

## Analysis Review of the Reliability-Availability-Maintainability for the OWTs

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**Abstract** –The paper analysis the failures and downtimes associated with WT's projects from the Onshore (i.e. Reliawind) to an extrapolation in the OWT's, and their effect on O&M cost development.

Diverse risks detailed on the FMECA, clearly can be notice a various types of failures, which ones probe and address OWT's into a situation mostly "luck of reliability", from Groups, Sub-assemblies and elements/components. For instance, it could be said that structural damage on Wind Turbine can set their mechanical robustness but not their ability to resist what followed, along their functional life cycle phases (Early Life, Normal Life, and Wear-Out).

As well as it happen in engineering projects about what increases or decreases costs, is the methodology developed, and the technical solutions applied. Nevertheless, controllable options, uncontrollable uncertainties, resources, O&M strategies, and SCADA data feedback, all those parameters that straightforward have an influence, becoming the outcome result of an O&M model. All in all, given O&M decision-make, in order to implement it into optimize costly way.

The high cost-competiveness along cross technologies in OWT's, besides the battle for reduction of operation and maintenance costs drives a crucial role in reducing the cost of offshore energy produced at any offshore wind farm. Where the principal cost drivers of O&M are, location of service station, logistics to and on site, and availability of crane or jack-up.

Even though, offshore failure data are limited, so then, was need it to apply an extrapolation ratio (Onshore vs. Offshore failures) from Mahmood Shafiee research work. (Shafiee, February 2017)

Risk assessment (FMEA) are used, in order to tackle the greatest group (Power Module, Rotor Module...etc) of failures and downtimes identify, and their Sub-assemblies (i.e. frequency converter, pitch system....etc).

The results found indicated what nature (Offshore Wind Forces) reports, in generally, the sub-assemblies more exposed (mechanical and structural ones) are the ones with higher failure rates accumulated, as result, major degradation during their own life cycle.

Concluding that for those ones, is required beforehand a robust design for reliability(DfR) in order to add reliability value during their functional service life, as well as increase the life span. All in all, is to optimize the O&M cost and to avoid failure (↓Risks) during production service operation and extend as much the reliability, as does CBM.

Last but not least, it demonstrated that as much monitored (i.e. CBM) is the functional asset, as much faster will be took the "decision-maker" and their corresponding outcome action, as well was resulted through Weibull and Gamma distributions.

**Keywords** –FMEA, O&M strategies, SCADA, DfR, CBM, Weibull and Gamma distributions.

### I. INTRODUCTION

Actual OWT's are deigned to work 120.000 hours (approx.) to route their estimate design life cycle of 20 - 25 years. Under the assumption, that the OWT's are on service operation approximately 66% (approx.) of the time over the 20 years. Although, it's essential to gather data remotely from every single OWT in operational services, keeping analyzing all of this data at real time, being crucial in order to keep the wind power farms operating efficiently and safety, as well as carrying out continuously inspection service, maintenance and repair properly. In addition to that, monitoring of the assets and gathering their data, is need it for the adaptive and preventive maintenance of the OWT's much faster.

In terms of offshore wind technology, there exist many technical and economical choices that have diverse effects on the CAPEX, OPEX, Ec (Energy Capture) and Risks.

The move forward from the available "state of the art" of OWT's to the next generation of OWT's represent a major development challenge to OEM Energy operators/companies. This requires a true multi-disciplinary environment

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for both customers and suppliers along with the implementation of the basic standardization system dynamism. Follow by a strong collaboration exchange in reliability and availability issues.

As it is known, always is going to be a cost associated with having to maintain and replace moving sub-assemblies elements/components. So, management and continuously doing assessments of the O&M can bring cost reductions to the OWT's in many ways.

Nowadays, offshore wind energy still being cost-competitive technology in most Europeans markets, following by handicap of having higher energy consumption (demand) vs. the cost-competitive OWT's technology. Based to the Global Wind Energy Council(GWEC) (GWEC, 2018), the growth in Offshore Wind Power is due to a listed reasons:

- a) The maturity of the Wind Industry.
- b) Improvement and maturity of the technology and its management.
- c) Growing investor confidence.
- d) The introduction and deployment of a new generation of turbines, with a higher swept area( $A_{swept}$ ) thus higher output( $E_{input}$ ).
- e) Jose V.Taboada, Vicente Diaz and Xi Yu (TABOADA, Jose V.; CASAS, Vicente Diaz; YU, Xi), a call to increase reliability standards in installations (i.e. Offshore Wind Farms), in order to extend their operational service life as it happens with much robust installations (i.e. Oil&Gas).

The major contributors come from “lost of production(downtime/failure)” and “transport costs”, being the ones that increasing O&M costs. Where those maintenance costs are large element in the OPEX, which can make up around 20% - 30% of the LCOE of an Offshore Wind Farm (James Carroll, 2017).

Consequently, being capable to predict and fine-tune the operations is the primarily advantage, being possible to analyze this information across a multitude of OWT's, which are connected each either into the same offshore wind farm. Where CBM helps to anticipate maintenance services(“advance costs provision”), given a major engineering integrity of the reliability and availability management of the sub-assemblies at real-time during the functioning service life.

As well as, the energy yield itself is also heavily affected by the integrity of O&M methodologies and strategies applied. Thus, optimization of O&M Cost (OPEX), as well as the reduction of LCOE is crucial to sustain an affordable Offshore Wind Energy development Industry.

Before an optimization can start, one has to know the current status (histograms of failures rates accumulated, downtime events...etc) and prioritize further improving actions. Where leading a low cost of energy for offshore/onshore wind power will always upfront, so then, it could compete against low-cost fossil fuels technologies.

In the last years, a number of quantitative studies[3] of offshore wind turbines reliability and numerous initiatives have begun to collect historical data (i.e. from SCADA Systems) on the performance and reliability of Wind Turbine onshore and offshore and to publish the results in various conferences and journals (E Gonzalez, 2016).

Nevertheless, the objectives of the various initiatives are similar, each initiative follows a different approach to tackle sub-assembly (e.g. Generators, Rotors...etc) components/elements reliability and failure predictability. Most publications focused on summarized analysis from downtime events to determines the distribution of downtimes and failure rates of the sub-assemblies, and the results are challenge difficult to compare.

By another side, in recent years, exist industrial development tendency of manufacturing large WTs/OWTs, due to the maintenance benefits add in the number of maintenance personnel, means and tools, spare parts and O&M facilities can be grouped or nearby to the WT/OWT farm location. Besides this tendency, also scale size has become both an increase performance (through longer blades and taller towers) and decreased up-front costs (Ryan Wiser, 2016).

This paper addresses this issue, gathers the failure real data from OWT's, classified and organized it, input the main parameters and variables into probabilistic model, analyzed and harmonizes the results.

This paper tries to measure the real reliability and availability of OWT's sub-assemblies(i.e. Gearbox, Drive-train, Yaw system...etc)according to the best source of information(failure histograms, downtimes...etc) for specific technical and functional needs. Paper prepares all information in such a way that it is easily accessible, analyses the relevance of the initiatives considered and looks for fundamental trends that O&M Industry demands. The overall aim is to enable

maintenance planners to feedback beforehand the maintenance schedule, base upon the available knowledge on performance and reliability of Wind Turbines to optimize future maintenance resources (Sebastian Pfaffel, November 2017).

### 1.1. Offshore Wind Turbine Sub-assemblies

Diverse types of OWT's are utilized in the Offshore Wind Industry. Wind turbines, generally in onshore or offshore, are categorized into two main groups (fixed and variable speed turbines). Where OWT's are organized according to their architectural design configuration concept types of Floating Offshore Wind Foundations (FOWF); Spar Bouy (Deep/Large Draft Buoy), Semi-Submersible, Tension Leg Platform (TLP).

Wind Turbines reliability data embrace the historical track record of failures, repairs, and downtimes of an entire turbine and its own sub-assemblies.

Although, wherever the wind turbine is placed in onshore or offshore, exist a common pattern system, that consists of several electrical, mechanical and structural components which ones are classified into these three sub-assemblies groups. Mostly of the components/elements are standardized, for both industries (Onshore and Offshore), in addition to that, some of them, are coming from other industries (i.e. Oil&Gas Platforms).

The Offshore Wind Turbines Sub-assemblies, can be find on next figure below;

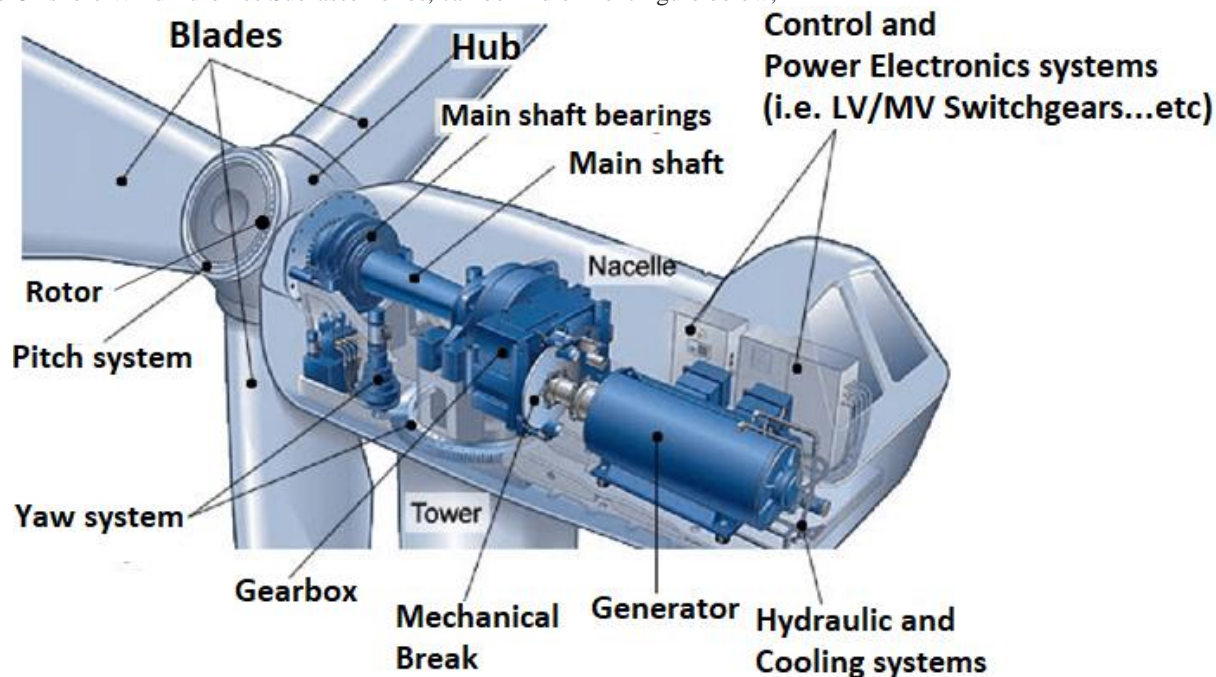


Fig1. Wind Turbine Sub-Assemblies (Courtesy of [7])

**Rotor:** The three blades together assembled with the hub, are known as the rotor compound, which transforms the kinetic energy from wind to mechanical-electrical power through the main shaft. The geometry and length of the blades, their position against the wind direction and their structural attributes, are essential technical and capacity potential generation characteristics of the rotor.

**Blades:** Blades geometry and shape profiles are twisted to obtain optimum angle of attack throughout the entire blade. Wind forces will bend the blades, allowing to rotate around the rotor hub (blades assembly).

**Yaw motor:** Receiving the input commands signals from the controller unit, the yaw motor turns (around the tower) the nacelle and rotor compound, according to the incoming wind direction. Allowing the optimal orientation efficiency, towards the power extraction that it could be performed if the yaw system fully operates without troubles.

**Pitch motor:** The double mode function of the pitch system, allows firstly attaining the higher amount of power at different wind state conditions, secondly as safety pitch system during harsh weather conditions, therefore, the blades angles orientation (pitch angle) shall be controlled which is achieved through pitch motor.

**Main shaft and bearings:** The main shaft(rotor shaft) rest on two bearings(rotor bearings), being a complete axe that connects the rotation transmission from the rotor hub to the gearbox.

**Gearbox:** Mechanical Power rotation transmitting gearbox in wind turbines changes the rotational speed from rotor speed to the speeds required by the generator. Gearboxes are characterized as having the high down times and failures, also with high CAPEX and maintenance costs.

**Mechanical Brakes:** For emergency situations like extreme weather conditions, or to carry out corrective maintenance and repair activities, the mechanical disk brake are used to lock the main shaft, so being the system safe against rotations.

**Drive Train:** Located between the hub and gearbox, existing different drive train component arrangements-concepts, where mostly are distinguished by the type of drive train technology(High Speed Modular Drivetrain, Medium Speed Drivetrain, Direct drive Drive-train), which ones provides a different overall ratio. The drain train can be consider the core one.

**Generator:** The generator consists of the stator and rotor, being available synchronous and asynchronous (induction) generators that convert the mechanical energy to electrical one. The pole number(4, 6 or 8 poles), together the grid frequency, determines the generator speed.

**Convertor:** The power convertor is formed by the power conditioning circuit that is capable of adjusting the generator rotor frequency and voltage to the grid network distribution. Connected to grid, via a DC link.

**Sensors:** Most of the environmental conditions physical properties, like wind speed, pressure, temperature, humidity, as well as other internal properties as the electrical, hydraulic, output power, voltage, current, are measure through these sensors. Important ones(i.e. anemometer, vane) sensors.

**Hydraulic and Cooling Systems:** Hydraulic systems and actuators are need it to perform rotary movements from turbine sub-assemblies(e.g. pitch and yaw). Although, wind turbines operated within a large temperature range from diverse sources(external climatic conditions, heat losses of gearbox, generator heat up...etc), so, temperature should not exceed the admissible functional operating range of the installed components/elements, being need a combined oil-water-cooling cycle systems.

**Controller and Power Electronics Systems:** Are the sub-assemblies parts formed by microcontrollers, microprocessors and electronic systems which all are in charge to control different functions of the wind energy control system unit.

**Nacelle:** This sub-assembly part encapsulates the high speed shaft, drive train, brakes, gearbox and generator.

**Tower:** That's the key structural sub-assembly component of the wind turbine system on which rotor hub and nacelle are mounted. The higher the tower is, the better absorption of wind speed curve and kinetic energy power.

**Foundation:** This structural base sub-assembly various(Fix Structure, Spar-Buoy, Semi-Submersible and TLP) diversely. Above the foundation is mounted the tower structure.

