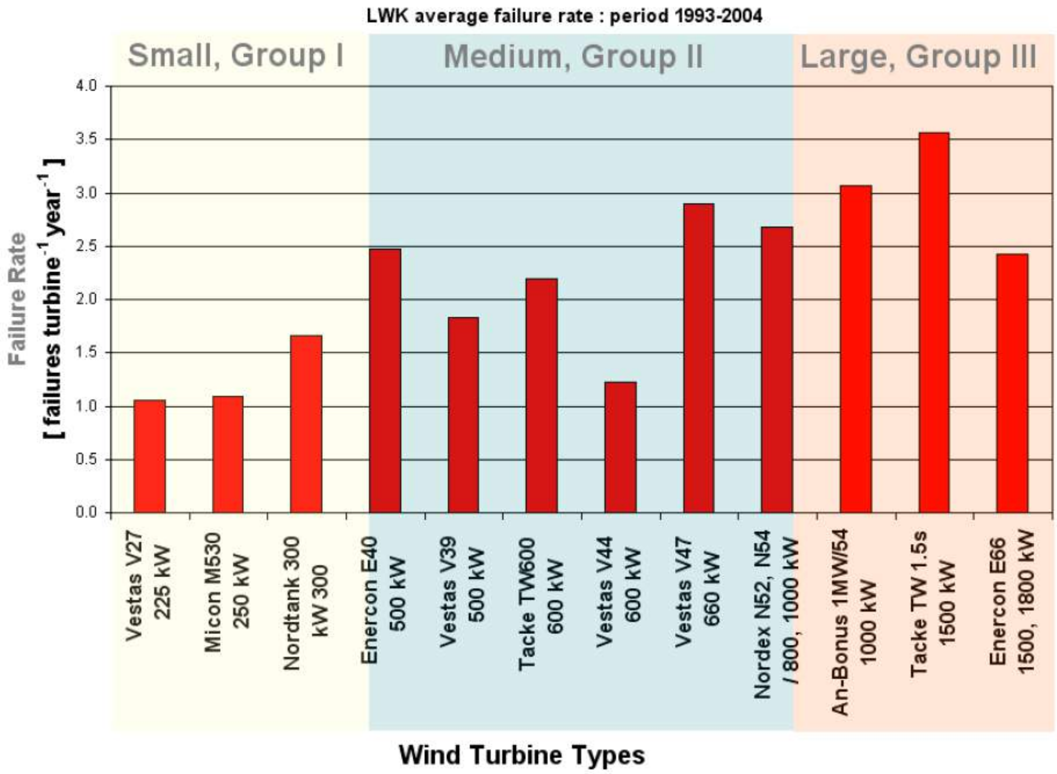


Figure 4-15 - LWK reliability study summary [32]

The relation between wind turbine size and its reliability is illustrated in Figure 4-15 based on LWK survey data. It summarizes the failure rate over 11 years for 12 wind turbine models within the surveyed population. It reveals rising trend of failure rate with turbine rating. Higher failure rate on a turbine with higher rating is due to rising complexity of the design.

It is important for tidal turbine developer to be aware of wind turbine reliability characteristics as a benchmark, given similarity on the working principle and their respective components, it is likely that tidal turbine failure rate will not be very far from wind turbine. Hence for this study various wind turbine reliability study had been examined and some are considered as surrogate data input for tidal turbine RAM simulation.

b) Wind turbine failure rate on component level

More detailed assessment of wind turbine failures is summarized in a study conducted by Dao et al [33]. Their study systematically review reliability data for both onshore and offshore wind turbine broken down by subassembly from 18 publicly available databases covering around 18.000 wind turbine, corresponding to over 90.000 turbine-years data.

This study offers an insight of the failure rate and downtime of wind turbine subassembly and their variations among the data sources. It is visible from the Figure 4-16 and Figure 4-17 that there are large variations in failure rates and downtime for some of the subassemblies. For the large variations of failure rate in some of the subassemblies, it is largely due to varied design approaches between wind turbine types, hence subassemblies with more design options often result in disparities in failures experienced.

Some turbine components deserve further scrutiny, for example due to their complexity like converter. Tavner [9] estimated the location of the fault of converter on subcomponent level and can bring more details when analysing the causes of failures of the converter in a RAM study. This type of information is also useful as a feedback for tidal turbine developer in identifying most susceptible sub component as illustrated in Table 4-3.

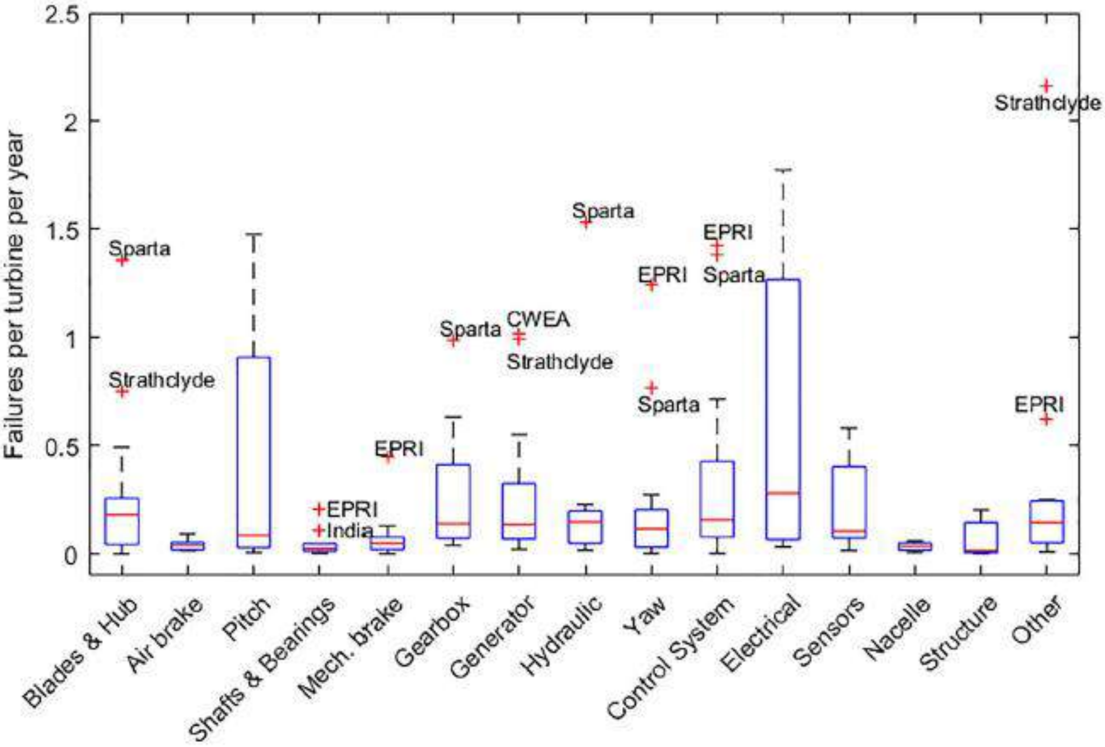


Figure 4-16 Boxplot of subassembly failure rate [33]

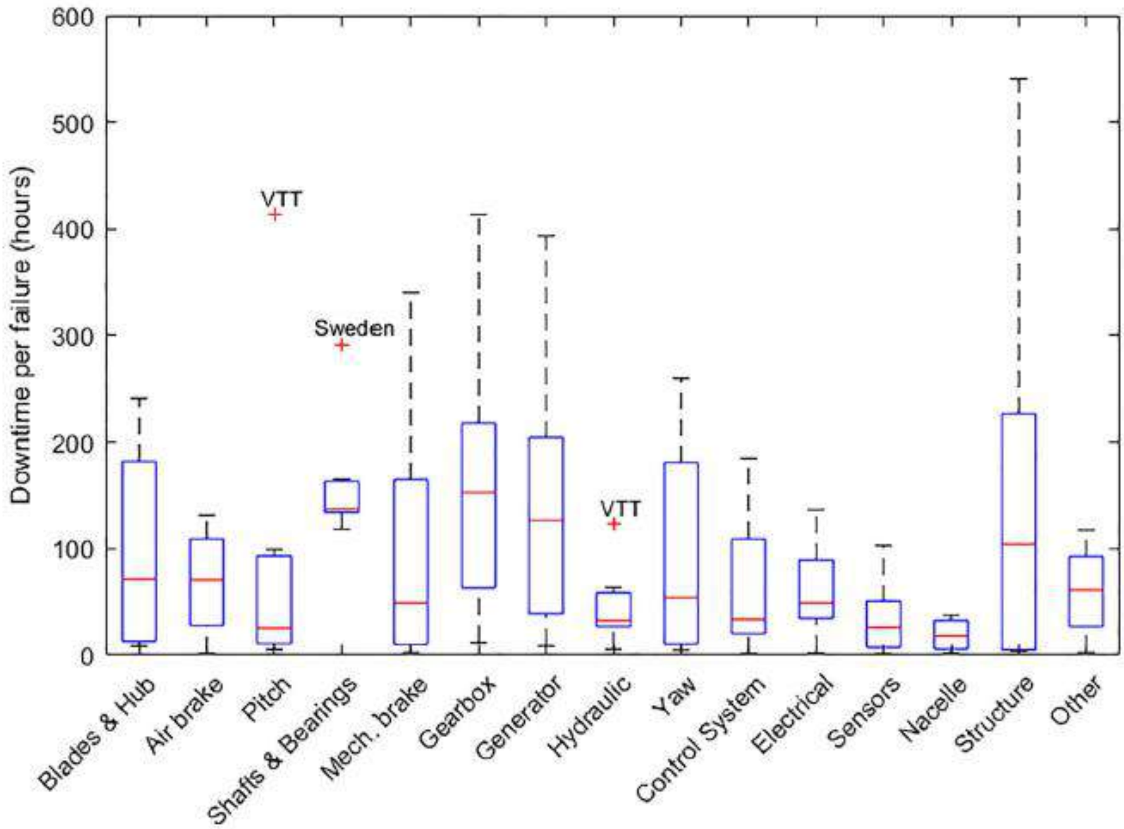


Figure 4-17 Boxplot of subassembly downtimes [33]

Table 4-3 – Wind turbine converter subcomponents failure rate [9]

	From WMEP D Data	From LWK D Data	From LWK D	From Reliawind		
Turbine years in the survey	209	1028	5719	679	366	1
Additional information	Large WTs	Total WTs	Total WTs	Specific data from WTs with partially rated or fully rated converter (E40, E66, Tacke 1.5s)	Specific data from WTs, about 2 MW with DFIG and partially rated converter	
Years surveyed	1998 - 2000	1986 - 2006	1993 - 2006	1993 - 2006	2007 - 2011	
Failure rate (Failure/unit/year)					From FMEA	
Whole WT	5.23	3.6	1.92	2.6	Not disclosed for confidentiality reason	23.37
Converter Total	1	0.45	0.22	0.32	Not disclosed for confidentiality reason	2.63
Converter as % of WT	19.10%	12.40%	11.60%	12.20%	11.60%	11.30%
Estimated location of the faults						
- Converter control unit	0.07	0.031	0.016	0.022		0.184
- Series Contactor	0.09	0.04	0.02	0.028		0.237
- Grid-side filter	0.03	0.013	0.007	0.009		0.079
- Grid-side inverter	0.189	0.085	0.042	0.06		0.5
- Pre-charge circuit	0.06	0.027	0.013	0.019		0.158
- DC link capacitor	0.11	0.049	0.024	0.035		0.289
- Chopper circuit	0.06	0.027	0.013	0.019		0.158
- Generator-side inverter	0.189	0.085	0.042	0.06		0.5
- Crow-bar circuit	0.06	0.027	0.013	0.019		0.158
- Generator-side filter	0.03	0.013	0.007	0.009		0.079
- Bypass Contactor	0.09	0.04	0.02	0.028		0.237
- Auxiliaries	0.025	0.011	0.006	0.008		0.066

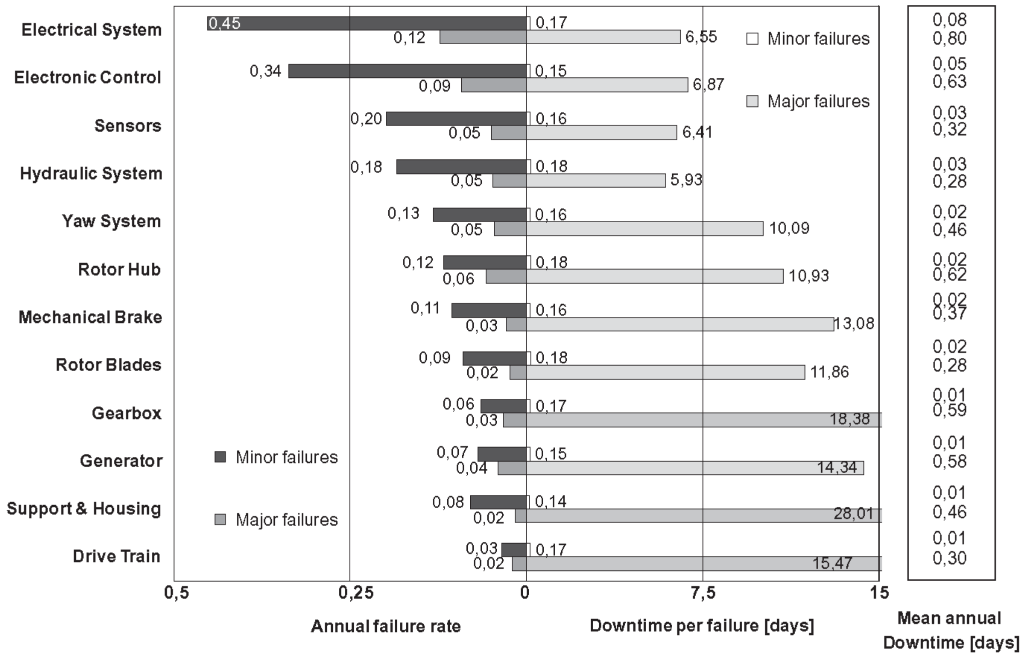


Figure 4-18 - WMEP wind turbine reliability characteristics considering failure category [32]

Another interesting reference is failure rate data from NREL's operation and maintenance cost model study [35]. They gathered failure data from various sources, covering manufacturer publication, published case studies, expenditures and service logs from operating wind farm, and interview with project managers. The data is summarized Table 4-4. It has been averaged and normalized to avoid distinguishing any particular entry.

Table 4-4 - NREL study (2008) wind turbine reliability characteristics data [35]

System	Component	Failure Prediction	Failures per 100 parts by Year 20	Weibull Curve Parameter – Alpha	Weibull Curve Parameter – Beta	Parts per Turbine	Parts Cost ($)	Crane?	Parts in Project	Failures in 20 Years
Rotor										
	Blade-struct. Repair	Constant Rate	5,0			3	87 500	YES	300	15
	Blade-nonstruct. Repair	Constant Rate	20,0			3	3 000	NO	300	60
	Pitch cylinder & linkage	Weibull Curve		10,0	3,5	3	3 800	NO	300	547
	Pitch bearing	Weibull Curve		50,0	3,5	3	13 100	YES	300	13
	Pump & hydraulics	Weibull Curve		12,0	3,5	1	2 200	NO	100	142
	Pitch position xdcr	Weibull Curve		12,0	2,0	3	1 800	NO	300	468
	Pitch motor	Weibull Curve		15,0	1,1	0	8 400	NO	0	
	Pitch gear	Weibull Curve		12,0	3,5	0	4 600	NO	0	
Drive Train										
	Main bearing	Weibull Curve		39,0	3,5	1	24 400	YES	100	10
	High-speed coupling	Weibull Curve		25,0	3,5	1	6 700	NO	100	39
Gearbox and Lube										
	Gearbox-gears & bearings	Constant Rate	5,0			1	154 700	YES	100	5
	Gearbox-bearings, all	Constant Rate	5,0	26,0	3,5	1	800	YES	100	35
	Gearbox-high speed only	Weibull Curve		26,0	3,5	1	36 700	NO	100	35
	Lube pumps	Weibull Curve		12,0	3,0	2	2 400	NO	200	294
	Gearbox cool. fan motor	Weibull Curve		19,0	1,1	2	2 000	NO	500	195
Generator and Cooling										
	Generator-rotor & bearings	Constant Rate	10,0			1	91 600	YES	100	10
	Generator--bearings only	Weibull Curve		17,0	3,5	2	2 100	NO	200	184
	Full converter	Weibull Curve		15,0	2,0	1	9 500	NO	100	117
	Gener. cooling fan motor	Weibull Curve		19,0	1,1	1	1 600	NO	100	98
	Contactor, generator	Weibull Curve		20,0	2,0	3	13 500	NO	300	235
	Partial converter	Weibull Curve		15,0	2,0	0	2 600	NO	-	-
Brakes and Hydraulics										
	Brake caliper	Weibull Curve		10,0	2,0	1	700	NO	100	194
	Brake pads	Constant Rate	200,0	10,0	2,0	1	5 900	NO	100	200
	Accumulator	Weibull Curve		6,0	3,0	4	1 500	NO	400	1 356
	Hydraulic pump	Weibull Curve		12,0	3,0	1	4 900	NO	100	146

System	Component	Failure Prediction	Failures per 100 parts by Year 20	Weibull Curve Parameter – Alpha	Weibull Curve Parameter – Beta	Parts per Turbine	Parts Cost ($)	Crane?	Parts in Project	Failures in 20 Years
Yaw System										
	Yaw gear (drive+motor)	Constant Rate	5,0			4	6 000	NO	400	20
	Yaw motor (with brake)	Weibull Curve		10,0	2,0	4	2 400	NO	400	776
	Yaw sliding pads	Weibull Curve		10,0	3,5	8	800	NO	800	1 462
Control System										
	Control board, top	Weibull Curve		15,0	2,0	1	5 500	NO	100	117
	Control board, main	Weibull Curve		15,0	2,0	1	8 600	NO	100	117
	Control module	Weibull Curve		15,0	2,0	13	6 100	NO	1300	1526
	Sensor, static	Weibull Curve		14,0	2,0	17	500	NO	1700	2184
Electrical and Grid										
	Main contactor	Weibull Curve		20,0	2,0	1	9 200	NO	100	77
	Main circuit breaker	Weibull Curve		30,0	2,0	1	10 800	NO	100	7737
	Soft starter	Weibull Curve		30,0	2,0	0	700	NO	-	-
Misc. (All others)										
	Miscellaneous parts	Constant Rate	5,0			1	100 900	NO	100	5

The level of detail in the databases has an impact on the RAM study, as the turbine components need to be modelled in the RAM analysis at the same level of the item from which the data was selected. In other words, the higher is the level of the components in the databases, the more detailed the turbine can be modelled in the RAM analysis.

What we can observe from the data presented above, it that most of the databases provide the data at different structure level of the Turbine. For example in Figure 4-16 and Figure 4-18, the data are at Assembly level (ex. Electrical System, Drive train) and others at equipment level (Ex.: Generator, Brake, Shaft) as per section 4.4.1.3. Thus, the selection of the database is an important factor to be considered in the RAM analysis.

In another hand, NREL [35] provides data at higher level (Table 4-4) however, most of the data are provided as Weibull parameters which is not commonly used in RAM analysis. Normally the reliability data used in RAM analysis are constant failures as presented in section4.4.4.

4.4.1.4Industrial databases

In the absence of data from wind turbine databases the project team collected reliability data from available industrial RAM studies as follows:

- **OREDA** (Offshore Reliability Data) [3][4] is a reliability database programme developed since early 80's. It provides comprehensive oil & gas equipment reliability data. It was initially intended to collect and exchange reliability data among the participating companies and is considered to be one of the most referred reliability database.

- **IEEE 493** Recommended Practice for the Design of Reliable Industrial and Commercial Power System [5]
  IEEE standard 493 also known as IEEE Gold Book intends to main information for reliability analysis of power system for industrial plants and commercial buildings. It contains the reliability data of various equipment utilized for power generation, distribution and HVAC, covering gas turbine generators, electrical switchgear, cable, circuit breakers, pumps, and motors. The data was collected from variety of commercial, industrial, and utility installations over 35 years of operation.

- **PARLOC** (The Pipeline and Riser Loss of Containment) report [41] is the preferred source of risk assessment data for generic loss of containment frequencies and covers pipelines and risers in the offshore oil and gas industry. The results presented in this report are based on data gathered for loss of containment incidents that occurred at pipelines and risers on the UK continental shelf (UKCS) during the 12-year period 2001 – 2012.

- **Public papers and websites**:
  Thanks to the easy accessibility to research websites, internet became almost an unlimited source of information for any kind of subjects. Several websites dedicated to engineering in general and to reliability specifically can be freely consulted in order to collect data from studies and whitepapers related to similar equipment or systems included in tidal turbines.
  For example, the **ROYMECH.CO** website brings a table [43] with indications of failure rates of several mechanical components such as bearings, filters, valves etc; and online libraries such as **WILEY.COM** propose several technical papers related to reliability where sets of data are published. Through this source, it was possible to access the paper "Reliability and Availability of Pod Propulsion Systems" [44] containing failure rates for elements of pod propulsion systems that are similar elements to the ones utilized in tidal turbines such as shafts, mechanical seals and lubricating systems.

4.4.1.5Generic Tidal Turbine FMEA [31]

The FMEA performed in task T1.1 [31], is a qualitative methodology that brings an exhaustive list of failures that can occur in tidal turbines. During this task, the Occurrence of tidal turbine component's failure was qualitatively assessed by the partners. In case the data cannot be found in any database described above, the FMEA can then give an order of magnitude of the failure occurrence and help in estimating the missing failure rates.

4.4.1.6 Partner's discussions and experience

Not all reliability data is available in databases or can be estimated from the FMEA, specially the P-F intervals described in section 4.4.6.2. The missing data has been defined in consensus among partners based on their knowledge and past experience.

4.4.2 Level of detail

In this stage of the RAM analysis, the project team defined the level of detail adopted in the modelling of the system components that should be evaluated.
The common terminology for the level of detail in RAM analysis in industry is as follows;

- Level 0: Complex (Multi Tidal Turbine Farms);
- Level 1: Installation (Tidal Turbine Farm);
- Level 2: Section (e.g. Subsea; Topside; Onshore…);
- Level 3: System / Sub-System (Tidal Turbine, Power Take-off);
- Level 4: Assembly / Sub-Assembly (Yaw, Rotor, Drive Train, Electric system);
- Level 5: Equipment (Generator, Transformer, Gearbox, Pump, Motor, Heater, etc.);
- Level 6: Element (Transducer, non-control valve, relay, bearing, sensor, etc.).

The RAM study was limited to the Assembly and equipment levels (level 4 and 5) since this is the level at which generic reliability data are presented in available databases (refer to section 4.4.1). As a consequence, the components listed in the FMEA [31] and their failure modes had to be grouped into lower levels in order to correspond to the available data in the databases. Therefore, the system could not be modelled at the same level of detail adopted in the FMEA.

4.4.3 Component Boundaries

The boundaries of each component regarding reliability data (MTTF & MTTR) will be considered in line with the boundary defines in each database where the data was collected.

As an example, hereafter is the description of component boundary as presented in page 20 of OREDA 2009 [4], section entitled Equipment Boundaries.
"For each equipment class, an equipment boundary has been defined to identify items that are part of the equipment class and to show interface between these items and their surrounding [..]. The following principles have been applied:

- *Connected units are generally not considered to be part of the equipment unit. Failures that occur in a connection (e.g. leak) are included unless it is known specifically that it has occurred on the connected item outside the boundary*
- *When a driver and the driven unit use common subunits (e.g. lubrication), failures of the subunit are generally related to the driven unit.*
- *Failures on drivers (e.g. gas turbine) and driven units (e.g. compressors) are recorded for each equipment class separately. When a failure rate for a combination of driver and driven units is needed (e.g. compressors driven by gas turbines) the combined values from these two equipment classes should be used.*

- *Failures on instrumentation are only included if the instrumentation has specific control and/or monitoring function for the equipment unit and/or is locally mounted (e.g. sensors). Instrumentation of a more general use, such as supervisory system (SCADA) is not included"*

An example of boundaries definition for pumps as presented in page 21 of the OREDA 2009 [4] is given in Figure 4-19.

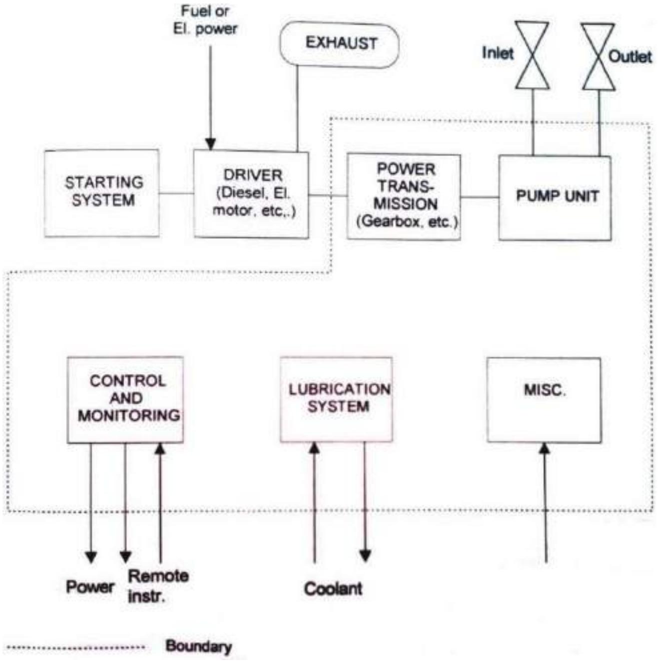


Figure 4-19 - Pumps Boundaries

Reliability data for Pumps will be then split in an item "pump" and an item "motor" including their respective Failure and Repair data.

4.4.4 Failure rate (λ)

Failure rate is the frequency with which a system or component fails, expressed in failures per unit of time. It is usually denoted by the Greek letter λ (lambda) and is one of the most important data for RAM studies.

As described in OREDA handbook 2002 [3] and illustrated in *Figure 4-20*, "*the failure rate function may be decreasing in the burn-in phase, close to constant in the useful life phase, and increasing in the wear-out phase. This curve is called "bath-tub" curve because of its characteristic shape, and is often claimed to be realistic model for mechanical equipment.*

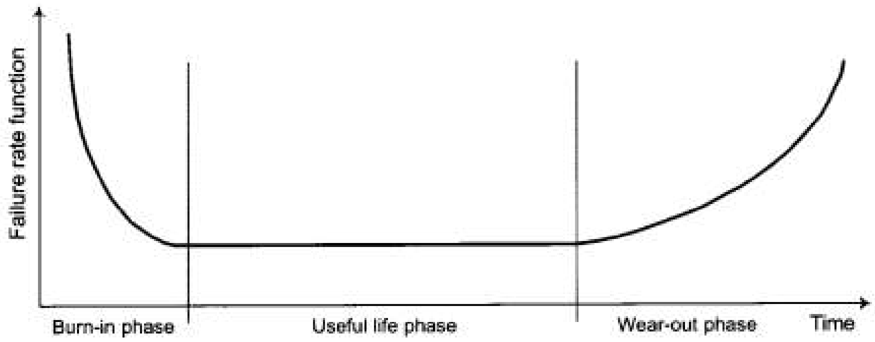


Figure 4-20 - Bath Tub Shape of the Failure Rate

If we assume that the failure rate function is constant during useful life phase, this means that the item is not deteriorating during this phase. The deterioration will start when, or if, the item enters the wear-out phase. Burn-in problems may be caused by inherent quality problems in the item, or by installation problems. Inherent quality problems may sometimes be removed by careful quality testing prior to installation. "

Data will mainly be collected from the reliability databases mentioned in section 4.4.1, where the main part of the failure events will therefore come from the useful life phase, where failure rate is close to constant. OREDA handbooks introduction mentions that "*all the failure rate estimates presented in this handbook are therefore based on the assumption that the failure rate function is constant and independent of time, in which case the failure rates are assumed to be exponential distributed with* **λ** *parameter*". In this case, it will be considered that the equipment will not last until the end of its useful life but that a random failure will occur in the same proportions than other identical industrial components.

Constant failure rate in useful life is estimated by:

$$\lambda = \frac{Number\ of\ failures}{Aggregated\ time\ in\ service}$$

(Equation 4)

The probability distributions used to model the failure distribution in this case is the exponential failure distribution, expressed by the following formula:

$$F(t) = 1 - e^{-\lambda t}$$

(Equation 5)

The model will systematically incorporate exponential distributions to represent the failure rate of a component.

Note: Burn-in phase failure related to post commissioning and wear-out phase failure due to aging have not been considered in the model.

Annex C presents all the reliability data proposed for the study for each component of both concepts 1 and 3, including their failure rates.

4.4.5 Mean Time To Fail (MTTF)

Mean Time To Fail (MTTF) is the average service time for an equipment to fail and is calculated from the reverse of failure rate as presented in following formula:

$$MTTF = \frac{1}{\lambda}$$

(Equation 6)

4.4.6 Failure modes - General Approach

4.4.6.1Functional Failures

Generally, the failures reported in the databases considered by the project team caused complete or partial loss of the system's function or led to an unacceptable situation (such as excessive vibration) that could escalade to very severe events. In all cases, the failures generated a corrective or unplanned maintenance. Those failures have been classified as functional failures and they have been considered in the model as causing an immediate effect on the system's functionality.
The "failed capacity" is defined as the resulting amount of production capacity that the item allows through its parent component when the component is in fail state. In this study, the failed capacity has been considered equal to zero when a functional failure occurs, except where explicitly stated. The failure rates that have been collected from databases listed in section 0 were used in the model as input to simulate the occurrence of components functional failures.

Apart from that, the failures of tidal turbines are repaired in different ways requiring different means of maintenance depending on the type of failure and also depending on type of concept. This is why some precautions must be taken when failures are modelled in the RAM study.
The failures occurring on bottom fixed tidal turbines require the turbine to be lifted up in an OSV or a barge in order to be repaired. In the case of floating turbines, the components maintenance can be performed in situ when the component is accessible from the nacelle while a major failure (equipment replacement or overhaul) may require the repair to be carried onshore.

In order to take into consideration the different logistics required for repairing components, the functional failures were split into 3 categories based on the following principles:

- **Major failures: Time to repair greater than 24 hours;**
- **Minor failure: Time to repair between 1hour and 24 hours;**
- **Trivial failures: Time to repair less than 1 hour.**

According to partner's experience, trivial failures are related to electronics or sensors failures that cause turbine trips and then its stoppage. Most of these failures are solved by a remote reset of the tidal turbine without the need to mobilize any maintenance mean to the turbine. These failures requesting remote interventions were excluded from this study as the downtime caused is considered negligible when compared to the other two types of failures (see also section 6.3.2).

Minor failures are failures that can be easily identified and repaired with available spare parts. In the case of floating turbines, these failures can be repaired in situ by the maintenance staff when the failed component is accessible from the nacelle.

Major failures are complex failures that requires most of times the disassembly of the turbine parts. These failures may be related to costly components without spare parts readily available. In those cases, the long time to repair is due to the lead time of the spare parts.

For each component modelled, the project team estimated which percentage of its failure rate correspond to each category of failure (Major, Manor and Trivial). This estimation was based on the Ingeteam database presented in section 4.4.1.2.

