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Using a Hybrid Cost-FMEA Analysis for Wind Turbine Reliability Analysis

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Abstract: Failure mode and effects analysis (FMEA) has been proven to be an effective methodology to improve system design reliability. However, the standard approach reveals some weaknesses when applied to wind turbine systems. The conventional criticality assessment method has been criticized as having many limitations such as the weighting of severity and detection factors. In this paper, we aim to overcome these drawbacks and develop a hybrid cost-FMEA by integrating cost factors to assess the criticality, these costs vary from replacement costs to expected failure costs. Then, a quantitative comparative study is carried out to point out average failure rate, main cause of failure, expected failure costs and failure detection techniques. A special reliability analysis of gearbox and rotor-blades are presented.

Keywords: failure mode and effects analysis (FMEA); wind turbine; criticality; expected failure cost; reliability analysis

1. Introduction

According to the Global Wind Energy Council, wind energy has been in a rapid growth mode since 2000, and the world now counts more than 310,000 spinning wind turbines. Wind turbine technology is constantly improving [1,2]. This rapid growth also affects the reliability and performance of wind turbines [3], since new technologies rely on more reliable components. Reliability of a component is "the probability that it will perform its required function under stated conditions for a specified period of time" [4–6]. Reliability analysis deals with causes of failure, their probabilities or frequencies of failure and how to prevent them to occur in systems. Several studies have been conducted to analyze the reliability of the main components of the wind turbine [7–9]. The different methods used for reliability analysis can be classified into three main kinds: qualitative, quantitative or hybrid [10]. While qualitative approaches are based on analytical estimation and are easy to apply, quantitative techniques cost more in resources and skill sets, but provide detailed understanding of the system [11]. A compromise between both methods provides best results. That is why hybrid methods that use both qualitative and quantitative methods or modify a method by adding new indicators have become more popular. The most used methodologies in industry in different phases of the product/process (1-Concept; 2-Process; 3-Design; 4-Commissioning; 5-Operation; 6-Modification; 7-Decommissioning) are briefly presented in Table 1 [10,12,13]. Methodologies are compared according on which phases of project are used, whether they are qualitative, quantitative and if they can be hybrid, if the results obtained can be reproduced (subjective/objective), the amount of data needed to perform the analysis and how precise the results of the analysis are (accuracy).

As seen in the Table 1, failure mode and effects analysis (FMEA), Fault tree analysis (FTA) and cause consequence analysis (CCA) methodologies are more suited for more detailed and objective analysis of wind turbine systems. However, the CCA technique is less accurate than FMEA and FTA [14]. Moreover, FTA is based on a deductive logic that supposes failures and their probability of occurrence are already known. That is why FMEA methodology is more suitable to study the failure behavior of system components. In addition to this, the assessment of FMEA indicators (severity, occurrence and detection) are often based on standard scales or empirical ranking (minor, marginal and catastrophic). Some hybrid FMEAs such as cost-FMEA used in the automotive industries have used these ranking techniques and present other methodologies to calculate the criticality of components without using the standard indicators [15,16].

Table 1. Brief description of risk assessment methods and their suitability to the different product/process phases. FMEA: failure mode and effects analysis.

Methodology	Phases of Project	Nature of Results			Subjective/ Objective	Data	Accuracy
		Qualitative	Quantitative	Hybrid			
Probabilistic risk assessment (PRA) [17,18]	1-2-3-7	√	-	√	Subjective	Less detailed	Low
Checklists [19]	1-2-3-4-5-6-7	√	-	√	Subjective	Less detailed	Low
What if [11,14]	1-3-4-5-6-7	√	-	√	Subjective	Less detailed	Low
HAZOP [20]	3-4-5-6-7	√	-	√	Subjective	Less detailed	Low
Fault tree analysis (FTA) [21,22]	1-2-3-4-5-6-7	√	√	√	Objective	More detailed	High
FMEA [23–25]	1-2-3-4-5-6-7	√	√	√	Objective	More detailed	High
Petri-nets [26,27]	2-3 (if used with another method)	√	-	√	Subjective	Less detailed	Low
Cause-consequence analysis (CCA) [28]	4-5-6-7	√	√	-	Objective	More detailed	Low

Notes: Phases: 1: Concept. 2: Process. 3: Design. 4: Commissioning. 5: Operation. 6: Modification. 7: Decommissioning.

The aim of this study is to apply hybrid cost-FMEA to wind turbines. It has as objectives the identification of:

- Average annual failure rates of wind turbines sub-systems;
- Main cause of failure;
- Expected failure costs;
- Critical components of wind turbine system (criticality). Criticality is calculated as the total expected failure costs times the relative failure rate.

The remainder of the study will compare the results obtained with similar FMEA analyses of wind turbine components. Besides, a special reliability overview of wind turbine gearbox and rotor-blades will be presented, since the results showed they are the most critical components in wind turbine systems.

The hybrid cost-FMEA presented in this paper is reliability analysis oriented, and safety analysis will not be part of this study. Indeed, the objective of this study is the reliability analysis of wind turbine components at entry level/design phases. At this step, no risk or safety analysis have been taken into account.

This paper is divided as follows: Section 2 describes the generic wind turbine sub-system components used in this study. Section 3 describes the hybrid cost-FMEA methodology. Section 4 presents the results and the objectives of this study, including a comparative study. Finally, Section 5 presents our conclusions and directions for future research.