- Sub-Assembly Classification diagram

It can be classify the major part groups(structural, mechanical and electrical) for an OWT standardized, that encloses all the sub-assembly components. The tree classification of theirs is represented on figure, below;

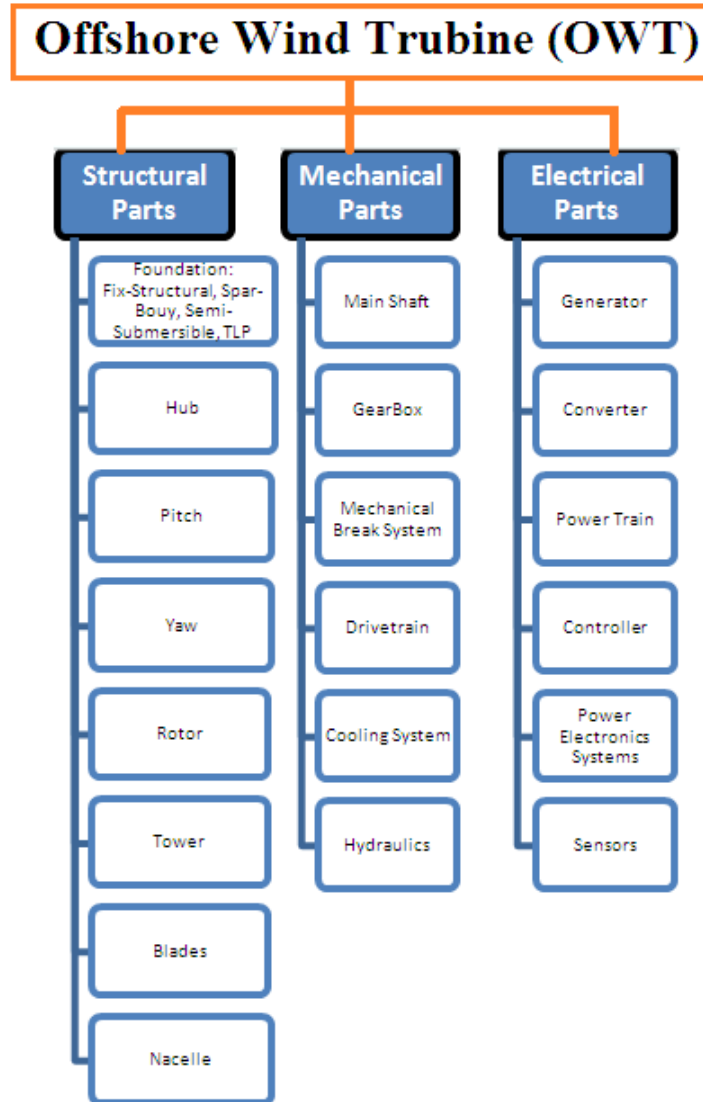


Fig2. Offshore Wind Turbine sub-assemblies components classification

### 1.2. P-F interval.

The degradation speed curve of the technical functional requirement condition state of any sub-assembly component/element is an on-going process the new to end life service.

Likewise, preventive maintenance (PM) is applied in two strategies: Time-Based Maintenance(TBM) and Condition-Based Maintenance(CBM).

Time-Based Maintenance (Age-Based + Constant-Interval) is carried out on equipment based on a calendar schedule. Meaning that time is the maintenance prompt for this kind of maintenance. Age-Based maintenance not being applicable for OWT's due to their high fixed costs, where this cost should be need paid when the preventive maintenance happens for any spare component/element at certain age. Conversely, Constant-Interval maintenance in general, applies for the preventive replacement of OWT's components/elements and systems after a fixed interval of time. Where the potential failure sets, are represented along the P-F interval curve.

Therefore, moving from old way(P-F Intervals) management to modern one as CBM(“set of maintenance actions on real-time assessment of equipment condition state health, which one mostly is obtained by embedded sensors transmitters installed or even from test and measurements taken by maintenance portable equipment”), has able to measure the degradation speed curve development at real-time. P-F Interval and CBM as such, can be summarized as one next figure below;

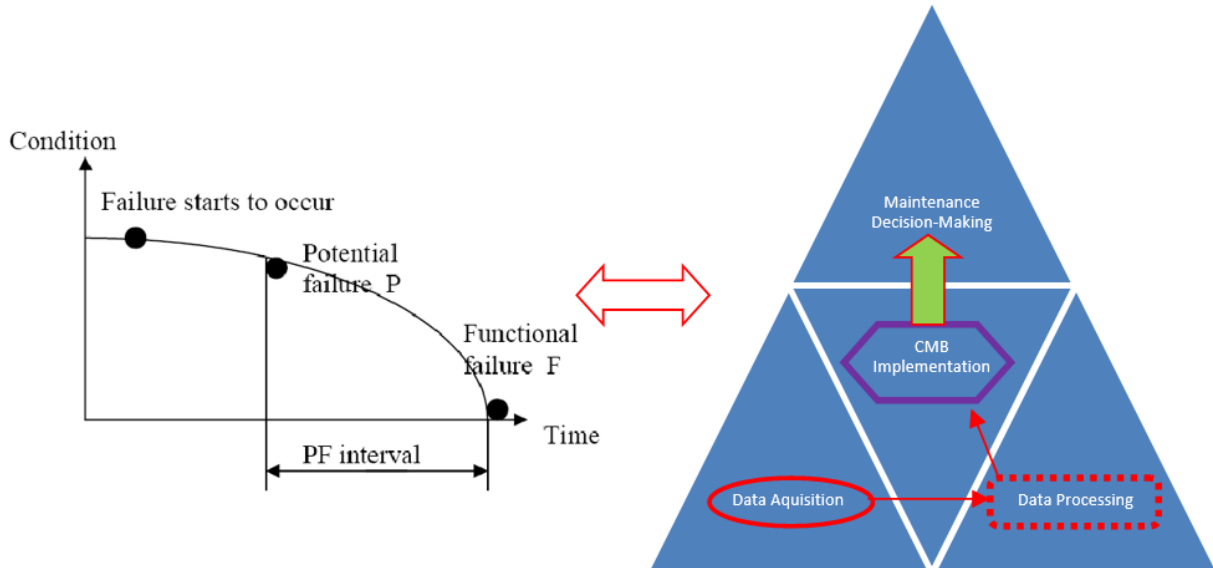


Fig3. Potential Failure Interval (Nilson, 2006) and CBM implantation.

As we can see from figure above, to feedback up the data processing, it shall be first collected the data acquisitions from the operation receivers (sensors) on the equipment’s. After data processing, the core data is fully transfer into essential information for diagnosis and feature extraction (i.e. analogical graphics, failures histograms...etc). Followed, by the CMB itself, that established the real-time intervals monitoring of the components/elements (“assets”). Lastly, from the outcome by the maintenance decision making, is decided whether sending maintenance technicians for the Offshore Wind Farms to replace spare components or not.

### 1.3. WT’s Failures and Downtimes.

Failures and downtimes are the mother of problems on any production installations(e.g. automotive assembly lines, wind farms...etc). Provocation potential looses from production generation as such. Where the reliability data, together with downtimes and failure rates, are crucial for the design, maintenance, operation, and performance assessment of WT’s but usually are difficult to obtain.

The figure 2, represents the remarkable as it shows that 25% of failures cause the 95% of downtimes, and 65%(approx.) of failures cause only the 5% remaining of the downtime. The gearbox failures stands causing the longest downtime, in compare with the electrical system that has the highest failure rate.

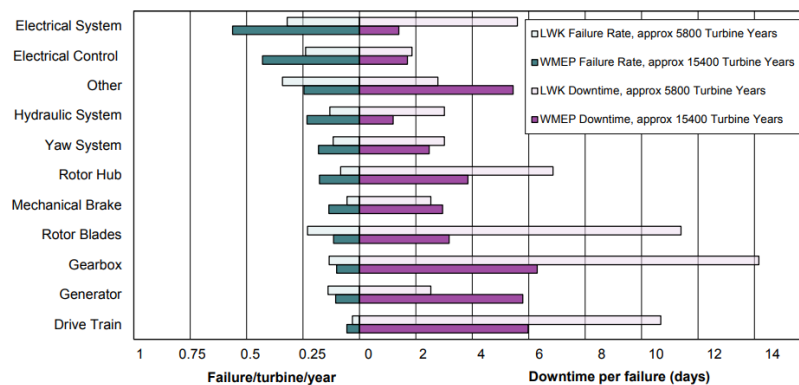


Figure 4. Failures and downtime from two large surveys of land-based European turbines[9]

- Normalized Failure and Downtimes

As we can see on the figure 5, which one shows one of largest surveys-studies (Reliwind) of land-based European turbines from multiple manufactures. The Reliwind normalized failure rate data shows how the subsystems(i.e. Power Module, Rotor Module...etc) contributes to the turbine's total failure rate variation.

It can be observed that the power module is the peak subsystem that brings failures. As single greatest factor of failures, it's the pitch system, with a 22%(approx.) contribution failure rates.

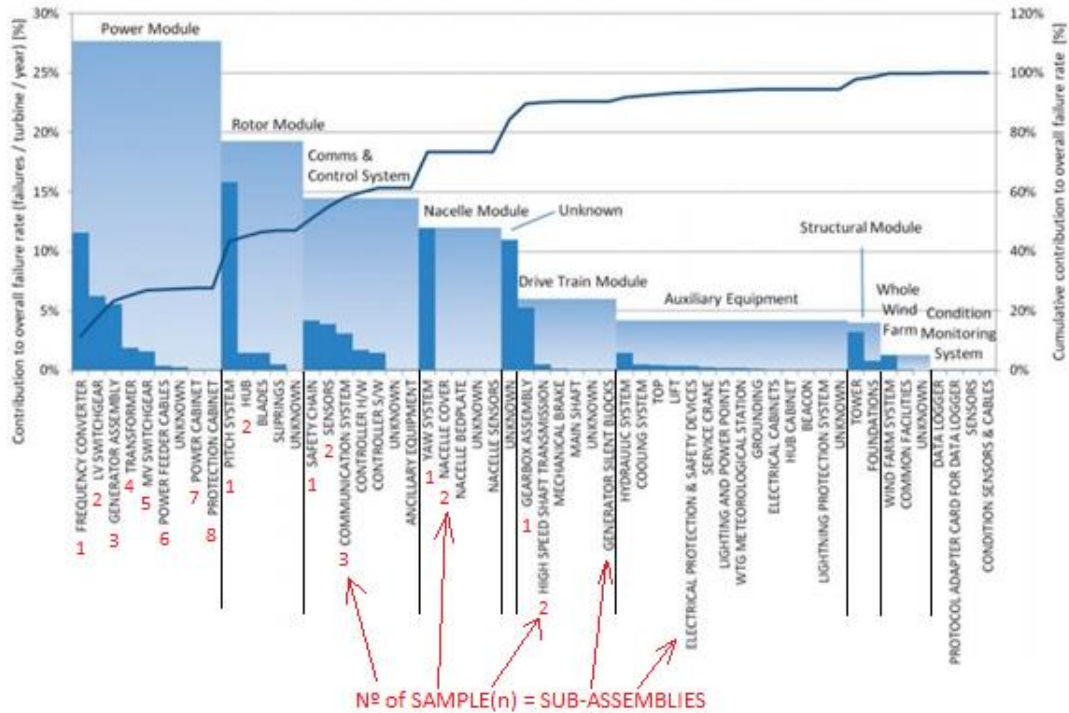


Figure 5. Distribution of normalised failure rate(failures/turbines/year) by sub-system and sub-assembly for WTs of multiple manufacturers from the ReliaWind survey. [10]

The graph below on figure 6, describes the Reliwind normalized percentage contribution down time(hours/year) data from multiple manufactures, where each part contributes to the subsystem's downtime and each subsystem contributes to the wind turbine's total downtimes. Top percentage contributing subsystems to the overall downtime are the converter, pitch, yaw and gearbox.

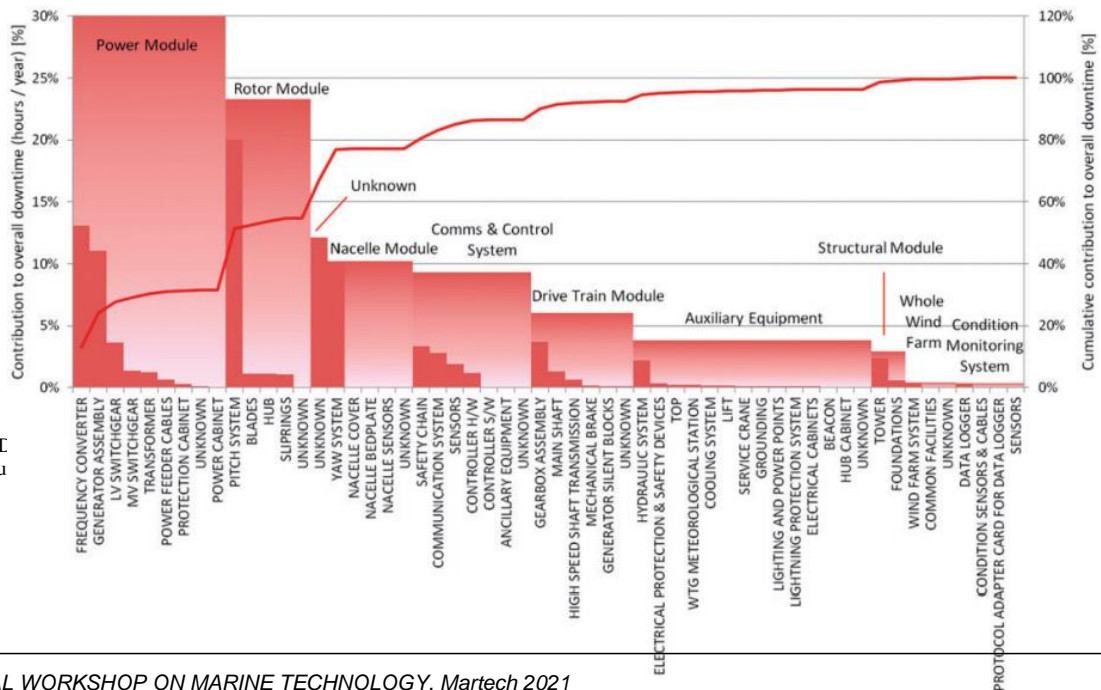


Figure 6. I ReliaWindsu

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Fig.5 and Fig.6, are showing results obtained from ReliaWind survey. From the downtime(Fig.6) lessons, are showed a much greater emphasis on power modules and rotor.