Annex C presents the reliability data utilised for each component of both concepts 1 and 3, including their failure rate and the percentage of failure that corresponds to each category.

4.4.6.2Potential Failure

According to [28],*" most of failures give some sort of warning that they are in process of occurring or are about to occur. If evidence can be found that something is in the final stages of failure, it may be possible to take action to prevent it from failing completely and/or to avoid the consequences. The Figure 4-21 – P-F Curve [28] illustrates what happens in the final stages of failure"* which are:

- Smooth running: It refers to normal working condition where no anomalies are detected.
- Degradation: A decrease in the condition of the components.
- Functional Failure: The component fails and becomes inoperative.

"The final stage is also called P-F curve, because it shows how a failure starts, deteriorates to the point at which it can be detected (point 'P') and then, if it is not detected and corrected, continues to deteriorate – usually at an accelerating rate – until it reaches the point of function failure ('F').

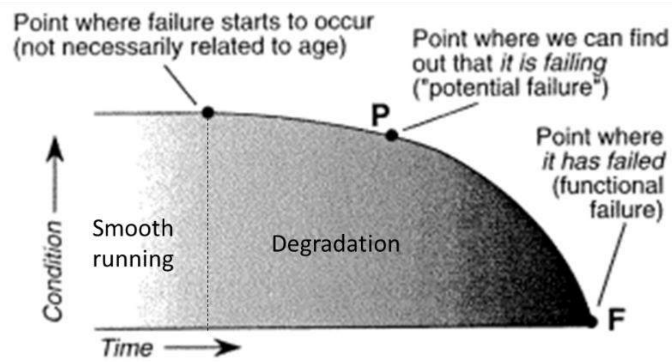


Figure 4-21 – P-F Curve [28]

The point in the failure process at which it is possible to detect whether the failure is occuring or is about to occur is known as a potential failure.
If a potential failure is detected between point 'P' and point 'F' in Figure 4-21, it may be possible to take action to prevent or to avoid the consequences of the functional failure."
Example of potential failure is vibration indicating imminent bearing failure, cracks showing metal fatigue, temperature increasing showing deteriration of electrical insulation.

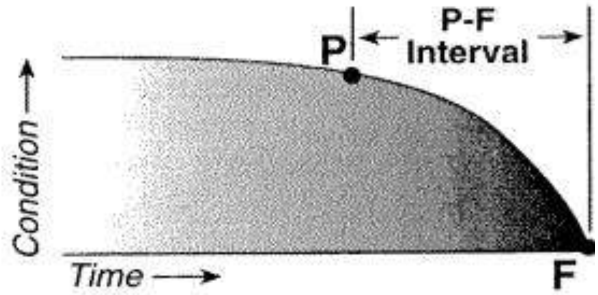


Figure 4-22 - P-F interval [28]

Always according to [28], *"in addition to the failure itself, we need to consider the amount of time (or number of stress cycles) which elapse between the point at which a potential failure occurs – in other words, the point at which it becomes detectable – and the point where it deteriorates into a functional failure. As shown* in Figure 4-22 this interval is known as the P-F interval.

The P-F interval is also known as the warning period, the lead time to failure or the failure development period. It can be measured in any units which provide an indication of exposure to stress (running time, units of output, stop-start cycles, etc.) but for practical reasons, it is most often measured in terms of elapsed time. For different failure modes, it varies from fractions of a second to several decades.

Unfortunately, it does not exist any database informing P-F intervals. This is because, not all equipment are monitored, but also P-F curve depends on the technique and its effectiveness to detect potential failures. Indeed, the degradation of a bearing can be detected few weeks or even months before it fails thanks to vibration analysis. But if bearing is monitored by temperature measurements, its degradation is detected only few days before failure

In this Base case model, P-F interval was assumed to be equivalent to 25% of the MTTF of the component for Major and Minor Failures or limited to 2 months in case MTTF is higher than 8 months. It was also considered that not all failures will be detected. A percentage of failure of detection was estimated based on the FMEA performed in Task T1.1 [31] according to the detectability level of the monitoring types in place for each failure mode expected for this component.

For trivial failures, it was assumed that they occur almost instantaneously, i.e. without any previous sign of detectable degradation. Therefore, trivial failures cannot be prevented by monitoring.

4.4.7 Mean Time To Repair (MTTR)

Mean Time To Repair is the maintenance calendar time required to repair and return the item to a state where it is ready to resume its functions, irrespective of the number of persons that may work in parallel and excluding logistic delays such maintenance mobilization and time to connect/ disconnect and retrieve the unit from the grid (lifting operations).
Times such as time to detect failure, issue work order, delay and waiting for spare parts, Active repair time, time for testing and restart after repair, etc are included as being an integrated part of repair activity time. Figure 4-23 illustrates the active repair time and other maintenance times.

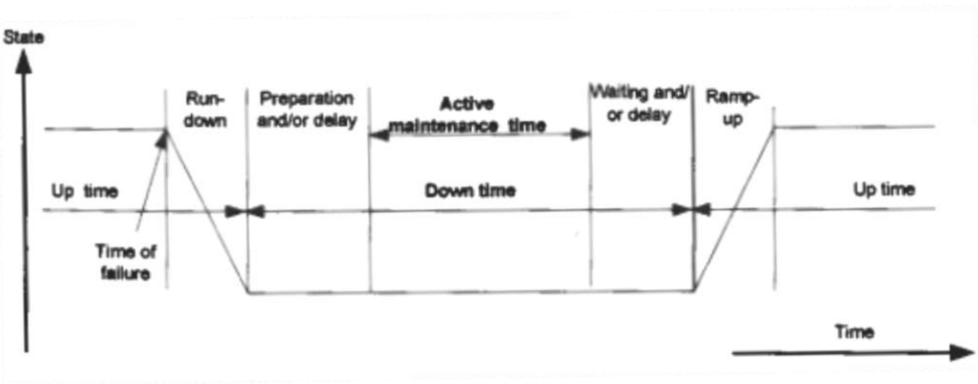


Figure 4-23 - Maintenance Times (ISO 14224)

Mean Time To Repair has been selected considering the same data sources defined in section 4.4.1: Exponential time distribution has been used to represent the repair duration. Mobilisation time is not taken into account in the MTTR and is presented separately in section 6.4.3 depending on the type of component and failure. Section 6.4 present general assumptions regarding all maintenance and logistic times considered in the RAM model.

Annex C presents the reliability data utilised for each component of both concepts 1 and 3, including Mean Time To Repair that corresponds to each category of failure.

4.4.8 Reliability data summary – Base case

The reliability data including failure rates and MTTFs utilised in this study is presented in the Annex C.

The Figure 4-24 presents the Sankey diagrams which represent the relationship between the failure rates and Mean Time To Failure of each component considered in the base case model.

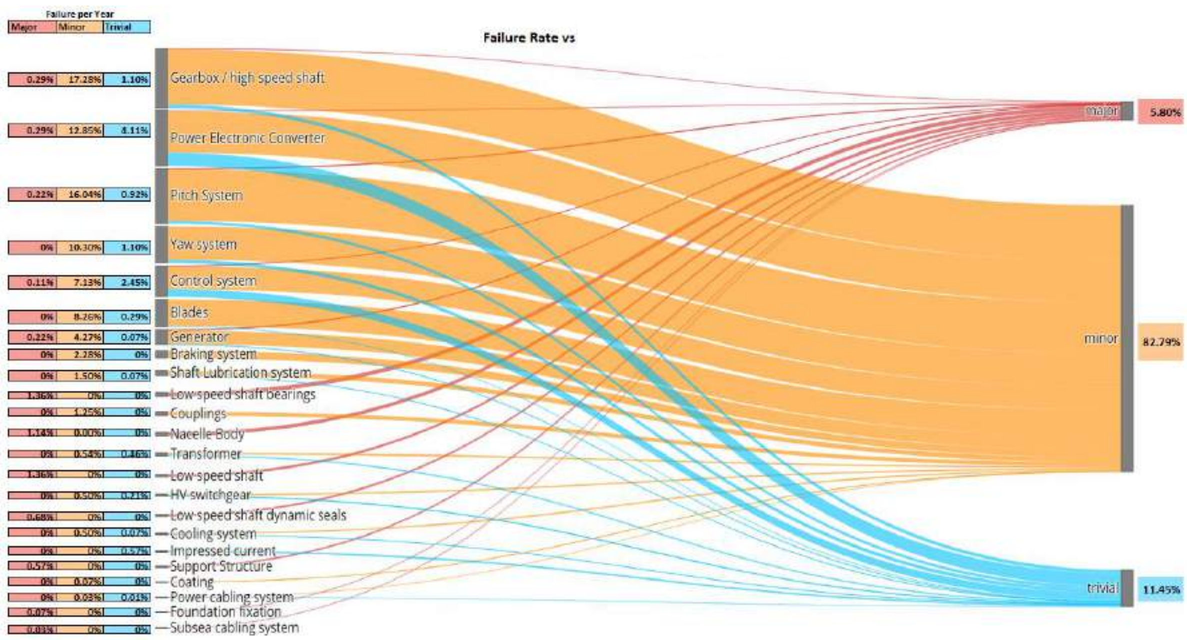


Figure 4-24 - Sankey diagram of reliability data used as an input for RMA base case models

On the left side of the Sankey graph, the components are ranked in descending order of failure rate. The failures categorisation are shown at the left side.

It is observed that the top components that present the highest failure rates are:

- Gearbox & high speed shaft;
- Power Electronic Converter;
- Pitch System;
- Yaw system;
- Control System;
- Blades, and
- Generator

Around 83% of failures were categorized as minor failures (repair time between 1 and 24 hours); less than 6% were categorized as major failures (repair time greater than 24 hours); the remaining 11% were categorized as trivial failures (repair time less than 1 hour).

5 DEFINITIONS

5.1 Terms and Definitions

For the purpose of this document, the following terms and definitions are applied.
Active Repair Time: Part of the maintenance time during which a maintenance action is performed on an item, either automatically or manually, excluding logistic delays.
Availability: Ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided.
Boundary: Interface between an item and its surroundings.
Calendar Time: Interval of time (surveillance time) between the start date and end date of Reliability/Maintenance data collection.
Condition Monitoring: the process of monitoring a parameter of condition in machinery (vibration, temperature etc.), in order to identify a significant change which is indicative of a developing fault.
Corrective Maintenance: Maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function.
Functional Failure: A failure which causes immediate and complete loss of a system capability of providing its output.
Potential Failure: an identifiable condition which indicates that functional failure is either about to occur or in the process of occurring [28].
Equipment Data: Technical, operational and environmental parameters characterizing the design and use of an equipment unit.
Failure Data: Data characterizing the occurrence of a failure event.
Failure mode: Effect by which a failure is observed on the failed item.
Service Time: Time interval during which an item is in servicing state.
Maintainability: Ability of a failed item to have its required function restored under given conditions for a given time interval.
Operation Philosophy: Rules describing how the installation is operated including safety, maintenance, spare issues as well as flaring policies.
Population: The total number of items of one particular type in service during the period of the event data surveillance.
Preventive maintenance: Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce probability of failure or the degradation of the functioning of an item (ISO 20815:2008 [42])
Reliability: Ability of an item to perform a required function under given conditions for a given time interval.
Severity Classification: Describes effect on operational status and the severity of loss of output from the system. The severity classification is connected to the ability of the item in question to perform its function.
Subunit: Assembly of items that provides a specific function that is required for the equipment unit within the main boundary to achieve its intended performance.
Taxonomy: Systematic classification of items into generic groups based on factors possibly common to several of the items.

5.2 Production Capacity

The tidal turbine rating for the RAM simulation is based on Sabella's D10 1 MW turbine over a operating life of 20 years with a production profile as defined in section 0**.** All component capacities for the concepts analysed in this study were calculated with respect to this production profile. There is no target availability defined over the 20 years life for this project.

5.3 Criticality

Systems and equipment are categorised as either '**critical**' or '**non-critical**' in terms of their impact on production. Failure of critical equipment results in the loss of normal production associated with that item. Conversely, failure of non-critical equipment has no impact on production.
Parallel equipment is described with a term such as "2 x 100%". 2 x 100% critical units do not cause production losses unless both items have failed and are failed simultaneously. Failure of either one of 2 x 80% critical units will cause normal production to reduce to 80%.

5.4 Production Availability

Production Availability is a measure of the actual performance of a production system accounting for production loss due to planned and unplanned outages against the potential production of the system given no outages have occurred within a given system life.
Thus Production Availability can be expressed as the percentage:

$$\frac{Actual\ production\ allowing\ for\ Planned\ and\ Unplanned\ downtime}{Potential\ production\ with\ no\ downtime} \times 100$$

(Equation 7)

Availability includes planned events and unplanned events.
Availability can be described in three ways:

- Inherent Availability – considering only the corrective downtime of the system;
- Achieved Availability – considering both corrective and preventative maintenance downtimes of the system; and
- Production Availability – is the average availability over time and includes all experienced sources of downtime, such as administrative downtime and logistics (i.e. the availability the customer actually experiences).

Production Availability was used as the performance measure for the RAM Model with the very important understanding that whilst repair and logistics downtimes are incorporated, no scheduled preventive maintenance scheme has been implemented.

6 ASSUMPTIONS

6.1 Overview

RAM models describe systems in terms of their components functional capacities and behaviours, redundancy and failure effects. The capacities, redundancies and failure effects used in a specific RAM model are collectively referred to as the model assumptions. The assumptions used for each component item are based on document "FMEA Report" [31], component levels and boundaries (sections 4.4.2 and 4.4.3), failure modes approach (section 4.4.6) and partner's experience.

Sections 6.2, 6.3, 6.4, 0 and 6.6 describe the current model assumptions for the RAM Base Case Model of each tidal turbine concept included in the scope of this study. The Reliability Block Diagram (RBD) that describes the operational dependency relationship between components within the system is provided as Annexes A and B for concepts 1 and 3 respectively. The asset register including reliability, failure effects and maintainability data for each component is provided as Annex C for concepts 1 and 3.

6.2 RAM Component Assumptions

6.2.1 General Assumptions

As mentioned in sections 4.4.2 and 4.4.3, the reliability data available in the databases are the key drivers to define the level of detail of each component to be modelled in the RAM analysis. This is why some components in the RAM was modelled essentially at Assembly/Sub-Assembly level (according to definition in section 4.4.2). Sometimes some sub-assemblies had to be grouped in the same RAM component because there is no reliability data available for the individual sub-assembly but only for a group of sub-assemblies. This is the case, for example, of Blades and Hub that are grouped in some databases as illustrated in Figure 4-16 and Figure 4-17 [33]. In this database, there is no data neither for the blades nor for the hub but only for the group "Bladed & Hub".

All sub-assemblies which failure to contributing to loss of production have been considered in the model and are presented in one of the RAM component as per Table 6-1 and Table 6-2 below.

The sub-assemblies not required in normal operation such as those related to safety of the Tidal Turbine (e.g.: Fire Fighting) or maintenance/installation operations (e.g.: ballast system) has been excluded from the RAM modem. Indeed, the failure of these items in normal operation doesn't impact the production, i.e. the system reliability. Moreover, those items are usually required when an incident had already occurred and the tidal turbine in such situation is already stopped or in a failed state. As a summary such items are considered as "non-critical" to production and then are not included in the RAM model.

It is to be noted that the architecture of each design was created in the simplest and standardized way. It means that all typical components of each concept were represented without any redundancy; except in the case were redundancy is considered as a best practice (such as the case of mechanical seals where the benefit of its duplication is well known for turbine integrity).

This section provides the considerations that have been made for the components in respect with the RAM modelling of each tidal turbine concept included in this study.

6.2.2 Concept 1 "Complex bottom fixed tidal turbine" Assumptions

6.2.2.1Components list

The assemblies and sub-assemblies included in the model of the Concept 1 "Complex bottom fixed tidal turbine" are presented in Table 6-1. The column "RAM Component" in this table represents in which component these sub-assemblies have been included or grouped in the RAM model.
The description of the functions, failure modes and effects presented in the FMEA Report [31] and is not reproduced in this report.

Table 6-1 - Components modelled in RAM study for concept 1 "Complex bottom fixed tidal turbine"

Sub-system	Assembly	Sub-Assembly	RAM Component
Hydrodynamic System	Nacelle (Openable Nacelle)	Nacelle shell	**Nacelle Body**
		Nacelle joints	
		Interface with supporting structure	
		Penetrations	
		Sub-assembly frame	
		Access into nacelle (hatches)	
	Rotor	Blades	**Blades**
		Hub	
		Front Bulb	
		Pitch System	**Pitch System**
	Yaw system	Yaw shaft (trunnion, crank ring)	**Yaw system**
		Yaw Gear	
		Yawing mechanism power actuator	
		Yaw locking / brake mechanism	
		Cable and pipe management system	
		Yaw load bearing	
Reaction System	Foundation system (Gravity base)	Foundation fixation	**Foundation fixation**
	Support Structure (Fixed structure + Fixation Piles)	Interface with foundation	**Support Structure**
		Main Structure (including auxiliary equipment)	
		Interface with turbine support	
Power take off	Auxiliaries	Cooling system	**Cooling system**
	Drivetrain	Low speed shaft	**Low speed shaft**
		Low speed shaft bearings	**Low speed shaft bearings**
		Low speed shaft dynamic seals	**Low speed shaft dynamic seals**
		Gearbox / high speed shaft	**Gearbox / high speed shaft**
		Couplings	**Couplings**
		Braking system	**Braking system**
		Shaft Lubrication system	**Shaft Lubrication system**
	Control & Communication system (SCADA & Emergency and safety chains)	Control system	**Control system**
		Condition monitoring	
		Systems cabinets	

Sub-system	Assembly	Sub-Assembly	RAM Component
	Electrical system	Generator	**Generator**
		Power Electronic Converter	**Power Electronic Converter**
		Transformer(s) - Liquid insulated transformer	**Transformer**
		HV switchgear	**HV switchgear**
		LV switchgear	**Power cabling system**
		Power cabling system	
		Auxiliary Cabling System and Connector	
		Subsea cabling system	**Subsea cabling system**
		Subsea cable joints	
Hydrodynamic System & Reaction System	Corrosion protection	Coating	**Coating**
		Impressed current	**Impressed current**

6.2.2.2 Component considerations

6.2.2.2.1 Nacelle

The nacelle for this concept is an openable nacelle. This means that the equipment inside the nacelle can be accessed without cutting the nacelle body.

The Nacelle assembly was modelled in a unique RAM component **Nacelle body.**
The "Nacelle Body" component includes and simulates the failure modes leading to turbine loss of production of the following nacelle sub-assemblies:

- Nacelle shell
- Nacelle joints
- Interface with supporting structure
- Penetrations
- Sub-assembly frame
- Access into nacelle (hatches)

The failure of the Nacelle body component is assumed to impact 100% of production.

The sub-assemblies "Seafastening / tug points" and "Lifting points" are considered as non-critical to production because their failures will not impact production in normal operation, and used only during maintenance and installation operations.

The corrosion protection sub-assembly was excluded from this component as this sub-assembly was grouped with the corrosion protection of the assembly Support Structure in a separate component (section 6.2.2.2.10)

6.2.2.2.2 Rotor

The Rotor assembly was modelled into two RAM components:

- **Blades**; which includes and simulates the failure modes leading to turbine loss of production of the following rotor sub-assemblies:
    - Blades;
    - Hub;
    - Front Bulb.
- **Pitch system**; which includes and simulates the failure modes leading to turbine loss of production of the Pitch system sub-assembly.

The failure of each Blades and Pitch System component is assumed to impact 100% of production.

6.2.2.2.3 Yaw system

The Yaw System assembly was modelled in a unique RAM component **Yaw System.**
The "Yaw System" component includes and simulates the failure modes leading to turbine loss of production of the following nacelle sub-assemblies:

- Yaw shaft (trunnion, crank ring);
- Yaw Gear;
- Yawing mechanism power actuator;
- Yaw locking / brake mechanism;
- Cable and pipe management system;
- Yaw load bearing.

The particularity of this component compared to the other ones, it that **the failure of the Yaw system will lead to a partial loss of production equivalent to 50%** of the tidal turbine production capacity before the failure. For example, let say that the production capacity is reduced to 96% because of fouling, and that the yaw system fails at that moment, then the production capacity of the tidal turbine will decrease to 48% (96% x 50%).
This is because the turbine, will no longer be able to be oriented to the tidal direction in a such manner that the turbine will be able to produce only the 50% of the time the tide flows in the direction the tidal turbines oriented.

6.2.2.2.4 Foundation system

The Foundation System for this concept is assumed to be a gravity based foundation.

The Foundation System assembly was modelled in a unique RAM component **Foundation System** which includes and simulates the failure modes leading to turbine loss of production of Foundation System sub-assembly.

The failure of the Foundation system component is assumed to impact 100% of production.

6.2.2.2.5 Support Structure

The Support Structure is a fixed structure with fixation piles and was modelled in a unique RAM component **Support Structure.**
The "Support Structure" component includes and simulates the failure modes leading to turbine loss of production of the following sub-assemblies:

- Interface with foundation;
- Main Structure (including auxiliary equipment);
- Interface with turbine support.

The failure of the Support structure component is assumed to impact 100% of production.

The corrosion protection sub-assembly was excluded from this component as this sub-assembly was grouped with the corrosion protection of the assembly Nacelle in a separate component (section 6.2.2.2.10)

The sub-assembly "Installation interface" is considered as non-critical to production because their failures will not impact production in normal operation, and are used only during installation operations.

6.2.2.2.6 Auxiliaries

In the Auxiliaries assembly, only the **Cooling System** sub-system has been modelled as a component which includes and simulates the failure modes leading to turbine loss of production of the Cooling System sub-assembly.

The failure of the Cooling system component is assumed to impact 100% of production.

According to section 6.3, the Fire Fighting System was excluded from the RAM Model as this system is safety system that is used only in abnormal situations. Thus its failures have no impact on production during normal operations.

The air treatment was not considered in the RAM Model as its failure will not impact the tidal turbine production in normal situation as the air treatment is only required when humidity is detected in the Nacelle, usually because of a sea leakage in the nacelle. Such leakages are caused by Nacelle or seal failures and then repair is assumed to be required no matter if air treatment is working or not.

6.2.2.2.7 Drivetrain

Each sub-assembly of the Drive Train assembly was modelled as an individual RAM component which includes and simulates their respective failure modes leading to turbine loss of production.
Then the following sub-assemblies has been modelled as a RAM component:

- **Low speed shaft;**
- **Low speed shaft bearings;**
- **Low speed shaft dynamic seals;**
- **Gearbox / high speed shaft;**
- **Couplings;**
- **Braking system;**
- **Shaft Lubrication system**.

Considering that, as a good practice, tidal turbines are usually designed with two shaft dynamic seals to prevent sea water ingress in the tidal turbine, the dynamic seals components have been modelled in the RAM model with 2x100% redundancy configuration. This means that no sea water ingress is possible unless both shaft seals are failed at the same time.

The failure of each component is assumed to impact 100% of production, except for the Low speed shaft dynamic seals which both need to fail in order to impact 100% of production;

6.2.2.2.8 Control & Communication system

The Control & Communication system was modelled in a unique RAM component **Control system.** The "Control system" component includes and simulates the failure modes leading to turbine loss of production of the following sub-assemblies:

- Control system;
- Condition monitoring;
- Systems cabinets.

The failure of the Control system component is assumed to impact 100% of production.

6.2.2.2.9 Electrical system

The Electrical System assembly was modelled into six RAM components:

- **Generator**, which includes and simulates the failure modes leading to turbine loss of production of the Generator sub-assembly;
- **Power Electronic Converter**, which includes and simulates the failure modes leading to turbine loss of production of the Power Electronic Converter sub-assembly;
- **Transformer**, which includes and simulates the failure modes leading to turbine loss of production of the Transformer(s) - Liquid insulated transformer sub-assembly;
- **HV switchgear**, which includes and simulates the failure modes leading to turbine loss of production of the HV switchgear sub-assembly;
- **Power cabling system**; which includes and simulates the failure modes leading to turbine loss of production of the following sub-assemblies:
    - LV switchgear;
    - Power cabling system;
    - Auxiliary Cabling System and Connector;
- **Subsea cabling system**, which includes and simulates the failure modes leading to turbine loss of production of the following sub-assemblies:
    - Subsea cabling system;
    - Subsea cable joints.

The failure of each component is assumed to impact 100% of production.

Regarding the **HV switchgears,** they are only required when there are **Power Electronic Converters** (or **Transformers**) in redundancy configuration (e.g. 2x100% redundancy). It means that when there is no redundancy of this components there is no HV switchgear in the electrical system.

In the case of a configuration of Power Electronic Converters (or Transformers) redundancy, the switchgear are responsible for switch from the duty Converter (or transformer) to the stand-by converter (or transformer) in case of failure of the duty converter (or transformer). In this configuration, a HV switchgear is installed at the inlet and another at the outlet of the redundant converters (or transformers). In case of HV switchgear failure in normal operation, there is no impact on production. However, the redundancy is lost in case of failure of the duty converter (or transfer) and the production is fully impacted even if the stand-by converter (or transformer) is not failed

The RAM Model Base Case assumes that the Electrical system includes one Power Electronic Converters and one Transformer, thus no HV Switchgear in not required and then not modelled in the RAM model Base Case.

According to section 6.3; the UPS systems and the Electrical Protection and Safety sub-assemblies were excluded from the RAM Model as they are safety systems. They are used only in abnormal situations; thus its failures have no impact on production during normal operations.

6.2.2.2.10 Corrosion protection

The corrosion protection sub-assembly from Hydrodynamic and Reaction Systems was grouped in a unique sub-assembly which was modelled into two RAM components:

- **Coating**;
- **Impressed current**.

Both components protect the tidal turbine integrity from corrosion degradation. It was assumed that corrosion will start only when both coating and impressed current components are in failed state. In case of corrosion occurring on the Tidal Turbine, it was assumed that there is no immediate loss of production however, recoating and structural repairs need to be performed when an opportunity arises (for example when a component is being repaired onshore).

6.2.2.2.11 External Factor - Fouling

In addition to the tidal turbine components failures, it has been assumed that fouling can occur in a general manner in the turbine.
Fouling is a natural process that starts since the first date of production and increases with time. It was assumed that tidal turbine loses 1% of production per year due to fouling growth.
It was also assumed that the fouling is removed each time the tidal turbine is cleaned during maintenance activities (for example when a component is being repaired onshore).

6.2.2.3Components included in BASE case model.

Further to the assumptions described in this section, the elements that are effectively modelled are listed below and presented in the RBD in the Annex A. The reliability data related to the modelled components including the loss of production in failed state are presented in the Asset Register in the Annex C.

- **Hydrodynamic System:**
  - Nacelle:
    - *Nacelle Body*
  - Rotor:
    - *Blades*
    - *Pitch System*
  - Yaw system:
    - *Yaw system*
- **Reaction System:**
  - Foundation system (Gravity base):
    - *Foundation system*
  - Support Structure:
    - *Support Structure*
- **Power take off:**
  - Auxiliaries:
    - *Cooling System*
  - Drivetrain:
    - *Low speed shaft*
    - *Low speed shaft bearings*
    - *Low speed shaft dynamic seals (2x 100%)*
    - *Gearbox / high speed shaft*
    - *Couplings*
    - *Braking system*
    - *Shaft Lubrication system*
  - Control & Communication system:
    - *Control System*
  - Electrical system:
    - Generator
    - Power Electronic Converter
    - Transformer
    - Power cabling system
    - Subsea cabling system

- **Multiple systems:**
  - Corrosion protection:
    - *Coating*
    - *Impressed current*

    } *(2x 100%)*
  - External:
    - *Fouling*

6.2.3 Concept 3 "Floating multi rotor tidal turbine"

The assemblies and sub-assemblies included in the model of the Concept 3 "Floating multi rotor tidal turbine" are presented in Table 6-2. The column "RAM Component" in this table represents in which component these sub-assemblies have been included or grouped in the RAM model.
The description of the functions, failure modes and effects presented in the FMEA Report [31] and is not reproduced in this report.

Table 6-2 - Components modelled in RAM study for concept 3 "Floating multi rotor"

Sub-system	Assembly	Sub-Assembly	RAM Component
Hydrodynamic System	Nacelle (Welded Nacelle)	Nacelle shell	**Nacelle Body**
		Nacelle joints	
		Interface with supporting structure	
		Penetrations	
		Sub-assembly frame	
		Access into nacelle (above sea water)	
	Rotor	Blades	**Blades**
		Hub	
		Front Bulb	
		Pitch System	**Pitch System**
Reaction System	Foundation system (Pretensioned anchor pile)	Foundation fixation	**Foundation fixation**
	Support Structure (Floating structure + Pretensioned anchor piles (Mooring lines + Turret))	Interface with foundation	**Support Structure**
		Main Structure (including auxiliary equipment)	
		Interface with turbine support	
Power take off	Auxiliaries	Cooling system	**Cooling system**
	Drivetrain	Low speed shaft	**Low speed shaft**
		Low speed shaft bearings	**Low speed shaft bearings**
		Low speed shaft dynamic seals	**Low speed shaft dynamic seals**
		Gearbox / high speed shaft	**Gearbox / high speed shaft**
		Couplings	**Couplings**
		Braking system	**Braking system**
		Shaft Lubrication system	**Shaft Lubrication system**
	Control & Communication system (SCADA & Emergency and safety chains)	Control system	**Control system**
		Condition monitoring	
		Systems cabinets	
	Electrical system	Generator	**Generator**
		Power Electronic Converter	**Power Electronic Converter**
		Transformer(s) - Liquid insulated transformer	**Transformer**
		HV switchgear	**HV switchgear**
		LV switchgear	**Power cabling system**
		Power cabling system	
		Auxiliary Cabling System and Connector	

Sub-system	Assembly	Sub-Assembly	RAM Component
		Subsea cabling system	**Subsea cabling system**
		Subsea cable joints	
Hydrodynamic System & Reaction System	Corrosion protection	Coating	**Coating**
		Impressed current	**Impressed current**

6.2.3.1.1 Nacelle

The nacelle for this concept is a floating nacelle. This means that the equipment inside the nacelle can be accessed by maintenance crew for maintenance as the access into nacelle is above sea water.

The Nacelle assembly was modelled in a unique RAM component **Nacelle body.**
The "Nacelle Body" component includes and simulates the failure modes leading to turbine loss of production of the following nacelle sub-assemblies:

- Nacelle shell
- Nacelle joints
- Interface with supporting structure
- Penetrations
- Sub-assembly frame
- Access into nacelle (hatches)

The failure of the Nacelle body component is assumed to impact 100% of production.

The sub-assembly "Lifting points" is considered as non-critical to production because their failures will not impact production in normal operation, and used only during maintenance and installation operations.

The corrosion protection sub-assembly was excluded from this component as this sub-assembly was grouped with the corrosion protection of the assembly Support Structure in a separate component (section 6.2.3.1.10)

6.2.3.1.2 Rotor

The Rotor assembly was modelled into two RAM components:

- **Blades**; which includes and simulates the failure modes leading to turbine loss of production of the following rotor sub-assemblies:
  - Blades;
  - Hub;
  - Front Bulb.
- **Pitch system**; which includes and simulates the failure modes leading to turbine loss of production of the Pitch system sub-assembly.