2. The Failure Mode and Effects Analysis (FMEA) Methodology

2.1. Introduction

Failure mode and effect analysis (FMEA) is a powerful reliability engineering methodology that provides a means of comparing and assessing the system configuration [29]. This methodology evaluates systems component by component and identifies their failure modes and their effects on system function and other system components. FMEA has been used in different industries, including nuclear [30], semiconductor and automotive industries [31]. This last industry requires the use of this methodology to support the design and manufacturing/assembly of its products (QS 9000) [32]. Different types of FMEA are used for different systems. This approach is also certified (CEI 60812:2006) [33]. Its major aim is to detect all the possible potential problems in a complex system and their occurrence probabilities.

2.2. State of the Art

Compared to other reliability methods such as FTA, FMEA is an inductive method and is more suited for systems that contain little or no redundancy [22,23]. It is also recommended for exhaustively identifying local and global failure effects [34,35].

We developed here some major references about FMEA methodologies applied for the wind turbines system. In this literature, Sheng and Veers [36] conducted a FMEA analysis focused on wind turbine drivetrain sub-systems, where criticality was weighted by the downtime caused by each component. Shafiee and Dinmohammadi [23] and Kahrobaee and Asgarpoor [24] investigated the cost-priority-number of wind turbine components based on non-detection possibility, cost consequence of failures and probability of failures. Arabian-Hoseynabadi et al. [37], Tavner et al. [38], Bharatbhai [39] and Sinha and Steel [40] weighted component criticality with basic rating scales for severity, occurrence and non-detection. Dinmohammadi and Shafiee in [41] developed a fuzzy indicator to assess component criticality. Das et al. in [42] and Zhou et al. [43] presented FMEA analyses based on expert assessment indicators. Fischer et al. and Andrawus et al. in [44,45] used this methodology to present an optimized maintenance policy for wind turbines. These last studies used large scales or empirical ranking for the identification of some indicators, mainly the rating for severity and detection of failure. Besides, according to the literature, only authors in [23,24] used cost-based indicators to assess the criticality of components. In these last studies, a cost priority number (CPN) (based on occurrence, cost and detectability) was developed for criticality assessment of wind turbine components, non-detectability indicator was based on failure vulnerabilities ranking, which is difficult to assess in real industrial cases [23]. Other significant references and how criticality was assessed are presented in Table 2.

2.3. Discussion: Criticality Assessment

The authors mentioned in the state of art above used different methodologies to assess the criticality of components, and the table below summarizes how authors in the literature define the criticality of wind turbine components.

As stated in Table 2, authors used to rely on standard ranking scales of severity, occurrence and detection. This method was then developed to make it more practical for wind turbine systems, and fuzzy or expert approaches were introduced at this step to parametrize the proposed scales. This methodology was efficient, but has several limitations and weaknesses, particularly for the risk priority number (RPN) value that was not informative enough to assess component criticality. To overcome these limitations, Shafiee and Dinmohammadi [23] and Kahrobaee and Asgarpoor [24] developed a CPN based on probability, incurred failure costs and fault detection possibility. This last method proved to be more suitable for wind turbine reliability analysis and has overcome the limitations of the RPN limitations. However, it also need more data to evaluate probabilities or indicators to calculate the components CPN.

Table 2. Criticality assessment according to authors. RPN: risk priority number; CPN: cost priority number.

Criticality	Component Downtime	Failure Rate	Failure Probability of Occurrence	Cost Consequence of a Failure	Fault Detection Possibility	Severity Rating Scale	Occurrence Rating Scale	Detection Rating Scale	RPN	CPN
[36]	√	-	-	-	-	-	-	-	√	-
[23]	-	-	√	√	√	-	-	-	-	Based on failure costs consequences and probabilities of failure
[24]	-	-	√	√	√	-	-	-	-	Based on cost of failures and number of failures
[37–40,46–50]	-	-	-	-	-	√	√	√	√	-
[41,51]	-	-	-	-	-	Fuzzy approach	Fuzzy approach	Fuzzy approach	√	-
[42,43]	-	-	-	-	-	Expert approach	Expert approach	Expert approach	√	-
This study	√	√	-	√	-	-	-	-	-	Based on component failure rates, its average downtimes and expected costs of failure

Nowadays, the wind turbine industry is more mature. More public data about component failure rates, their downtime and repair costs are available and therefore CPNs used to evaluate the criticality of wind turbine component can be updated and optimized.

In order to overcome these limitations, this study presents a hybrid cost-FMEA [15,16]. This methodology combines failure rates (based on failure downtimes), expected failure costs and loss of production costs to identify the criticality of system components. The novelty of this method is that all the three indicators are based on available data in wind turbine industry and does not need probability or scaling assessment. The three indicators (failure rate, expected failure costs and loss of production costs) need less data than the compared references [23,24] for criticality assessment. Besides, they are not based on ranking scales like other previous references [37–39].

The criticality of each sub-system is calculated as the total expected failure costs times the corresponding failure rate. Expected failure cost can be estimated using the following Equation (1):

$$\text{Expected failure cost} = \sum_{n_{components}} p_n c_n + \text{loss of production cost} \tag{1}$$

$$\begin{aligned}\text{Loss of production cost} &= \text{expected production during downtime} \times \\ &\quad \text{Capacity factor} \times \text{Selling tariff}\end{aligned} \tag{2}$$

$$\text{Component criticality} = \text{Expected failure cost} \times \text{Failure rate} \tag{3}$$

where "p_n" and "c_n" are the probability and the cost associated to a particular failure occurring in component "n", respectively. The loss of production cost (Equation (2)) takes into account the energy supposed to be generated during the downtime of wind turbine components. To calculate the loss of production indicator, a standard electricity selling tariff in France (0.082 €/kWh) and a capacity factor of 30% is used in this Equation (2). Loss of production costs can also represent the severity of each sub-system. The proposed criticality will be discussed in Section 4.3.