In addition to that, from the previous Fig.5 and Fig.6, has been classified the Group of Failures from the ReliaWind survey along respective Tables 2 and 3 (See into the Appendix section).

Overall, the ReliaWind work, showed in Fig.5 and Fig.6, and summarized on Tables(2 and 3, in the Appendix)determined the six least reliable sub-assemblies in a cross survey of 1400 turbine-year, shorted in downward unreliability as follows(Gearbox, Generator, Control System, Yaw System, Power Electronic Converter, Pitch Mechanism, Electric/Hydraulic). (Tavner, 2012)

- Reliability vs. Operational Service Years

As can be observed from the below figure 7, the number of faults caused by technical failures per turbine shows an increasing failure rate once wind turbines have been in operational service for over 15 years. Although, a drop down to 10 WT's after 13 years. Higher downtimes due to technical failures per turbine, happens mostly in older turbines (i.e. with 15 and 16 years).

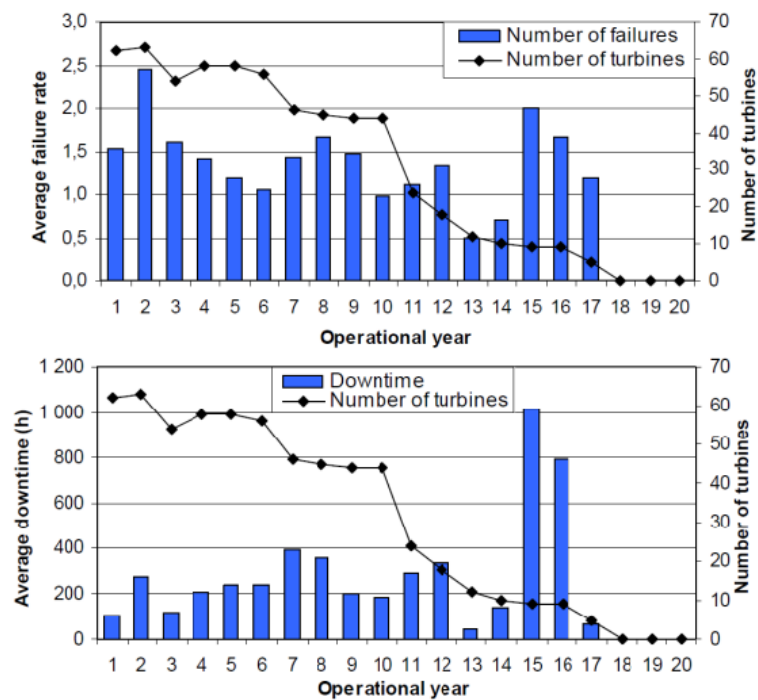


Figure 7. Wind Turbine failure rates and downtimes vs. operational years (Holtinen, 2010)

All these high figures emphasizes clearly the need for optimizing the O&M strategy of the offshore wind farms, in order to reduce unexpected turbine downtimes, so by reducing the deferred energy production as well as improving revenue losses. Therefore, by increasing the reliability of the WT's, and progressing the failure data, in order to improve the overall reliability and to optimize O&M strategies, hence, meaning higher availability, lower OPEX and safety.

This section clearly demonstrated how WT reliability data can be used to provide tendency forward results and to benchmark WT performance behaves for anticipate planning and management for O&M activities. Therefore, figures (Fig.5, Fig.6) shows the least reliable sub-assemblies WT's, as well as their operation service life as demonstrated on Fig.7, so then, quantifying the failure modes originating that unreliability accumulate during years.

#### 1.4. Objectives

The purpose of this paper is to investigate the reliability and operation and maintenance of a wind farm and their single wind turbines, in order to measure the real reliability and availability available on OWT's, to quantify the real functional technical necessity, before to carried out any maintenance management program. The overall objective, comes from reducing O&M costs (OPEX) which one is the main driver for the end-user(owners, operators, utilities) of the Wind Turbines Industry. So, the outcome obtained from the diagnosis and prognosis of common faults identify in those group of failures/sub-assemblies(i.e. Generators, Drivetrain...etc), will be able to raise the OWT's reliability and availability at early phases(e.g.Design development), thus, being able to reduce the OPEX in the long term. To do it, will be essential to anticipate risk or at least to measure the actual risk from the most failure ones(Power Module and Rotor Module) subsystems, so then, carry out a quantitative analysis as FMEA, will be the background to learn and improve, in order to go ahead with future consolidations improvements into the Wind Turbines Industry. Where basically, the design process integrity requires to be fully integrated by a process(Testing, Data collection, and Checking). So then, FMEA tool is going to be used as a means to check progress development.

Therefore combining results of failure statistics data, quantitative analysis (i.e. FTA, FMEA...etc) and assessment knowledge of expert technical judgment, the analysis will assess the most critical sub-assemblies (i.e. gearbox, generator, electrical system...etc) with respect to failure frequencies and consequences, hence, those ones have the lower availability, meaning lower O.E.E level. This paper entitles the basis for the development of quantitative models for maintenance strategies and optimization from the reliability and availability measured, as well as deploying technical experience for further improvements on early phases (e.g. Design). Hence, providing guidelines, that can enhance WT's reliability and availability, and the overall O.E.E. In addition to that, the paper tends to carry out research progress against costly maintenance, due to operators make a call to decrease maintenance, instead, add more reliability, and so then, is already avoid costs in maintenance programs (P.J. Tavner, 2007). All in all, objective goal is to achieve higher reliability and availability with decreased maintenance.

## II. BACKGROUND

Literature review helped us to pave the way for analysis the current reliability-availability and maintainability achieved so far on OWT's. Researchers have proved, from research feasibility studies and statistical survey-analysis the necessity to find ways to reduce OPEX expense, along the LCC for the wind turbines. Where the strengths shall come firstly, from measuring the real data of reliability and availability from each single sub-assemblies (i.e. convertor, rotor...etc) components/elements that forms a production installation, and then, adjusting the maintenance program towards the functional technical capability necessity of those sub-assemblies.

Although, real challenges in offshore, relays on "window time for repair", due to the "weather window available", logistics and operational constraints, may be short (Tavner, 2012). Offshore "maintenance weather window" is conditional by six factors; accessibility (depending maintenance vessels), location (distance from shore vs. water depth) meteorological, oceanographic variables, the wave height and the wind speed. The vessels offshore accessibility is a challenge, being most capable and expensive a FSV, due to take advantage of short weather windows remaining on location (Tavner, 2012). So then, first and for most, to carry out a much safety maintenance is useful to use a FSV, which one have larger functions and capabilities in compere with CTV/small vessels.

As well as, maintenance is living functional and operational need, due to degradation state, and the OWT's components/elements for their spare parts need it, in order to replace them when their operational life service ends. Hence, based up the functional maintenance requirements and the associated CBM implemented data-driven predictive remaining useful life information, it is crucial the on-going reliability of the remaining useful service life and the finances for ahead maintenance actions in order to determine maintenance planning management for the OWT's components/elements

As was indicated, and explained on (TABOADA, Jose V.; CASAS, Vicente Diaz; YU, Xi.) as set of maintenance methodologies, maintenance decision-making tools were defined based on the two different alternatives for Offshore Wind farms and Oil&Gas Platforms(TABOADA, Jose V.; CASAS, Vicente Diaz; YU, Xi.). It have been demonstrated, that the location offshore distance, impact directly into the transport logistics costs, as well the maintenance frequency (rounds/trips) made, so, it's critical, not only for the costs but to guaranty the health performance management the OWT's. Therefore, to increase as much as possible the reliability and availability of the OWT's, always will be a plus, due to it will endure higher robust installation, thus, being able to reduce the cost expenses (OPEX) about the transport logistics and the maintenance frequency to be implemented.

Intelligent maintenance management, is based upon a set of maintenance decision-making tools that were defined based upon the failure detection, location, and prognosis made. Common, overall systematic level reliability analysis are based to integrate the whole systems reliability OWT model using regular OWT system functional block diagram(FBD) specification.

All in all, the objective of the presented research is to increase reliability-availability and maintainability for the OWT's. Therefore, designing proper maintenance alternatives, reliability and analyzing their feasibility, it will be crucial.

### 2.1. Design Maintenance Alternatives (Out vs. For)

The manufacturer of a product has the choice of either design out maintenance or design for maintenance. To design out maintenance, can prove impossible due to technological limitations or cost. To design for maintenance means to balance cost and benefits with respect to Reliability and Maintenance(R&M).

In generally, Maintenance in design can be depicted in two options:

- Try to design out maintenance.
- Try to optimize the design with respect to maintenance issues.

Although, after having targeted and identified maintenance related characteristics in the design one has the possibility to try to eliminate those factors that would originate maintenance costs.

However, if maintenance is to be designed out, one has to consider the cost of reliability throughout the product's Life Cycle. In addition, has to consider reliability against maintainability issues.

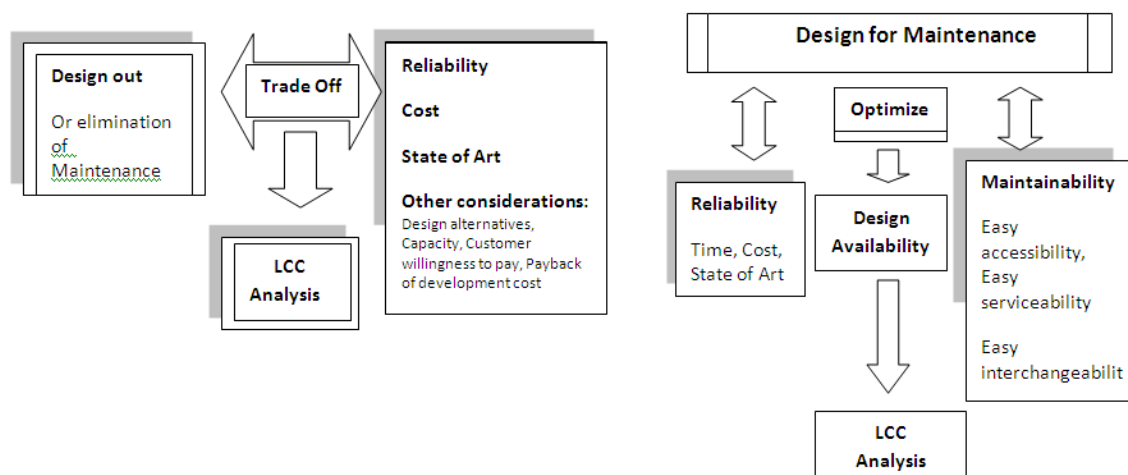


Figure 8. Design Out vs. Design For Maintenance (Markeset)

As we can see from above flow-diagrams above, Reliability is a single factor that control failure events. So, when adjusting design for maintenance(“Out or For”) first one shall have to examine the reliability characteristics and then go for deciding the Maintainability characteristics. Therefore, R&M are traded off to meet a design requirement and budgetary constraints using LCC Analysis. Any improvement in R&M will cost money, but may result in saving when whole life performance of the asset is take into account.

### 2.2. Design for Reliability (DfR) and Reliability Processes.

General approach on the **DfR**, is based on verify and highly accelerated Life Test of the Equipment. The Reliability of the system subjected to loads should be considered, as well as checking structural integrity of the structures for different Limit States (FLS, ULS, ALS, SLS)that should be considered over the Design approved.

As was cited (James Carroll, 2017) failure criticalities O&M costs can came from gearboxes, generators...etc. So then, O&M cost reduction may be lead a “redesigning” of those components so that the most severe failures can be repaired without the use of HLVs(Heavy Lift Vessels).

The idea is based, on make it fail the equipment, to identify the weakness of the Design, so learn from it. Followed, by assigned appropriate Reliability and meeting the Survivability (e.g. 90%) during 20 Life Cycle years.

The **DfR** requires the next stages and tools:

Table 1. DfR Stages and Tools[5].

Define (D)	Bases of Design, O&M Operational Philosophy, IO Principles, Reliability target, Survivability (90%?)...etc
Identify (I)	FMECA, FTA, RBD,...etc.
Analyze (A)	Estimate product Baseline Reliability
Verify (Ver)	Accelerated Life Test (HALT, ALT)
Validate (Val)	Reliability Demonstration Test
Monitoring (M)	FRACAS

The reliability of a component or product as the probability that it will function properly for at least a specified time under specified experimental conditions (TerjeKvaløy)

After have designed a Reliability strategy, is required a development of a reliability process. How to implement the strategy, shall depends on the **Processes Associated (Identification+Implementation+Investment)**. Here bellow, the flow-diagram structured for the Reliability Processes:



Figure 9. Flow-Diagram of the Reliability Processes (TerjeKvaløy)

2.3. Analysis for Safety Reliability, Availability and Maintenance.

Effective analysis of Reliability, Availability, Maintenance relies on the RAMS (Reliability, Availability, Maintainability and Supportability) which ones are fully applied for WT's models. As can be observe on the next figure below;

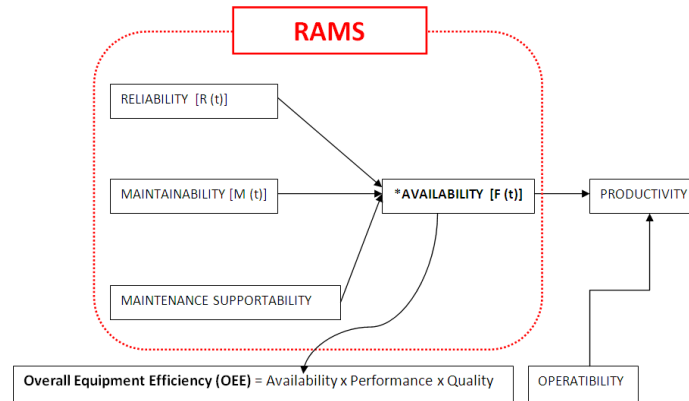


Figure 10. RAMS, OEE and Productivity.

RAMS philosophy/methodology have been applied in the OWT's Industry for some years ago, in order to meet the functional technical specifications demands for the documented RAMS procedures and LCC analysis. Although, the performance and effectiveness of any production installation, will be based on design requirements set on the RAMS characteristics combined with maintenance strategy, thus, leading to a well schedule maintenance program.

As we can see on the fig.10, the key issue is to reach the greatest availability, in order to enhance as much as possible the productivity, on behind of having a high O.E.E. Easily, it can be concluded, that components/elements that have lower O.E.E. during the current condition state (functional service active) at the installation, demands a faster preventive maintenance to be accomplishment, in compare with higher O.E.E. Therefore, having increasing the O.E.E., the availability, performance and quality are greater, so, increasing the functional service operability, as result, higher productivity.