It is assumed that for this concept that there are two rotors, each one responsible to 50% of production. Therefore, both rotors need to be in operation at the same time to ensure 100% of production. The failure of one of the components included in the rotor, is assumed to lead to rotor stoppage and then to loss of 50% of production. In case both rotors fail, the production rate drops to 0%.

6.2.3.1.3 Yaw system

The Yaw System assembly was not modelled in the RAM model as it is considered that there is no active yaw mechanism although the floating structure can rotate around the turret which is moored to the seabed via mooring lines (which are included in the Support Structure component).

6.2.3.1.4 Foundation system

The Foundation System for this concept is assumed to be a pretensioned anchor pile.

The Foundation System assembly was modelled in a unique RAM component **Foundation System** which includes and simulates the failure modes leading to turbine loss of production of Foundation System sub-assembly.

The failure of the Foundation system component is assumed to impact 100% of production.

6.2.3.1.5 Support Structure

The Support Structure is a floating structure with pre-tensioned anchor piles (including mooring lines and turret) and was modelled in a unique RAM component **Support Structure.**
The "Support Structure" component includes and simulates the failure modes leading to turbine loss of production of the following sub-assemblies:

- Interface with foundation;
- Main Structure (including auxiliary equipment);
- Interface with turbine support.

The failure of the Support structure component is assumed to impact 100% of production.

The corrosion protection sub-assembly was excluded from this component as this sub-assembly was grouped with the corrosion protection of the assembly Nacelle in a separate component (section 6.2.3.1.10)

The sub-assembly "Installation interface" is considered as non-critical to production because their failures will not impact production in normal operation, and are used only during installation operations.

6.2.3.1.6 Auxiliaries

In the Auxiliaries assembly, only the **Cooling System** sub-system has been modelled as a component which includes and simulates the failure modes leading to turbine loss of production of the Cooling System sub-assembly.

The failure of the Cooling system component is assumed to impact 100% of production.

According to section 6.3, the Fire Fighting System was excluded from the RAM Model as this system is safety system that is used only in abnormal situations. Thus its failures have no impact on production during normal operations.

The air treatment was not considered in the RAM Model as its failure will not impact the tidal turbine production in normal situation as the air treatment is only required when humidity is detected in the

Nacelle, usually because of a sea leakage in the nacelle. Such leakages are caused by Nacelle or seal failures and then repair is assumed to be required no matter if air treatment is working or not.

Ballast and bilge system were not considered as they are not used in normal operation. They are used only in abnormal situations; thus its failures have no impact on production during normal operations. Beacons and lights also don't have a direct impact in production, therefore it was considered that their failure will not lead to loss of production.

6.2.3.1.7 Drivetrain

Each sub-assembly of the Drive Train assembly was modelled as an individual RAM component which includes and simulates their respective failure modes leading to turbine loss of production.
Then the following sub-assemblies has been modelled as a RAM component:

- **Low speed shaft;**
- **Low speed shaft bearings;**
- **Low speed shaft dynamic seals;**
- **Gearbox / high speed shaft;**
- **Couplings;**
- **Braking system;**
- **Shaft Lubrication system**.

Considering that, as a good practice, tidal turbines are usually designed with two shaft dynamic seals to prevent sea water ingress in the tidal turbine, the dynamic seals components have been modelled in the RAM model with 2x100% redundancy configuration. This means that no sea water ingress is possible unless both shaft seals are failed at the same time.

It is assumed that for this concept that there are two drivetrains, each one driven by one rotor, thus responsible to 50% of production. Therefore, both drivetrains need to be in operation at the same time to ensure 100% of production.

The failure of one of the component included in the drivetrain (except for Low speed shaft dynamic seals which are redundant*) is assumed to lead to its stoppage and then to loss of 50% of production. In case both drive trains fail, the production rate drops to 0%.

*Both low speed shaft dynamic seals need to fail at the same time in order to stop the drivetrain where there are fitted.

6.2.3.1.8 Control & Communication system

The Control & Communication system was modelled in a unique RAM component **Control system.**
The "Control system" component includes and simulates the failure modes leading to turbine loss of production of the following sub-assemblies:

- Control system;
- Condition monitoring;
- Systems cabinets.

The failure of the Control system component is assumed to impact 100% of production.

6.2.3.1.9 Electrical system

The Electrical System assembly was modelled into six RAM components:

- **Generator**, which includes and simulates the failure modes leading to turbine loss of production of the Generator sub-assembly;
- **Power Electronic Converter**, which includes and simulates the failure modes leading to turbine loss of production of the Power Electronic Converter sub-assembly;
- **Transformer**, which includes and simulates the failure modes leading to turbine loss of production of the Transformer(s) - Liquid insulated transformer sub-assembly;
- **HV switchgear**, which includes and simulates the failure modes leading to turbine loss of production of the HV switchgear sub-assembly;
- **Power cabling system**; which includes and simulates the failure modes leading to turbine loss of production of the following sub-assemblies:
    - LV switchgear;
    - Power cabling system;
    - Auxiliary Cabling System and Connector;
- **Subsea cabling system**, which includes and simulates the failure modes leading to turbine loss of production of the following sub-assemblies:
    - Subsea cabling system;
    - Subsea cable joints.

The failure of each component is assumed to impact 100% of production.

Regarding the **HV switchgears,** they are only required when there are **Power Electronic Converters** (or **Transformers**) in redundancy configuration (e.g. 2x100% redundancy). It means that when there is no redundancy of this components there is no HV switchgear in the electrical system.
In the case of a configuration of Power Electronic Converters (or Transformers) redundancy, the switchgear is responsible for switching from the duty Converter (or transformer) to the stand-by converter (or transformer) in case of failure of the duty converter (or transformer). In this configuration, a HV switchgear is installed at the inlet and another at the outlet of the redundant converters (or transformers). In case of HV switchgear failure in normal operation, there is no impact on production. However, the redundancy is lost in case of failure of the duty converter (or transfer) and the production is fully impacted even if the stand-by converter (or transformer) is not failed

The RAM Model Base Case assumes that the Electrical system includes one Power Electronic Converters and one Transformer, thus no HV Switchgear in not required and then not modelled in the RAM model Base Case.

According to section 6.3; the UPS systems and the Electrical Protection and Safety sub-assemblies were excluded from the RAM Model as they are safety systems. They are used only in abnormal situations; thus its failures have no impact on production during normal operations.

6.2.3.1.10 Corrosion protection

The corrosion protection sub-assembly from Hydrodynamic and Reaction Systems was grouped in a unique sub-assembly which was modelled into two RAM components:

- **Coating**;
- **Impressed current**.

Both components protect the tidal turbine integrity from corrosion degradation. It was assumed that corrosion will start only when both coating and impressed current components are in failed state. In case of corrosion occurring on the Tidal Turbine, it was assumed that there is no immediate loss of production however, recoating and structural repairs need to be performed when an opportunity arises (for example when a component is being repaired onshore).

6.2.3.1.11 External Factor - Fouling

In addition to the tidal turbine components failures, it has been assumed that fouling can occur in a general manner in the turbine.

Fouling is a natural process that starts since the first date of production and increases with time. It was assumed that tidal turbine loses 1% of production per year due to fouling growth.
It was also assumed that the fouling is removed each time the tidal turbine is cleaned during maintenance activities (for example when a component is being repaired onshore).

6.2.3.2Components included in BASE case model.

Further to the assumptions described in this section, the elements that are effectively modelled are listed below and presented in the RBD in the Annex A. The reliability data related to the modelled components including the loss of production in failed state are presented in the Asset Register in the Annex C.

- **Hydrodynamic System:**
  - Nacelle:
    - *Nacelle Body*
  - Rotors (2 x50%):
    - *Blades*
    - *Pitch System*
- **Reaction System:**
  - Foundation system (Pretensioned anchor pile):
    - *Foundation system*
  - Support Structure:
    - *Support Structure*
- **Power take off:**
  - Auxiliaries:
    - *Cooling System*
  - Drivetrains (2x 50%):
    - *Low speed shaft*
    - *Low speed shaft bearings*
    - *Low speed shaft dynamic seals (2x 100%)*
    - *Gearbox / high speed shaft*
    - *Couplings*
    - *Braking system*
    - *Shaft Lubrication system*
  - Control & Communication system:
    - *Control System*
  - Electrical system:
    - Generator
    - Power Electronic Converter
    - Transformer
    - Power cabling system
    - Subsea cabling system

- **Multiple systems:**
  - Corrosion protection:
    - *Coating*
    - *Impressed current*

    (2x 100%)
  - External:
    - *Fouling*

6.3 Control and Safety Systems

6.3.1 Overview

Control and safety systems have different effects on operational availability.

Safety Systems such as Fire Fighting, UPS and Electrical Protection and Safety, Emergency and safety chains etc. are not used during normal operation and their failures will not affect production. Therefore safety systems are not modelled in the RAM model.

Control systems including communication systems, condition monitoring, SCADA, etc. are used during normal operation and lead to loss of production in case of failure.

6.3.2 Spurious Trips

Spurious trips represent all the system shutdowns due to human error or failure of equipment.

These spurious trips are assumed to be trivial failures, i.e. failures which can be solved in less than 1 hour (as per section 4.4.6.1).

The effect of spurious trips that can be solved by remote intervention (such as reset) are considered negligible Therefore, all identified spurious trip solved remotely in Ingeteam historic have been removed from their reliability data (see 4.4.1.2).

6.4 Maintenance and Operations

6.4.1 General

The maintenance required for unplanned failures is carried out in different manners depending on the tidal turbine concept and the component accessibility.

For the concept 1 which is a fixed bottom tidal turbine, the maintenance is always carried at onshore workshops. It is assumed that an Offshore Supply Vessel (OSV) equipped with a Remote Operated Vehicle (ROV) is required to disconnect, lift and transport the turbine to shore. Once the turbine is restored, an OSV transport the turbine back to its location at sea, then lay it down and connect before restarting production.

The Figure 6-4 summarises the assumption for the repair logistic that is considered in the base case for concept 1 according to failure category.

The complete sequence of maintenance operations and times from failure to restart considered for the concept 1 is illustrated in Figure 6-1. The correspondence of the impact at each operation can be deduced by the colour of the lines in Figure 6-1 representing the component state and the Figure 6-2. When the failure occurs, the component goes to a failed state that may impact partially or totally tidal turbine production. This period lasts until the OSV arrives at turbine location at sea. From the moment that the tidal turbine is disconnected until it is repaired and reconnected, the component is under repair state and production is totally stopped. When reconnection is achieved, the component comes back to it functional state and production restarts at 100% capacity.

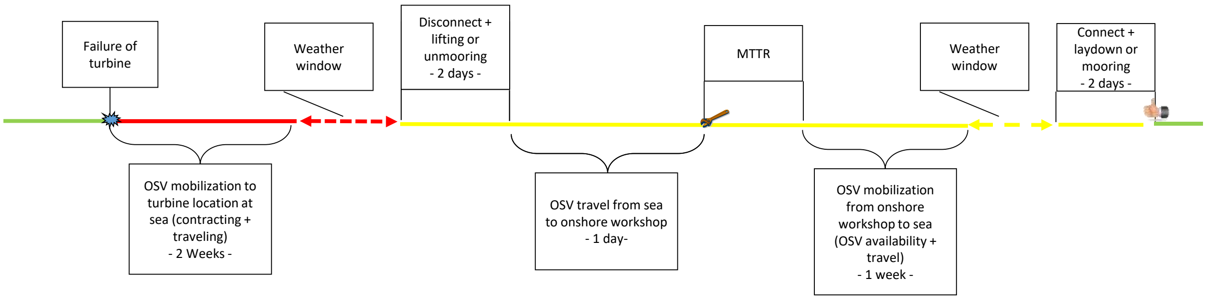


Figure 6-1 – Sequence of maintenance operations and times for unplanned maintenance requiring OSV (base case values).

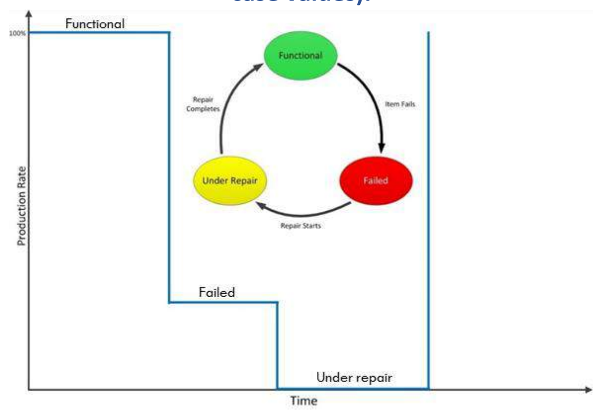


Figure 6-2 – The tree component states and corresponding impact on production

For the concept 3 which is a floating tidal turbine:

- The maintenance is carried at onshore workshops to repair major failures (repair higher than 24 hours; refer to section 4.4.6.1). It is assumed that an OSV is required to disconnect, unmoor and transport the turbine to shore. The sequence of maintenance operations is similar to concept 1 and is illustrated in Figure 6-1
- For minor failures (repairs between 1 and 24 hours; refer to section 4.4.6.1), there are two possible scenarios:
  - When the component is accessible from Nacelle (for example, any electrical component), it can be repaired in situ without the need to move the turbine from its location. It is assumed that a Crew Transport Vessel (CTV) is required to transport the maintenance crew and materials to carry out the repair. The sequence of maintenance operations is illustrated in Figure 6-3.
  - When the component is outside the Nacelle (for example blade and pitch system), the tidal turbine must be removed from sea and repaired onshore. In that case, the repair logistic is the same as for the major failures, i.e. it is required the mobilisation of an OSV.
- For trivial failures (repairs lower than 1 hour; refer to section 4.4.6.1), it is considered that repairs can be performed in situ without the need to move the turbine from its location. It is assumed that a Crew Transport Vessel (CTV) is required to transport the maintenance crew and materials to carry out the repair. The sequence of maintenance operations is illustrated in Figure 6-3.

The Figure 6-4 summarises the assumption for the repair logistic that is considered in the base case for concept1 3 according to failure category.

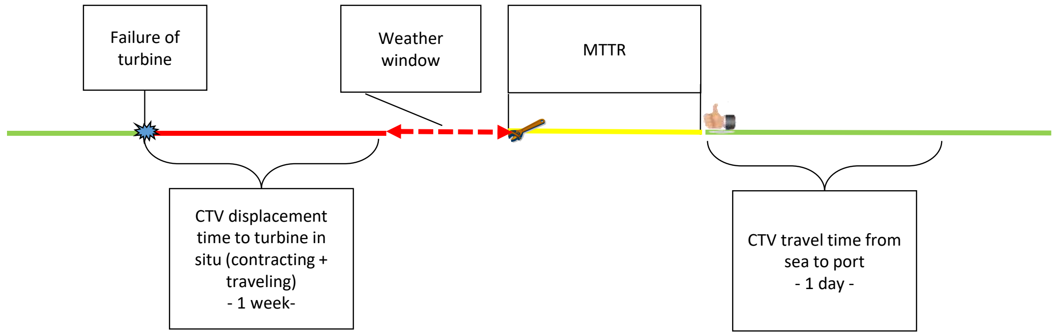


Figure 6-3 – Sequence of maintenance operations and times for unplanned maintenance requiring CTV to repair floating tidal turbine (base case values)

The correspondence of the impact at each operation can be deduced by the colour of the lines in Figure 6-3 representing the component state and the Figure 6-2.

When the trivial and minor failure occurs, the component goes to a failed state that may impact partially or totally tidal turbine production. This period lasts until the Crew Transport Vessel arrives at turbine location at sea. From that moment, the component is under repair state and production is totally stopped. When repair is achieved, the component comes back to its functional state and production restarts at 100% capacity.

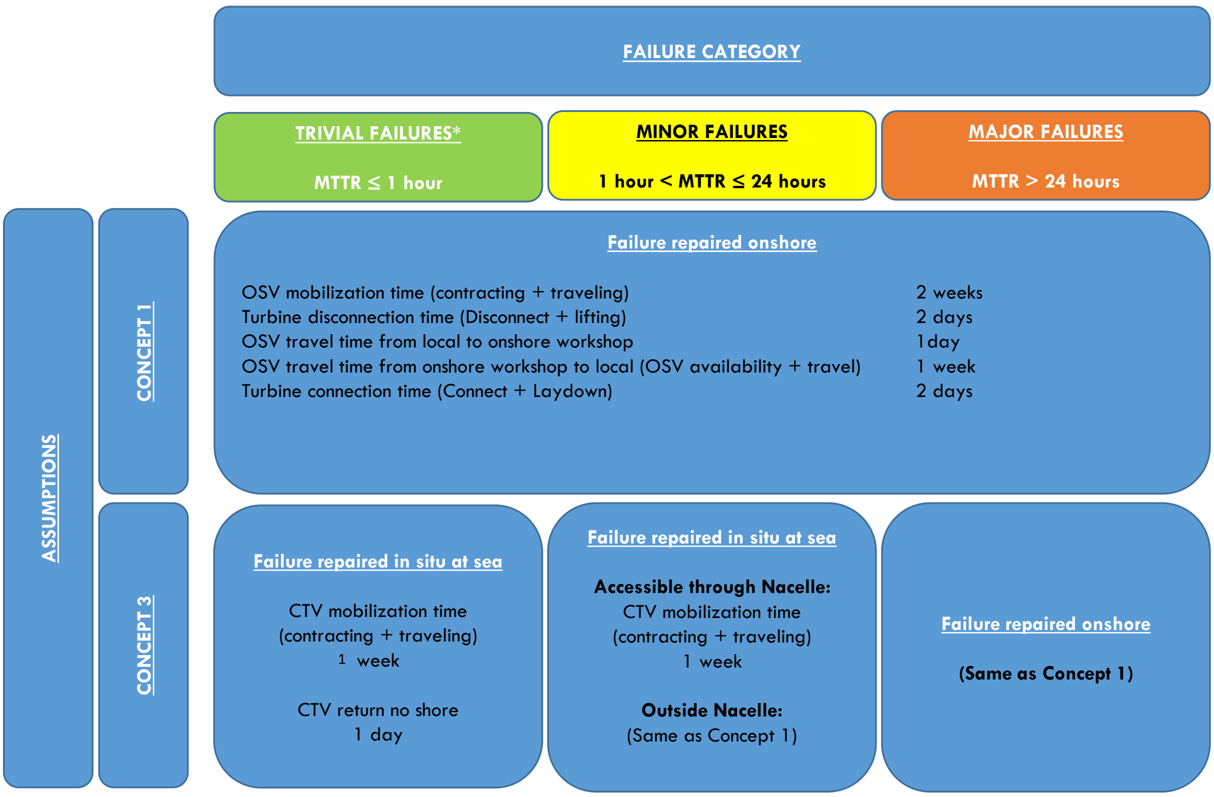


Figure 6-4 – Repair logistic assumptions according to failure category(base case values)

All mobilisation time, operations time, spares lead time as well as sparing philosophy required for any maintenance are assumed to follow the assumptions described in the following sections.

It should be noted that any activity during repair is always assumed properly performed in a safety point of view.

6.4.2 Maintenance Mobilisation Strategy

Depending on the component and its failure, the impact on production can vary from none to total loss. When the impact is not significant, it is not worth to mobilise the maintenance for the repair. In other hand, if production is totally lost, the maintenance should be mobilised as soon as possible.

In the Base case model, it is assumed that maintenance is mobilised as soon as a failure leads to the total loss of production.

6.4.3 Maintenance Utilities Mobilisation and Delays

Normally the reaction time to a turbine shutdown is defined by contract with the maintenance utilities providers (such as Offshore Supply Vessel (OSV) and Crew Transport Vessel (CTV) by the time for this maintenance utilities to travel to location of the turbine, and also by the type of failure which dictate the required vessel type for intervention. For 1st concept turbine, OSV is always required despite of failure category, whereas for 3rd concept, only major failure needs OSV for intervention, while minor and trivial failure are to be serviced by Utility vessel.
The overall mobilisation time from the moment of the failure occurrence or detection until the arrival of the OSV or the Crew Transport Vessel is generally between few days to 1 month.

For the base case study, it will be considered that 1 OSV will be available at a time with a mobilisation time of 2 weeks. This time includes contract delays and vessel traveling time.

The time for the OSV to travel from turbine location to onshore workshop after the turbine is disconnected and lifted is assumed to be 1 day.

The mobilisation time of OSV by the moment the tidal turbine is repaired from onshore workshop to turbine location at sea is assumed to be 1 week. This time also includes contract delays and vessel traveling time.

For CTV, it is assumed that one vessel is readily available on the port at a time, and mobilization time including logistics for crew and material preparation and travel time from port to turbine location at sea is assumed 1 week.

When CTV returns, it is assumed that the travel duration to the port is 1 day, and that CTV cannot be mobilized to a further repair cycle until the vessel is not arrived to port.

Figure 6-1 and Figure 6-3 summarise the sequence of maintenance operations and times for unplanned maintenance requiring OSV and CTV respectively with the time values assumed for the base cases.

6.4.4 Disconnection/connection operation delays

As mentioned in section 6.4.1, when an OSV is mobilized to repair a component **for concept 1**, one of the operation consists in disconnect and lift the tidal turbine up to the OSV and another operation is the laydown and connection of the tidal turbine when it is installed back at sea after its repair. **The duration of each operation is assumed to be 2 days**.

When an OSV is mobilized to repair a component **for concept 3**, one of the operation consists in disconnect and unmoor the tidal turbine up to the OSV and another operation is the mooring and connection of the tidal turbine when it is installed back at sea after its repair. **The duration of each operation is assumed to be 2 days**.

6.4.5 Maintenance staff delays

Repairs are performed either at onshore workshop or at sea (when failed components are accessible from supply vessel) by maintenance staff. Mobilisation of maintenance staff for maintenance activities at sea or at the workshop is assumed to be included in the mobilisation of the OSV or Utility Vessel. Staff members are assumed in a sufficient number to carry out any repair of different equipment simultaneously as per assumed in section 6.4.8.

6.4.6 Preparation Time

Depending on the failure of the Tidal Turbine, it will need some preparation activities before the repair/maintenance activities can take place. The preparation activities will be performed at the same time when the required maintenance utility (OSV with a ROV or Small Utility Vessel) is coming. It is assumed that:

- preparation for the repairing will be done while the OSV or Utility Vessel is being contracting
- preparation time is usually shorter than the mobilisation delay of the maintenance utility (1 month), and
- there is no extra preparation time required after the repair.

Then preparation time will not be considered in the RAM simulation.

6.4.7 Sparing Philosophy

In most cases, the components or spare parts necessary for the repair are located in logistics warehouses strategically located to minimize supply time. For these cases, the spare supply is considered to be performed at the same time that the OSV or the Utility Vessel is being contracted. Therefore, the spare lead time is included in the maintenance utility mobilization time.

For the case when spare part is not normally available in the logistics warehouse, the spare lead time is reflected in the MTTF of the failure which is longer than other components.

As both cases, the spare lead is already included either in the mobilization time or in the MTTF, it is assumed that there is no need to include extra time in the maintenance logistics for spare parts.

6.4.8 Component Maintenance and Repair Time

The RAM Base case model repair time will be assumed from the data collected from the databases and reported in Annexes A and B for concepts 1 and 3 respectively.

When several components need to be repaired, it is assumed that all repairs are performed by the maintenance staff at the onshore workshop or at turbine location at sea in parallel. This means that the duration of the repair of turbine is the MTTR of the component under repair with the longest MTTR.

For concept 1, when a maintenance is required, all component in failed state are repaired at this occasion even the equipment that are in degraded state. When the tidal turbine is repaired onshore, failures related to fouling and corrosion are also repaired at this occasion.

For concept 3, it is assumed that trivial and minor potential failures can be detected and then repaired by the crew maintenance staff. However, major potential failures cannot be detected in this case and are not automatically repaired.

On the other hand, if the tidal turbine is repaired onshore due to a major functional failure, the potential trivial and minor failures can be detected and then repaired at this occasion.

As mentioned in section 6.4.9, **equipment that is repaired in degraded stated (i.e. before its function failure) will have its repair time optimized by 15% of the component's MTTR.**

6.4.9 Condition Monitoring

The RAM base case model does not consider that condition monitoring is installed in tidal turbines. However, condition monitoring will be considered in alternative cases in order to evaluate the potential benefits of implementing such techniques in order to prevent minor and major failures on tidal turbines.

It was considered that when a condition monitoring device is installed to monitor the condition of the components, this device has a chance to detect the occurrence of a potential failure of the monitored component. The chance of detection depends on the detectability of the failures by the device selected in the Alternative cases that includes condition monitoring, and is based on the information provided in the reports [31] and [30]. The Table 6-3 presents the assumed detectability rate of the monitoring types defined in the FMEA report [31], which represents the efficiency/likelihood of detecting a failure with the corresponding monitoring.

Table 6-3 – Detectability rate according to monitoring type

Monitoring type :	Detectability rate
MUID. - Multiple integrated detection	99%
DM. - Direct measurement. Cause or effect	95%
MBE. - Model based estimation	85%
IDE. - Indirect detection. Integrated effect	70%
IVT. - Inspection visit tools	50%

Also in the FMEA study reports [31], it was defined which type of monitoring can be implemented for each component failure modes. The Table 6-4 presents the percentage of failure modes that can be monitored by each monitoring type. The table shows only the top critical components as per sections 0 and 8.2.1.2.

By combining the number of failure modes that can be detected by each monitoring type with their respective detectability rate, it is possible to estimate the likelihood of detecting the component potential failures if monitoring is implemented. The results are present in the column "Failure Mode Detectability rate" in Table 6-4.

It is to be noted that the detectability rate here presented are conservative as it does not take into account that a monitoring type implemented for a deed failure mode can also contribute to detect other failure modes which is monitored with none or less effective monitoring types. Indeed some failure modes are not so critical that IDE or MBE is proposed for them, because these techniques are effective enough for them. Nevertheless, in some other cases due to the criticality of the failures a MUID technique must be implemented. The fact of implementing a MUID because is needed for some failures makes that other failures less critical (and which could be detected just by using IDE or MBE for example) can be also detected by the multiple measurements system and therefore, MUID should be predominant over the less effective ones.

Moreover, in the methodology defined to estimate detectability rate, the occurrence of the failures has not been taken into account. This aspect could also impact positively the detectability rates. For example, let's suppose that a certain failure mode which is very difficult to be monitored but very unlikely to occur. According to the current procedure, this failure which might not be relevant, would be reducing the overall detectability rate of the component.

Consequently the present study reflects conservative scenarios for the Condition Monitoring analysis. It means that the expected results from this study should be better that they are presented.
Therefore, those assumptions may affect conclusions in WP4 and the cost model in WP5. In that case, the detectability rates should be reviewed in these WP by taking into account the occurrence factors and also verifying if MUID and DM can be compatible for all the other failures modes with less effectives or none monitoring types.

Table 6-4 – Critical Components Failure Modes detectability

Component	% of Failure Modes monitored by each monitoring type:					Failure Mode Detectability rate:
	MUID:	DM:	MBE:	IDE:	IVT:	
Pitch System		100%				**95%**
Control System	47%	29%		18%	6%	**90%**
Power Electronic Converter	23%	8%	38%	31%		**84%**
Yaw System		67%		33%		**87%**
Blades	27%		8%	65%		**79%**
Generator			56%	44%		**78%**
Gearbox / Highspeed shaft & bearing		42%		58%		**80%**

When a potential failure is detected, a repair is automatically planned and the maintenance is mobilized to the tidal turbine while the component is under degraded mode but still functioning without any impact to production during the P-F Interval of the failure mode (see section 4.4.6.2 for more details). In case the P-F interval is higher than the maintenance mobilization time, the component will be repaired before its Functional Failure occurs. Otherwise, the maintenance mobilization will arrive after the Functional Failure.
This is the criteria that has been followed in the alternative and sensitivity cases presented in sections 0 and 8. As we have more information about the condition of the components arises from WP4 or WP5, the CBM process can be optimized in order to avoid breakdowns and to reduce the OSV/CTV mobilization (for example when combining with preventive maintenance which is not considered in the RAM analysis).Again, these strategies could be taken into account in the cost study in WP5.

A component that is repaired before its functional failure occurs (i.e. in degrade state) thanks to condition monitoring has a repair time lower than if this component is repaired after its functional failure occurs. This assumption is based in the fact that this maintenance can be better prepared and then maintenance time is optimized. Furthermore, the prevention of the functional failure will also prevent potential escalation of the failure to other components that will need to be repaired, then increasing the time of the overall repair. As per partner's consensus, the gain of repair time thanks to condition monitoring is estimated in 15% of the component's MTTR.

In the case of "2x100%" redundant equipment which are monitored with CBM, the maintenance will be mobilized only when one equipment has already failed and the degradation has been detected on the other equipment.

6.4.10 Redundancy

There are two types of 2x 100% redundancy considered in the RAM model:
- The one considered on mechanical seals and the corrosion protection; both components are in service and can fail at the same time
- The one considered in other components, one component "called duty component" is in service and the other one is in stand-by mode. In case the duty component fails, the standby component is automatically put in service.

In both types of redundancy, the failure of one component will not impact production capacity, but only when both components are failed at the same time.

6.4.11 Planned Maintenance

The Base Case RAM model does not include planned shutdown activities.

6.4.12 External Factors – Weather Conditions

In addition to the equipment failures and maintenance already described, operations can be halted by events outside of maintenance staff control. The main external factor that can significantly impact on delaying maintenance operations is bad weather and sea conditions. Indeed, OSV operations for tidal turbine connection/disconnection, lifting/laydown and mooring/unmooring can be performed only under a certain limit of wave, wind and current conditions. Similarly, CTV maintenance crew can only operate under certain weather conditions. In order to take into consideration weather conditions, current, wave, and wind data of the D10 turbine location are compared with the vessel requirement.

6.4.12.1 Tidal Current

The tidal current data was provided by Sabella. This provides an estimate of speed and direction in proximity of the D10 deployment location for the period between 28th August, 2015 and 1st September, 2016. The model data are derived at different levels in the water columns up to the surface. The model surface speed was considered for the analysis. The tidal current statistics over the period of available wave and wind data were derived from the U-Tide harmonic prediction. Table Table 6-5 presents the main model information.

Table 6-5 - Tidal current input data summary

Source	SABELLA
Variable extracted for the study	current_speed, current_direction
Temporal resolution	10 min
Data height above seabed	SL (Surface Level)
Temporal range	28/08/2015 00:10 - 31/08/2016 23:50

6.4.12.2 Wave Characteristics

The wave database used in this study is HOMERE, part of the Meteocean Analytics database. The HOMERE database was performed by Ifremer using the numerical wave model WaveWatchIII® (WW3) version 4.09. WW3 is a third-generation spectral wave model based on the conservation equation for the density of wave action. The model has been validated with data recorded at the site. Table 6-6 presents the main model information.

Table 6-6 - Wave input data summary

Source	HOMERE
Variable extracted for the study	hs
Temporal resolution	1 h
Data height above sea surface	10 m
Time period analysis	01/01/1994 00:00 – 31/12/2013 23:00

6.4.12.3 Wind Characteristics

The wind database used in this study is the France-WRF9k, part of the Meteocean Analytics database. The wind database over the French west and north coasts was performed by VORTEX using the computer code Weather Research and Forecasting (WRF). WRF Model is a next-generation mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting needs. The model provides wind speed statistics at different level above the sea surface. The study was performed considering the wind speed modelled at 10 m above the sea surface as suggested by DNV RP C205 2.1.1 [40]. Table 6-7 presents the main model information.