The aim of the FMEA presented in this work is to identify failure modes along with possible causes and effects for a generic wind turbine. The general hybrid cost-FMEA flowchart used for this study is presented in Figure 1.

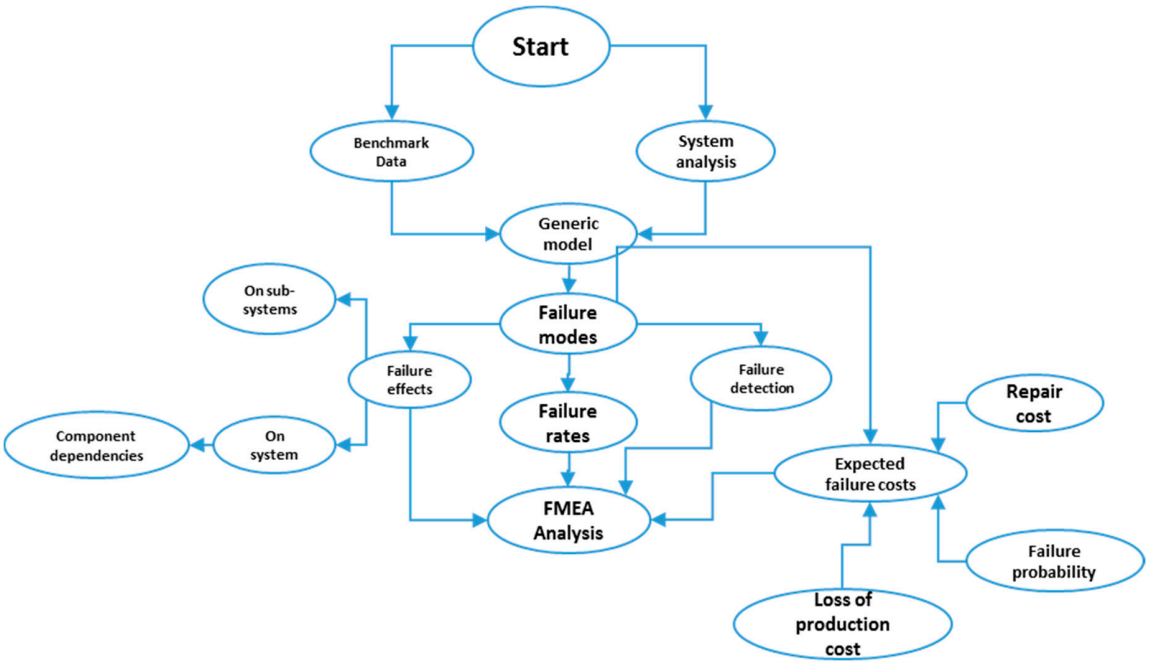


Figure 1. Flowchart representing the hybrid cost-FMEA process followed in this study.

As seen in Figure 1, we firstly proceed with a system analysis. This step generates the global configuration of the wind turbine system, its sub-systems, components and sub-components (Section 3). Next failure modes are investigated for each sub-system. The identification of failure causes has been performed by looking at the system in a holistic way. For each failure mode how it can be detected on the one hand and the failure effects on sub-systems and the global system on the other hand are investigated. This will allow us to describe the dependencies in the wind turbine system (this part was not presented in this paper). In order to define critical components and sub-systems, an expected failure cost was developed. This indicator was extracted from the life cost-based FMEA [15,16]. Cost is a universal factor that can be easily understood in terms of criticality and severity among engineers and others.

In order to simplify calculus, no failure dependency is supposed between wind turbine system components. The holistic causes will allow us to determine the expected failure costs of each sub-systems. A benchmark was made in the literature and from real wind farms in Europe. Thus, failure rates are compiled from [23,37] and from:

- Windstats data of 7000 wind turbines, from Denmark and Germany [52];
- LWK data of 650 wind turbines, from Germany;
- WMEP data of 1500 wind turbines, from Germany [53];
- Vindstat (VPC) data of 80 wind turbines, from Sweden [54];
- VTT data of 105 wind turbines, from Finland [55];
- Former Garrad Hassan energy consultancy data collected from 14 GW wind farms [56].

Since failure rates extracted from these database are location-dependent, data may be influenced by humidity, temperature, wind distributions, etc. Failure rates will be adjusted with standard deviation. This measure will be used to quantify the variation of dispersion of a set of data [57]. It will thus identify how much data vary from the average value. Consequently, a high standard deviation shows that data is widely spread (so less reliable), whereas low standard deviation shows that data are clustered closely around the average value.

The benchmarking method for failure rates used data extracted from the 10th European database and investigated. Then, the average failure rate for each sub-system is calculated with a standard deviation for every sub-system average failure rate.

Based on this data, a general overview of the analysis is proposed in Table A1. As seen in this table, for each component of wind turbine sub-systems is given:

- Failure modes;
- Failure causes;
- Failure consequences;
- Annual average failure rate
- Failure effects on sub-system and on global system
- Failure detection techniques.

Expected failure costs and the criticality of each sub-system are presented in Section 4.