Maintenance and Safety, are directly correlate, in order to have performance of the OWT's in terms of their functional variables(i.e. rotational speed, pressure, temperature...etc), preventive actions (round inspection, condition-monitoring) will increase safety, and reduce machines unexpected failures along term. Hence, to boost continuously the performance, will be need quick maintenance reactions from maintenance technicians, being an asset to carry out appropriate balance for the distribution of maintenance actions between maintenance specialists and operators.

III. METHODOLOGY  
 3.1. Offshore Wind O&M Model.

As any methodology, is based upon model that integrates all the inputs and outputs need it, in order to recreate the diagram flow distribution of the know-hows capabilities. Here the core flow diagram Offshore Wind O&M Model;

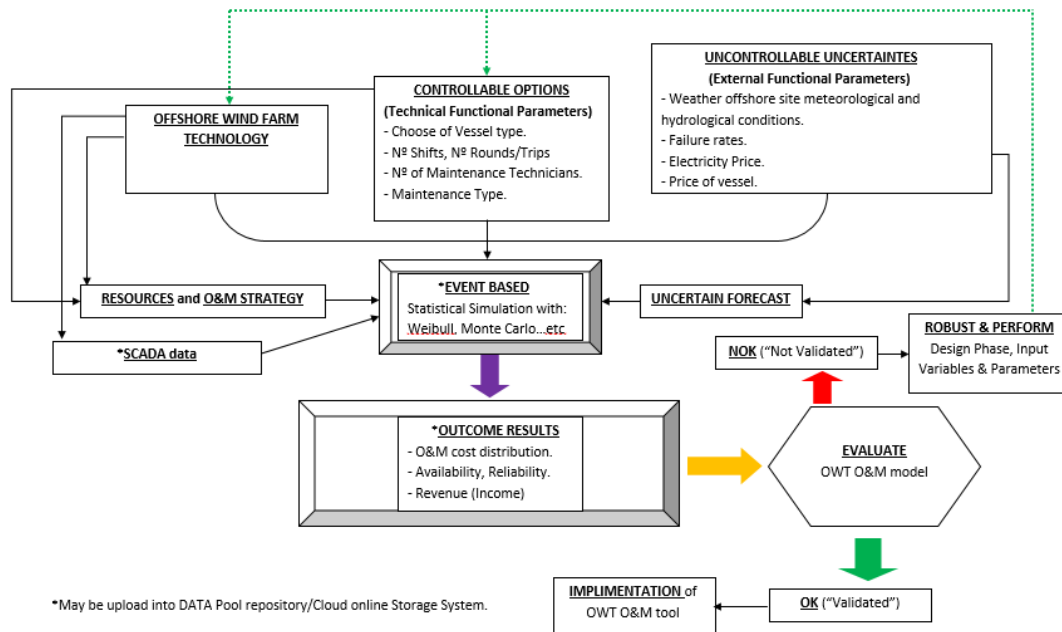


Figure 11. Offshore Wind O&M Model flow diagram distribution.

As we can observe, from the figure above. Clearly, to validate and implement a valid OWT O&M tool could be need various rounds of “fail/pass” that will lead to feed a learning process (into a “closed loop control system”) in order to get better outcome results, then, making robust an OWT O&M tool for their continues implementation.

The reasoning behind such as architecture concept (Fig.11) is straight forward; the development of O&M Model tool design. That subtend the integrity behave as O&M Model, from the three main input variables (Offshore Wind Farm Technology, Controllable Options, and Uncontrollable Uncertainties), which ones are subjected to changes.

Beside that, SCADA software monitoring system provides real-time remote functioning and alarms from the OWT’s to the OWT OEM corporative house. Where SCADA data, acts as input into the event based statistical and mathematical analysis, which one increase the capability of the reliability-availability-maintainability.

All in all, the Fig.11, reflects the outcome found from Paper (TABOADA, Jose V.; CASAS, Vicente Diaz; YU, Xi.), where has been target the controllable options and uncontrollable uncertainties, with different technical practical examples.

3.2. Reliability and Failure densities functions.

The reliability of a sub-assembly is defined as the probability that it will meet its functional requirements or required function under stated conditions for a specified period of time. As can be observed on the Fig.5 and Fig.6, the heights failure rate and downtimes relay the subsystems Power Module (Frequency Converter, Generator Assembly.....etc) and Rotor Module (Pitch System, Blades, Hub.....etc), so, the failure density function distribution will rest mostly over Power and Rotor Modules. Due to the high concentration of failure rates and downtimes over them (Sørensen, 2011) & (Commission, 2015).

Although, the unreliability, is allied to a failure intensity function is normalized to the number of survivors,  $\lambda(t)$ . See next figure below;

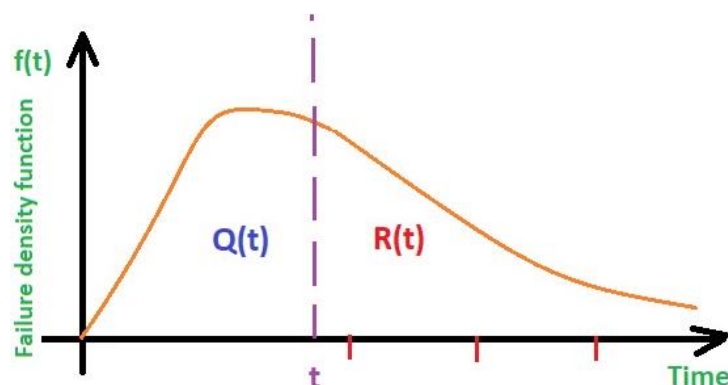


Figure 12. Failure density function vs. time representing Reliability  $R(t)$  and Unreliability  $Q(t)$  functions.

As we observed from Fig.12, the relationship between reliability function,  $R(t)$  and unreliability function,  $Q(t)$  is the time frame. Where at any time( $t$ ), the reliability/survivor function,  $R(t)$ ;

$$R(t) = \frac{N_s(t)}{N_0}$$

The same goes, with the probability of failure or unreliability function,  $Q(t)$ ;

$$Q(t) = \frac{N_f(t)}{N_0}$$

$N_s(t)$  = number surviving at time( $t$ ).

$N_f(t)$  = number failed at time( $t$ ).

$$\text{Therefore; } N_0 = N_s(t) + N_f(t)$$

Where;

$$R(t) = 1 - Q(t)$$

OWT's, are continuously operated systems, which tolerate failures that can be repaired. Therefore, the most appropriate measure is "availability", well-defined as the probability of finding the system in the operating condition state at some time/interval into the future.

- Sorts of Failures

Failure occurrences distinctions between the Random Failures and Systematic (or design). Described below;

- **Random Failures** are failures which happen at random times owing to physical deterioration and degradation functional mechanism in components/elements. This is believed to be attributed to excess stress in components/elements, for instance, by self-vibration, outsider applied conditions or the environment.
- **Systematic Failures** happen due to functional errors in the design of the integrity system, resulting in failure under particular input conditions. Design errors can happen due to an error implementing defined functional requirements or an error in the functional requirements specification datasheet. As example, badly designed programmable routines of a code programing Software(i.e. SCADA).

In the view of the further increasing application and complexity of OWT's, there is a need for wider system analysis than simply random functional mechanism failures. The measures and techniques repeatedly being applied to Software Systems (i.e. SCADA) should be considered in respect of increasingly complex Hardware solutions.

Therefore, emerging standards are supporting the control of risk by addressing random mechanism failures and systematic (or design) failures.

### 3.3. Reliability Method.

#### 3.3.1. The Bathtub curve

The usual behavior failure rate of a component/element, is extended expressed by the failure rate/risk function (“The Bathtub Curve”)’ are useful tool in estimating analytical reliability engineering. The bathtub curve represents as such, the failure function probability of item, that it can be divided it into three zones;

- The first zone is the **“infant mortality (early life)”**:  $\beta < 1$  (**decreasing failure rate**)  
 Resents a failure rate decreases and failures happens due to the equipment’s/technology has been produced with lower technical characteristics from the design specifications, addressing that to defective parts. This zone, also is known as burn-in period, where failure rate ( $\lambda$ ) usually is high along this initial phase, because the unknown defects of the components/elements, soon appear when are in functional service(active mode). Also is known, as zone where materials defects, wrong design and poor assembly happens.
- The second zone is the **“normal life (constant failure rate)”**:  $\beta = 1$  (**constant failure rate**)  
 Represents a constant failure rate and lower. Since components/elements have survived the early life, the failure rate becomes calm down during the useful-life period. Known, as zone where constant changes are applied into the functioning conditions.
- The third zone is the **“wear out”**:  $\beta > 1$  (**increasing failure rate**)  
 Represents the failure rate increases, which one happens commonly due to wear out effect, rate failures increases as the component/element exceeds its own design lifetime. As well as, known as zone where occurs excess of use and disused.

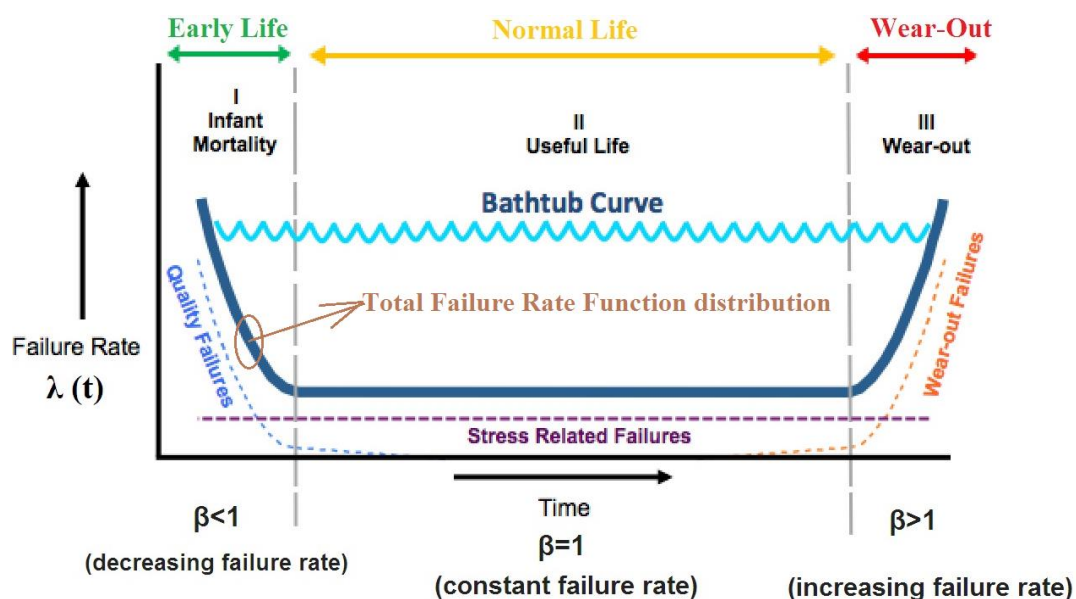


Figure 13. The Bathtub curve model distribution.

As we can observed from the figure above, the bathtub curve has a great utility, in order to measure the total failure rate along the time, as well as helps towards the decision about the convenience or not, to replace components/elements in service.

As whole, the bathtub curve for the intensity function showing how the reliability varies throughout the entire life of repairable machinery.

Therefore, in practically, make sense to replace an component/element when is at the wear out zone, although, to replace it when the failure rate are resulting constant (“normal life”), can be harmful, due to in the best scenario is not winning nothing with this change at this zone, and on the contrary can introduce infant mortality failures, so being uncertainty add into the functionality system behave.

#### IV. RELIABILITY AND AVAILABILITY MODELING

##### 4.1. Core Maintenance Probability Distributions.

###### 4.3.1. Weibull distribution model.

As we know, the weibull distribution is used to model times until failures for components and systems (TerjeKvaløy) Being easier computations rather than gamma distribution. Here bellow the Weibull function density probability;

$$f(t) = \frac{\partial F(t)}{\partial t} = \frac{\beta}{\alpha^\beta} t^{\beta-1} e^{[-(\frac{t}{\alpha})^\beta]}, x \geq 0$$

Function Reliability for probability;

$$R(t) = e^{[-(\frac{t}{\alpha})^\beta]}, x \geq 0$$

The **cumulative distribution function (cdf)** for the Weibull distribution is given by;

$$F(t) = 1 - R(t) \quad \text{for } x \geq 0$$

For  $\alpha > 0$  and  $\beta > 0$ . cdf is certainly useful in computing probabilities. (Zaiontz, s.f.)& (Vladimir, s.f.)

By another side, the “time of failure from a determined percentage (%)” of the sample:

$$t_p = \alpha [-\ln(1 - p)]^{\frac{1}{\beta}}$$

Where “t” represents “time-to-failure” or “length of life”(i.e. secs/mins/hours), of an item(i.e. Gear Box, Rotor, Generator...etc) that bellows into industrial machine(i.e. OWT, Wind Turbine....etc). Also, the Weibull distribution applies, it is frequently helpful to determine the “failure-rate”(also known as “hazard rate”) in order to get a sense of deterioration or wear of the component/element under their own on-going life cycle status availability. In summary, Weibull distribution calculation is ideal towards to give a reliability analysis (see section 5.2), for instance, the calculation for the average life of component/element until happens a “failure”. Hence, OWT during their operation life cycle functioning, it shall be modelled in advance their own “hazard rate”, so then, allowing to prevent in advance from unexpected risks, due to thankfully the precise planning of the O&M management applied.

###### 4.3.2. Gamma distribution model.

Simulation methods are based on building equivalent mathematical models, so, those models are easily analyzed by computer. Although, between the large list of simulation models, exist the Gamma distribution that also it can be deduced as a generalization of the exponential. (Pérez A & C., s.f.)

Therefore, the density function of the Gamma distribution is:

$$f(t) = \frac{\lambda(\lambda t)^{k-1} * e^{-\lambda t}}{\Gamma(k)}$$

Where,  $\Gamma(k)$  is the Gamma function;

$$\Gamma(k) = \int_0^\infty x^{k-1} * e^{-x} dx$$

In general, a close form for the distribution function  $F(t)$ :

- If  $k > 1$   $h(t)$  is increasing.
- If  $k = 1$   $h(t)$  is constant.
- If  $0 < k < 1$   $h(t)$  is decreasing.