Table 6-7 - Wind input data summary

Source	France-WRF9k
Variable extracted for the study	magw
Temporal resolution	1h
Data height above sea surface	10 m
Time period analysis	01/01/1991 00:00 – 31/12/2013 23:00

6.4.12.4 Suitable Weather Window for OSV Operation

Table 6-8 is the typical operational constraints used for the D10 marine operations, including all the marine operation steps: first survey, cable recovery, cable connection/disconnection, cable re-deployment, turbine deployment, final survey. It should be noted that the current direction and the wave spectral peak period (Ts) were not considered for this study. The current, wave and wind datasets were interpolated in order to have the same time step of 10 minutes. A suitable weather window is defined as a window during which all the criteria summarised in Table 6-8 are respected. A suitable weather window duration must be minimum 1.5 days. For this study a 2 consecutive days suitable weather window is selected.

Table 6-8 – Typical operational constraints for D10 Turbine

Items	**Marine operation limits**
Current speed max (Vmax)	6 knots
Hs max	2 m
Wind speed max (Wmax)	15 m/s
Duration of a weather window	2 days

Figure 6-5 illustrates an example of weather windows derived from imposing the requirement in Table 6-8 against the current, wind, wave datasets for 1995.

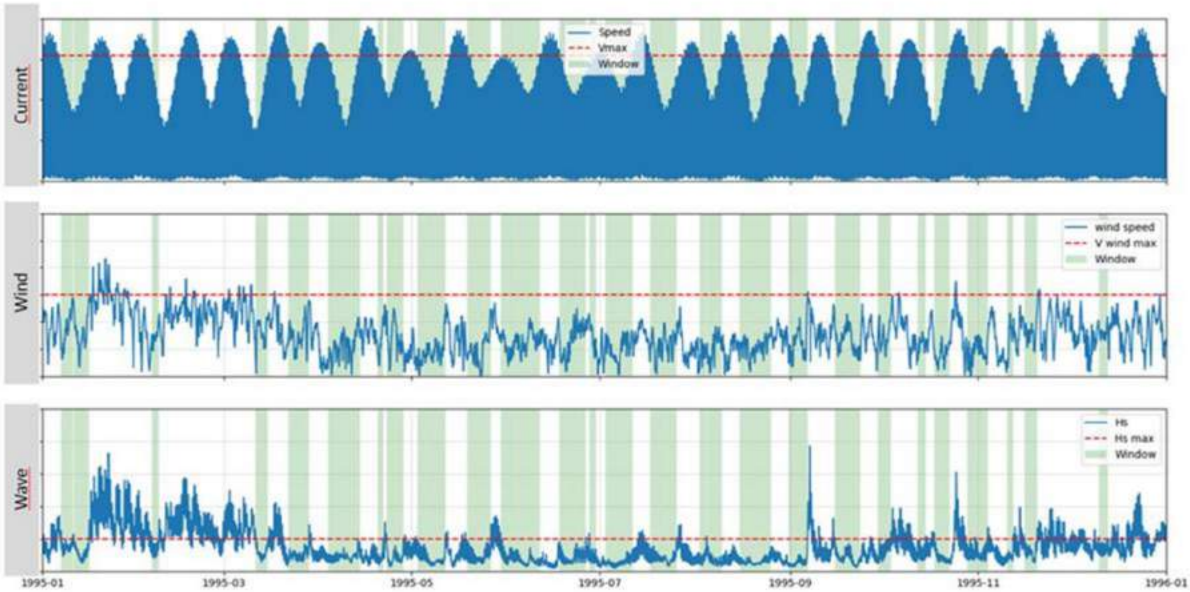


Figure 6-5 - Weather windows historic for connection/disconnection OSV operations

The green zones represent the periods where the combination of good conditions of wave, wind and current allows the OSV operating, whereas white zones are period where wave wind and/or current condition is above the OSV allowable operational limit. This process is applied throughout the length of 19 years environment datasets. Figure 6-6 provides an example for weather windows heatmap from 1994 to 1998 where the green colour indicates suitable weather windows for OSV operation, while the red ones indicate unsuitable days.

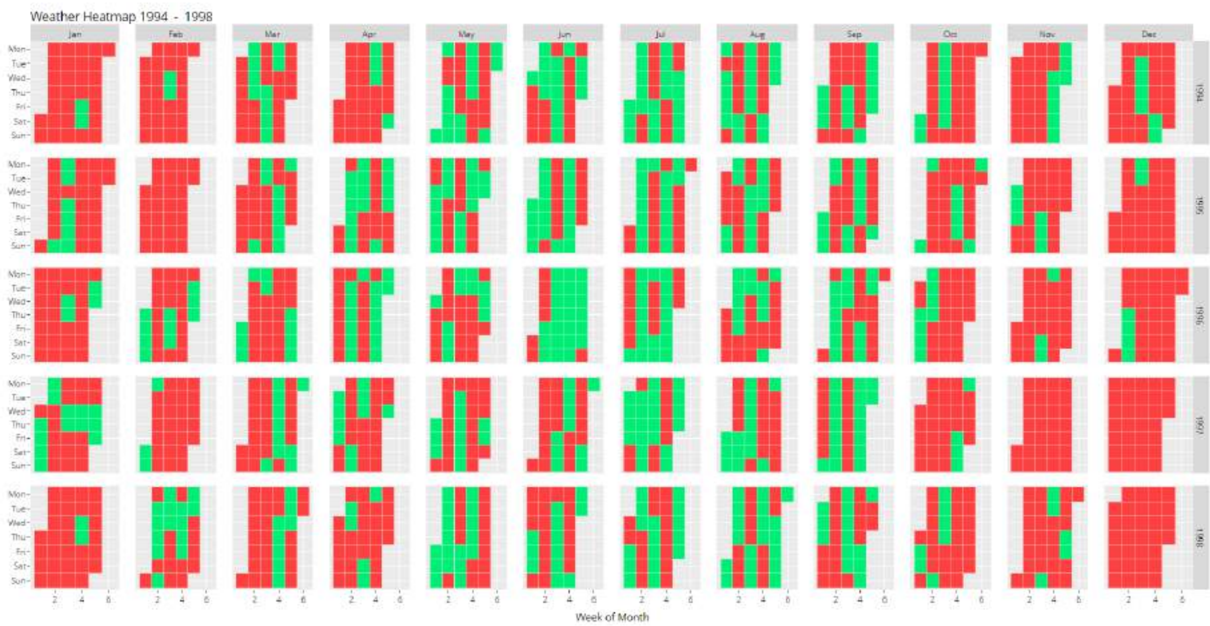


Figure 6-6 - Suitable weather window heatmap for OSV operation in 1994-1998

Figure 6-7 shows the range of favourable days for OSV operation for every month in 1994-1998. In general there are more suitable days for maintenance in summer than in winter. This situation is driven by higher Hs and more stormy days in winter compare to in summer.

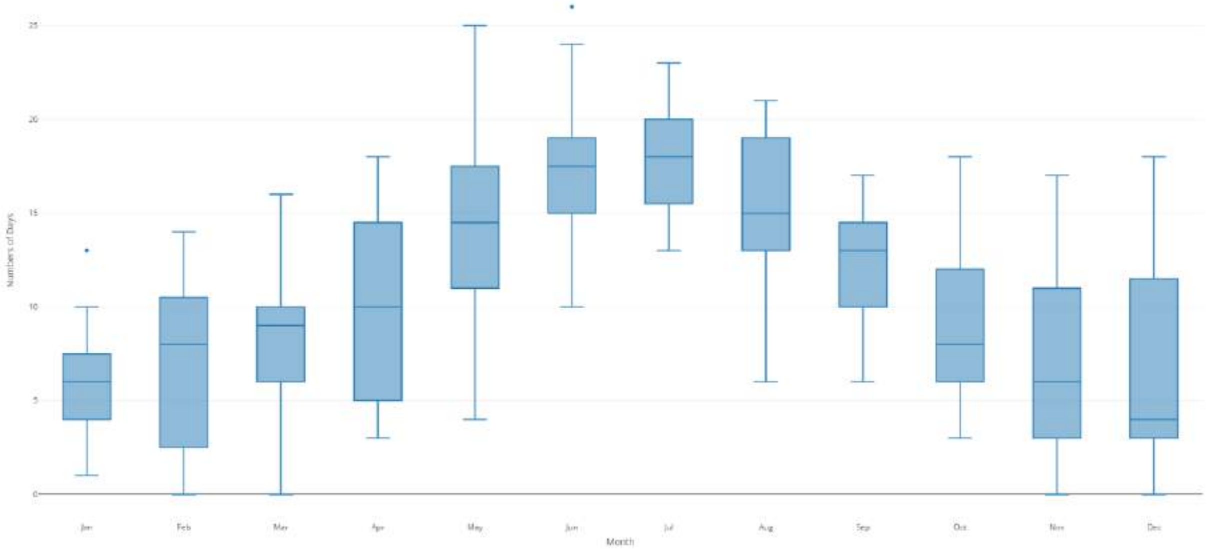


Figure 6-7 - Numbers of suitable days for OSV operation in 1994-2013 boxplot

Based on this approach, the probability of having suitable weather windows for the next two days can be estimated, i.e, for each day of the year, the probability of having good conditions to perform the OSV operation for removal and installation the tidal turbine can be drawn. Figure 6-8 provides the daily probability of having suitable condition for OSV operation.

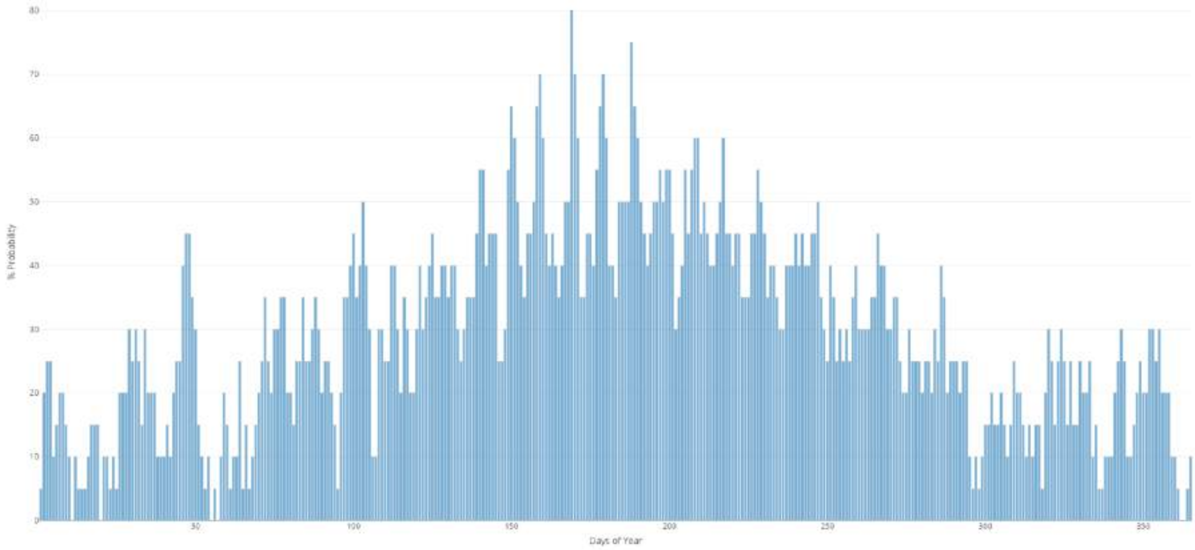


Figure 6-8 - Daily probability of having suitable condition for OSV operation

This weather windows probability is used for all categories of maintenance for 1st concept turbine and for major failure for 3rd concept turbine. It is to be noted that the weather conditions do not affect the displacement of the vessel but only the operations requiring dynamic positioning for removal and installation of the tidal turbine for maintenance purposes.

6.4.12.5 Suitable Weather Window for CTV Operation

For Minor and trivial failures of 3rd concept turbine Crew transfer vessel (CTV) is considered as the preferred option. Literature study from offshore wind turbine provides a benchmark of the vessel type and environment limitation for the simulation. Table 6-9 and Table 6-10 summarize the typical vessel for offshore wind turbine Crew transfer.

Table 6-9 - Different CTV characteristics [36]

Vessel Type	Benefits	Drawbacks
Monohull	Very high speed (± 30 knots)	Limited passenger
	Reasonably lower charter rates	Limited cargo capacity
	Lower fuel consumption	Uncomfortable for passengers
	High availability in the offshore market	Limited safe access to turbine (Hs < 1m)
Catamaran	High speed (± 20 knots)	Limited passenger (12 and more) and cargo capacity
	Operational Hs = 1.5 m	Relatively higher charter rates
	Safe access to turbine (Hs < 1.2 m)	
SWATH	Capacity of 12 to 60 passengers	Limited cargo capacity
	High speed (± 20 knots)	Low availability in the offshore market
	Operational Hs = 2 m	Relatively higher charter rates
	Safe access to turbine (Hs < 1.5 m)	
	Comfortable for passengers	

Unlike OSV operation that requires specific current, wave, and wind condition for allowable operation, CTV operation is only limited by Significant Wave Height (Hs). Refer to both tables, the accepted wave range for CTV operation is ranging from 1-2 m, depends on the vessel type. For this study it is assumed that CTV operation can be conducted for Hs lower than 1.5 m.

Table 6-10 - Governing weather criteria for CTV and other vessel [37]

Vessel Characteristics	Crew Transfer Vessel	Field Support Vessel	Heavy-Lift Vessel
Governing weather criteria	Wave	Wave	Wave / Wind
Weather criteria	1.5 m	1.5 m	2 m / 10 m/s
Speed of vessel	20 knots	12 knots	11 knots
Technician capacity	12	60	100

Typical required maintenance windows for offshore wind turbine is around 10-14 hours and generally the maintenance only performed during daylight hours. Based on this benchmark, required weather window for this study is assumed to be 10 hours during daylight (08:00 – 18:00) all year. Figure 6-9 shows the time series data of Hs from 1994 to 2013 where the red line indicates the maximum allowable Hs for minor and trivial maintenance of 3rd concept turbine.

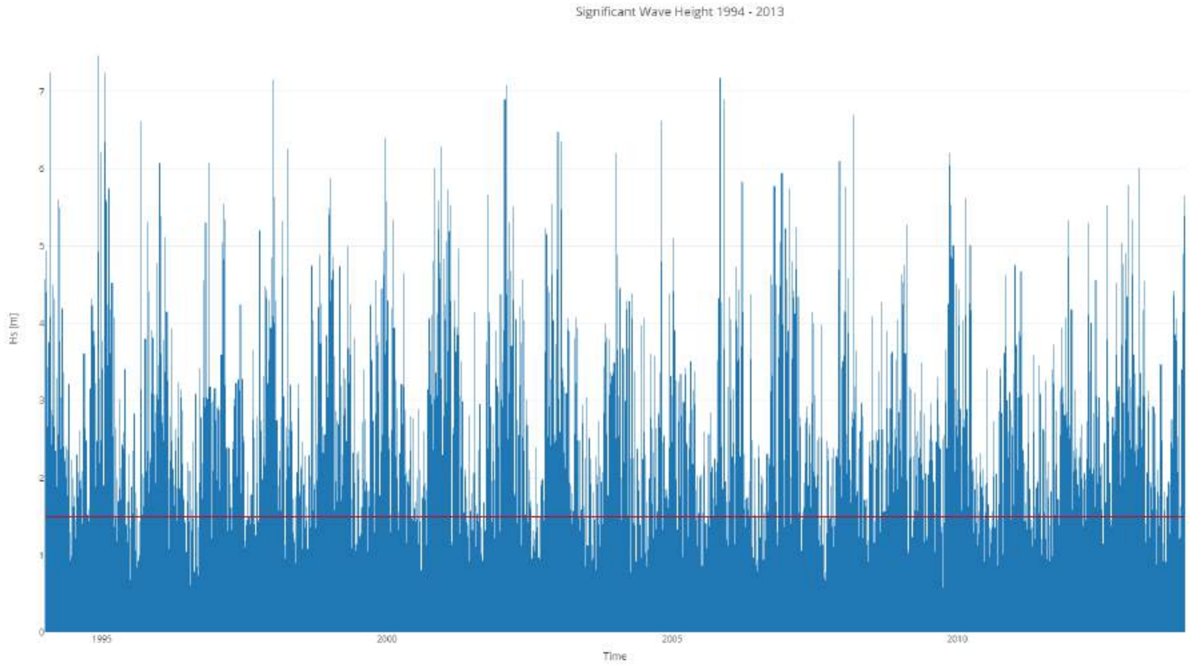


Figure 6-9 - Significant wave height (Hs) time series

A Heatmap example presented in Figure 6-10 takes into account the requirement of 10 hours duration during daylight hours, where green colour indicates during daylight hours there are at least 10 hours consecutive of Hs lower than 1.5 m between 08:00 to 18:00 hour that allow crews in CTV to intervene to the turbine for 1994 to 1998. The red ones indicate unsuitable condition for CTV operation.

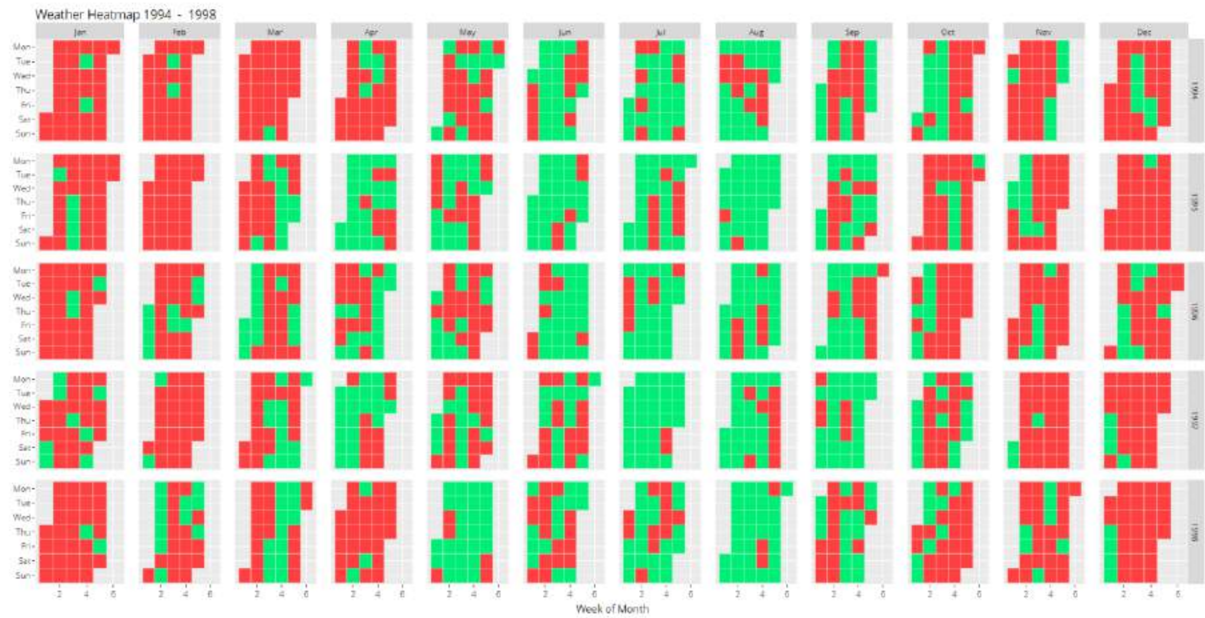


Figure 6-10 - Suitable weather window heatmap for CTV operation in 1994-1998

Similar with the approach for OSV operation explained previously, this process is applied for 19 years of data from 1994-2013, afterwards daily probability of having suitable condition for CTV operation can be drawn as shown in Figure 6-11.

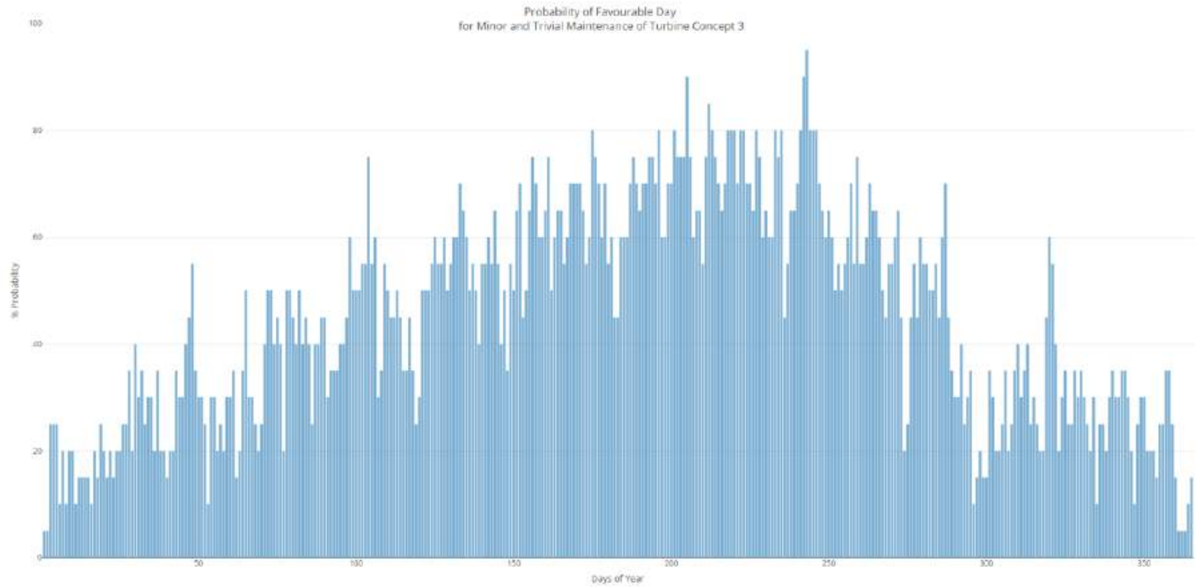


Figure 6-11 - Daily probability of having suitable condition for CTV operation

Similar with the weather window resume for OSV operation, there are more suitable days in summer than in winter as depicted in Figure 6-12.

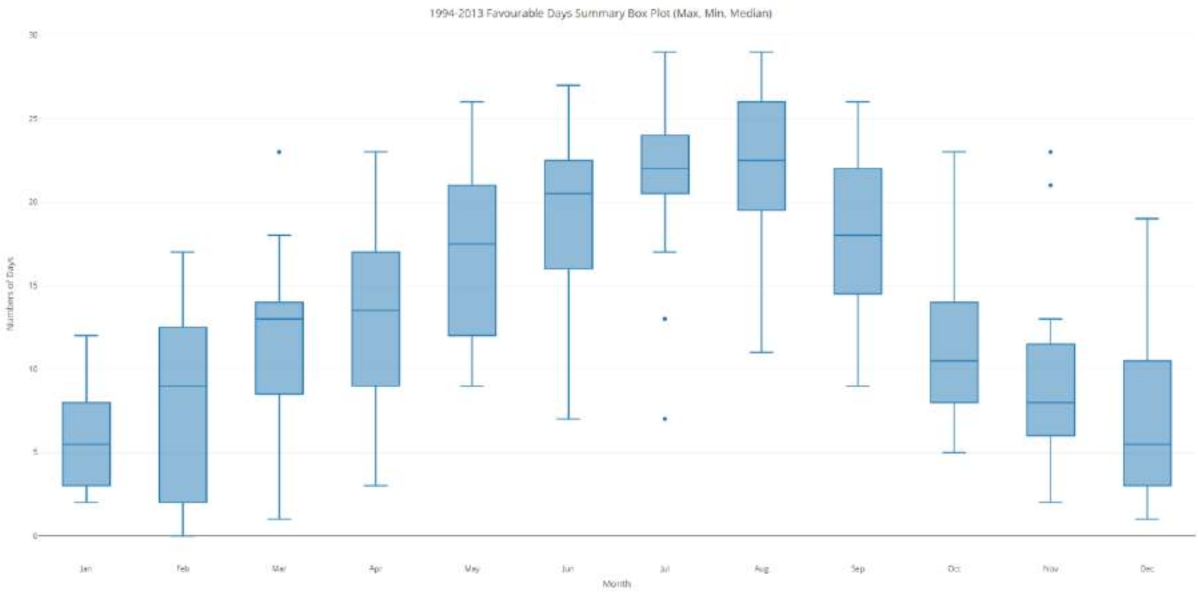


Figure 6-12 - Numbers of suitable days for CTV operation in 1994-2013 boxplot

6.5 Production profile

As per section 5.4, The Production Availability calculation is based on the potential production of the system within its operating life time.

The potential production used in the model follows the estimated daily energy production profile of the Sabella's D10 tidal turbine according to typical tidal variations as presented in Figure 6-13. For confidentiality purpose the production capacity is presented as percentage. It corresponds to the nominal power of D10.

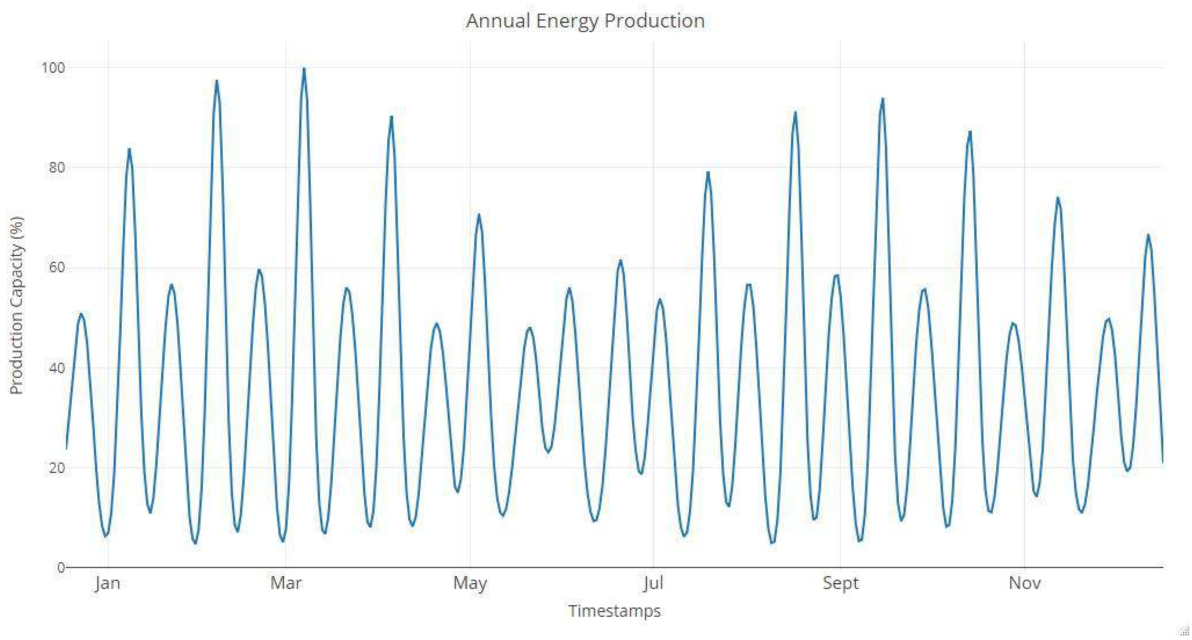


Figure 6-13 – Sabella's D10 Tidal Turbine - Annual Daily Energy Production Profile

6.6 System lifecycle

It is considered that Tidal turbines are designed for a life cycle period of 20 years.

It is not considered in the model any eventual update of components or any complete or partial refurbishment or any other upgrade during the lifecycle of the Tidal turbines

7 RESULTS CONCEPT 1

7.1 Concept 1 Base Case

7.1.1 Results Overview

In order to establish average results and confidence levels, the RAM model Base Case for the Concept 1 was run for 100,000 individual lifecycles considering 20 years as the system life. The Base Case was simulated for the production profile as per presented in section 0.
Summary results are presented first, followed by Components Criticalities overview in section 0.
Table 7-1 presents the average production availability for the Concept 1 Base Case.

Table 7-1 - Result overview – Concept 1 (Base Case)

Performance measured	Value
Average Production Availability (%)	71.82%
Annual Average Downtime (days/year)	102.84
Annual Average OSV Mobilisation	2.45

7.1.2 Components Criticalities Overview

Criticality analysis identifies the components or events that contribute the most to overall production losses, thus enabling the project team to focus on the areas of a design that will give the biggest improvements. This section presents the list of tidal turbine components with their overall contribution to downtime. The losses are presented in absolute terms (as a percentage of potential production) and as a total figure (all losses summing to be 100%). Table 7-2 presents a breakdown of losses for each component. Figure 7-1 presents the same data graphically.

The critical components are considered those that contributes to 90% of tidal turbine unavailability in the base case.

Table 7-2 – Base Case Component Criticalities-– Concept 1 (Base Case)

Component	Total Losses (%)	Average Absolute Loss (%)	Days/year
Gearbox_and_High_Speed_Shaft	20.37%	5.74%	20.95
Power_Electronic_Converter	18.23%	5.14%	18.75
Pitch_System	18.19%	5.12%	18.70
Yaw	11.60%	3.27%	11.93
Control_System	9.26%	2.61%	9.52
Blade	7.87%	2.22%	8.09
Generator	4.15%	1.17%	4.26
Braking_System	2.09%	0.59%	2.15
Shaft_Lubrication_System	1.45%	0.41%	1.50
Couplings	1.23%	0.35%	1.27
Low_Speed_Shaft_Bearing	1.20%	0.34%	1.23
Nacelle_Body	1.08%	0.30%	1.11
Transformer	0.95%	0.27%	0.97
Low_Speed_Shaft	0.85%	0.24%	0.88
Structure_Support	0.74%	0.21%	0.76
Cooling_System	0.62%	0.17%	0.64
Gravity_Based	0.06%	0.02%	0.06
Power_Cabling_System	0.04%	0.01%	0.04
Subsea_Cabling_System	0.03%	0.01%	0.03
Fouling	0.00%	0.00%	0.00
Low_Speed_Shaft_Dynamic_Seal	0.00%	0.00%	0.00
Corrosion_Protection	0.00%	0.00%	-
HV_Switchgear	0.00%	0.00%	-
Main_Structure	0.00%	0.00%	-
TOTAL	**100%**	**28.2%**	**102.84**

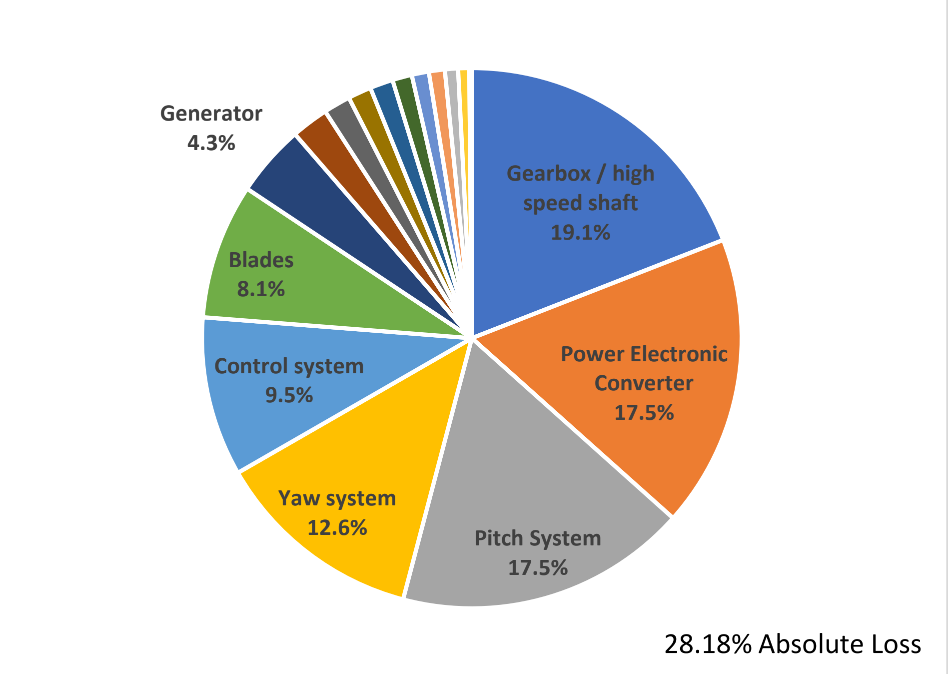


Figure 7-1 - Base Case System Components Chart – Concept 1 (Base Case)

Key findings from the system critical components are:

- Gearbox / high speed shaft is the highest contributor to unavailability, responsible for 19.1% of all losses. This high contribution can be attributed to the high frequency of failure (18.6% of overall failures).
- In addition, due to high frequency of failure, Pitch system (17.1% of overall failures) and Power electronic converter (17.1% of overall failures) have equivalent high contribution to unavailability, each one is responsible for 17.5% of all losses.
- Yaw is responsible for 12.6% of all losses and is the 4th highest contributor to unavailability due to its high frequency of failure (11,3% of overall failures) and maintenance strategy assumed in based case (i.e. OSV will not be mobilised immediately when Yaw is failed as it is assumed that failure of yaw will only impact 50% of production rate, refer to section 6.4.2)
- Furthermore, control system and blades are respectively responsible for 9.5% and 8.1% of unavailability due to their high frequency of failure (9.63% and 8.5% of overall failures). It is considered in the assumption that control system includes control and monitoring systems which include also sensors.
- Generator failures contributes to 4.3% of unavailability (4.3% of overall failures come from Generator).