3. Wind Turbine System Model

Different wind turbines with different configurations exist in the market, and they are classified by different electrical, mechanical, control designs or power control ability [23,37]. To perform our analysis, we chose the most common type of wind turbines installed in onshore wind farms. These wind turbines vary from 2 to 3 megawatts (MW) [58]. Table 3 presents the main existing wind turbine systems available in European and French markets. As seen in the table, most wind turbine configurations are equipped with gearboxes, converters and other main sub-systems [2,59–61]. These common sub-systems will help us to define a generic configuration for the FMEA analysis. Figure 2 presents the

main components of this configuration. Each main component (sub-system) contains a variety of other components. The generic wind turbine system is composed of 11 sub-systems (see Figure 2). Failure cause, failure rate, failure effects, failure detection and expected failure costs will be generated for each one of these sub-systems.

Table 3. Main existing wind turbine systems in European and French Market.

Type of Generator	Turbine Concept	Gearbox/Gearless	Converter
Single cage induction generator (SCIG)	Fixed speed	Gearbox (multiple stage)	No
	Variable speed	Gearbox (multiple stage)	Yes (full scale)
Permanent magnet synchronous generator (PMSG)	Variable speed	Gearless	Yes (full scale)
	Variable speed	Gearbox (single or multiple stage)	Yes (full scale)
Doubly fed induction generator (DFIG)	Variable speed	Gearbox (multiple stage)	Yes (partial scale)
Electrically exited synchronous generator (EESG)	Variable speed	Gearless	Yes (partial & full scale)
Wound rotor induction generator (WRIG)	Limited variable speed	Gearbox (multiple stage)	Yes (partial scale)
Brushless Doubly Fed Induction Generator (BDFIG)	variable speed	Gearbox (multiple stage)	Yes (partial scale)

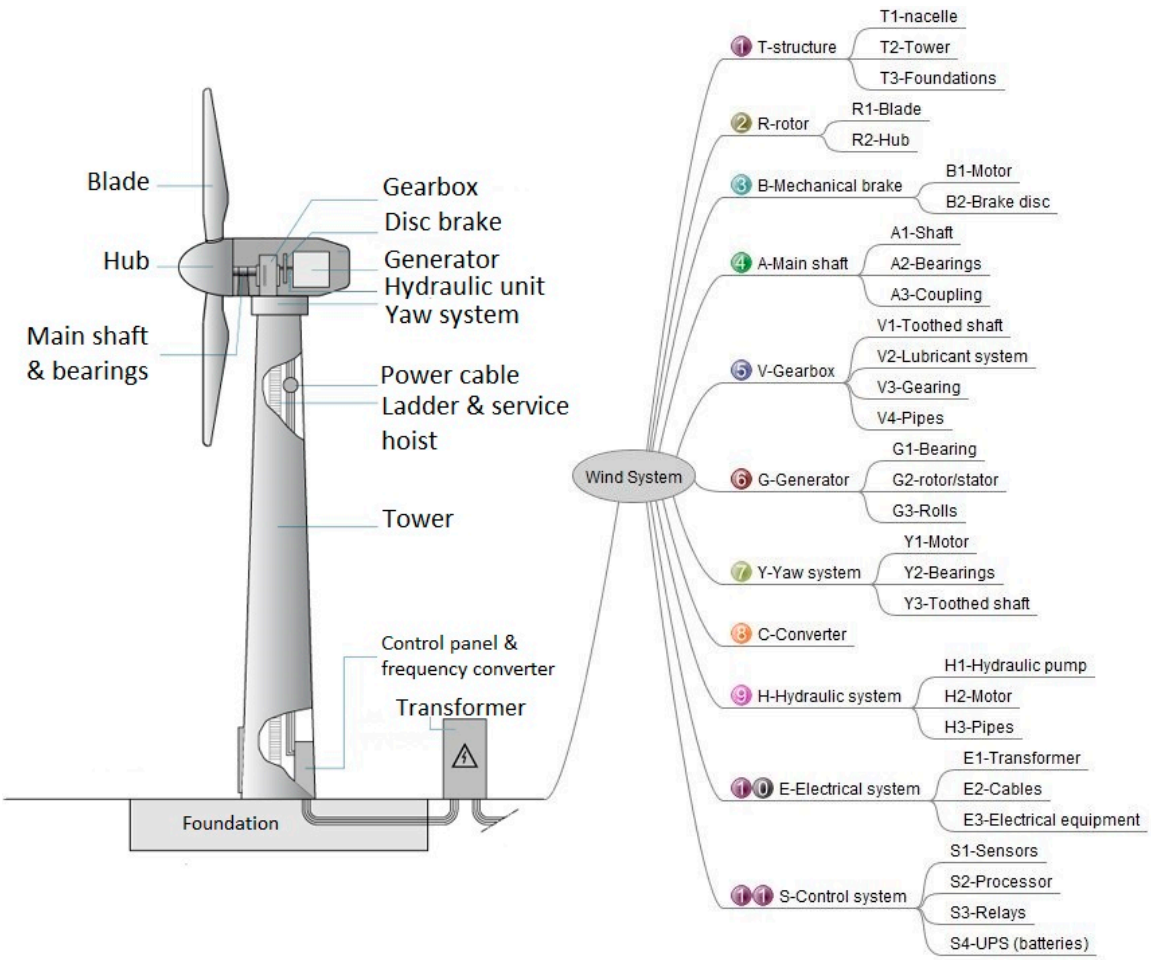


Figure 2. Main components of a 2–3 MW wind turbine.