## V. FUNCTIONAL ANALYSIS

Functional analysis arose after carry out the mathematical and statistical reliability modeling. General principles were indicated that resulted in a common and unified approach along the calculus, in both (mathematical and statistical) fields, showing their interrelations. As results, has been point out first an assessment risk (through FMEA's for: Power Module, Rotor Module and Comms & Control System) and four (Weibull, Monte Carlo, Cumulative and Normal) core maintenance probabilities distributions calculations.

### 5.1. FMECA's

Failure Modes and Effects and Criticality Analysis (FMECA) or Failure Modes and Effects Analysis (FMEA), where failure rates are listed and considered, are the best quantitative analysis (i.e. FTA, FMEA) which gives the probability or frequency of failure determined from reliability data.

As it is presented on Fig.5 the location of failures. Hence, to increase reliability it is necessary target the root causes, so then, being possible to categorical identify them. Here then, so need the FMEA, in order to perform a root cause analysis, which ones allows to eliminate or "obsolete" them with further implementation solutions.

The FMEA is a powerful design quantitative tool that delivers a means, from a risk point of view, of comparing diverse alternative machine configurations. Being the first step in the FMECA procedure is getting a comprehensive understanding of the integrity of WT system and their main sub-assemblies.

Between the aspects, FMEA principles tries to target the most recognized generic failure modes (i.e. mechanical/structural failures, insulation failure, software/hardware failures, electrical failures....etc), after being identify those frequent failures modes, easily will support advance design improvement and the corresponding maintenance optimization.

The main goal is to identify and then limit or avoid risk within a design. So then, the FMEA drives towards higher reliability, enhanced safety and higher quality. Where a typical standard will outline the Risk Priority Number (RPN = Occurrence x Severity x Detectability) metric.

Therefore, the FMEA's tool has been applied (see on the Appendix's Pages) for the heights failure rate and downtimes relay the Sub-Systems/assembly Power Module (Frequency Converter, Generator Assembly....etc), Rotor Module (Pitch System, Blades, Hub....etc) and Comms & Control System (Safety Chain, Sensors...etc), being the heights weakness ("failures density function distribution") with high concentration of failure rates and downtimes over them, and the critical ones. Refer to the Fig.5 and Fig.6, from backward pages.

As we can observed from the FMECA for measuring the prospect of failures, and RPN (Occurrence x Severity x Detectability) metrics, results shows a variety of scenarios (i.e. poor maintenance management ...etc) that causes economical risk, as well loss of energy production.

Those FMECA's demonstrate under usual offshore wind energy industries circumstances, mostly technical functional ones, compromises risks and therefore, their expected life. It have been studied just one failure mode for each single Sub-Systems/assembly (Power Module, Rotor Module...etc), however, it can be more robust ("decreasing risks") FMECA if instead, have been studied more failure modes about each Sub-Systems/assemblies.

Overall, targeting high RPN values, the most risky components/elements of a design can be addressed. As well as, point out a list of safety measures (Corrective Actions/Risk Reduction Measures) that will help to reduce future risks into those critical subsystems (Power Module vs. Rotor Module), thus, bring up functional safe.

### 5.2. Overview Results.

Overall results, through respective distributions (Weibull vs. Gamma) may be target different approaches in which one the end results is different. Where Weibull in general, focus into the "failures during time", instead, Gamma distribution focus in the "maintenance need it" for the amount of failures accumulated for each Group.

Here bellow, has been calculate analysis through each respective statistical and mathematical distributions.

### - Weibull distribution.

As well as was explained the theory above(Section 4.3.1.). Weibull results, has provided diversity of values, for the CDF and Weibull Reliability at time(t). Based upon the Calculations made:

- % of Failures, that will have at 115 days?

<b>At 115 days:</b>	<b>Weibulldistrib.[= Cumulative Distrib. Function(CDF)]</b>		<b>Weibull Reliability at time(t)</b>
	F(t)=	0,926524714	R(t)= 0,073475286
		92,65247144 %	

- % of Failures, that will have at 64 days?

<b>At 64 days:</b>	<b>Weibulldistrib.[= Cumulative Distrib. Function(CDF)]</b>		<b>Weibull Reliability at time(t)</b>
	F(t)=	0,782419032	R(t) = 0,217580968
		78,24190322 %	

- % of Failures, that will have at 10 days?

<b>At 10 days:</b>	<b>Weibulldistrib.[= Cumulative Distrib. Function(CDF)]</b>		<b>Weibull Reliability at time(t)</b>
	F(t)=	0,242616998	R(t)= 0,757383002
		24,26169982 %	

Table 2. Groups of Failures vs. ti, F(t), F(t)% and R(t)

	$\lambda$ _ FAILURE TIMES(days)_ Offshore	Weibulldistrib.[= Cumulative Distrib. Function(CDF)]		Weibull Reliability at time(t)
<i>Group</i>	<i>Ti</i>	<i>F(t)</i>	<i>F(t) %</i>	<i>R(t)</i>
<b>POWER MODULE</b>	128,2105	0,9441	94,4125	0,055874781
<b>ROTOR MODULE</b>	83,2628	0,8565	85,6510	0,143489564
<b>COMMS &amp; CONTROL SYSTEM</b>	65,9788	0,7916	79,1618	0,20838162
<b>NACELLE MODULE</b>	99,7132	0,8987	89,8798	0,101201787
<b>DRIVE TRASIN MODULE</b>	91,0416	0,8784	87,8427	0,121572986
<b>AUXILIARY EQUIPMENT</b>	25,8585	0,4853	48,5333	0,514666901
<b>STRUCTURAL MODULE</b>	23,6733	0,4580	45,8040	0,541959763
<b>WHOLE WIND FARM</b>	13,0712	0,2990	29,9015	0,700984539
<b>CONDITION MONINTORING SYSTEM</b>	2,48976	0,0746	7,46889	0,925311026

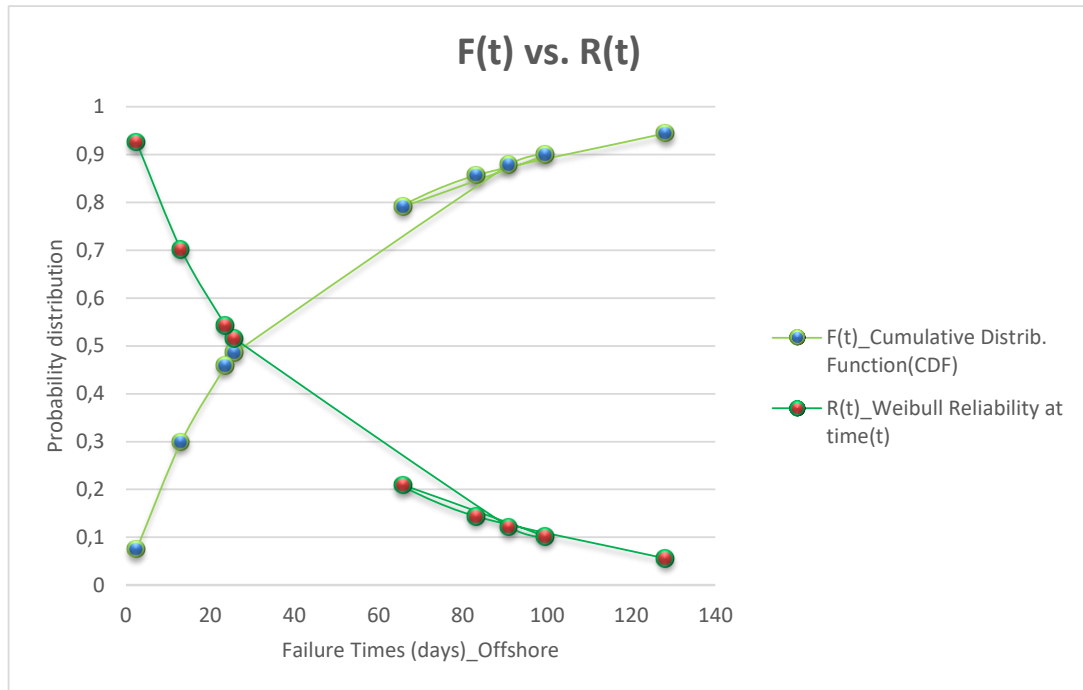


Figure 14. Probability distribution vs. Failure Times (days)\_Offshore

- Time (tp\_time for the failure) in which would have failed in 10% of the Groups?

**At 10%:**  
 tp= 3,473801126 days

- Time (tp\_time for the failure) in which would have failed in 90% of the Groups?

**At 90%:**  
 tp= 100,2803354 days

- Time (tp\_time for the failure) in which would have failed in 50% of the Groups?

**At 50%:**  
 tp= 27,0880641 days

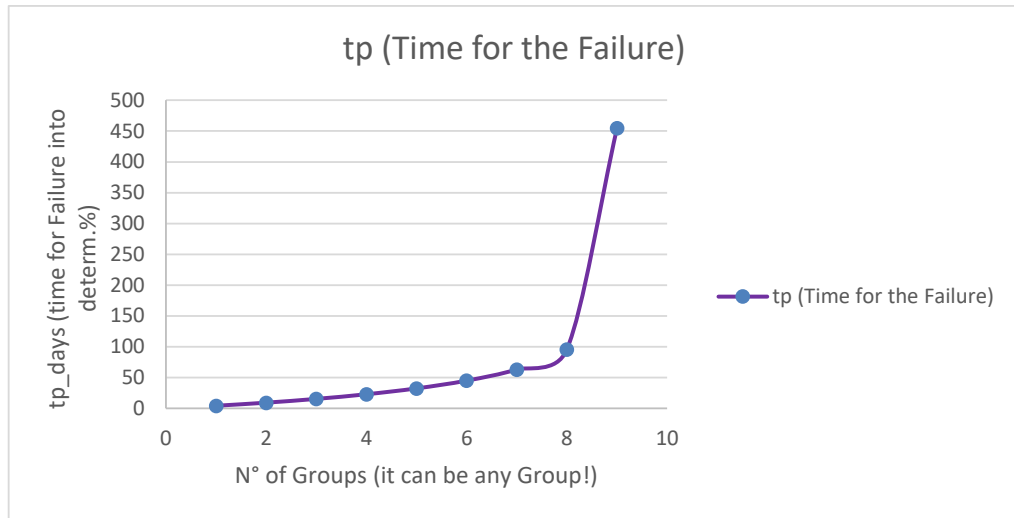
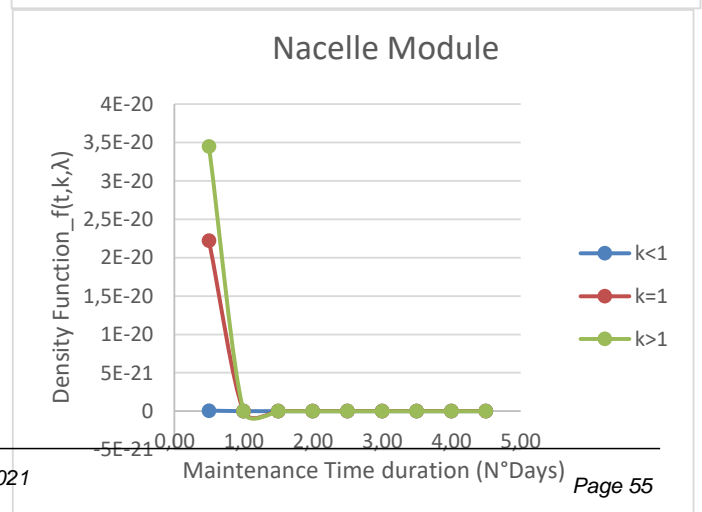
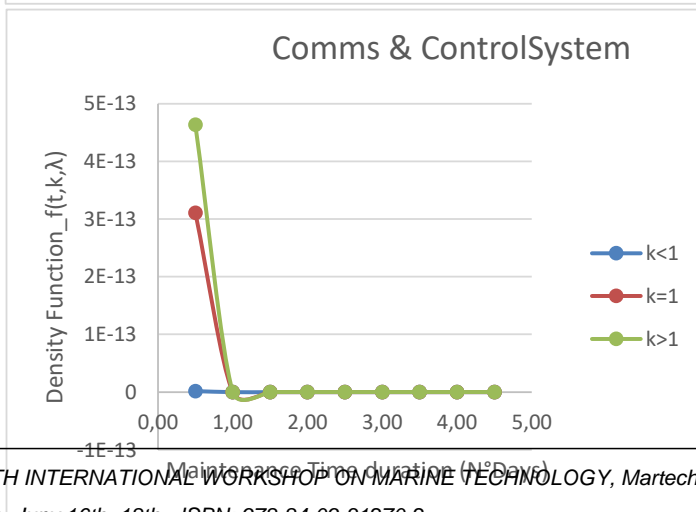
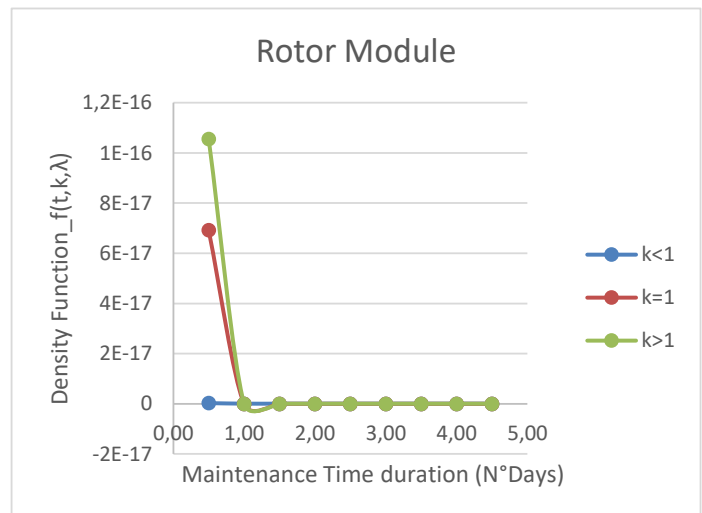
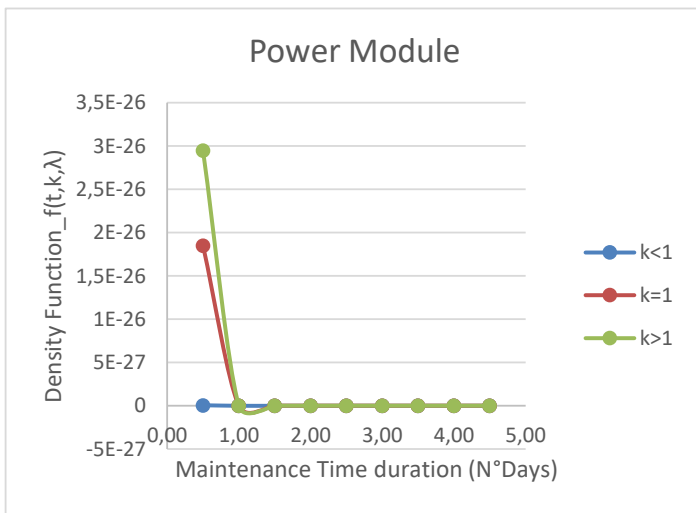


Figure 15. tp vs. N° of Groups

**- Gamma distribution.**

Following the theory explained (Section 4.3.2). Gamma distribution for each single Group will be different. Where the key question; is to find out the necessary maintenance time(days) need it, for each Group? (According to the amount of Failures accumulated on each single Group). Also, it can be questioned as; Duration of the Maintenance time(days) need it, for each Group?