The 7 components/systems described above represent 89.66% of all losses. This analysis enables to focalise improvement effort at these most critical items. Alternative cases described in the following section present how design modifications and CBM implementation can reduce the criticality of these 7 components and contribute to increase turbine availability. Another reason to choose the top 7 components to implement improvement is due to their “mask effect” to unavailability (refer to section 7.3.4 for detailed explanation).

7.2 Alternative cases

After gathering the results from the base case, the most critical elements to tidal turbine availability are highlighted and alternatives to design and monitoring are proposed. Each alternative was modelled and simulated as "Alternatives case".
Each Alternative case is compared with the Base Case models in order to assist in determining the options that best meet the project's objectives which is the optimization of the tidal turbines reliability and performance.
The alternative cases models and results for concept 1 are described in the following sections

7.2.1 Alternative case 1 (AC1) – Design improvement + Condition Monitoring implementation

For this first Alternative case, a full set of implementations are proposed on each critical component. These implementations are modelled and simulated in the RAM tool in order to assess the maximum availability that concept 1 can reach:

1. Removal of gearbox/ high speed shaft assuming that permanent magnet generator with elastic coupling is implemented without impact on failure rate of generator. However this design will require a bigger nacelle and bigger blades that will increase the cost of design.
2. Removal of pitch system and implementation of a rotor design with more blades (e.g. 6 blades instead of 3) in order to balance the loss of production efficiency. And it is also assumed that failure rate of blades won't change.
3. Implementation of a 2x100% redundant Power Electronic Converter. Redundant Power Electronic Converters need 2 HV switch gears (1 before and 1 after the converters) to switch from the running power electronic converter when it fails to the standby power electronic converter. HV switch gears are added in AC1 RAM model.
4. Removal of the Yaw system and implementation of rotor with blades which profile is designed to function in 2 tidal directions. In this case, it is assumed that production is not impacted, however this assumption must be revised in WP5.
5. Improvement of the Control system reliability using internal redundant sensors. Failure rate of control system is estimated to decrease to 0.2 times per year on average as per reference [33].
6. Condition monitoring implementation on Blades, Power Electronic Converter, Control System and Generator. The detectability of potential failures of the listed components and the manner that failure prevention is considered are described in section 6.4.9.

7.2.1.1Results Overview

Thanks to the above design improvement and implemented Condition Monitoring, not only the availability is increased from 71.82% in base case to 86.03% in AC1, but also OSV mobilisation is reduced from 2.45 in base case to 1.54 mobilisation per year in AC1, which could largely increase revenue and reduce OPEX.

Table 7-3 – Result overview – Concept 1 (Alternative Case 1)

Performance measured	Value
Average Production Availability (%)	86.03%
Total Average Downtime (days/year)	51.01
OSV Mobilisation per year	1.54

7.2.1.2Component criticality overview

Table 7-4 presents a breakdown of losses for each component. Figure 7-2 presents the same data graphically.

Table 7-4 – Alternative Case 1 Component Criticalities

Component	Total Losses (%)	Average Absolute Loss (%)	Days/year
Control_System	18%	2.58%	9.43
Blade	17%	2.31%	8.42
Generator	16%	2.19%	8.00
Power_Electronic_Converter	8%	1.10%	4.00
Braking_System	8%	1.06%	3.88
Shaft_Lubrication_System	5%	0.72%	2.64
Low_Speed_Shaft_Bearing	5%	0.65%	2.38
Couplings	4%	0.60%	2.19
HV_Switchgear	4%	0.56%	2.04
Nacelle_Body	4%	0.55%	2.00
Transformer	3%	0.46%	1.66
Structure_Support	3%	0.39%	1.44
Low_Speed_Shaft	3%	0.39%	1.43
Cooling_System	2%	0.26%	0.95
Fouling	1%	0.08%	0.31
Gravity_Based	0%	0.02%	0.07
Power_Cabling_System	0%	0.02%	0.07
Subsea_Cabling_System	0%	0.01%	0.05
Low_Speed_Shaft_Dynamic_Seal	0%	0.01%	0.04
Yaw	0%	0.00%	-
Pitch_System	0%	0.00%	-
Gearbox_and_High_Speed_Shaft	0%	0.00%	-
Corrosion_Protection	0%	0.00%	-
TOTAL	**100%**	**13.97%**	**50.99**

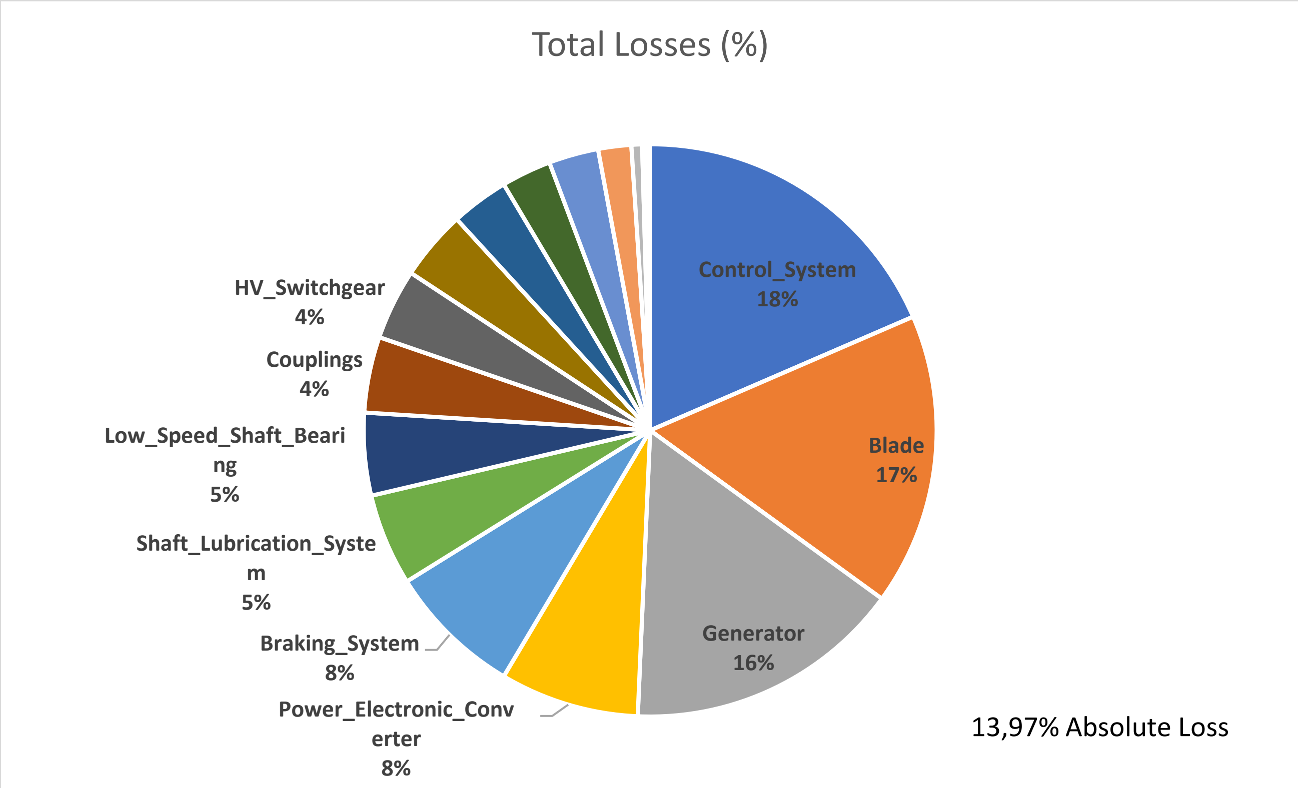


Figure 7-2 - Alternative Case 1 System Components Chart

Key findings from the system components are:

- Despite design improvement and Condition Monitoring are implemented for Control system, Generator, Blades and Power electronic converter are kept as the highest contributors to unavailability. They are responsible for 59% of total loss. Further design improvement should be considered on these components if reliability improvements are still required.
- Braking System, Shaft lubrication system, Low speed shaft and bearing; Couplings; HV Switchgears, Nacelle Body and Transformer are the following most critical components with a total contribution of 33% to total losses. These are the new components to be improved in case a better turbine reliability is required and there is not possibility to reduce the contribution of the above top 4 critical equipment.

According to this alternative case, availability would be hard to be "increased" to more than 90%. The need to repair the turbine onshore and long OSV mobilisation time (i.e. approximately 1 month to repair cycle, refer to analysis in section 0) and weather factors (refer to analysis in section 7.3.1) are the 2 main reasons that "restrict" the capability to improve the overall availability. In another way, the less tidal turbine depends OSV intervention and the best are the weather conditions, the best would be the availability.

7.2.2 Alternative case 2 (AC2) – Condition Monitoring implementation on all critical components

In order to understand the interest of Condition Monitoring implementation, the Alternative case 2 is carried out considering that the most critical components, i.e., Gearbox/ high speed shaft, Blades, Control system, Power electronic converter, Yaw, Pitch and Generator are monitored.

The detectability of potential failures of these components and the failure prevention is described in section 6.4.9.

7.2.2.1Results Overview

According to Table 7-5, implementation of CBM on critical equipment will bring improvement of availability from 71.82% up to 77.04%. On other side, annual average OSV mobilisation is increased to 3.74 (compare to 2.45 in base case). Indeed, Condition Monitoring System will inform operator to mobilise the OSV before failure occurs as a prevention measure. However, this strategy could also bring “over-mobilisation” issue of OSV and increase OPEX if not combined with a good design and/or an efficient maintenance strategy.

Table 7-5 – Result overview – Concept 1 (Alternative Case 2)

Performance measured	Value
Average Production Availability (%)	77.13%
Annual Average Downtime (days/year)	83.48
Annual Average OSV Mobilisation	3.74

7.2.2.2Component criticality overview

Based on comparison with Table 7-2, the top contributors to unavailability in AC 2 remain the same order as in base case. In order to have better understanding in availability gain for each Condition Monitoring applied, other alternative cases are carried out and results are recorded in section 7.2.3.

Table 7-6 – Alternative Case 2 Component Criticalities

Component	Total Losses (%)	Average Absolute Loss (%)	Days/year
Gearbox_and_High_Speed_Shaft	21%	4.74%	17.30
Pitch_System	19%	4.31%	15.74
Power_Electronic_Converter	18%	4.22%	15.40
Yaw	11%	2.56%	9.33
Control_System	9%	2.13%	7.78
Blade	8%	1.86%	6.78
Generator	4%	0.96%	3.50
Braking_System	2%	0.43%	1.57
Shaft_Lubrication_System	1%	0.29%	1.07
Low_Speed_Shaft_Bearing	1%	0.27%	0.97
Couplings	1%	0.24%	0.89
Nacelle_Body	1%	0.22%	0.82
Transformer	1%	0.19%	0.68
Structure_Support	1%	0.16%	0.60
Low_Speed_Shaft	1%	0.16%	0.58
Cooling_System	0%	0.11%	0.39
Gravity_Based	0%	0.01%	0.03
Power_Cabling_System	0%	0.01%	0.03
Subsea_Cabling_System	0%	0.00%	0.02
Low_Speed_Shaft_Dynamic_Seal	0%	0.00%	0.01
Fouling	0%	0.00%	0.00
Corrosion_Protection	0%	0.00%	-
HV_Switchgear	0%	0.00%	-
TOTAL	**100%**	**22.87%**	**83.48**

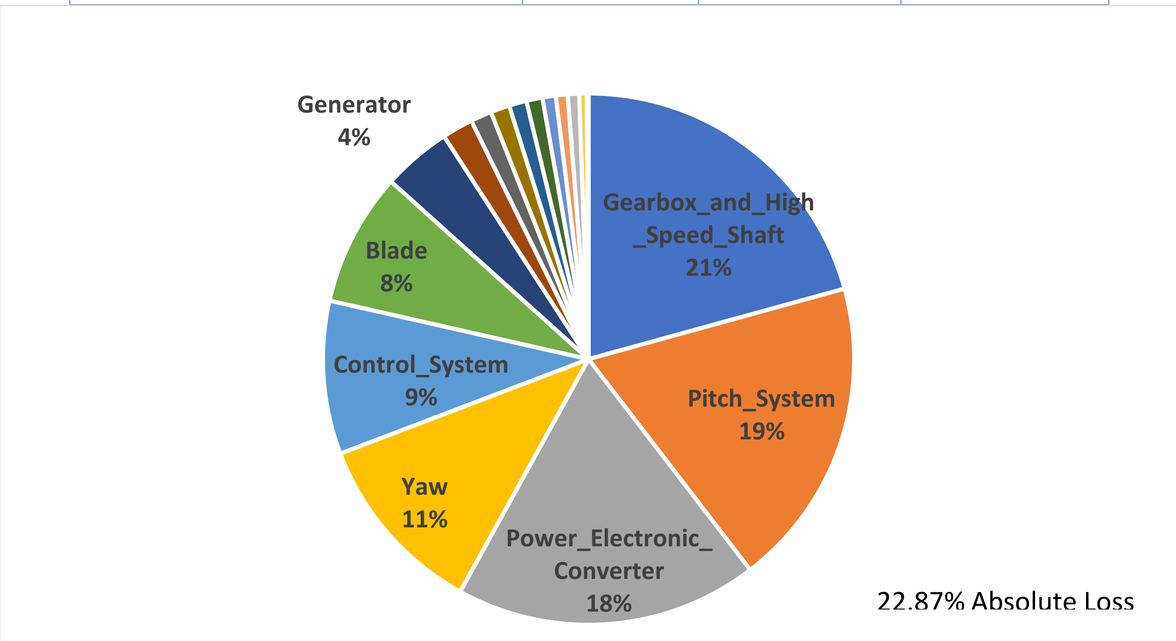


Figure 7-3 - Alternative Case 2 System Components Chart

7.2.3 Alternative cases 3 (AC3) – Condition Monitoring implementation on individual critical component

Other alternative cases are carried out to understand the impact of availability when condition monitoring is implement to one individual critical component at a time. The result for each component is presented in Table 7-7.

Table 7-7 – Other Alternative Cases Component Criticalities

Other ACs - Concept 1 (BC FP interval at 2M)	Availability	Benefit of CBM in terms of availability Compare with BC	OSV mobilisation (per year)	Additional OSV mobilisation (per year) Compare with BC
CBM only applied on Pitch	73.84%	+2.01%	2.75	+0.3
CBM only applied on Gearbox	73.68%	+1.86%	2.72	+0.28
CBM only applied on Yaw	73.37%	+1.55%	2.63	+0.19
CBM only applied on Power Electronic converter	73.18%	+1.35%	2.63	+0.18
CBM only applied on Control system	72.70%	+0.88%	2.54	+0.09
CBM only applied on Blade	72.60%	+0.77%	2.52	+0.08
CBM only applied on Generator	72.40%	+0.57%	2.49	+0.04

According to above Table 7-7, Condition Monitoring applied on Pitch and Gearbox are the most efficient to increase availability (i.e. +2.01% availability if Condition Monitoring applied on Pitch, +1.86% availability if Condition Monitoring applied on Gearbox). This is because Pitch and Gearbox have the highest failure frequency than other components, in other words, the more the component is critical, the more is beneficed (i.e. in terms of efficiency) to implement CBM.

For that reason, it is very important to define the most convenient monitoring strategy according to the criticality of the component. In WP4 [30], 3 different monitoring strategies have been defined for its application to tidal turbines: Spot measurements, basic permanent monitoring, and permanent monitoring.
On the other hand, OSV will be mobilised more frequently if Condition Monitoring is applied. For example, with implementation of Condition Monitoring on Pitch, OSV will be mobilised 1 extra time every 3 years than base case.

In the cost analysis in WP5, the most efficient monitoring techniques for each component are to be combined with optimized maintenance strategies and redesign in order to really highlight the benefits of implementing a CMS.

7.2.4 Alternative Cases summary

The Figure 7-4 and Figure 7-5 summarise the results of the above alternative cases in comparison with base case.

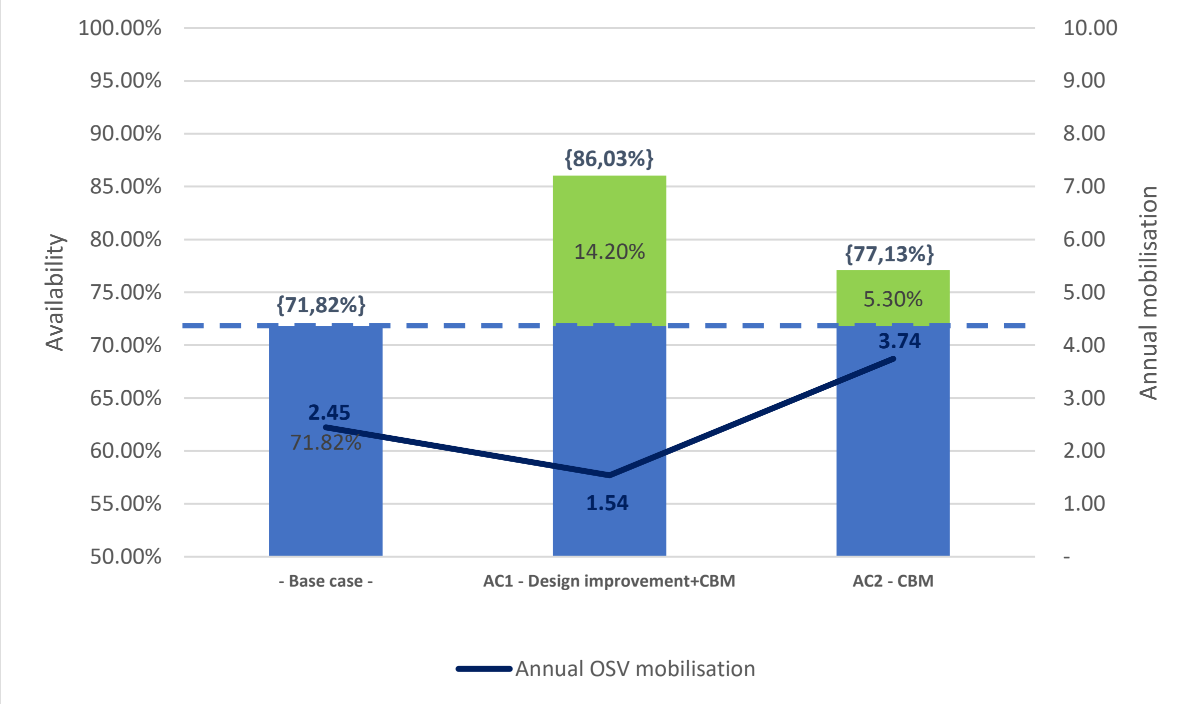


Figure 7-4 – Alternative cases summary – Concept 1

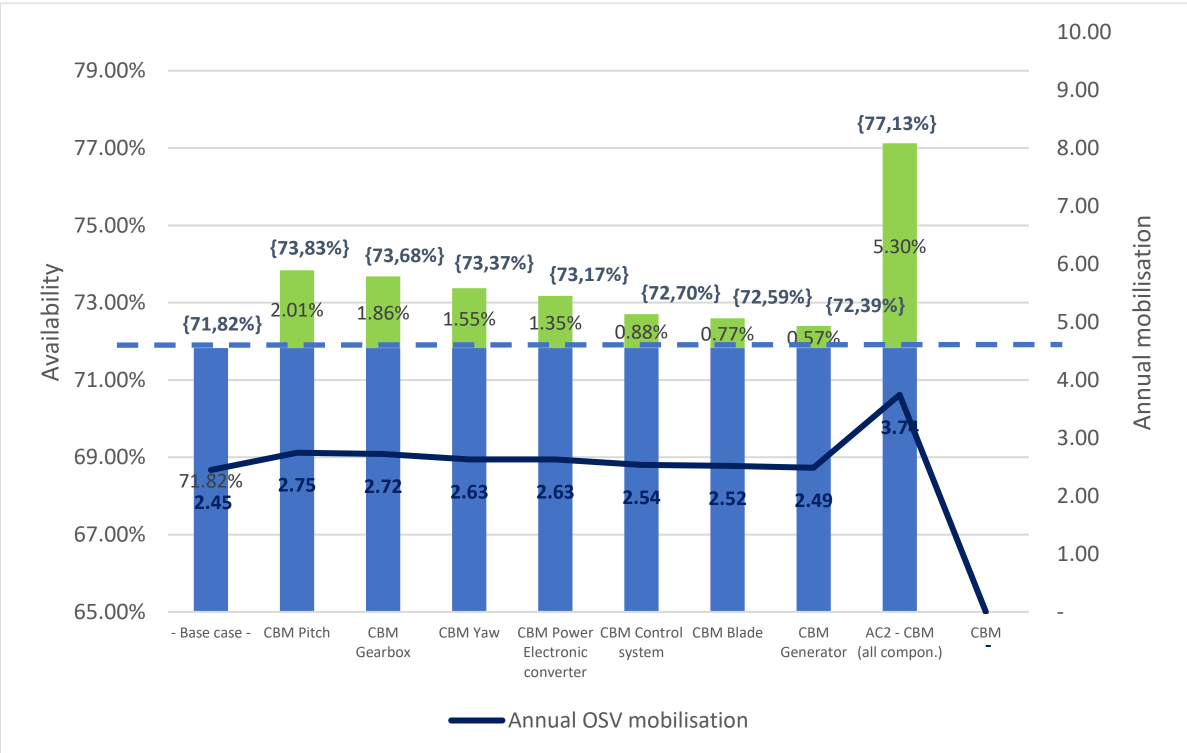


Figure 7-5 – Condition Monitoring Alternative cases summary – Concept 1

7.3 Sensitivity cases

The sensitivity cases are scenarios that are simulated and compared to each other in order to identify the robustness of the model to the variation of certain assumptions. The following sections describe the different sensitivity cases analysed for concept 1.

7.3.1 Sensitivity case 1 (SC1) – Weather condition analysis

Weather condition is a factor that impacts OSV operations and consequently the tidal turbine unavailability. Furthermore, weather conditions has a great uncertainty as explained in section 6.4.12.4. In order to assess how much weather condition would influence availability, the SC1 is carried out based on the base case but without considering the weather condition effect, in other words, the OSV operations will not be delayed due to weather conditions.

7.3.1.1Results Overview

According to Table 7-8, availability has increased from 71.82% (from base case) to 78.54%. The difference between the base case and SC1 means that the contribution of weather condition to unavailability is 6.72%. It corresponds that the turbine is unavailable on average during 24.5 days/year due to weather conditions factor.

Table 7-8 – Result overview – Concept 1 (Sensitivity case 1)

Performance measured	Value
Average Production Availability (%)	78.54%
Annual Average Downtime (days/year)	78.32
Annual Average OSV Mobilisation	2.21

7.3.1.2Component criticality overview

Table 7-9 presents a breakdown of losses for each component.

Table 7-9 – Sensitivity Case 1 Component Criticalities

Component	Total Losses (%)	Average Absolute Loss (%)	Days/year
Gearbox_and_High_Speed_Shaft	19%	4.16%	15.18
Power_Electronic_Converter	18%	3.92%	14.31
Pitch_System	17%	3.74%	13.66
Yaw	14%	3.04%	11.10
Control_System	9%	1.91%	6.98
Blade	8%	1.66%	6.08
Generator	4%	0.91%	3.32
Braking_System	2%	0.40%	1.45
Shaft_Lubrication_System	2%	0.33%	1.21
Low_Speed_Shaft_Bearing	1%	0.24%	0.88
Couplings	1%	0.24%	0.88
Nacelle_Body	1%	0.22%	0.79
Transformer	1%	0.20%	0.72
Structure_Support	1%	0.19%	0.71
Low_Speed_Shaft	1%	0.14%	0.52
Cooling_System	1%	0.11%	0.41
Gravity_Based	0%	0.01%	0.05
Power_Cabling_System	0%	0.01%	0.04
Subsea_Cabling_System	0%	0.01%	0.03
Fouling	0%	0.00%	0.00
Low_Speed_Shaft_Dynamic_Seal	0%	0.00%	0.00
Corrosion_Protection	0%	0.00%	-
HV_Switchgear	0%	0.00%	-
Main_Structure	0%	0.00%	-
TOTAL	**100%**	**21.46%**	**78.32**

Comparing with Base Case, Top contributors do not change in SC1. The main difference between to 2 cases is that average absolute loss is reduced.

7.3.2 Sensitivity case 2 (SC2) – OSV mobilization when production rate is 50% or lower

It was defined for the base case that OSV will be mobilised as soon as the turbine production rate is totally lost. Considering that the impact of Yaw failure is the reduction of production to 50%, this sensitivity case was defined in order to assess the variation of availability in case the OSV is mobilised when production rate is 50% or lower. This case would allow to better understand the impact of different maintenance strategy.

7.3.2.1Results Overview

According to Table 7-10, availability has increased 1.60% in comparison with base case (i.e. 71.82%). In the meanwhile, OSV mobilisation increased from to 2.45 times/year in base case to 2.54 times/year (around 1 more OSV mobilisation every 10 years). However, in case Yaw system is removed from design as per proposed in AC1 (section 7.2.1), this present scenario is not valid as all component failures would lead to complete loss of production.

Table 7-10 – Result overview – Concept 1 (Sensitivity case 2)

Performance measured	Value
Average Production Availability (%)	73.43%
Annual Average Downtime (days/year)	97.00
Annual Average OSV Mobilisation	2.54

7.3.3 Sensitivity case 3 (SC3) and 4 (SC4) – OSV logistic times variation

OSV logistic time is one of the factors that impact the most the availability of tidal turbine. In reality, OSV logistic time has important uncertainty (see section 6.4.3). In order to assess how much the OSV mobilisation influences the turbine availability, it was defined the two following cases, one with higher OSV mobilisation times and another with lower OSV mobilisation times:

1) SC3 is carried out with the assumption that OSV logistic time is multiplied by 2. Detailed assumptions are:
   - OSV mobilisation time (contracting + traveling): 1 month (instead of 2 weeks in BC)
   - OSV return to onshore time (from local to onshore workshop): 2 days (instead of 1 day in BC)
   - OSV return to installation time (from onshore workshop to local): 2 weeks (instead of 1 week in BC)

2) SC4 is carried out with assumption that OSV logistic time is divided by 2. Detailed assumptions are:
   - OSV mobilisation time (contracting + traveling): 1 week (instead of 2 weeks in BC)
   - OSV return to onshore (from local to onshore workshop): 0.5 day (instead of 1 day in BC)
   - OSV return to installation time (from onshore workshop to local): 0.5 week (instead of 1 week in BC)

7.3.3.1Results Overview

According to Table 7-11, the SC3 presents 9.9% lower availability comparing with Base Case (i.e. 71.82%). Total average downtime increases 36.14 days/year comparing with Base Case.
While looking at SC4 results in Table 7-11, availability is 5.65% higher comparing with Base Case. Total average downtime decreases 20.62 days/year comparing with Base Case.
These results confirm that OSV logistic time has important influence on availability. If we considered SC3 as worst case and SC4 as best case in terms of OSV logistic, the availability could vary from 61.92% to 77.5%.

Table 7-11 – Result overview – Concept 1 (Sensitivity case 3)

Performance measured	Value
Average Production Availability (%)	61.92%
Annual Average Downtime (days/year)	138.98
Annual Average OSV Mobilisation	2.11

Table 7-12 – Result overview – Concept 1 (Sensitivity case 4)

Performance measured	Value
Average Production Availability (%)	77.5%
Annual Average Downtime (days/year)	82.2
Annual Average OSV Mobilisation	2.6

7.3.4 Other sensitivity cases (SC5 to SC8) – Different PF intervals

PF interval, which represents the time that a component is in degraded mode (*) before the functional failure occurs (see section 4.4.6.2), is one of the factors with the highest uncertainty. Indeed there is no existing database that can provide such information, and then the PF intervals was defined based on partner's judgement. Actually, the PF interval can vary from several weeks to several year depending but the maximum PF interval of all components was assumed to be 2 months in base case (refer to section 4.4.6.2).
(*) Degraded mode is the degraded condition of a component which is detectable before its complete failure.

7.3.4.1Results Overview

It is shown in Table 7-13 that availability ranges from 56.66% to 76.55% depending on the PF interval value. It is noted that the greater is the PF interval, the better is the availability. However, the increase of availability is asymptotic and will not exceed 78% as it can be deduced from Figure 7-6 (i.e. 9.19% different between SC5 and SC6 and only 0.45% difference between SC7 and SC8).
According to this result, the availability would be relatively "stable" if PF interval of components are considered more than 6 months. This is why to simulate PF interval more than 6 months is not necessary.

On other hands, in order to understand the big influence of PF interval on availability, a more detailed analysis is described in section 7.3.4.2.