4. Failure Mode and Effects Analysis (FMEA) Results

4.1. Failure Distribution in Wind Turbine Sub-Systems

According to different data from the literature [23,37] and from wind farms [52–55,62], average failure rates of generic 2–3 MW wind turbine sub-systems are presented in Figure 3, where we can see that only 20% of the sub-systems (control, electric and converter sub-systems) cause more than 50% of the total failures of the wind turbine system. Indeed, control, electrical and converter sub-systems fail frequently during operation. Besides, the standard deviation for wind turbine components is low, which means that data are clustered closely around the average value token for this analysis (ratios of standard deviation values and average value are up to 5% for the first eleven sub-systems, and 9% for the others (see Figure 3), this ratio is 2% for gearbox and 4% for rotor-blades).

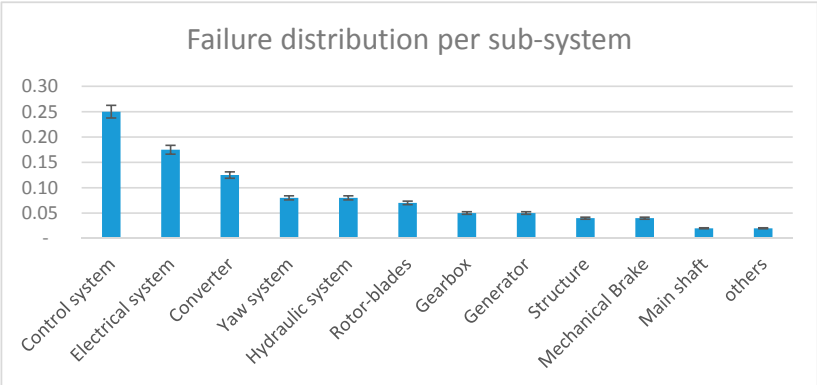


Figure 3. Failure distribution per sub-system.

4.2. What Other Large Surveys in Europe Say

LWK and WMEP [53] are one of the largest wind turbine surveys that studied more than 21,000 turbine years and their downtime over 13 years. Figure 4 presents an overview of this study. We notice in this figure that electrical and control systems cumulate the most failures in a wind turbine, which is in line with the Figure 3. However, sub-systems such as gearbox causes an important downtimes if failures occur. This is also explained by the complexity of maintenance of this sub-system [36].

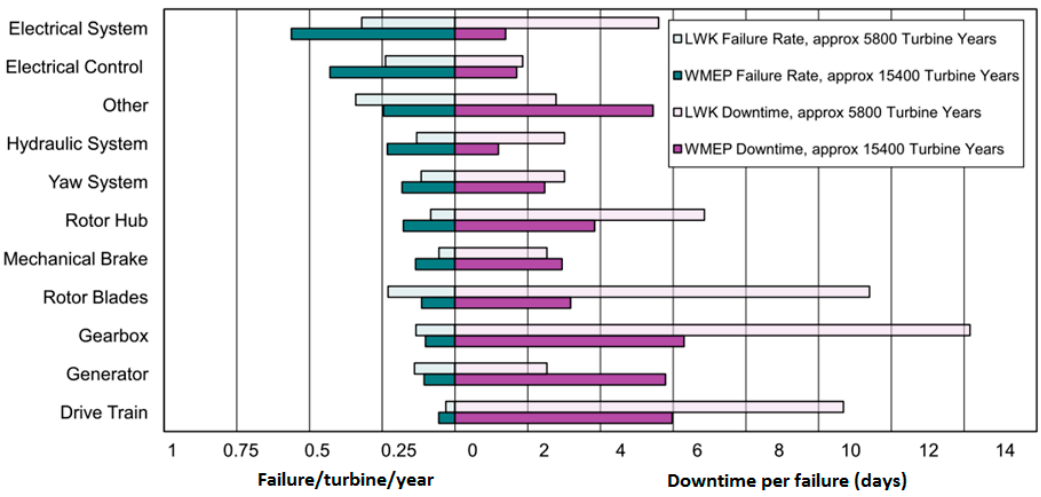


Figure 4. Failure per turbine per year and downtime from two large surveys of European onshore wind turbines over 13 years (LWK and WMEP).

4.3. The Main Cause of Failure

Wear is the main and most frequent cause of failure revealed by this analysis. Wear is defined as the progressive loss of substance resulting from mechanical interaction between two contacting surfaces [63]. In comparison with other studies, authors in [37,64] revealed that corrosion (wear) is in the top root causes in wind turbine components. Ribrant [63] stated that wear causes the majority of failures in wind turbine mechanical components. Sheng in [65] presented the main results of the upwind project in the UK wind farms, where wear is the main cause of failure. Figure 5 shows the most frequent failures in the wind turbine system revealed from this last study.