See on next graphs bellow, the answers:



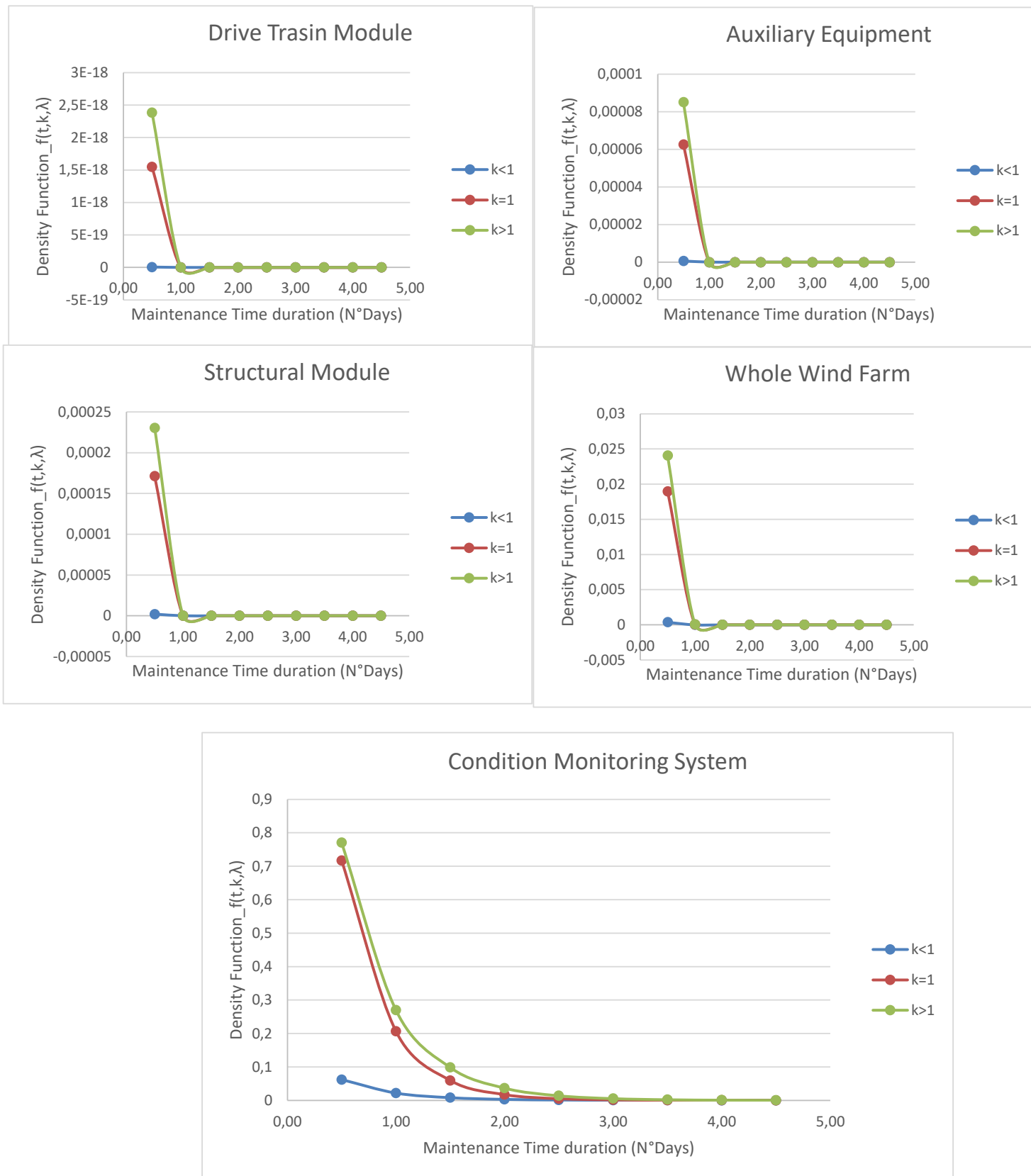


Figure 16. Density Functions vs. Maintenance Time duration for each N° of Groups

As we can see from the graphs above, is point wise the maintenance time duration varies upon the type of failure Group (Power Module, Rotor...etc). Most of them, between “1 – 1.5 days” is optimal maintenance time, for the failures registered for each Group. Although, the difference happens with Condition Monitoring System in which one at least “3 days” are need for maintenance time. It requires longer maintenance, due to the higher robustness ( $\downarrow$ Failures &  $\uparrow$ Reliability( $1-F(t)$ )) that wholes, in compare with the rest.

## VI. DISCUSSION

Along this analysis review, we have tackled and described a range of methodologies and approaches, in order to analyze the Reliability-Availability-Maintainability, as well as how this on-going OWT's Industry uses reliability from each single failure to downtimes, cross Group of Failures(i.e. Power Module, Rotor Module...etc) accumulated along the operational life cycle production service.

Has been discussed how the OWT reliability and accessibility in offshore has a considerable impact on its availability and downtime. Section 1.1. defines and explain the functionality of the sub-assemblies with their components/elements, with a clear picture to understand the Subsystems(Power Module, Rotor Module, ...etc) and the add value to the FMEA consolidation. Along Section 1.2. is described and detailed P-F interval curve and how is the CBM implementation into it.

Section 1.3., focused on failures and downtimes of the sub-assemblies and components/elements into the Groups (Power Module, Rotor Module...etc) of failures modes, and their reliability vs. operational service years according to the averages of failure and downtimes rates. The figure 7, point out optimizations of the O&M strategy.

Section 2 broadly explains what is the Design for Reliability (DfR) and Reliability Process, and how much important into the development and design a reliability strategy. As well as ends with explanation of RAMS, where is diagramed the impact from O.E.E factors, where the key for reaching robustness and productivity, will rest of having a higher O.E.E. and operability beforehand.

Section 3 describes the essential offshore wind O&M Model flow diagram distribution, where are represented the inputs/outputs along the diagram, resulting that an "event based outcome results" various from diverse scenarios situations in a given time. Follows Section 3.2 explaining reliability and sort of failures. Along Section 3.3. details the Bath Curve itself, how curve changes along the life cycle and what it's the risks("Failure Rate distribution") at given time.

Section 4 mostly explains the theory of Weibull and Gamma distribution models. Section 5, carry out a functional analysis in both ways (FMEA for critical subsystems and results outcome by Weibull and Gamma distributions), where the overall is target failures at different life cycle times, as well as the consuming maintenance timing too.

## VII. CONCLUSIONS.

The present research study have provided a study research and analysis about a general approach of Reliability-Availability-Maintainability of OWTs. Emphasis has been focused on the reliability from Groups(Power Module, Rotor Module, Comms & Control system....etc) the ones that accumulated mayor failures rates.

As we can observed and explained from Fig 8. (Design Out vs. Design For Maintenance), always is going to exist a "Trade Off" between Design Out, LCC Analysis, Reliability, Costs....etc. Where mainly adjusting design for maintenance ("Out or For") first one shall have to examine the reliability characteristics and then go for deciding the Maintainability characteristics as such.

Although, along the section 2.2., has been made emphasis especially on the "Design for Reliability (DfR) and Reliability Processes", due to between the core values, are the ones from the design phase. Where having robust DfR, it will bring high reliability for each component/element designed. Carried out pre-design OWT model, with the highs reliability as possible, also, it will bring high quality of being trustworthy or of performing consistently well behaves of the WT, during the service life in production.

Along the Fig.10(RAMS, OEE and Productivity), we can easily concluded is that Effective analysis of Reliability, Availability, Maintenance relies on the RAMS(Reliability, Availability, Maintainability and Supportability), where having a high OEE value brings an outstanding Availability[F(t)] performance, as a result, a great productivity.

In general, the differences between Offshore vs. Onshore failure rates can fairly be explained by the offshore extreme operating conditions, for example higher mean wind speed and corrosive saltwater effects over structural components.

Under the effects of the offshore-marine environment, counting soil and wave conditions, due to the larger loading variation and frequency in the high wind speeds the offshore WT's structures suffer more than onshore WT's. Hence, failure rates from the major subassemblies (i.e. blades, hub, gearbox, generator, electrical components....etc) offshore WT's are higher than onshore ones. Beside that, larger size's of WT's tend to capability more failures, in compared with

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small size's, mostly due to the fact that larger size's of WT's, their natural manufacturing condition has been made base upon a lower degree of robustness.

Despite the simplicity of the methodological approach carried out, the case study gives valuable insights about the reliability vs. failures, and provide advisor decision makers with a set of tools and methods to contrast different O&M strategies and alternatives.

Beside that, the FMECA's has been applied for the critical ones ("Power Module, Rotor Module and Control System"). Where the FMECA's are effective when it is applied to the analysis of the components/elements that cause a failure of the entire OWT's functional system or a major functionality of the system. However, FMECA is difficult and too long due to the complex systems (i.e. Power Module, Rotor Module, Control System, Converter...etc) that have multiple functions comprising different sets of system components/elements.

For new OWT's installations shall be kept a similar (as previous ones designed and set up) safety reliability standards. So then, providing reliable reliability to the cross hold OWT's installations (old vs. new) at the same Offshore Wind farm field. Even better, it will be great to measure real-time reliability into old Offshore Wind Farms installations and add the differential lacking (from old OWT's) need, into new Offshore Wind Farms installations. Overall, making happen a balance reliability (between old vs. new ones) and helping to extend the operational life cycle of bigger Offshore Wind farm field.

Conversely, we point out that through the risk assessment demonstrated on the FMEA, has been target the risks as well as the way to mitigated them. Nevertheless, overall objective has been firstly identify the weakness (as probed on FMEA), and after that, with the list of technical proposed solutions (into the FMEA) that allows to give a much stronger input towards further reliability development.

Finally, after have measured (Appendix, Fig.17  $\lambda$  vs. Group of Failures) their Failure Rates and Reliability (Appendix, Fig.18) for each single group(Power Module, Rotor Module...etc), where the Availability and Reliability are their Technical Functional need(for being on production status =  $\uparrow\uparrow$ ) cross components/elements of the OWT's. Notice higher Reliability in Groups(Condition Monitoring Systems and Auxiliary Equipment), being the more unailing ones.

Quantitative results supporting the conclusion that the reliability-availability-maintainability analysis of OWT diverse depending upon the number of failures accumulate on each group (Rotor Module, Auxiliary Equipment ...etc), having each density function vs. maintenance time duration have their own curves dependability, as we can see on Fig 16. The more amount of Failures accumulated into each Group, the "less is the Maintenance time dedicated" or "Weaker is the Group". In addition, as temporary solution, dedicated "more Maintenance time" or carry out punctual "replacements" on each Group, until becomes "Stronger (i.e. higher Reliability Design) the Group" [ $\uparrow\uparrow$ Reliability (1-F(t))].

All in all, the present paper have the goal set of saving O&M costs, from the perspective of "adjust" the real functionality necessity (" $\uparrow$ Reliability +  $\uparrow$ Availability &  $\downarrow\downarrow$ Failure rates") from the most suffering components/elements(Structural & Mechanical ones: Rotor Module, Blades, Tower, Nacelle Module....etc), the ones with high failure rates. Concluding that a decision-make combination (" $\uparrow$ Early Design Reliability for the weakest Sub-Assemblies + Appropriate Transport logistics & Frequency Vessels Offshore + Robust and Higher Reliability & Availability") will be crucial to optimized as much as possible the costs.

Last but not least, as major the reliability integrity of the whole OWT system, minor will be their operation costs (OPEX), due to the lower number of faults/failures during the operation life cycle. But at some extend, OPEX slightly increase for CMS or other Groups of failures, due to larger maintenance days are need it, in order to guaranty high reliability-safety.

### VIII. FUTURE PERFORMANCES AND IMPROVEMENTS.

Between the lessons learned, is that an organized asset maintenance program management is essential. From the moment that the asset is into “functional service”, it shall include operational expenses (OPEX) actions for the preventive maintenance (“prognostic”), grounded upon the OWT design, and corrective maintenance (“diagnosis”), driven by CBM detection and SCADA monitoring through time to the full asset life cycle.

As idea, the results from the maintenance applied, shall also be a “feedback” into the online database systems of reliability information for the specific OWT. Therefore, in practical, improving ahead the reliability of the future manufacturing of OWT’s, particularly, during the design phase.

Beside that, CBM is based upon the Internet of Things and connectivity between electrical devices, where the next coming development will be to have individual OWT’s sharing information(dialogue/communicating) between themselves, and through an online database system service unit acting as “data functional online repository”, allowing to adjust their technical functional characteristics of their own components/elements, effectively rising operation efficiency across all OWT’s into a single wind farm.

Since connectivity and dialogue protocols are set between OWT’s, automated intelligent maintenance management, will carry out automating maintenance decision-making tools being defined base on the failure detection, location, and prognosis at real-time. These future automated tools will allow maintenance planners to feedback quickly the maintenance schedule and optimize maintenance resources better ahead.

In addition to that, applying “know-how exchange industrial expertise” from Condition monitoring of Marine Machinery(i.e. Gearboxes....etc) based on Wireless, Energy-Autonomous Sensor Nodes, will be a plus. Therefore, the whole system operating through wirelessly and without external energy supply ( $E_{input}$ ), whereby the OWT installation and maintenance costs decrease considerably. All in all, functionally, Autonomous Energy Supply, Sensor and Radio Technology are to be conveyed together to a Condition Monitoring System (CMS).

By another side, CFD’s analysis of any Offshore Wind Farm further development will be crucial, in order to anticipated a reliable design, being able to assign a high degree of reliability during the design phase and lay-out configuration of the entire Offshore Wind Farm. Nevertheless, output results from CFD’s simulations and analysis, shall allow to give a “clear decision-making” of which OWT’s and their associate parts/components/elements (mechanical & structural) are suffering higher stress distribution. Hence, it can be easily deduced, that in compare with onshore wind farm(lower energy generation), offshore wind farms catch up higher wind energy, as result, most likely exist high wear along parts/components/elements (mechanical & structural) during their operational life cycle, so then, more maintenance procedures are need it.