Table 7-13 – Result overview – Concept 1 (Sensitivity cases 5 to 8)

Concept 1	PF interval	Availability	OSV mobilisation (per year)
SC5	0 Month	56.66%	3.74
SC6	1 Month	65.85%	2.95
BC	2 Months	71.82%	2.44
SC7	4 Months	76.11%	2.12
SC8	6 Months	76.55%	2.05

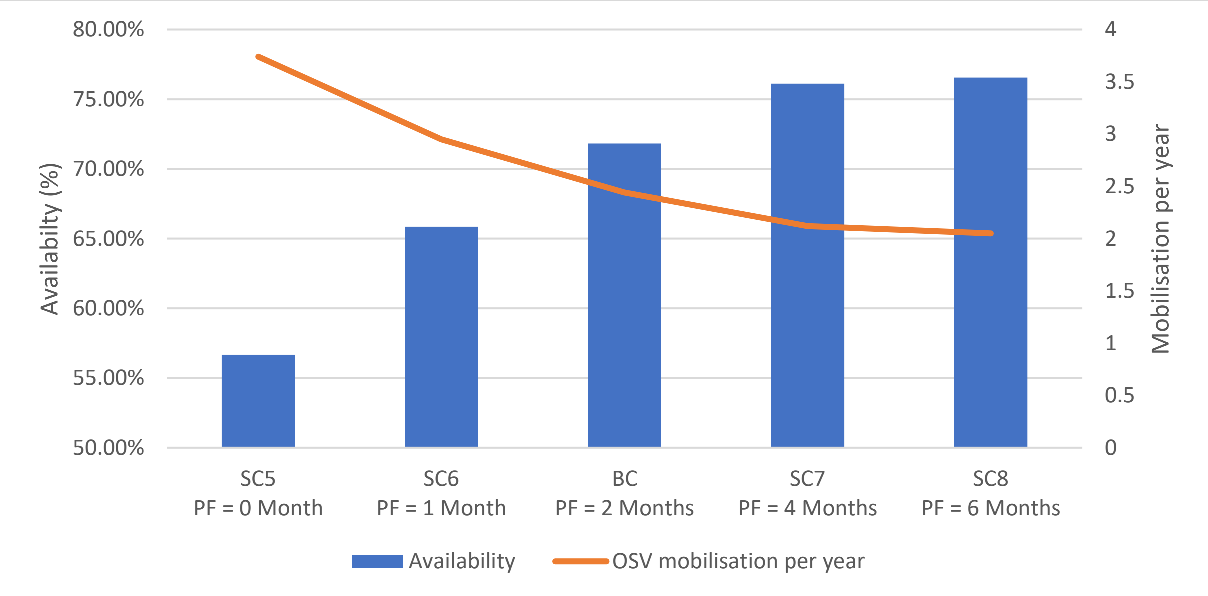


Figure 7-6 – Result overview – Concept 1 (Sensitivity cases 5 to 8)

7.3.4.2Component criticality analysis

As explained in above section, the greater is the PF interval, the better is the availability. This phenomena is due to "mask effect" caused by the fact that when a failed component is repaired, the degraded component are repaired at the same occasion as described hereafter.

Figure 7-7 shows that in case degraded mode appears for component A, it takes several months (i.e. PF interval time) to fail and then trigger the OSV for repair (PF interval is 2 months in base case). If another component is in degraded mode (during its PF interval) at that moment component B will be repaired together with component A at onshore workshop. As component B actually did not fail but was repaired even so, its contribution to unavailability is not counted and is "masked" by the component A contribution to unavailability.

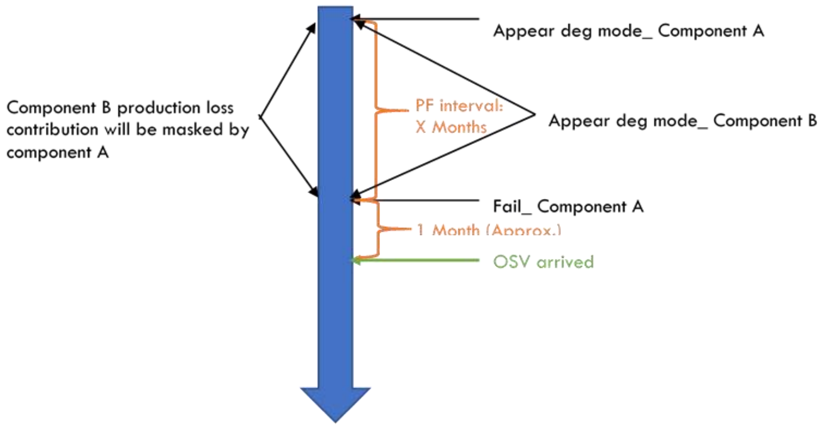


Figure 7-7 – Mask effect mechanism

For a better understanding, Figure 7-8 illustrates in a simple way what happens in the case 5, 8 and the base case.

In SC 8, PF interval of each component is 6 months. It means, in this scenario, that repairs are performed to equipment that have failed and also to all components that are in degraded mode up to 6 months before these component will failure. In the figure, Component A fails 6 months after it starts degradation. Supposing that, during this 6 months period, Components B and C also start their degradation phase. When Component A fails, the turbine is stopped and the process repairing starts by triggering an OSV (or CTV). At the end of the repair process, Component A is repaired and components B and C are restored as well, as per assumption described in section 6.4.8. After repair process all components are repaired and considered as good as new and no failure is expected in the next months for these 3 components.

In base case, the PF interval of each component is 2 months, i.e. in this particular scenario, the repairs are performed to equipment that have failed and also to all components that are in degraded mode up to 2 months before these components fail.

In the figure, Component A fails 2 months after it starts degradation. In that case, during this 2 months period, only Components B start its degradation phase because PF interval is shorter than in SC 8. When Component A fails, the turbine is stopped and the process of repairing starts by triggering an OSV (or CTV). At the end of the repair process, Component A is repaired and only components B is restored, as per assumption described in section 6.4.8. Meanwhile component C is not restored in this case because when the repairing process started this component had not initiated its degradation phase. After repair process, Components A and B are repaired and considered as good as new no failure is expected for these 2 components in the next months. Then, component C starts its degradation phase and fails 2 months later triggering at this moment the OSV (or CTV) and a second repairing process, this time to repair only the Component C. It is noted that, in this scenario, the Turbine had to be stopped 2 times to repair the 3 components in the same period of time impacting the availability of the tidal turbine.

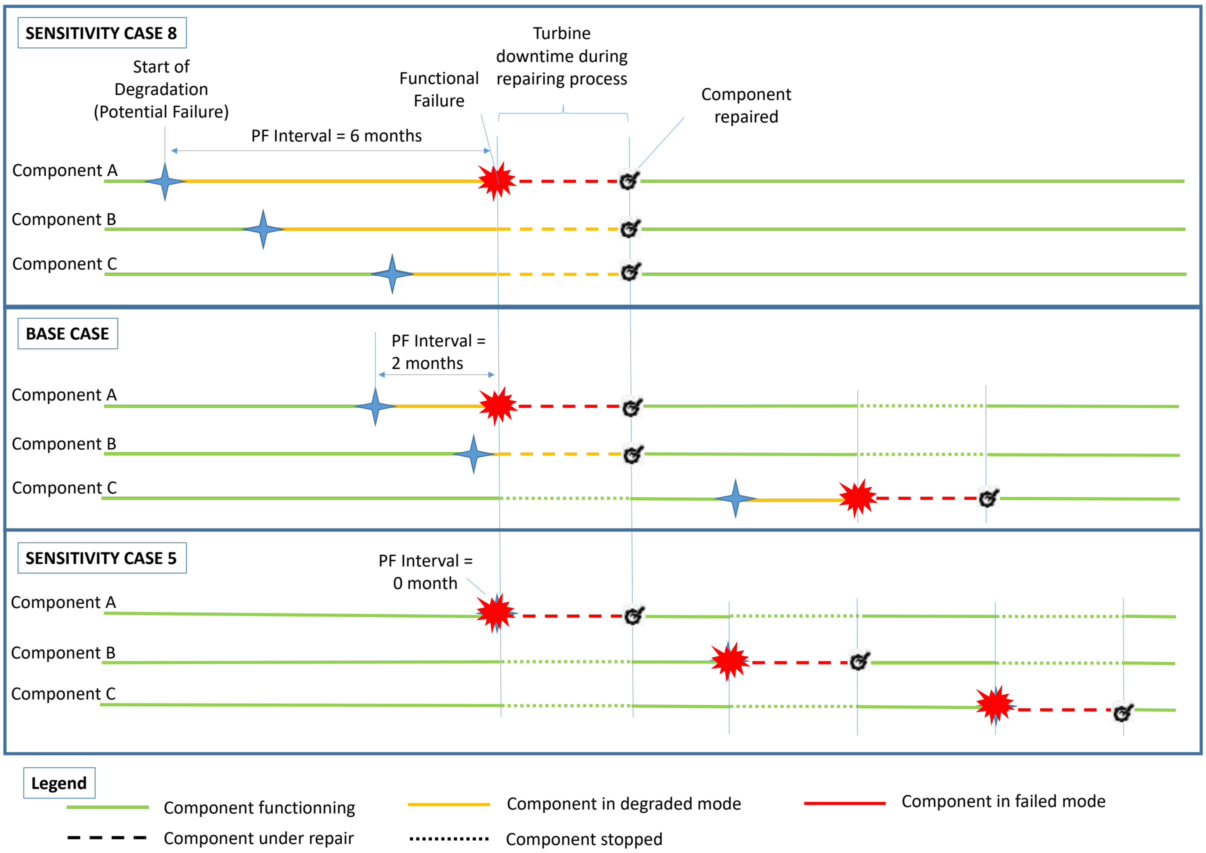


Figure 7-8 – Base case and sensitivity cases 5 and 8 illustration: the PF interval effect on availability and "mask effect"

In SC 5, there is no PF interval (or PF interval = 0 month). It means, in this scenario, that repairs are performed only to equipment that have failed. And there is no possibility that degraded component are repaired.

It is noted that, in this scenario, the Turbine had to be stopped 3 times to repair the 3 components in the same period of time impacting even more the availability of the tidal turbine than in Base case.

At component level, The Table 7-14 shows that the unavailability in SC 5 (PF interval is 0 month) are always higher than in other sensitivity cases. This means that in other sensitivity cases where PF interval > 0 month, components unavailability are masked. For example, Yaw system has 5.85% of absolute production loss when PF intervals is 0 month (i.e. No mask effect). In the base case where PF interval is equal to 2 months, Yaw system presents only 3.27% of absolute production loss when. In this case, Yaw system masked contribution to loss of production is 2.58% (i.e. 5.85% - 3.27%).

According to Table 7-14 and Figure 7-9, in base case, Yaw system is the component which masked effect on unavailability contribution is the highest. This phenomena is related to the failure rate of each component: the higher is the failure rate, the higher is the probability to be in degraded mode at the same time of other components and be repaired with these components and then have its contribution to downtime masked.

Another finding from Table 7-14 is that the lowest unavailability contribution considering variation of PF interval is different from component to component. For example, Gearbox and High speed shaft presents the lowest unavailability contribution in the base case where PF interval is 2 months (i.e. availability is 5.74%). Whereas, the Yaw system presents the lowest unavailability contribution in SC 6 where PF interval is 4 months (i.e. availability is 1.77%). And Cooling system presents the lowest unavailability contribution in SC 8 where PF interval is 6 months (i.e. availability is 1.77%). Summarising, the mask effect for gearbox and high speed shaft is more important when PF interval is 2 month, for Yaw system is when PF interval is 4 months, and for Cooling system when PF interval is 6 months.

With above findings, we can conclude that the real contribution to unavailability from the components can not be provided due to the mask effect caused by the PF interval and the fact that degraded components are restored at the same occasion that failed component is being repaired. **As a conclusion, the mask effect causes a "distortion" of the contribution of the component to unavailability that increases proportionally with the value of the PF interval. In a general way, the equipment with high failure rates have their relative contribution over estimated in comparison to the components with lower failure rates and this over estimation increases when PF interval is higher. As the contribution is over estimated on top critical equipment, the improvement that are proposed to reduce their contribution to unavailability are not as efficient as expected because part of their contribution is due to mask effect that come from other components.** Indeed, when the contribution of a top critical component is reduced (thanks to design improvement for example), masked unavailability contributions of other less critical components are "revealed" making these one more critical than it was before implementation of the improvement. For example, if all design improvement are implemented except for generator, the unavailability contribution of generator could be increased from 1.17% and to around 2.02%.

This is why it is important to assess the masked unavailability contributions for each component in order to find the "real" unavailability contribution and the adequate top contributors' unavailability. Further to analyse based on Table 7-14, Top 7 components in base case are chosen (to implement design improvement or CBM) according to their "real" unavailability contribution (i.e. SC5 components' average absolute loss, refer to Table 7-14)

Table 7-14 – Component criticality overview – Concept 1 (Sensitivity case 5 to 8)

Concept N°1	SC5(PF0M) Average Absolute Loss (%)	SC6(PF1M) Average Absolute Loss (%)	Base Case (PF2M) Average Absolute Loss (%)	SC7(PF4M) Average Absolute Loss (%)	SC8(PF6M) Average Absolute Loss (%)	Masked Contribution to loss of production (SC5 vs BC)
Yaw	5.85%	4.30%	3.27%	1.77%	2.13%	2.58%
Pitch_System	7.33%	5.98%	5.12%	5.61%	5.88%	2.21%
Gearbox_and_High_Speed_Shaft	7.92%	6.51%	5.74%	6.81%	7.04%	2.18%
Power_Electronic_Converter	7.30%	5.98%	5.14%	5.68%	5.96%	2.16%
Control_System	4.20%	3.26%	2.61%	1.23%	1.16%	1.59%
Blade	3.52%	2.77%	2.22%	1.02%	0.67%	1.30%
Generator	2.02%	1.46%	1.17%	0.52%	0.18%	0.85%
Braking_System	1.04%	0.76%	0.59%	0.28%	0.09%	0.45%
Shaft_Lubrication_System	0.74%	0.55%	0.41%	0.16%	0.05%	0.33%
Couplings	0.64%	0.47%	0.35%	0.14%	0.04%	0.29%
Low_Speed_Shaft_Bearing	0.62%	0.48%	0.34%	0.14%	0.05%	0.29%
Transformer	0.48%	0.35%	0.27%	0.12%	0.05%	0.22%
Nacelle_Body	0.51%	0.40%	0.30%	0.13%	0.04%	0.21%
Low_Speed_Shaft	0.43%	0.33%	0.24%	0.09%	0.03%	0.19%
Structure_Support	0.36%	0.27%	0.21%	0.09%	0.03%	0.15%
Cooling_System	0.32%	0.23%	0.17%	0.06%	0.02%	0.14%
Power_Cabling_System	0.02%	0.02%	0.01%	0.01%	0.00%	0.01%
Gravity_Based	0.03%	0.02%	0.02%	0.00%	0.00%	0.01%
Subsea_Cabling_System	0.01%	0.01%	0.01%	0.00%	0.00%	0.00%
Fouling	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Low_Speed_Shaft_Dynamic_Seal	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Corrosion_Protection	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
HV_Switchgear	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Main_Structure	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

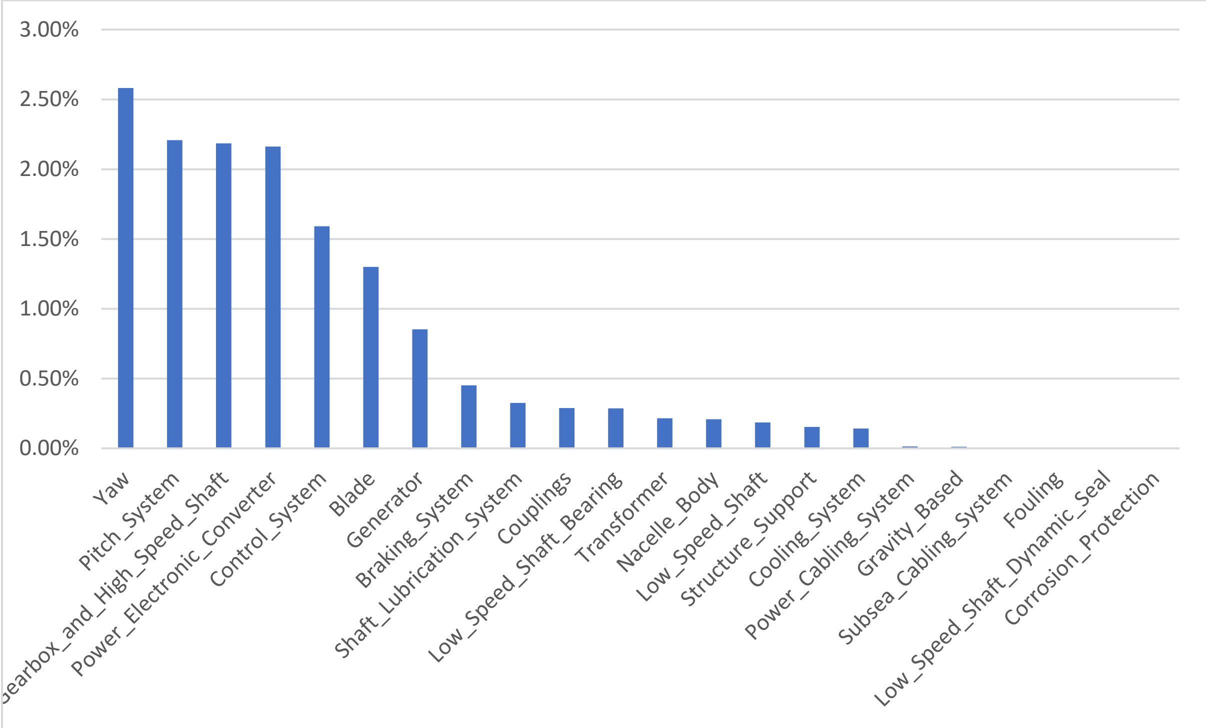


Figure 7-9 – Contribution to loss of production masked (SC5 vs BC)

7.3.5 Sensitivity Cases summary

The Figure 7-10 summarises the results of the above sensitivity cases in comparison with base case.

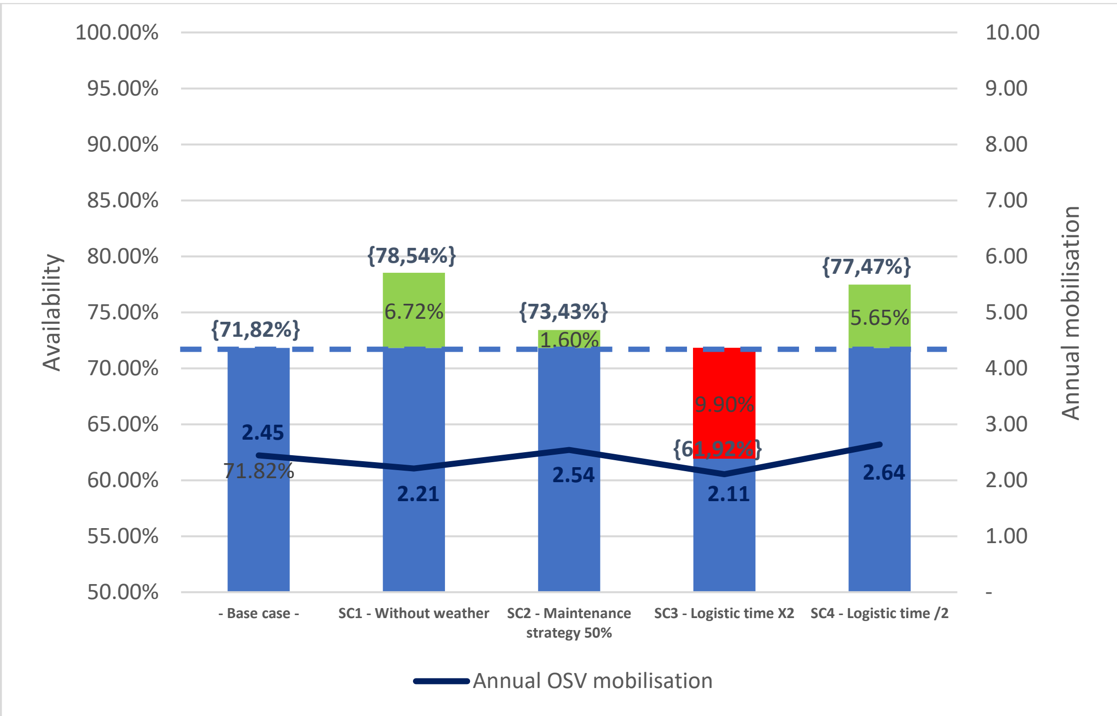


Figure 7-10 – Sensitivity cases summary – Concept 1

8 RESULTS CONCEPT 3

8.1 Base Case

8.1.1 Results Overview

In order to establish average results and confidence levels, the RAM model Base Case for the Concept 3 was run for 100,000 individual lifecycles considering 20 years as the system life. The Base Case was simulated for the production profile as per presented in section 0.
Summary results are presented first, followed by Components Criticalities overview in section 8.1.2.
Table 8-1 presents the average production availability for the Concept 3 Base Case.

Table 8-1 – Result overview – Concept 3 (Base Case)

Performance measured	Value
Average Production Availability (%)	80.09%
Annual Average Downtime (days/year)	72.68
Annual Average OSV Mobilisation	1.87
Annual Average CTV Mobilisation	1.43

In comparison with Concept 1, the number of CTV mobilisation is an additional important indicator to calculate OPEX. In concept 3, CTV is mobilised when minor/trivial failure occurs for components installed inside the Nacelle (according to section 6.4.1).

8.1.2 Components Criticalities overview

Criticality analysis identifies the components or events that contribute the most to overall production losses, thus enabling the project team to focus on the areas of a design that will give the biggest improvements. This section presents the list of tidal turbine components with their overall contribution to downtime. The losses are presented in absolute terms (as a percentage of potential production) and as a total figure (all losses summing to 100%). Table 8-2 presents a breakdown of losses for each component. Figure 8-1 presents the same data graphically.
The critical components are considered those that contributes to 90% of tidal turbine unavailability in the base case.

Table 8-2 – Base Case Component Criticalities– Concept 3 (Base Case)

Component	Total Losses (%)	Average Absolute Loss (%)	Days/year
Pitch_System	42.58%	8.48%	30.94
Blade	20.50%	4.08%	14.90
Gearbox_and_High_Speed_Shaft	9.57%	1.91%	6.96
Power_Electronic_Converter	7.40%	1.47%	5.38
Control_System	3.85%	0.77%	2.80
Low_Speed_Shaft_Bearings	3.02%	0.60%	2.20
Couplings	2.65%	0.53%	1.93
Generator	2.36%	0.47%	1.72
Nacelle_Body	2.30%	0.46%	1.67
Low_Speed_Shaft	1.79%	0.36%	1.30
Mooring_Line	1.65%	0.33%	1.20
Braking_System	0.89%	0.18%	0.64
Shaft_Lubrication_System	0.68%	0.13%	0.49
Transformer	0.35%	0.07%	0.25
Cooling_System	0.19%	0.04%	0.14
Pretensioned_Anchor_Pile	0.08%	0.02%	0.06
Subsea_Cabling_System	0.07%	0.01%	0.05
Low_Speed_Shaft_Dynamic_Seal	0.05%	0.01%	0.03
Power_Cabling_System	0.01%	0.00%	0.01
Fouling	0.00%	0.00%	0.00
Corrosion_Protection	0.00%	0.00%	0.00
HV_Switchgear	0.00%	0.00%	0.00

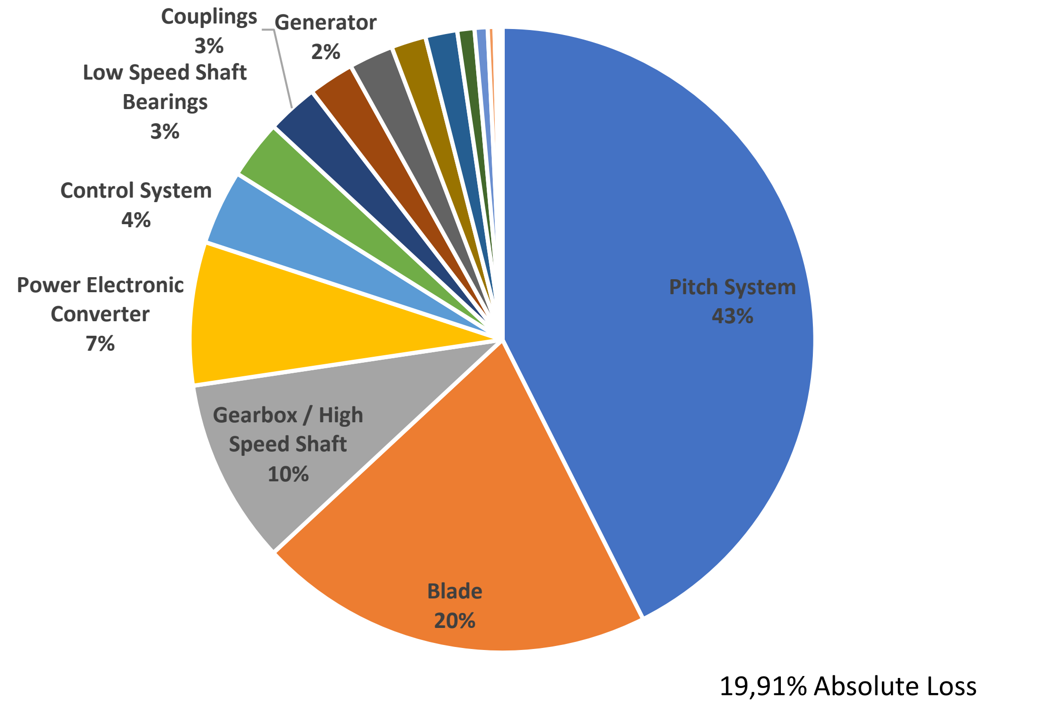


Figure 8-1 - Base Case System Components Chart– Concept 3 (Base Case)

Key findings from the system components are:

- Pitch system is the highest contributor to unavailability, responsible for 42.58% of all losses. This high contribution is not only due to the high frequency of failure (17.1% of overall failures), but also due the fact that the majority of its failures require an OSV to be repaired even the minor failures because this component cannot be accessible from the Nacelle.
- Blade is the 2nd highest contributor to unavailability, responsible for 20.50% of all losses. The failure rate of blades (8.5% overall failures) is lower than gearbox/high speed shaft (18.6% of overall failures) and power electronic converter (17.14% of overall failures), however the majority of its failures require an OSV to be repaired whereas Gearbox/ high speed shaft and Power Electronic Converter failures required CTV to be repaired because they are be accessible from the Nacelle.
- Gearbox/ high speed shaft and Power Electronic Converter unavailability represent respectively 9.57% and 7.40% of all losses. The high contribution of theses 2 components can be attributed to high failure frequency (i.e. 18.6% and 17.1% overall failures respectively).
- Control System, Low speed shaft bearings, Couplings and Generator contributes to 3.85%, 3.02%, 2.65% and 2.36% of all losses respectively. Their individual contributions are smaller than previous components (less than 4%), however the sum of their contributions reach almost 12% of all losses.

The 8 components described above represent 91.93% of all losses. This analysis enables to focalise improvement effort at these most critical items. Alternative cases described in the following section present how design modifications and CBM implementation can reduce the criticality of these 8 components and contribute to increase turbine availability. Another reason to choose the top 8 components to implement improvement is due to their "mask effect" to unavailability (refer to section 8.3.2.2 for detailed explanation).

8.2 Alternative cases

After gathering the results from the base case, the most critical elements to tidal turbine availability are highlighted and alternatives to design and monitoring are proposed. Each alternative was modelled and simulated as "Alternatives case".
Each Alternative case is compared with the Base Case models in order to assist in determining the options that best meet the project's objectives which is the optimization of the tidal turbines reliability and performance.
The alternative cases models and results for concept 3 are described in the following sections

8.2.1 Alternative case 1 (AC1) – Design improvement + Condition Monitoring implementation

For this first Alternative case, a full set of implementations are proposed on each critical components. These implementations are modelled and simulated in the RAM tool in order to assess the maximum availability that concept 1 can reach:

1. Removal of pitch and implementation of a rotor design with more blades (e.g. 6 blades instead of 3) in order to balance the loss of production efficiency. And it is also assumed that failure rate of blades won't change.
2. Removal of gearbox/ high speed shaft assuming that permanent magnet generator with elastic coupling is implemented without impact on failure rate of generator. However this design will require a bigger nacelle and bigger blades that will increase the cost of design.
3. Implementation of a 2x100% redundant Power Electronic Converter. Redundant Power Electronic Converters need 2 HV switch gears (1 before and 1 after the converters) to switch from the running power electronic converter when it fails to the standby power electronic converter. HV switch gears are added in AC1 RAM model.
4. Improvement of the Control system reliability using internal redundant sensors. Failure rate of control system is estimated to decrease to 0.2 times per year on average as per reference [33].
5. Condition Monitoring implementation on Blades, Power Electronic Converter, Control System, Generator, Low speed shaft bearings and Couplings. The detectability of potential failures of these components and the failure prevention is described in section 6.4.9.

The detectability of potential failures of the listed components and the manner that failure prevention is considered are described in section 6.4.9.

8.2.1.1Results Overview

Thanks to the above design improvement and implemented Condition Monitoring, not only the availability is increased from 80.09% to 89.39%, OSV mobilisation and CTV mobilisation are also reduced respectively from 1.87 in base case to 1.15 mobilisation per year in AC1, and from 1.43 in base to 0.86 mobilisation per year in the AC1, which could largely increase revenue and reduce OPEX.

Table 8-3 – Result overview – Concept 3 (Alternative Case 1)

Performance measured	Value
Average Production Availability (%)	89.39%
Annual Average Downtime (days/year)	38.72
Annual Average OSV Mobilisation	1.15
Annual Average CTV Mobilisation	0.86

8.2.1.2Component criticality overview

Table 8-4 presents a breakdown of losses for each component. Figure 8-2presents the same data graphically.