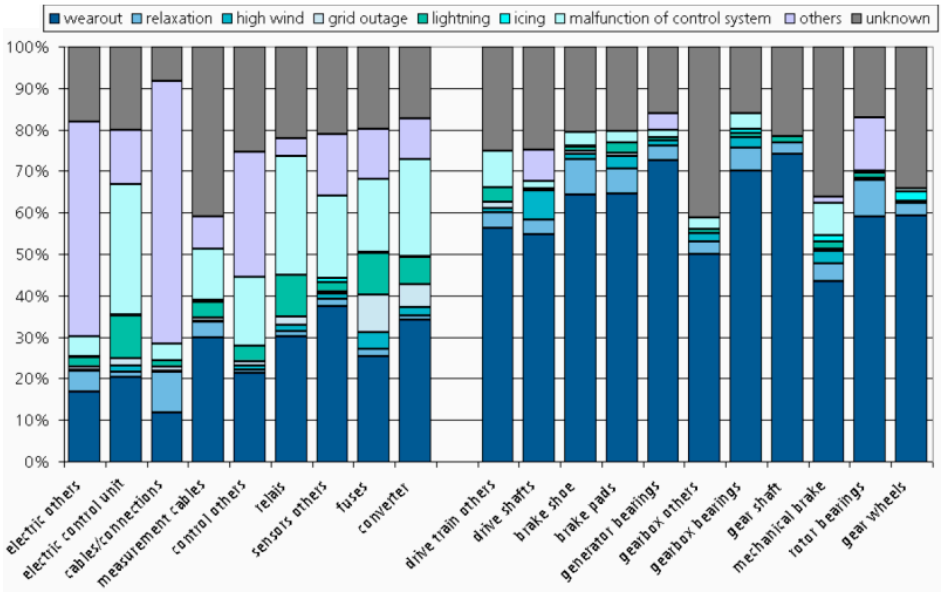


Figure 5. Share of failures in the wind turbine system [65].

Different wear types can be present in wind turbine components. According to [63], wear can be present in components as an abrasive, corrosive or erosive wear. Abrasive and corrosive wears seem to be the most frequent wear types in components. This cause of failure (wear) leads to damage in drivetrain systems whereas the failure rate of composite sub-systems such as blades are more influenced by material fatigue (crack evolution).

4.4. Expected Failure Cost

Cost is a universal term that can be easily understood in terms of criticality and severity among engineers and others. Expected failure cost can be estimated using Equation (1). To assess the sub-systems failure costs, an exponential failure rate (Number/year); that lead to component replacement; is used [21,63]. Average replacement costs of wind turbine sub-systems (2–3 MW) were taken from different references [66–68]. The replacement cost takes into account the cost of the components, crane cost and labor cost. Loss of production cost takes into account a standard selling tariff and capacity factor in France (see Section 3). Table A2 presents the failure rates (Number/year), reliability data, replacement cost of each sub system, final expected failure cost and average loss of production cost. Figure 6 presents the expected costs of failure for wind turbine sub-systems (extracted from Table A2). Structure failure supposes a complete failure of the structure (Tower/foundations/nacelle), this component rarely fail in a holistic way (annual average failure rate: 0.09). Thus, it will not be taken into account for reliability and criticality analysis. Thus, the components that generate high expenses are Gearbox and Rotor-blade sub-system. Shafiee & Dinmohammadi and Kahrobaee & Asgarpoor in [23,24] using CPN indicators also confirmed that these two sub-systems (gearbox and rotor-blade) are on the top most critical sub-systems in wind turbines.

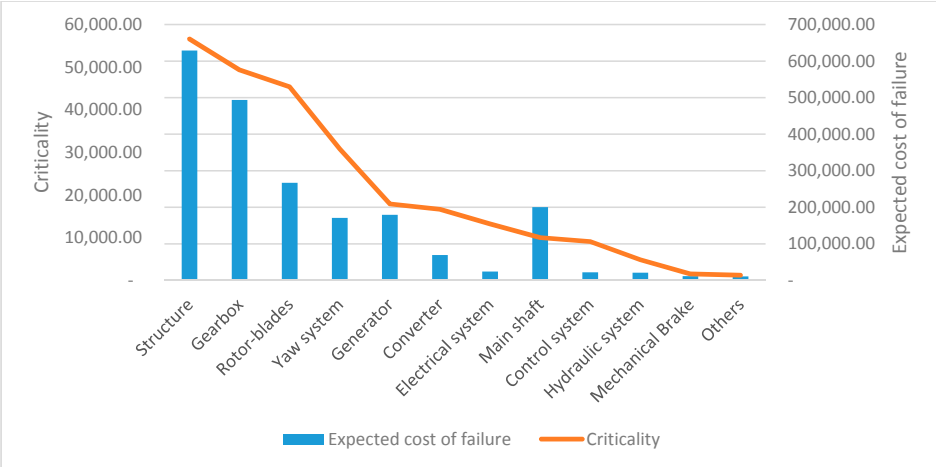


Figure 6. Expected costs of failure and criticality for wind turbine sub-systems.

4.5. Criticality of Sub-Systems

Criticality is calculated as the expected failure cost of each sub-system times its failure rate. Results are presented in Table A2 and Figure 6 presents the criticality for wind turbine sub-systems (extracted from Table A2). According to the Figure 6 (based on Table A2), and without taking into account the structure's failure, we can notice that the most critical components are the gearbox and rotor-blade sub-systems. Figure 4 also shows that these sub-systems generate high downtimes. Besides, according to Table A2, replacement and loss of production costs generated by the gearbox and rotor-blade sub-systems are the highest. These critical components, inter alia, exist in almost all industrial wind turbine systems (excluding gearless wind turbines) [69]. The next two sections present an overview of gearbox and rotor-blade reliability analysis.

Results of this study show similar main results as other cost-FMEA analyses [23,24], the novelty of this analysis being the need of less data for reliability and criticality analysis than previous studies. In this paper, cost factor was based on expected failure cost, occurrence factor was based on average failure rate extracted from wind turbine databases and weighted with standard deviation and severity factor was based on loss of production caused by failure modes. Standard criticality or risk/cost-priority-number based on ranking scales or probabilities have been overcome.