Nevertheless, refocus the failure model development, will be plus. Where, future Failure Models, shall be distinguished and organized from beginning by two questionable technical failure modes; “Repairable components/elements (i.e. Turbine, Gearbox...etc)” and “Non-Repairable components/elements (i.e. Blade, Electrical motor...etc)”.Hence, analysis shall well-known which parts must be model as “Non-Repairable vs. Repairable ones”. Even though, carry out a study research for the two Spares Parts categories;

- Major Spares (Long manufacturing Lead Times): Blades, Gearbox, Generator...etc
- Consumables Spares (Predictable and Frequency demand need): Pump motors, Filters, control relays...etc. (Tavner, 2012)

Follow up model analysis, in order to measure the control as delivery stock. So then, targeting optimization of costs between categories, as well as from the manufacturing side to the OWT installation needs.

Last but not least, is point out that to achieve higher availability and lower cost of energy for the OWT’s, it will be need it much stronger metric of the availability and reliability to be expected on the offshore wind farm and its elements/components that shape the OWTs. As well as, it shall be follow up a flawless O&M strategy that allows to achieve those metrics. Finally, is not only about the battle (“higher availability vs. lower cost of energy”) is also, about safety measures. Carry out many (“as much as possible”) and diverse “failure modes” for each listed Sub-Systems/assembly (Power Modulo, Rotor Module, Nacelle Module...etc), so recreating a much complete FMEA. Therefore, becoming more robust (“decreasing risks”) the OWT’s installations, for both, actual ones (“may be need it a retrofitting process”) and new ones. Results outcome from a large FMEA, shall act as input in early phases (“design”).

#### NOMENCLATURE

OPEX = Operate Expenditure / Operating Cost.  
CAPEX = Capital Expenditure / Acquisition Cost.  
RISKEX = Risk Expenditure.  
CBM = Condition Base Monitoring.  
LCC = Life Cycle Cost.  
CBA = Cost-Benefit Analysis.  
CMS = Condition Maintenance System  
MMS = Maintenance Management System.  
FMEA = Fault Maintenance Element Analysis.  
P-F = Predictive Failure.  
PM = Preventive Maintenance.  
H = Wave Height.  
MAs = Maintenance Actions.  
RCMS = Reliability Centered Maintenance Strategy  
AMS = Asset Management Strategies.  
RCFA = Root Cause Failure Analysis.  
HSE = Health Safety Environment.  
HLVs = Heavy Lift Vessels.  
IMS = Inspection Monitoring System.  
ICT = Information and Communications Technology.  
DfR = Design for Reliability.  
FTA = Fault Tree Analysis.  
RBD = Root Block Diagram.  
CMC = Cost Management Center.  
CDF = Cumulative Distrib. Function.  
CFD's = Computational Fluid Dynamics.  
OEM = Original Equipment Manufacturer.  
R&M = Reliability and Maintenance.  
IMR = Integrity Maintenance Reliability.  
OEE = Overall Equipment Efficiency.  
MTTR = Maintenance Activities and Time to Repair.  
TBM = Time-Based Maintenance  
AIM = Asset Integrity Management.  
RAM = Reliability, Availability and Maintainability.  
O&M = Operation and Maintenance.  
OWT = Offshore Wind Turbine.  
WT's = Wind Turbines.  
FOWF = Floating Offshore Wind Foundations.  
TLP = Tension Leg Platform.

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APPENDIX

1. FMEA for subsystem: Power Module.

Subsystem:

POWER  
Module

DESCRIPTION OF UNIT				DESCRIPTION OF FAILURE			EFFECT OF FAILURE		Failure (F) Rate	(S)_Severity/ Criticality	Corrective Action/Risk Reduction Measure
Comp. Number.	Component name	Function	Operation mode	Failure Mode	Type of Failure/Failure cause	Detection of failure	Local/Subsystem Effect	System Function Effect			
1	Frequency converter	Responsible to manage the generator, and controlling the voltage applied by either the Rotor or Stator.	Normal	Leak voltage current	High current	Monitor fault indicator alarm signal activated	Over amount of current flowing into the generator	Generator Windings and the Rotating speed of the Rotor gets out of normal control.	2	3	Re-enforce and Improve Insolation, as well as perform control safety functional procedures.
2	Generator assembly	In charge of producing AC Electricity, is required high rotation speed in order to produce electricity.	Normal	Generator Gear Temperature High	Lack of precise assembly during installation phase	High level of noise from the Generator Gear	High Temperature of Gear Teeth's and wear of them.	Continuous increase of the wear effect around the rest of Teeth's along the Gear. And increase of disgusting noise.	3	4	Improve assembly Procedures and Control Jigs industrial means during the Check-out Surveillance installation of the Generator into the whole Machinery.
3	Transformer	Adjust the internal voltage of the turbine, to the voltage of the collector grid.	Normal	Shut down Cooling System	Poor maintenance management	Alarm signal indicator activated	Over Heat into the Transformer functioning	Ignition Fire due to the lack of dissipated heat into the Transformer mechanism.	6	5	Increase Training Maintenance teams more specialist in Cooling Systems, as well improve CBM techniques.
4	Power Feeder Cables	Transmits and Transport Electrical Power	Normal	Cable damage	High Corrosion around the cable	Visual reactions from H2S and other chemicals on the surface of the cables.	Corrosion spread to beside cables	System Unit gets Shut Down.	2	3	Increase Visual Inspections, as well substitute future material protection of Cables.
5	LV Switchgear	Low Voltage Switchgear device that allows associated Control(Functional switching, Emergency switching/stopping, Switching Off for mechanical maintenance), Measuring, Protective and Regulating electrical equipment	Normal	Electrical Protection remove	Bad electrical installation or wrong maintenance surveillance	Short-circuits currents	Lack of Isolation, and lack of functioning in circuit-breaker/isolators....etc	Unreliable Control Management Systems(i.e. Functional switching, Emergency switching/stopping...etc)	3	3	Improve specialist Maintenance Training, and robust Certification of LV Switchgear installations.
6	Power Cabinet	Complete Electrical device that is intended to provide supply and	Normal	Insulation deterioration	Not enough Thermal Heat Insulation	Handheld thermal leak detector	Lack of Insulation conducts to wrong functioning	Unreliable functioning of the Electrical	3	3	Change manufacturing supplier of Power Cabinets, and robust safety

		redistribution of electrical energy, protection of electrical power lines and protection of the overload and short-circuit currents.					of the Electrical Equipment	Equipment installed.			certifications of new Power Cabinets.
7	MV Switchgear	Medium-Voltage Switchgear device that allows associated Control(Functional switching, Emergency switching/stopping, Switching Off for mechanical maintenance), Measuring, Protective and Regulating electrical equipment	Normal	Incompatible interconnections(/O) installed	Wrong doing during installation process	Impossible to running Tests and Trial-Runs during Start-Up phase	Lack of Work functioning for the Start Mode	Unrecognized Inputs/Outputs signals for inner relays, contactors.... etc. Whole System Unit still OFF	2	2	Improve background skills of Maintenance Technicians.
8	Gear Oil Pump Unit	Pumping oil and lubricated continuously all the Gear mechanism	Normal	Fault Filter Pump	Lack of filter replacement on-time	Mayor consumption of Oil, than normal condition state. Plus, higher frequency of renewable Oil.	Inappropriate Oil Lubrication	Gear oil pump overload, and unexpected fails.	4	4	Replace maintenance team for a new one, and establish robust surveillance measures for maintenance procedures.

2. FMEA for subsystem: Rotor Module.

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Subsystem: Rotor Module

DESCRIPTION OF UNIT				DESCRIPTION OF FAILURE			EFFECT OF FAILURE		Failure (F) Rate	(S)_Severity /Criticality	Corrective Action/Risk Reduction Measure
Comp. Number.	Component name	Function	Operation mode	Failure Mode	Type of Failure/Failure cause	Detection of failure	Local/Subsystem Effect	System Function Effect			
1	Hub	Mechanical connection node of the Blades. It pitch the blades and their bearings.	Normal	Rupture	Fatigue/Overload/Vibration	Human inspection	Increase stress-fatigue of comp./elements, as well as nearby.	Bearings Blade disconnection/Rotor falling apart	3	4	More conservative and robust design with higher Safety Factor Coeff.
2	Hub cover	Housing of Hub connection	Normal	Corrosion	Corrosion Protection Layer has been Degraded	Human inspection	Water filtrations into the Hub	Rust formation, electrical breakdown connectivity	1	1	Increase frequency of repaint for diverse anti-corrosion layers.
3	Blades	Conversion of kinetic energy of wind to rotary-mechanical energy.	Normal	Local Delamination of an Airfoil Shape.	Deformation/Fatigue	Human inspection	Extension of Delamination along the Airfoil Shape affected.	Lack of Strength along the Blade	3	4	Improve Thickness of the Airfoil Shape during the manufacturing process.
4	Blades bearings	Allow blades to rotate and to support blades.	Normal	Gripage	Over deformation of Blade/Hub connections	Sensor of Pressure in the pitch control system	Immobilization of Blade Angel	Blade Angle mismatch	2	2	Pitch system should operate at normal rate weather condition.
	Rotor	To catch wind power, in order to		Blade discrepancy	Poor installation criteria and	Human	Fatigue at Blade union points	Fatigue at tower	2	2	Improve installation methodology.

			Normal	Aerodynamic variance/imbalance	Elastic-Plastic deformation	Vibration Sensor	Potential Vibrations	High Fatigue of Hub and Tower structures	3	2	Increase robustness and conservative design with higher Safety Factor Coeff.
6	Pitch System	Enables rotor to regulate speed, by turning the blades to maximize output power extracted from the rotor.	Normal	Motor Failure	Motor Overloading and High Current Input	Loss of data communication from motor, plus irregular power supply at the terminals	motor burn out due to overheating, plus cannot adjust blade angle	Increase load at blade, and loss of efficient of WT's	2	3	Install loading work limitator and anti-current safety system
			Normal	Hydraulic oil leak	Poor maintenance control	sensor hydraulic oil circuit down pressure becomes Activated(O N)	Loss of hydraulic pressure	Unfunctional Blade angle	2	2	Improve training routines for the Maintenance Teams
			Normal	Overload	Ice Load on Blade	pressure sensor of hydraulic oil circuit becomes Activated(O N)	High Temperature accumulation at Motors	Wrong blade angle positioning	1	2	Install homogeneous heating system along surface at blade.
			Normal	Blade angle Control	Loss of Hydraulic oil circuit pressure	Digital Oil Manometer	Cannot be adjusted Blade angle positioning	Loss of management control, efficiency of WT's. And	5	3	Robust inspection control and monitoring
				&Management Loss				increase working load movement at blade			alarms of hydraulic circuit sensors
			Normal	Angle mismatch	Wrong input signal sent to system unit	Angle sensor positioning	Wrong blade angle	Deformation/Fatigue along the Blades	2	1	Use a back up control system unit that can resist noise or even incomplete data communication
7	Low Speed Shaft	Turns the low-speed shaft at lower rpm by the wind turbine rotor.	Normal	Shaft failure	Torsional twist	Over Twisting of the entire shaft more than it is natural allowed	Damage of bilateral connection parts	Tendency of leading the whole functional system failure later	2	2	Improve Hardness and Twisting Tests of the shafts, during manufacturing process
8	Slip rings	Transmission of Power and signals from stationary cables in the nacelle to rotating equipment/structure in the hub.	Normal	Abrasion	misalignment and lack of adjustment of brushes	Human inspection	Up & down effect in the Unsynchronisation of Generator	Cannot generate electrical power energy source	2	3	Improve geometry of slip rings

3. FMEA for subsystem: Comms& Control System

Subsystem: Comms & Control System

DESCRIPTION OF UNIT				DESCRIPTION OF FAILURE			EFFECT OF FAILURE		Failure(F) Rate	(S)_Severity/Criticality	Corrective Action/Risk Reduction Measure
Comp. Number.	Component name	Function	Operation mode	Failure Mode	Type of Failure/Failure cause	Detection of failure	Local/Subsystem Effect	System Function Effect			
1	Safety Chain(~safety protection)	Ensure the design limits of the WT's/OWT's are not exceeded (i.e.overspeed) and if exceed output relays directly connected to the safety chain shall be opened.	Normal	Safety Relays fails	Wrong revision and checks by maintenance teams	Security Signal/Alarm gets ON into central control monitors	Whole integrity system goes out of control functional production limits	All safety modes(i.e. Fail-Safe, ...etc) gets into "Emergency Mode", as result, unreliable maintenance previously carried out.	6	6	Establish a new training procedures for maintenance teams and shifts, where is reflected a new checking control for integrity of Safety Chains Technology.
2	Sensors	Collect information and distribute them to the controller unit for required functional actions. Also, some of the data gather are stored for further investigations(i.e. surveillance, maintenance checks....etc)	Normal	Unrecognized Sensor(i.e. rotational speed) Failure	Wrong adjustment or Lack of Calibration during the replacement( for new one) of the Sensor	Main control monitor does not show activation signal of the Sensor(Rotational Speed)	Rotor overspeed	Unsafety continuously monitoring, so then, yaw system, the generator and the blade pitch system are exposed to uncertain management Safety Control	6	6	Increase training of maintenance technicians, as well as hired a service contract with Sensor Specialist for those Sensors.
3	Communication System	Responsible to established online communications from devices, sensors, machinery...etc with the Control Unit and Power Electronics systems	Normal	Shut down intranet	Lack of IT management	Main monitors has been shut down	Online surveillance software's (i.e. SCADA) are shut down	Whole integrity control system gets into STOP/EMERGENCY Mode.	6	5	Increase Training IT technicians and simulate similar scenarios/situations
4	Controller H/W	Controls the Yaw System, the Blade Pitch system and the Generator. Also, maintains the power above the rated wind speed to avoid excessive Aerodynamic Loads. Controller is need to perform(Rotor speed control, Load rejection, Damping and Power command tracking).	Normal	Lack of Energy feed-in	Not enough Electrical Energy feed-in	Monitor panel view reports red Alarm on the Controller Unit	Lack of functioning , control and surveillance.	Controller Unit gets into "ill Mode", as consequence, "power production and limits of loads for structural parts" are out of control.	6	6	Establish Energy Back up system, with a secondary electrical feed-in line. In order to feed-in electrical energy automatically, when the first line fails.
5	Controller S/W	Controls the Yaw System, the Blade Pitch	Normal	Security Actuator fails	Lack of maintenance	Monitor panel view reports red Alarm into	"Fail-Safe Mode System" is	Security Cabinet Module gets	6	6	Increase training of maintenance

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		system and the Generator. Also, maintains the power above the rated wind speed to avoid excessive Aerodynamic Loads. Controller is need to perform(Rotor speed control, Load rejection, Damping and Power command tracking).			management control	the Security Cabinet Module	not functional	into "ill Mode", as consequence, "lack of maintenance management technicians control"			technicians for first shift, as well as establish second shift of maintenance technicians specialized on inspection routines for "Security Actuators" revisions.
6	Ancillary Equipment	Support the transmission of electrical power from generator to downstream given obligations of control areas and transmitting utilities within those control areas, in order to maintain(i.e. through Frequency Regulator) reliable	Normal	Main Electrical Grid connection fails	Lack of right electrical dimensioning	Main monitors have reported a shut down production distribution from the Main Electrical Grid	Electrical Grid connection "collapse", becoming not functional	Whole Electrical Grid connection distribution gets into "Emergency Mode", as results, over tension and over temperature.	6	6	Hired a new Engineering team, for re-dimensioning Electrical Grid connections. As well as, for future Projects, the Design &Development Phase shall be review & validate in several occasions.
		operations of the interconnected transmission system.									