Table 8-4 – Alternative Case 1 Component Criticalities

Component	Total Losses (%)	Average Absolute Loss (%)	Days/year
Blade	50.73%	5.38%	19.64
Low Speed Shaft Bearings	8.30%	0.88%	3.21
Couplings	7.73%	0.82%	2.99
Low Speed Shaft	6.02%	0.64%	2.33
Generator	5.76%	0.61%	2.23
Nacelle Body	5.57%	0.59%	2.16
Mooring Line	4.40%	0.47%	1.70
Braking System	3.29%	0.35%	1.27
Shaft Lubrication System	2.46%	0.26%	0.95
HV Switchgear	1.39%	0.15%	0.54
Transformer	1.10%	0.12%	0.42
Power Electronic Converter	1.08%	0.11%	0.42
Cooling System	0.71%	0.08%	0.27
Control System	0.49%	0.05%	0.19
Fouling	0.33%	0.04%	0.13
Pre-tensioned Anchor Pile	0.25%	0.03%	0.10
Low Speed Shaft Dynamic Seal	0.23%	0.02%	0.09
Subsea Cabling System	0.13%	0.01%	0.05
Power Cabling System	0.04%	0.00%	0.02
Pitch System	0.00%	0.00%	0.00
Gearbox / High Speed Shaft	0.00%	0.00%	0.00
Corrosion Protection	0.00%	0.00%	0.00
Sum	**100.00%**	**10.61%**	**38.72**

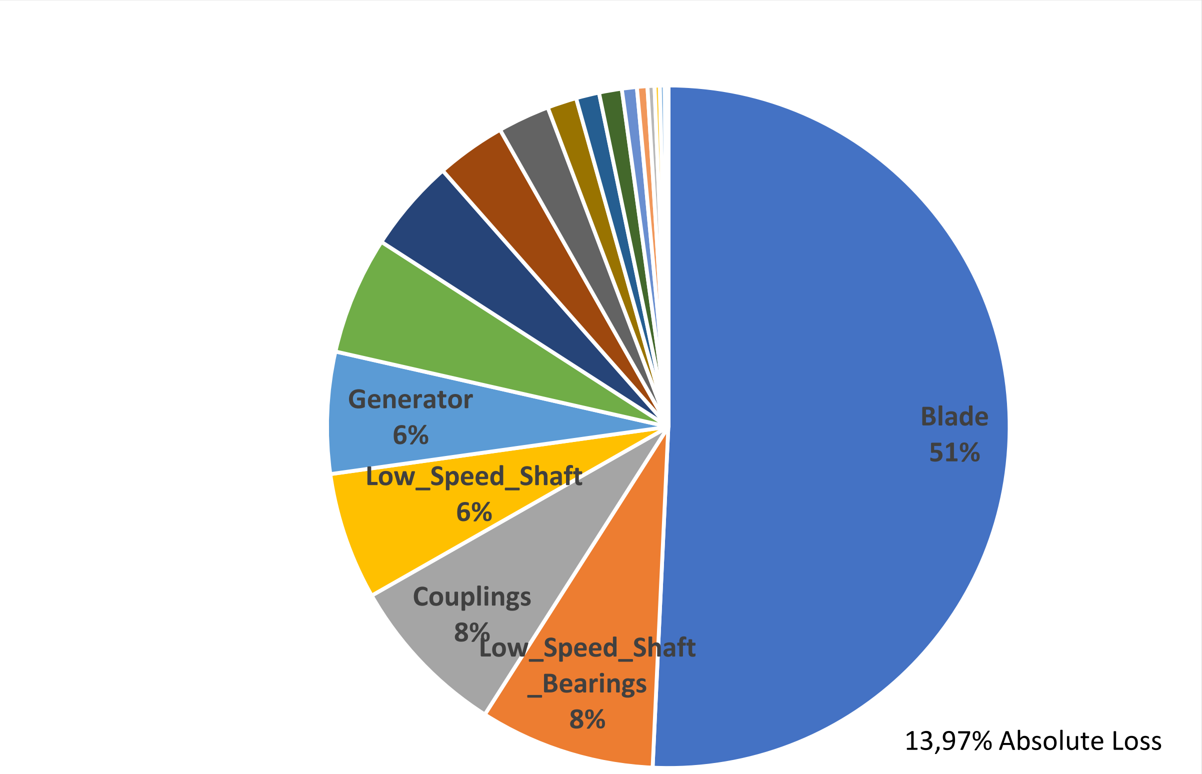


Figure 8-2 - Alternative Case 1 System Components Chart

Key findings from the system components are:

- Despite Condition Monitoring is implemented for Blades, this component is the highest contributor to unavailability because the majority of failures of blades are repaired onshore by means of OSV. Blades are responsible for 51% of total loss. Further design improvement should be considered on blades as the priority task if reliability improvement are still required. Retractable blade which could be realised by CTV would make important improvement for blade.
- Despite implementation of CBM on Low speed shaft bearing, Coupling and Generator, these components remains as critical with 21% of cumulated contribution to total loss. This effect due to “mask effect” explained in section 8.3.2.2. Further design improvement should be considered on these components if reliability improvement are still required.
- Low Speed Shaft, Nacelle Body, Mooring Line and Braking System are the next critical equipment and may be considered in case improvements on above equipment are not possible or efficient to increase turbine availability if required.

8.2.2 Alternative case 2 (AC2) – Condition Monitoring implementation on all critical components

In order to understand the interest of Condition Monitoring implementation, the Alternative case 2 is carried out considering that the most critical components, i.e., Gearbox/ high speed shaft, Blades, Control system, Power electronic converter, Pitch, Low speed shaft bearing, Coupling and Generator are monitored.

The detectability of potential failures of these components and the failure prevention is described in section 6.4.9.

8.2.2.1Results Overview

According to Table 8-5, implementation of Condition Monitoring will bring improvement of availability from 80.09 up to 82.53%. On other side, OSV and CTV mobilisation are increased respectively to 2.97 (compare to 1.87 per year in base case) and to 2.47 (compare to 1.43 per year in base case). Same as for concept 1, Condition Monitoring system will inform operator to mobilise the CTV/OSV before failure occurs as a prevention measure. However, this strategy could also bring "over-mobilisation" issue of CTV/OSV and increase OPEX.

Table 8-5 – Result overview – Concept 3 (Alternative Case 2)

Performance measured	Value
Average Production Availability (%)	82.53%
Annual Average Downtime (days/year)	63.77
Annual Average OSV Mobilisation	2.97
Annual Average CTV Mobilisation	2.47

8.2.2.2Component criticality overview

Based on comparison with Table 8-2, the top contributors to unavailability in AC 2 remain the same order as in base case. In order to have better understanding in availability gain for each Condition Monitoring applied, other alternative cases are carried out and results are recorded in section 8.2.2.3

Table 8-6 – Alternative Case 2 Component Criticalities

Component	Total Losses (%)	Average Absolute Loss (%)	Days/year
Pitch System	51.87%	9.06%	33.08
Blade	22.59%	3.95%	14.41
Gearbox / High Speed Shaft	6.54%	1.14%	4.17
Power Electronic Converter	2.06%	0.36%	1.31
Control System	0.70%	0.12%	0.44
Low Speed Shaft Bearings	3.93%	0.69%	2.51
Couplings	3.73%	0.65%	2.38
Generator	1.85%	0.32%	1.18
Nacelle Body	1.65%	0.29%	1.05
Low Speed Shaft	1.49%	0.26%	0.95
Mooring Line	1.34%	0.23%	0.86
Braking System	0.99%	0.17%	0.63
Shaft Lubrication System	0.65%	0.11%	0.41
Transformer	0.29%	0.05%	0.19
Cooling System	0.19%	0.03%	0.12
Pretensioned Anchor Pile	0.02%	0.00%	0.01
Subsea Cabling System	0.04%	0.01%	0.03
Low Speed Shaft Dynamic Seal	0.05%	0.01%	0.03
Power Cabling System	0.01%	0.00%	0.01
Fouling	0.00%	0.00%	0.00
Corrosion Protection	0.00%	0.00%	0.00
HV Switchgear	0.00%	0.00%	0.00
Sum	**100.00%**	**17.47%**	**63.77**

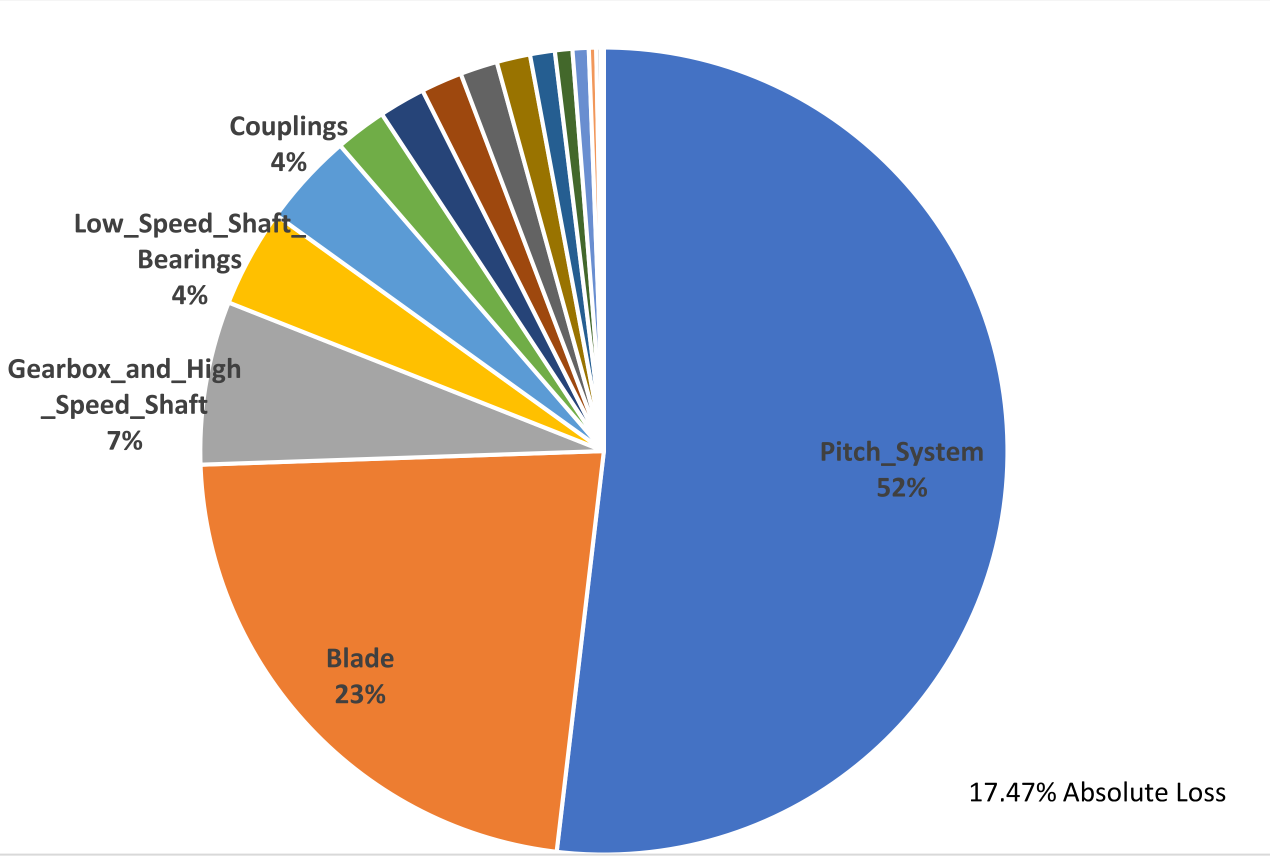


Figure 8-3 - Alternative Case 2 System Components Chart

8.2.2.3Alternative cases 3 (AC3) – Condition Monitoring implementation on individual critical component

Other alternative cases are carried out to understand the impact of availability when condition monitoring is implement to one individual critical component at a time. The result for each component is presented in Table 8-7.

According to above Table 8-7, Condition Monitoring applied on Pitch is the most efficient to increase availability (i.e. +3.11% availability). This is because Pitch is the most critical component. It is also noted that the majority of failure of Pitch (i.e. Minor failure) need to be repaired by OSV which has long mobilisation time. As the Condition Monitoring system can diagnoses in advance the coming of a failure, OSV is mobilised before the failure occurs, leading to the increase of the tidal turbine availability. However, additional OSV mobilisation are required (2 more mobilisations every 3 years) which could largely increase the OPEX. Condition Monitoring implementation for this component need also to consider this factor in order to choose the best cost effectiveness CBM strategy. CBM on other component/system need also to consider this factor.

For Blades, as majority of failures are repaired onshore by means of OSV, the result of Condition Monitoring implementation is similar as for the Pitch system(i.e. important increase of OSV mobilisation).

This is the worst case scenario for blades and pitch and the one adopted in this RAM analysis. Other strategies could allow some failures being repaired in-situ or remotely (if the CMS system allows for it). This cases can be further assessed in WP5, if it is required.

Another finding for these 2 components, is that CTV mobilisation would be less mobilised (1 mobilisation less every 7 years) than base case if Condition Monitoring is carried out on Pitch. This phenomena is due to that failures which can be repaired using CTV can also be repaired using OSV. I.e., the more OSV is mobilised, the more potential failures which normally requires CTV will be repaired when OSV is mobilised, and thus CTV mobilisation rate decreases.

In the cases when Condition Monitoring is implemented for components accessible from the Nacelle (such as: Power Electronic converter, Gearbox/high speed shaft, Control system, Generator), the availability always increases (from +0.19% to 1.1%), and the increase of OPEX would be less impacted as the OSV mobilisation will not be increased but while CTV is less expensive. The CTV mobilisation will be increased in the cases from around 1 more mobilisation every 2 years (for Power Electronic Converter case) to 1 more mobilisation every 10 years (for Generator case).

In the cost analysis in WP5, the most efficient monitoring techniques for each component are to be combined with optimized maintenance strategies and redesign in order to really highlight the benefits of implementing a CMS

Table 8-7 - Other Alternative Cases Component Criticalities

Other AC - Concept 3 (BC FP interval at 2M)	Availability	Benefit of CBM in terms of availability	OSV mobilisation (per year)	Additional OSV mobilisation (per year) Compare with BC	CTV mobilisation (per year)	Additional CTV mobilisation (per year) Compare with BC
Condition Monitoring applied only on Pitch	83.20%	+3.11%	2.56	+0.69	1.29	-0.14
Condition Monitoring applied only on Power Electronic converter	81.19%	+1.1%	1.86	-0.01	1.87	+0.45
Condition Monitoring applied only on Gearbox/high speed shaft	81.15%	+1.06%	1.85	-0.02	2.03	+0.6
Condition Monitoring applied only on Control system	80.76%	+0.68%	1.86	-0.01	1.68	+0.25
Condition Monitoring applied only on Blade	80.57%	+0.49%	2.11	+0.24	1.38	-0.04
Condition Monitoring applied only on Generator	80.28%	+0.19%	1.87	+0	1.52	+0.09
Condition Monitoring applied only on Coupling	80.16%	+0.07%	1.91	+0.04	1.42	-0.01
Condition Monitoring applied only on Bearing	80.15%	+0.07%	1.91	+0.04	1.42	-0.01

8.2.3 Alternative Cases summary

The Figure 8-4 and Figure 8-5 summarises the results of the above alternative cases in comparison with base case.

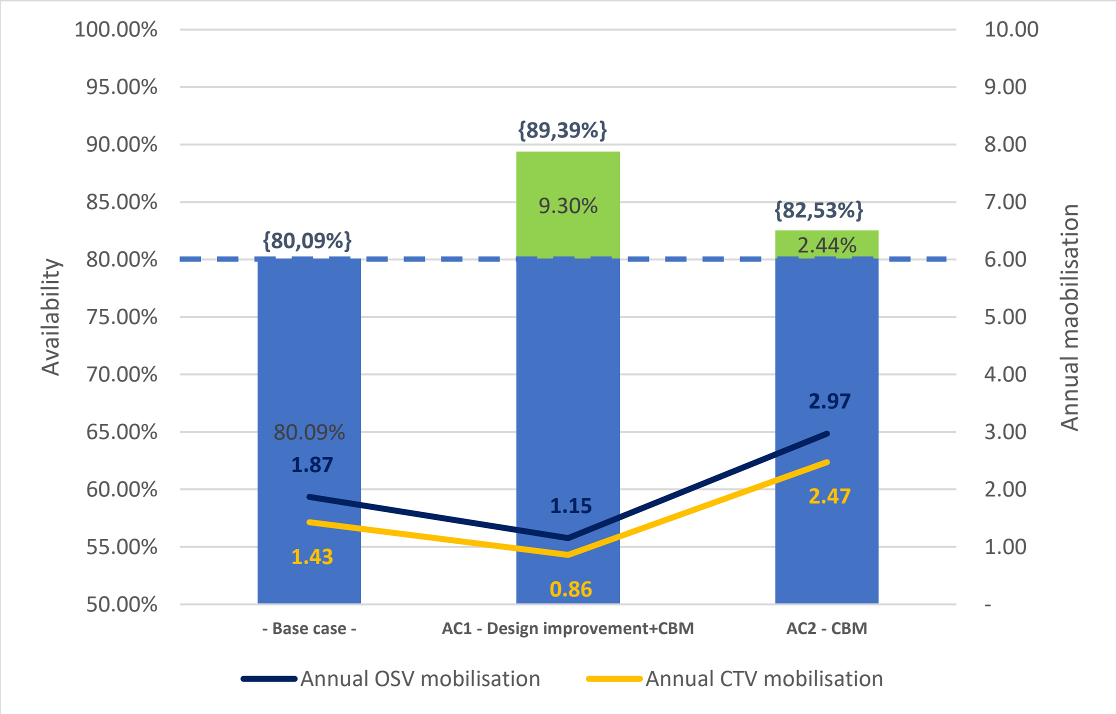


Figure 8-4 – Alternative cases summary – Concept 3

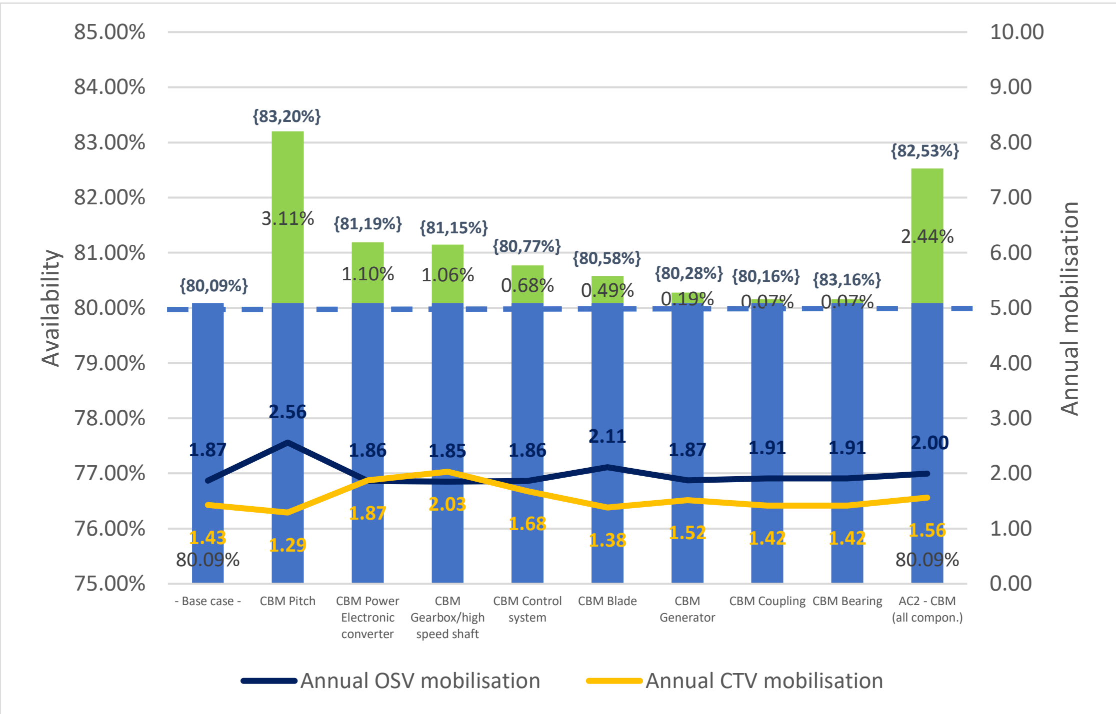


Figure 8-5 - Condition Monitoring Alternative cases summary – Concept 3

8.3 Sensitivity cases

The sensitivity cases are scenarios that are simulated and compared to each other in order to identify the robustness of the model to the variation of certain assumptions. The following sections describe the different sensitivity cases analysed for concept 3.

8.3.1 Sensitivity case 1 (SC1) – Weather condition factor analysis

Weather condition is a factor that impacts CTV and OSV operations and consequently the tidal turbine unavailability. Furthermore, weather conditions has a great uncertainty according to explanations in section 6.4.12.4 and 6.4.12.5. In order to assess how much weather condition would influence availability, the SC1 is carried out based on the base case but without considering the weather condition effect, in other words, the CTV and OSV operations will not delayed due to weather conditions.

8.3.1.1Results Overview

According to Table 8-8, availability has increased from 80.09% (from base case) to 85.64%. The difference between the base case and SC1 means that the contribution of weather condition to unavailability is 5.55%. It corresponds that the turbine is unavailable on average during 20.26 days/year due to weather conditions factor.

Table 8-8 – Result overview – Concept 1 (Sensitivity case 1)

Performance measured	Value
Average Production Availability (%)	85.64%
Annual Average Downtime (days/year)	52.42
Annual Average OSV Mobilisation	2.01
Annual Average CTV Mobilisation	1.55

8.3.1.2 Component criticality overview

Table 8-9 presents a breakdown of losses for each component.

Table 8-9 – Sensitivity Case 1 Component Criticalities

Component	Total Losses (%)	Average Absolute Loss (%)	Days/year
Pitch System	42.87%	6.16%	22.47
Blade	21.67%	3.11%	11.36
Gearbox / High Speed Shaft	8.92%	1.28%	4.68
Power Electronic Converter	6.97%	1.00%	3.65
Low Speed Shaft Bearings	3.34%	0.48%	1.75
Control System	3.32%	0.48%	1.74
Couplings	2.82%	0.40%	1.48
Nacelle Body	2.27%	0.33%	1.19
Generator	2.02%	0.29%	1.06
Low Speed Shaft	1.96%	0.28%	1.03
Mooring Line	1.61%	0.23%	0.84
Braking System	0.86%	0.12%	0.45
Shaft Lubrication System	0.62%	0.09%	0.33
Transformer	0.40%	0.06%	0.21
Cooling System	0.20%	0.03%	0.10
Pretensioned Anchor Pile	0.09%	0.01%	0.05
Subsea Cabling System	0.03%	0.00%	0.01
Low Speed Shaft Dynamic Seal	0.02%	0.00%	0.01
Power Cabling System	0.02%	0.00%	0.01
Fouling	0.00%	0.00%	0.00
Corrosion Protection	0.00%	0.00%	0.00
HV Switchgear	0.00%	0.00%	0.00
Sum	**100.00%**	**14.36%**	**52.42**

Compare with Base Case, Top contributors do not change in SC1. The main difference between to 2 cases is that average absolute loss reduced.

8.3.2 Sensitivity cases 2 (SC2) and 3 (SC3) – OSV logistic times variation

CTV and OSV logistic times are ones of the factors that impact the most the availability of tidal turbine. In reality, CTV and OSV logistic times have important uncertainty (see section 6.4.3). In order to assess how much the CTV/OSV mobilisations influence the turbine availability, it was defined the two following cases, one with higher CTV/OSV mobilisation times and another with lower CTV/OSV mobilisation times:

1) SC2 is carried out with the assumption that CTV/OSV logistic times are multiplied by 2. Detailed assumptions are:
    - OSV mobilisation time (contracting + traveling): 1 month (instead of 2 weeks in BC)
    - OSV return to onshore time (from local to onshore workshop): 2 days (instead of 1 day in BC)
    - OSV return to installation time (from onshore workshop to local): 2 weeks (instead of 1 week in BC)
    - CTV mobilisation time (contracting + traveling): 2 weeks (instead of 1 week in BC)

2) SC3 is carried out with assumption that CTV/OSV logistic times are divided by 2. Detailed assumptions are:
    - OSV mobilisation time (contracting + traveling): 1 week (instead of 2 weeks in BC)
    - OSV return to onshore (from local to onshore workshop): 0.5 day (instead of 1 day in BC)
    - OSV return to installation time (from onshore workshop to local): 0.5 week (instead of 1 week in BC)
    - CTV mobilisation time (contracting + traveling): 0.5 week (instead of 1 week in BC)

8.3.2.1Results Overview

According to Table 8-10, the SC2 presents 7.85% lower availability comparing with Base Case (i.e. 80.09%). Total average downtime increases 28.64 days/year comparing with BC.
While looking at SC3 results in Table 8-11, availability is 4.53% higher comparing with Base Case. Total average downtime decreases 16.54 days/year comparing with BC. This information confirms that OSV and CTV logistic times have important influence on availability. If we considered SC3 as worst case and SC3 as best case in terms of OSV and CTV logistic times, the availability could vary from 72.24% to 84.62%.

Table 8-10 – Result overview – Concept 3 (Sensitivity case 2)

Performance measured	Value
Average Production Availability (%)	72.24%
Annual Average Downtime (days/year)	101.32
Annual Average OSV Mobilisation	1.65
Annual Average CTV Mobilisation	1.22

Table 8-11 – Result overview – Concept 3 (Sensitivity case 3)

Performance measured	Value
Average Production Availability (%)	84.62%
Annual Average Downtime (days/year)	56.13
Annual Average OSV Mobilisation	2.00
Annual Average CTV Mobilisation	1.56

8.3.2.2Other sensitivity cases– Different PF intervals

PF interval, which represents the time that a component is in degraded model (*) before the functional failure occurs (see section 4.4.6.2), is one of the factors with the highest uncertainty. Indeed there is no existing database that can provide such information, and then the PF intervals was defined based on partner's judgement. Actually, the PF interval can vary from several weeks to several year depending but the maximum PF interval of all components was assumed to be 2 months in base case (refer to section 4.4.6.2).
In order to analyse this uncertainty, a set of sensitivity cases were carried out varying PF intervals from 0 to 6 months for all components.
(*) Degraded mode is the degraded condition of a component which is detectable before its complete failure.

8.3.2.3Results Overview

It is shown in Table 8-12 that availability ranges from 69.35% to 84.35% depending on the PF interval value. It is noted that the greater is the PF interval, the better is the availability. However, the increase of availability is asymptotic and will not exceed 85% as it can be deduced from Figure 8-6 (i.e. 6.56% different between SC5 and SC6 but only 0.67% different between SC7 and SC8).
According to this result, the availability would be relatively "stable" if PF interval of components are considered more than 6 months. This is why to simulate PF interval more than 6 months is not necessary.

Regarding "mask effect" for each components' unavailability contribution, a more detailed analysis is described in section 8.3.2.4. A detailed explanation of the mask effect is presented in section 7.3.4.2.

Table 8-12 – Result overview – Concept 3 (Sensitivity case 5 to 8)

Concept 3	PF interval	Availability	OSV mobilisation per year	CTV mobilisation per year
SC5	0 Month	69.35%	2.72	4.07
SC6	1 Month	75.91%	2.24	2.68
BC	2 Months	80.09%	1.87	1.93
SC7	4 Months	83.68%	1.52	1.65
SC8	6 Months	84.35%	1.44	1.65

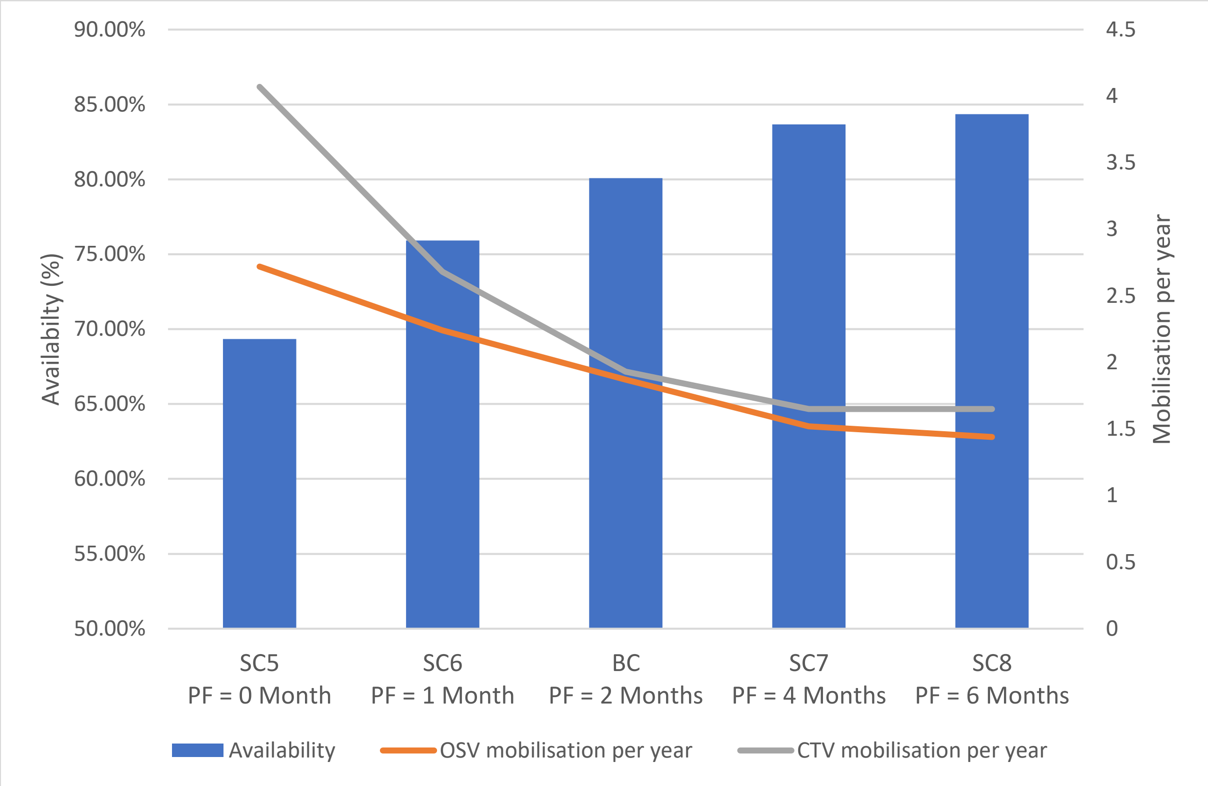


Figure 8-6 – Result overview – Concept 3 (Sensitivity case 5 to 8)

8.3.2.4Component criticality analysis

A reminder regarding mask effect conclusion mentioned in section 7.3.4.2:
"
the real contribution to unavailability from the components can not be provided due to the mask effect caused by the PF interval and the fact that degraded components are restored at the same occasion that failed component is being repaired. ***As a conclusion, the mask effect causes a "distortion" of the contribution of the component to unavailability that increases proportionally with the value of the PF interval. In a general way, the equipment with high failure rates have their relative contribution over estimated in comparison to the components with lower failure rates and this over estimation increases when PF interval is higher. As the contribution is over estimated on top critical equipment, the improvement that are proposed to reduce their contribution to unavailability are not as efficient as expected because part of their contribution is due to mask effect that come from other components.*** *Indeed, when the contribution of a top critical component is reduced (thanks to design improvement for example), masked unavailability contributions of other less critical components are "revealed" making these one more critical than it was before implementation of the improvement […].* ***This is why it is important to assess the masked unavailability contributions for each components in order to find the "real" unavailability contribution and the adequate top contributors' unavailability.***
"

Based on this observation, average absolute losses presented in SC5 are the real contribution to unavailability which have to be used as a guide in order to propose improvement on the Concept 3 design.

According to Table 8-13, in Base Case, the highest masked unavailability contribution comes from Pitch system (i.e. 2.61% of Average Absolute Loss). This is probably related to failure rate of Pitch system.

In some cases, the resulting unavailability contribution of some components seems to be "not consistent". For example, in SC8 (i.e. considering PF intervals are 6 months), Average Absolute Loss of Pitch system is 10.46% whereas the Average Absolute Loss of Blades is only 0.79% (more than 10 times more). However Pitch system's failure rate is only 2 times higher than Blade's failure rate (and repair logistic and active times are very similar). In that case, it is clear that the Pitch system contribution is masking the real contribution of the Blade. This is why, it is important to check average absolute loss using result in SC5. Further analyse according to Table 8-13 allows to choose top 8 components (to implement design improvement or CBM) according to their "real" unavailability contribution (i.e. SC5 components' average absolute loss, refer to Table 8-13).