4.6. Gearbox—A Reliability Overview

Data from the literature shows that gearboxes usually don't reach their design lifetime (20 years) [65,70,71]. The failure of these critical components directly affects the wind turbine and the wind farm performance. Other studies [65,72,73] also show that wind turbine gearboxes could fail in drastically different ways. The study [72] summarized in Figure 7 covered 289 gearbox failure incidents with 257 confirmable damage records. Figure 7 presents a report of this failure distribution of the gearbox components, where it shows that 70% of the failures occur in the bearings.

Lantz [71] noticed that the average failure rate during 10 operational years can be estimated at 5%, peaked in years 4, 5 and 8. Also, Lantz [71] remarked that serial failures were observed to have a noteworthy effect on the components. Figure 8 confirms this hypothesis, where it seems that at least two failure modes occur and cause gearbox damage (bimodal distribution) that take turns in 6th–7th year. Besides, since wear is predominant in gearboxes, its failure rate is expected to increase after the 10th year if no good maintenance policy is adopted, further research will be needed in this part to prove the application of the double distribution to gearbox failure rate. Besides, gearbox replacement costs are very high, a cost of 445,000 to 628,000 € is needed for the replacement of a 2–3 MW wind turbine gearbox [66,68,74]. An average expected failure cost of this critical sub-system is around 493,000 € (see Table A2), it also causes the highest loss of production cost (16,000 €).

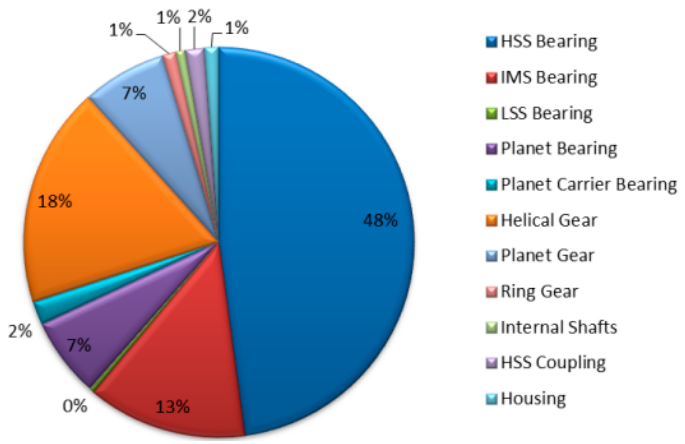


Figure 7. Failure distribution of gearbox components [72].

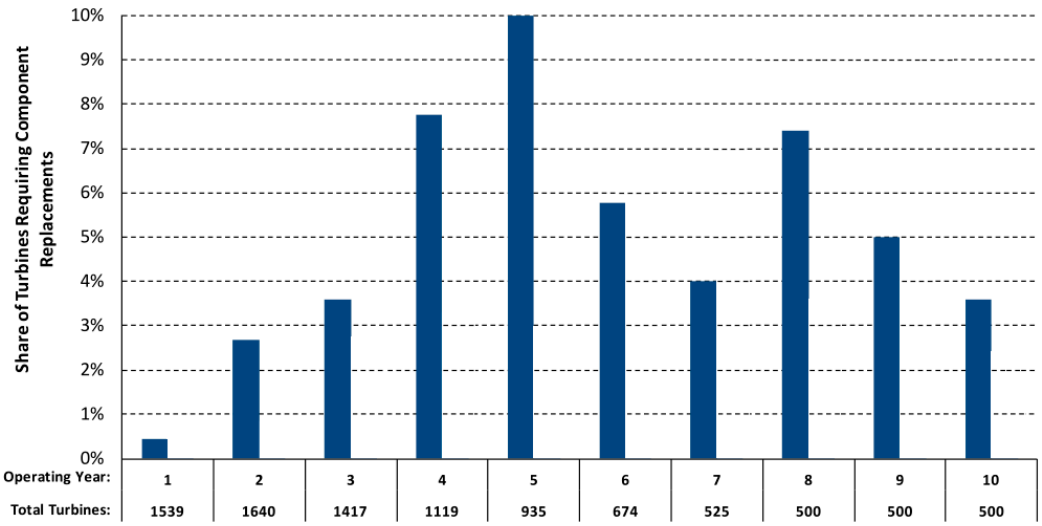


Figure 8. Average annual replacement rate of gearboxes [71].

Figure 8 states about average annual replacement rate of gearboxes, this replacement is not only caused by wear, since several failures can lead to component replacement. To prevent these failures, several solutions are proposed to improve the maintenance process such as condition monitoring solutions.

4.7. Rotor-Blades Sub-System—A Reliability Overview

According to Figure 4 and failure rate data extracted from different wind farms [52–55,62], rotor-blade sub-system causes high downtimes if failures occur. Figure 9 describes the proportion of this sub-system downtime regarding its failure rate.

Hill et al. in [75] and this FMEA analysis point out the most frequent reported damages in rotor-blades, they can be:

- Manufacturing issues (waving and overlaid laminates)
- Bad bonds
- Delamination
- Voids
- Leading edge erosion/trailing edge splits
- Scorching and split (due to lightning)