Table 2. Listed of Group Failures accumulated (ReliWind survey)

ReliaWindsurvey		Failure rate translation from Onshore to Offshore from the ReliaWind survey		
		ONSHORE (original)	OFFSHORE (*ponderedvalue)	OFFSHORE_ Reliability Rate_ A(t)
Group	Sub-Assemblies	$\lambda(\text{onshore\_ FailureRates})$	$\lambda(\text{offshore\_ FailureRates})$	[Reliability (1- F(t))]
POWER MODULE	Frequencyconverter	0,12	0,13642562	0,86357438
	LV Switchgear	0,065	0,073897211	0,926102789
	GeneratorAssembly.	0,055	0,075	0,925
	Transformer	0,02	0,022737603	0,977262397
	MV Switchgear	0,018	0,020463843	0,979536157
	PowerFeeder Cables	0,01	0,011368802	0,988631198
	PowerCabinet	0,005	0,005684401	0,994315599
	ProtectionCabinet	0,005	0,005684401	0,994315599
ROTOR MODULE	Pitch System	0,16	0,173333333	0,826666667
	Hub	0,018	0,020677686	0,979322314
	Blades	0,018	0,020463843	0,979536157
	Suprings	0,012	0,013642562	0,986357438
COMMS & CONTROL SYSTEM	Safety Chain	0,04	0,045475207	0,954524793
	Sensors.	0,035	0,039790806	0,960209194
	Communicationsystem	0,03	0,034106405	0,965893595
	Controller H/W	0,025	0,028422004	0,971577996
	Controller S/W	0,024	0,027285124	0,972714876
AncillaryEquipment.	0,005	0,005684401	0,994315599	
NACELLE MODULE	Yawsystem	0,12	0,141818182	0,858181818
	NacelleCover	0,005	0,12	0,88
	NacelleBedplate	0,005	0,005684401	0,994315599
	NacelleSensors	0,005	0,005684401	0,994315599
DRIVE TRASIN MODULE	GearboxAssembly. High	0,115	0,153619403	0,846380597
	Speedshafttransmission	0,055	0,062528409	0,937471591
	Mechanicalbrake	0,02	0,021666667	0,978333333
	Mainshaft.	0,005	0,005930233	0,994069767
	GeneratorSilent Blocks	0,005	0,005684401	0,994315599
AUXILIARY EQUIPMENT	HydraulicSystem	0,02	0,022737603	0,977262397
	CoolingSystem	0,01	0,011368802	0,988631198
	Top	0,008	0,009095041	0,990904959
	Lift	0,005	0,005684401	0,994315599
	ElectricalProtection& Safety devices	0,005	0,005684401	0,994315599
	Servicecrane	0,0025	0,0028422	0,9971578
	Lighting and PowerPoints	0,002	0,00227376	0,99772624
	WTG	0,002	0,00227376	0,99772624
	Meteorologicalstation	0,002	0,00227376	0,99772624

STRUCTURAL MODULE	Grounding	0,0018	0,002046384	0,997953616
	ElectricalCabinet	0,0015	0,00170532	0,99829468
	HubCabinet	0,0015	0,00172314	0,99827686
	Beacon	0,0015	0,00170532	0,99829468
	LightingProtectionSystem	0,0015	0,00170532	0,99829468
WHOLE WIND FARM	Tower	0,038	0,039847222	0,960152778
	Foundations	0,022	0,025011364	0,974988636
	WindFarmSystem	0,03	0,034106405	0,965893595
CONDITION MONITORING SYSTEM	CommonFacilities	0,0015	0,00170532	0,99829468
	Data Logger	0,0015	0,00170532	0,99829468
	Protocol Adapter Card for data logger	0,0015	0,00170532	0,99829468
	Sensors	0,0015	0,00170532	0,99829468
	ConditionSensors& Cables	0,0015	0,00170532	0,99829468

\*Pondered value:

$\lambda(\text{off}^{**})$ vs. $\lambda(\text{on})$
Ratio(mayor÷minnor)

&

(applicable for the rest)
Average Ratio
1,136880165

\*\*Ref's: MahmoodShafiee. "An FMEA-Based Risk Assessment Approach for Wind Turbine Systems: A Comparative Study of Onshore and Offshore".

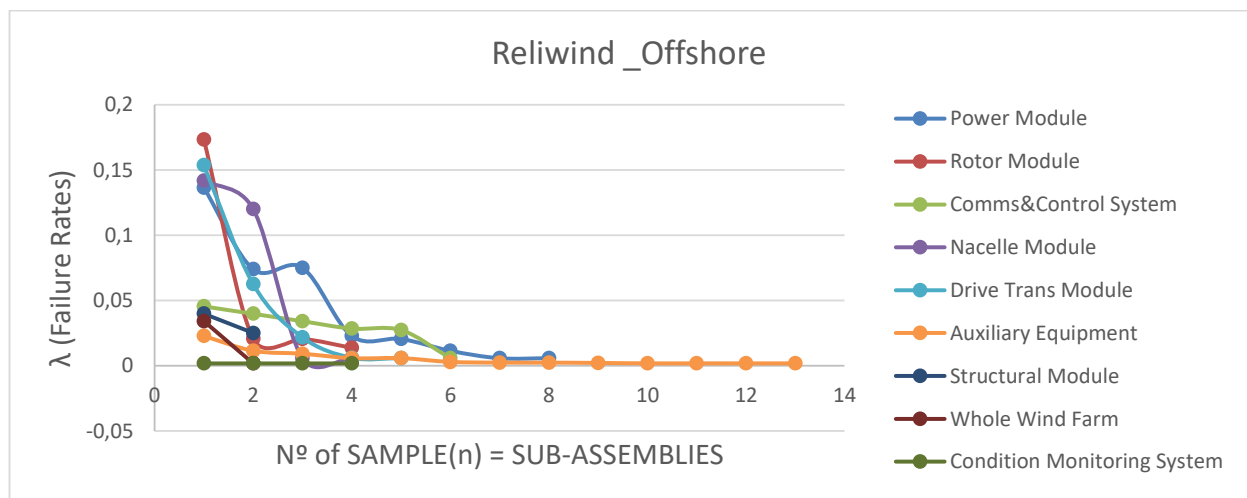


Fig.17. Failures Rates vs. Group of Sub-Assemblies

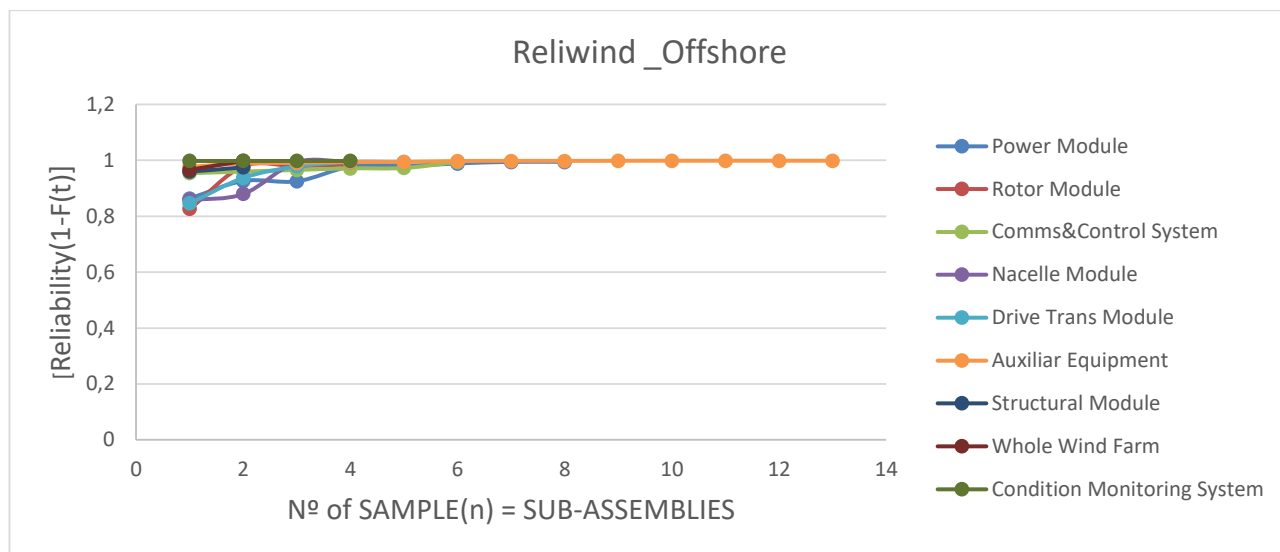


Fig.18. Reliability vs. Group of Sub-assemblies

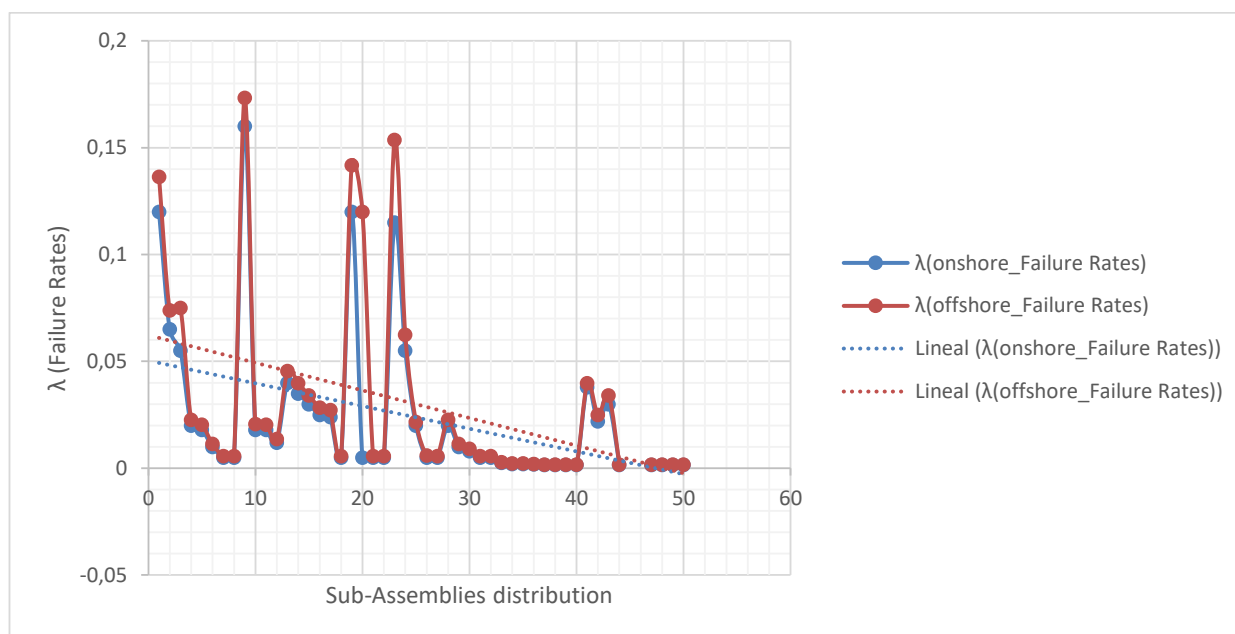


Fig.19. Offshore vs. Onshore failure rates

Table 3. Listed of Group Downtimes accumulated (ReliWind survey)

<b>GROUP</b>	<b>FAILURE</b>	<b>%_approx. (Downtime/Turbines/Year)</b>
POWER MODULE	Frequency Converter	13,5
	Generator Assembly	11,5
	LV Switchgear	4
	MV Switchgear	2
	Transformer	1,9
	Power Feeder Cables	1
	Protection Cabinet	0,8
	Unknown	0,5
	Power Cabinet	0,2
ROTOR MODULE	Pitch System	20
	Blades	1,9
	Hub	1,9
	Sliprings	1,9
	Unknown	0,2
UNKOWN	Unknown	12,2
NACELLE MODULE	Yaw System	10
	Nacelle Cover	0
	Nacelle Bedplate	0
	Nacelle Sensors	0
	Unknown	0
COMMS & CONTROL SYSTEM	Safety Chain	3,5
	Communication System	3
	Sensors	2
	Controller H/W	1,5
	Controller S/W	0
	Ancillary Equipment	0
	Unknown	0
DRIVE TRAIN MODULE	Gearbox Assembly	3,8
	Main shaft	1,5
	High Speed Shaft Transmission	1
	Mechanical Brake	0,8
	Generator Silent Blocks	0,5
	Unknown	0,5
	AUXILIARY EQUIPMENT	Hydraulic System
Electrical Protection & Safety Devices		0,8
Top		0,8
WTG Meteorological station		0,8
Cooling System		0,6

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	Lift	0,6
	Service Crane	0,5
	Grounding	0,5
	Lighting and Power Points	0,5
	Lighting Protection System	0,5
	Electrical Cabinets	0,5
	Beacon	0
	Hub Cabinet	0
	Unknown	0
STRUCTURAL MODULE	Tower	2,2
	Foundations	1
WHOLE WIND FARM	Wind Farm System	0,8
	Common Facilities	0,8
	Unknown	0,8
CONDITION MONITORING SYSTEM	Data Logger	0,5
	Condition Sensors & Cables	0,5
	Protocol Adapter Card for Data Logger	0,5
	Sensors	0,5