Table 8-13 – Component criticality overview – Concept 3 (Sensitivity case 5 to 8)

Concept N°3	SC5(PF0M) Average Absolute Loss (%)	SC6(PF1M) Average Absolute Loss (%)	Base Case (PF2M) Average Absolute Loss (%)	SC7(PF4M) Average Absolute Loss (%)	SC8 (PF6M) Average Absolute Loss (%)	Contribution to loss of production masked (BC vs SC5)
Pitch_System	11.07%	9.49%	8.46%	9.97%	10.46%	2.61%
Gearbox_and_High_Speed_Shaft	3.61%	2.49%	1.90%	2.27%	2.38%	1.71%
Blade	5.68%	4.76%	4.08%	1.37%	0.79%	1.60%
Power_Electronic_Converter	2.86%	1.98%	1.48%	1.54%	1.63%	1.38%
Control_System	1.65%	1.06%	0.77%	0.21%	0.18%	0.88%
Generator	0.97%	0.66%	0.47%	0.12%	0.03%	0.50%
Couplings	0.96%	0.77%	0.53%	0.17%	0.03%	0.43%
Low_Speed_Shaft_Bearings	0.99%	0.78%	0.61%	0.18%	0.03%	0.38%
Braking_System	0.44%	0.26%	0.18%	0.05%	0.01%	0.26%
Low_Speed_Shaft	0.59%	0.45%	0.36%	0.11%	0.02%	0.24%
Nacelle_Body	0.68%	0.56%	0.46%	0.14%	0.02%	0.21%
Shaft_Lubrication_System	0.33%	0.20%	0.13%	0.03%	0.00%	0.20%
Mooring_Line	0.49%	0.42%	0.33%	0.10%	0.02%	0.16%
Transformer	0.17%	0.10%	0.07%	0.02%	0.00%	0.10%
Cooling_System	0.10%	0.06%	0.04%	0.01%	0.00%	0.06%
Pretensioned_Anchor_Pile	0.02%	0.02%	0.02%	0.01%	0.00%	0.01%
Low_Speed_Shaft_Dynamic_Seal	0.01%	0.01%	0.01%	0.00%	0.00%	0.00%
Power_Cabling_System	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%
Fouling	0.02%	0.02%	0.02%	0.03%	0.05%	0.00%
Subsea_Cabling_System	0.02%	0.02%	0.01%	0.00%	0.00%	0.00%
Corrosion_Protection	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
HV_Switchgear	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

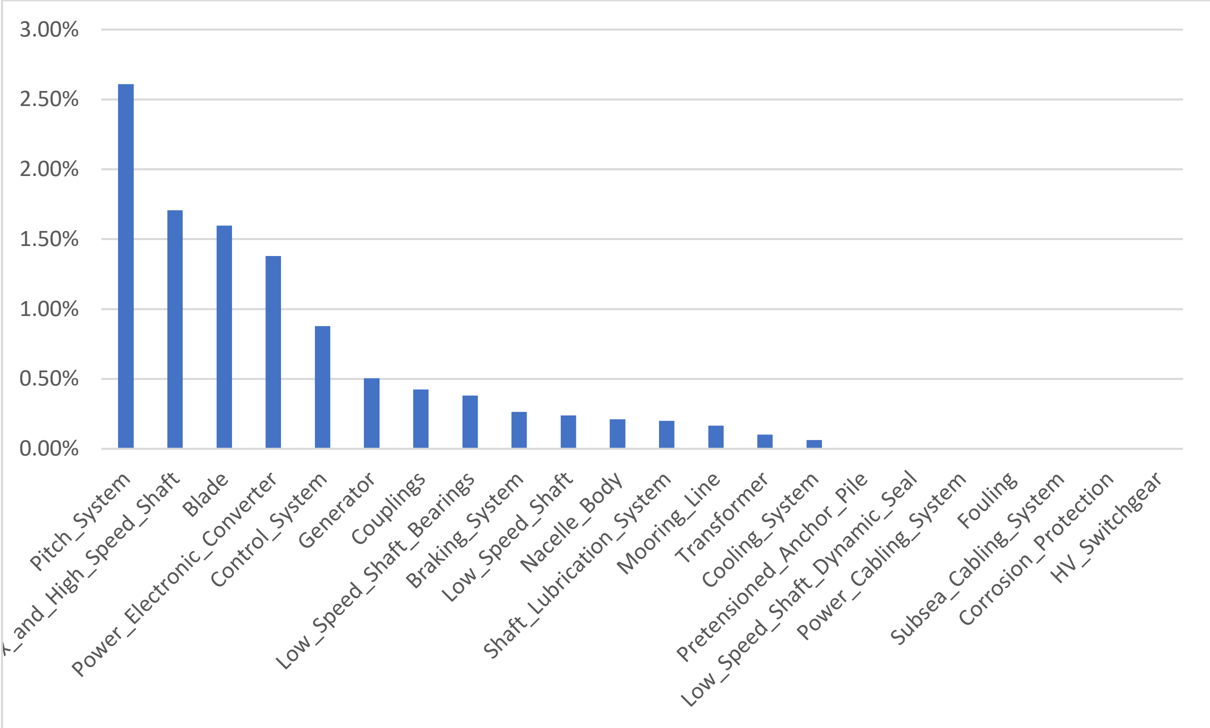


Figure 8-7 – Contribution to loss of production masked (SC5 vs BC)

8.3.3 Sensitivity Cases summary

The Figure 8-8 summarises the results of the above sensitivity cases in comparison with base case

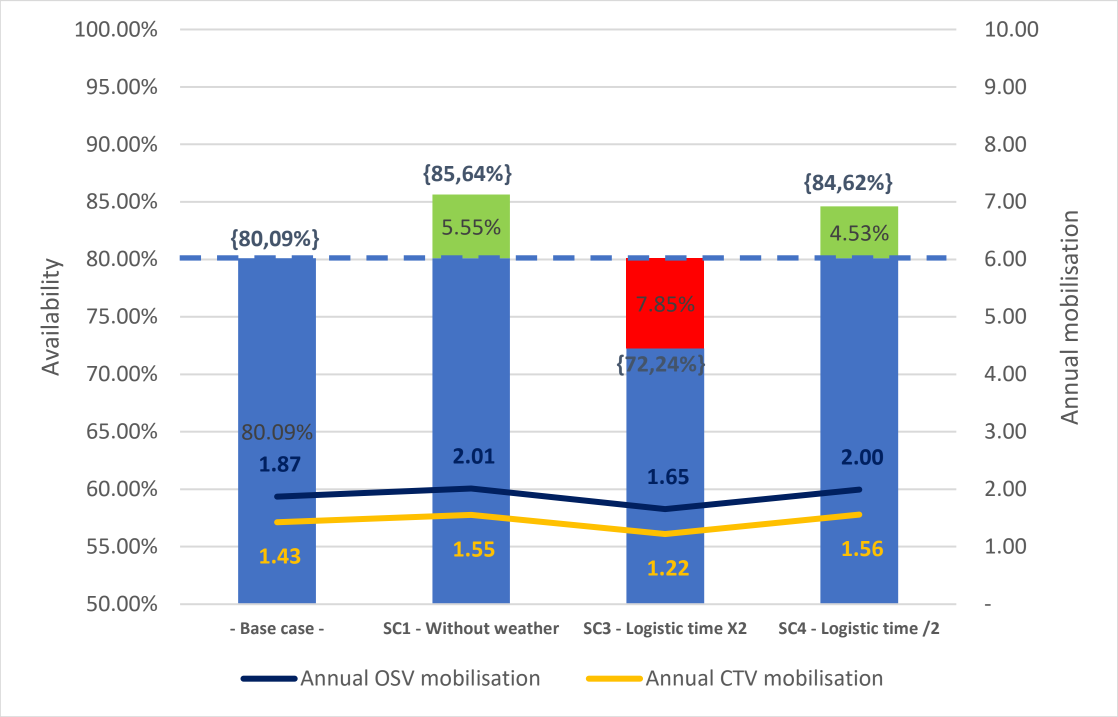


Figure 8-8 – Sensitivity cases summary – Concpet 3

9 CONCLUSIONS

The main results are summarised together with the conclusions of the RAM analysis which are presented hereafter.

9.1 Concept 1

The availability of the base case over 20 years of operation is 71.82%. The OSV mobilisation was required 2.45 times per year for turbine's components repair.

The most critical components responsible for 89.66% of all losses are:

- Gearbox and High Speed Shaft,
- Power Electronic Converter,
- Pitch System,
- Yaw system,
- Control System,
- Blade,
- and Generator;

The alternative case 1 (AC1) defined to maximise the turbine availability combining tidal turbine design simplification combining with condition monitoring of critical components increased the tidal turbine availability to 86.03% (+14.21%) reducing the OSV mobilisation to 1.54 time per year.

The alternative case 2 (AC2) implemented condition monitoring on critical components. The turbine availability increased to 77.13% (+5.30%), however, if not integrated in the system in an effective way; this strategy will require, in average, the additional mobilisation of 1.3 OSV per year.

In order to understand the benefit on availability of implementing the condition monitoring on each critical component and the consequent impact on OSV mobilisation, other alternative cases were evaluated. The condition monitoring on Pitch system seems to be the most efficient one, the availability increased to 73.83% (+2.01%) however require 0.3 additional OSV mobilisation per year (around 1 mobilisation every 3 years). In the cost analysis in WP5, the most efficient monitoring techniques for each component are to be combined with optimized maintenance strategies and redesign in order to really highlight the benefits of implementing a CMS based on Table 7-7.

The sensitivity case 1 (SC1) was carried out focusing on the impact of the weather conditions for OSV operations. The weather conditions causes up to 6.72% of unavailability, i.e. equivalent to 24.5 days/year of downtime. This is a considerable impact on the tidal turbine performance.

The sensitivity case 2 (SC2) been carried to assess the variation of availability in case the OSV is triggered when production rate is 50% or lower. The availability increased 1.60% in comparison with the base case while 1 additional OSV mobilisation every 10 years is required.

The sensitivity cases 3 and 4 (SC3 and SC4) focused on the OSV logistic time. The logistic time has important influence on availability and also great uncertainty. The availability range varies from 61.92% to 77.50% comparing the worst scenario (SC3 - OSV logistic time is multiplies by 2) and the best one (SC4 - OSV logistic time is divided by 2). This difference (15.58%) confirms the high influence of the OSV logistic time in the availability.

The remaining sensitivity cases (SC 5 to SC8) were carried out focusing on the Potential to Functional (P-F) intervals of critical components. Different scenarios with P-F intervals ranging from 0 to 6 months resulted in different availability from 56.66% to 76.55%. The availability increases with greater P-F time interval. It was further verified that the P-F interval caused a “mask effect” on components' contribution to unavailability. The real impact on unavailability were so distorted that while some components had their contribution over estimated, others were under estimated. As a consequence the top critical equipment should be set up based on the scenario where the P-F time interval is equal to 0.

9.2 Concept 3

The availability of the base case over 20 years of operation is 80.09%. The OSV mobilisation was required 1.87 times per year and the CTV mobilisation 1.43 times per year.
The most critical components responsible for 83.91% of all losses are:

- Pitch system,
- Blades;
- Gearbox and High Speed Shaft,
- Power Electronic Converter,
- Control System;

Taking into consideration the “mask effect” resulting from the sensitive case 5 (SC 5) the following components should be considered as critical as well:

- Generator,
- Low speed shaft bearings, and
- Couplings

If design improvements and/or Condition Monitoring are implemented only on the above top 5 components, unavailability of other components could increase which make the design improvement inefficient. So, it was proposed recommendations in term of design modifications and conditioning monitoring focusing on the 8 above critical components.

The alternative case 1 (AC1) defined to maximise the turbine availability combining tidal turbine design simplification combining with condition monitoring of critical components increased the tidal turbine availability to 89.39% (+9.30%) reducing the mobilisation of the OSV and the CTV to 1.15 and 0.86 times per year respectively.

The alternative case 2 (AC2) implemented condition monitoring on critical components. The turbine availability increased to 82.53% (+2.44%) however requires the OSV and the CTV to be mobilised additionally, in average, 1.1 and 1.05 times per year respectively.

In order to understand the benefit on availability of implementing the condition monitoring on each critical component and the consequent impact on OSV mobilisation, other alternative cases were evaluated. The condition monitoring on Pitch system seems to be the most efficient one, the availability increased to 83.2% (+3.11%) however require 0.69 additional OSV mobilisation per year and less 0.14 CVT mobilisation respectively. In the cost analysis in WP5, the most efficient monitoring techniques for each component are to be combined with optimized maintenance strategies and redesign in order to really highlight the benefits of implementing a CMS based on D4.3 [30].

The sensitivity case 1 (SC1) was carried out focusing on the impact of the weather conditions for OSV and CTV operations. The weather conditions causes up to 5.55% of unavailability, i.e. equivalent to

20.26 days/year of downtime. As for concept 1, this is a considerable impact on the tidal turbine performance.

Sensitivity cases 2 and 3 (SC2 and SC3) focused on the OSV and CTV logistic times. The availability range varies from 72.24% to 84.62% comparing the worst scenario (SC2 - OSV and CTV logistic times are multiplies by 2) and the best one (SC3 - OSV and CTV logistic times divided by 2). This difference (12.38%) confirms the high influence of the OSV and CTV logistic times in the availability also for this concept.

Sensitivity cases 5 to 8 (SC5 to SC8) focused on the Potential to Functional (P-F) intervals of critical components. Different scenarios with P-F intervals varying from 0 to 6 months resulted in different availability from 69.35% to 84.35%. Again, as for the concept 1, the availability increases with greater PF interval. The same "mask effect" has been observed and so the top critical equipment should be set up based on the scenario where PF interval is equal to 0.

9.3 Final considerations

This RAM analysis identified the most critical components for each turbine concept which contribute the most to loss of production. Several scenarios of improvements in terms of design modifications and monitoring were proposed and assessed.

The critical components highlighted must be prioritized in WP4 for the development of the condition monitoring system.

The design improvement recommendations suggested in the alternative cases are to be addressed in WP5 for future developments. The outcomes of the RAM study provides valuable information to the cost model (WP5) about CAPEX (based on the Turbine Design structure), OPEX (based on components' failure rates and on OSV/CTV mobilisations) and revenues (based on turbine availability).

The alternative and sensitivity cases assessed the impact of key choices such as: design structure architecture and maintenance strategies

Evaluating the results it is possible to conclude that the design modifications are potentially more efficient than CBM (when not combined) to improve availability and to reduce OSV/CTV mobilisation frequency. However, in order to reach the highest availability result, the combination of design improvement and CBM is required.
Comparing the results from the 2 concepts, it can be concluded that bottom fixed turbines will be more benefited of the Condition Monitoring implementation. This is because the complexity of repair in such turbine is higher than for floating turbines, and consequently the condition monitoring will reduce the impact of this complexity on unavailability by anticipating the critical failures.

It is to be noted that all the CBM strategies considered in this report are generic and do not take into account the improvements that can be obtained after the RealTide project. In addition, it has been investigating in the WP4 new monitoring strategies and techniques, which certainly will contribute to a most efficient CBM strategy, more reliable tidal turbines and a vast cost reduction. This new findings could also be assessed in further RAM analyses in WP4 if required

It is also to be noted that it was also considered the weather conditions of a location with harsh climate location and difficult access. As the weather conditions has a significant impact on the tidal turbine availability, the results might change significantly for other locations.

Anyway, the RAM analysis presented in this report highlighted that CMS could be powerful when combined with redesign. However, it should also be investigated the effect of the combination of CBM implementation with an adequate planned maintenance strategy, which has not been taken into account in the present study. It will be an important aspect to be considered in the future (cost model) as explained hereafter.

The implementation of the proposed improvements impacts directly or indirectly the CAPEX and also the OPEX of tidal turbines. The sole analysis of the potential increase of the turbine availability provided by the recommended improvements is not enough to take decisions without considering the impact on the costs of investment and operation. This is why a cost model analysis needs to be performed based on the results of the RAM analysis, which is proposed to be performed in the WP4 for the condition monitoring definition and WP5 for the design improvements. In case the case models are not conclusive and the availabilities of provided in this study till need to be improved in order to make the tidal turbine cost-effectives, further investigations have to be provided focusing on the critical components, but also on the optimisation of the logistics for repairing (for example reducing time of mobilisation of OSV/CTV) defining preventive maintenance strategies combined with CBM or mitigating the effect of the weather conditions on CTV/OSV operations.

It is to be noted that Condition Monitoring is not commonly taken into consideration in RAM analysis. The fact that degraded modes are modelled and that degradation can be monitored and repaired before the component completely fails brings complexity to the modelling and also to the results interpretation. This is why a PetriNet based tool was selected introducing more flexibility in the RAM modelling. This innovation led to new challenges resulting in unexpected findings such as the “mask effect” described in section 7.3.4.

An important issue for this RAM analysis is related to the reliability data i.e. the lack of data available in the tidal turbine domain. As explained in the previous sections, most of the data used in this study were collected from reliability databases from wind turbine farms, based on the existing similarities between these types of turbines. However it should be observed that differences also exist and are mainly related to the component technologies and the operational environment/behaviour. This will bring uncertainties to the project results.

The results from this study cannot be considered the ultimate reference to decide if tidal turbines are an effective alternative source of renewable power production. This study should be considered as a primary step in the development of tidal turbines. Anyway, this work will help in achieving a better knowledge of tidal turbines and will help to increase their availability in the future as it provides important findings which can be used in the development of the next generation of tidal turbines. For example, in new turbine designs or in new specific development designs which allow to perform maintenance strategies in more situations

Nevertheless, even that the estimated availabilities in the base cases of both concepts could not be 100% representative to the reality due to the lack of data available, this report remains valid to identify potential source of unavailability by the identification of the most critical components, also to identify the influence of factors such as weather conditions and logistic times and then to define potential improvements and estimate their impact on tidal turbine performance.

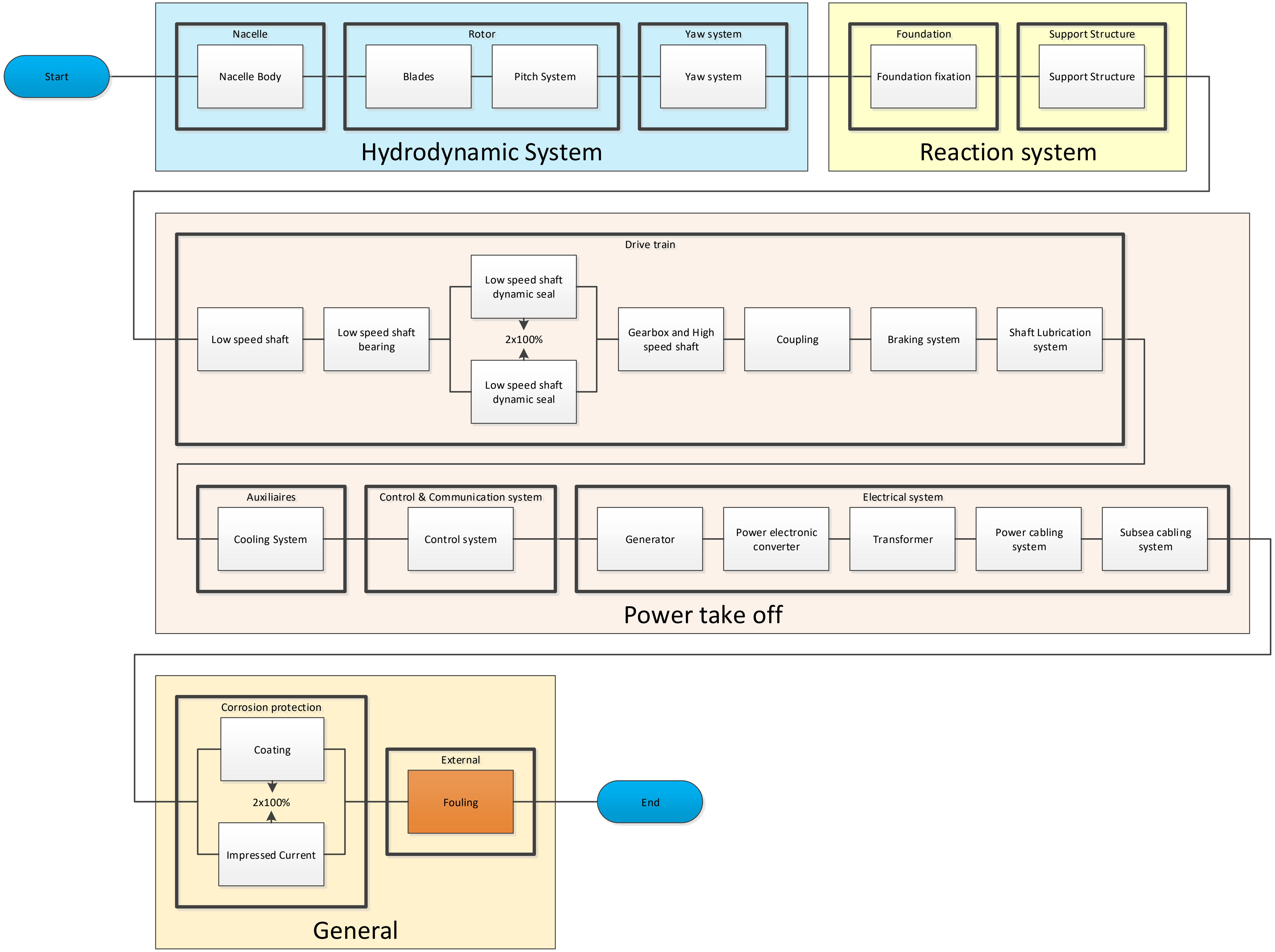
However, this RAM simulation doesn’t substitute the necessity to invest on the implementation tidal turbines farms in real scales. These farms, when implemented, will bring more experience and understanding on the tidal turbine behaviours and its specific employed technologies and will help to

constitute databases dedicated to Tidal Turbine devices that can be used in the future as a support to improve more and more tidal turbine technology and performance.
This reflexion highlights the importance of performing a reliability database specifically adapted to Tidal Turbines which is the objective of the task 1.6 of the RealTide project. These initiatives are essential to increase experience and constitute the necessary feedback to perform RAM analysis on the next tidal turbines concepts that will result in the development of Tidal Turbine of the future even more reliable and cost effective.

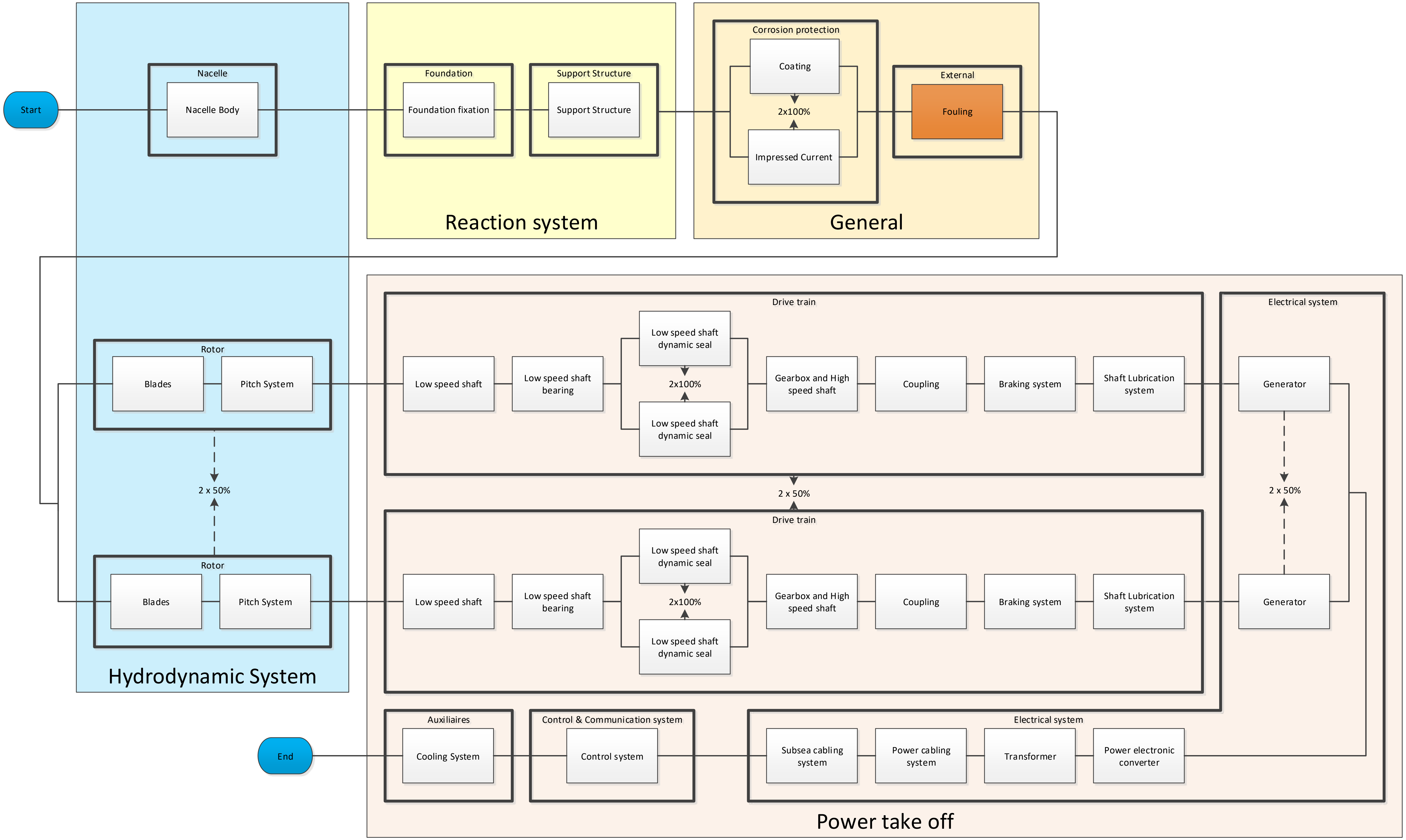
Finally, it is important to note that this study was performed considering a unique tidal turbine. In order to go further in the optimisation, the next step will be to extend the scope of the analysis to the farm level including several tidal turbines with more accurate data. With this new approach, it will be possible to optimise the maintenance resources such as OSV/CTV but also spare parts strategy and also to set up the better configuration for the farm network. Results from these studies will provide guidance to the technology developers to achieve a better design, not only more reliable but also much easier to maintain resulting to a global optimized O&M strategy.

ANNEX

ANNEX A – RELIABILITY BLOCK DIAGRAM – CONCEPT 1 – COMPLEX BOTTOM FIXED TIDAL TURBINE



ANNEX B – RELIABILITY BLOCK DIAGRAM – CONCEPT 3 – FLOATING MULTI ROTOR TIDAL TURBINE



ANNEX C – ASSET REGISTER

Sub-system	Assembly	RAM Component	Failure rate (/year)	Reference	Failure Category Probability (FCP)			MTTR (Hours)			Production Impact
					Major	Minor	Trivial	Major	Minor	Trivial	
Hydrodynamic System	Nacelle	**Nacelle Body**	1.13%	Dao et al (2019) [33]	100%	0%	0%	1.69%	0.14%	0.01%	100%
	Rotor	**Blades**	8.50%	Ingeteam database (section 4.4.1.2)	0%	97%	3%	1.69%	0.18%	0.02%	100%
		Pitch System	17.07%	Ingeteam database (section 4.4.1.2) & Expertise (Newer technology estimation)	1%	93%	5%	1.21%	0.16%	0.01%	100%
	Yaw system	**Yaw system**	11.33%	Ingeteam database (section 4.4.1.2)	0%	90%	10%	1.69%	0.13%	0.01%	50%
Reaction System	Foundation system	**Foundation fixation (Concept 1 : Gravity base)**	0.03%	FMEA [31]	100%	0%	0%	14.16%	0.14%	0.01%	100%
		Foundation fixation (Concept 3 : pretensioned anchor pile)	0.07%	FMEA [31]	100%	0%	0%	14.16%	0.14%	0.01%	100%
	Support Structure	**Support Structure (Concept 1 : Fixed structure + Fixation Piles)**	0.57%	Dao et al [33]	100%	0%	0%	14.16%	0.14%	0.01%	100%
		Support Structure (Concept 3 : Floating structure + Pretensioned anchor piles (Mooring lines + Turret))	0.57%	FMEA [31]	100%	0%	0%	14.16%	0.14%	0.01%	100%
Power take off	Auxiliaries	**Cooling system**	0.57%	Ingeteam database (section 4.4.1.2)	0%	88%	13%	1.69%	0.16%	0.00%	100%
	Drivetrain	**Low speed shaft**	0.81%	NREL [35]	100%	0%	0%	1.69%	0.14%	0.01%	100%
		Low speed shaft bearings	1.35%	NREL [35]	100%	0%	0%	1.69%	0.14%	0.01%	100%
		Low speed shaft dynamic seals	0.68%	Serap Aksu et al (2006) [44]	100%	0%	0%	1.69%	0.14%	0.01%	100%
		Gearbox / high speed shaft	18.55%	Ingeteam database (section 4.4.1.2)	2%	93%	6%	1.26%	0.12%	0.02%	100%
		Couplings	1.24%	FMEA [31]	0%	100%	0%	1.69%	0.14%	0.01%	100%
		Braking system	2.27%	Ingeteam database (section 4.4.1.2)	0%	100%	0%	1.69%	0.10%	0.01%	100%
		Shaft Lubrication system	1.56%	Ingeteam database (section 4.4.1.2) (hydraulic system)	0%	95%	5%	1.69%	0.15%	0.01%	100%
	Control & Communication system	**Control system**	9.63%	WMEP [32] (Better reliability than Ingeteam)	1%	74%	25%	1.23%	0.12%	0.00%	100%

Sub-system	Assembly	RAM Component	Failure rate (/year)	Reference	Failure Category Probability (FCP)			MTTR (Hours)			Production Impact
					Major	Minor	Trivial	Major	Minor	Trivial	
	Electrical system	**Generator**	4.53%	Ingeteam database (section 4.4.1.2)	5%	94%	2%	3.93%	0.13%	0.00%	100%
		Power Electronic Converter	17.14%	Ingeteam database (section 4.4.1.2)	2%	74%	24%	1.41%	0.14%	0.00%	100%
		Transformer	0.99%	Ingeteam database (section 4.4.1.2)	0%	54%	46%	1.69%	0.06%	0.02%	100%
		HV switchgear	0.71%	Ingeteam database (section 4.4.1.2)	0%	70%	30%	1.69%	0.09%	0.01%	100%
		Power cabling system	0.04%	IEEE 493 [5]	0%	80%	20%	1.69%	0.14%	0.01%	100%
		Subsea cabling system (Concept 1 : Seabed zone)	0.03%	PARLOC 1996 [41]	100%	0%	0%	1.69%	0.14%	0.01%	100%
		Subsea cabling system (Concept 3 : Surface area)	0.01%	PARLOC 1996 [41]	100%	0%	0%	1.69%	0.14%	0.01%	100%
Hydrodynamic System & Reaction System	Corrosion protection	**Coating**	0.07%	FMEA [31]	0%	100%	0%	1.69%	0.14%	0.01%	0%
		Impressed current	0.57%	FMEA [31]	0%	0%	100%	1.69%	0.14%	0.01%	0%
	Fouling	**Fouling**	N/A	Expertise	0%	100%	0%	1.69%	0.14%	0.01%	1% / year