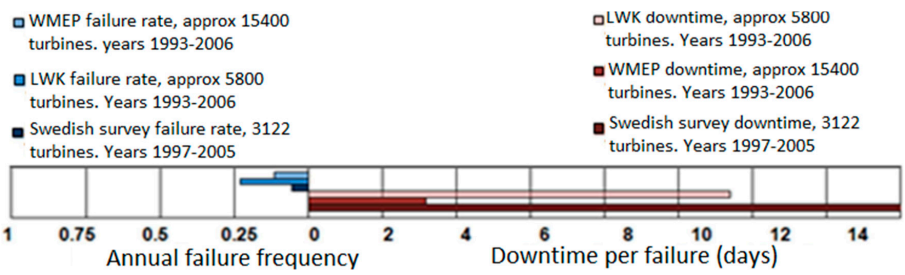
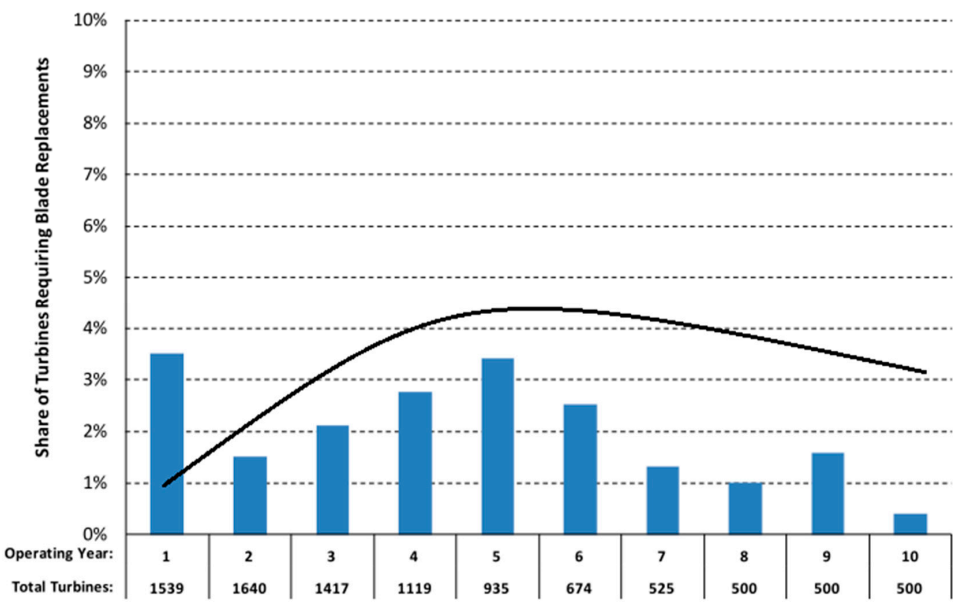
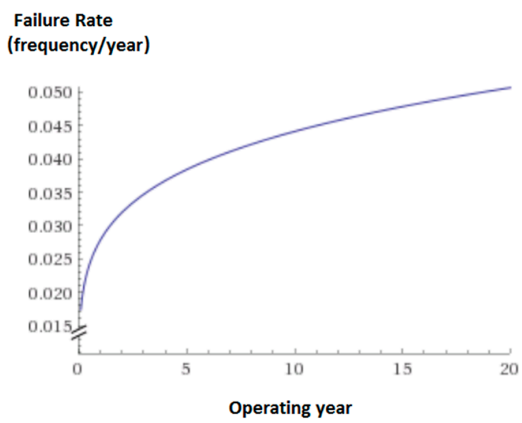


Figure 9. Annual failure frequency and downtime per failure for rotor-blades sub-system [53].

This last cause of failure (lightning strikes) is the most common noted cause of failure in [71]. Besides, in winter or when the temperature gets down 2 °C, icing appears and can cause rotor imbalance. Ice falling from blades can even cause human or animal accidents. Lantz presented in [71] the average blade replacements during 10 operational years over more than 1000 wind turbines. Figure 10a represents this study, where we notice a 1% to 3% of the surveilled wind turbines require blade replacement, with spikes in the 1st and 5th year.



(**a**)



(**b**)

Figure 10. (**a**) Average annual probabilities for blade replacements dependent on the operational—the black curve is a fitted Weibull curve; (**b**) failure rate of blades over 20 years.

Lantz in [71] points out that blade replacements in the 1st and 2nd years are typically the result of manufacturing defects or damage occurring during the construction process. Besides, he calculates about 2% of wind turbines blade replacements per year (over 10 operational years). From the other side, we could say from the figure that a similar curve can be found if we describe a Weibull behavior of blade failures, the inconsistency between failure rate curve and replacement rates between the 7th and the 10th year is mainly due to the maintenance policy adopted. Wind extreme load, bad maintenance and delamination leading to fatigue are expected to increase blade failure rates (even after the 10th year) Figure 10b presents the evolution of the blade failure rate during 20 years, under Weibull function with a shape parameter of $\beta = 1.2$ and a scale parameter of $\eta = 23.02$. Further research will be needed in this part to prove the application of this distribution to this sub-system during his lifetime. Figure 10a states the average annual replacement rate of blades, and this replacement is not only caused by fatigue, since several failures can lead to component replacement.

4.8. Failure Detection

Visual inspection remains one of the most present failure detection techniques in wind turbine systems. It remains necessary for making decisions on maintenance or safety related to wind turbine shutdown [76]. FMEA analysis shows that failure detection can vary from simple visual detection to complex tools and methods. It can be thus more efficient in wind turbine systems in order to reach high reliability and minimize failures.

The literature shows that 99% of equipment failures are preceded by certain signs, conditions, or incitation that a failure is going to occur [77]. Nowadays, one of the most used techniques in wind farms are condition monitoring systems (CMSs) [78–81]. This technique rely on sensors or other components that monitor the mechanical, heat or pressure behavior of the observed component. Nowadays, the most predominant CMSs for wind turbines are "vibration-based systems monitoring the rotating drivetrain components". CMS is generally applied to the main bearing, gearbox, generator bearings and tower oscillations. This choice is justified by the recommendation of main insurance companies since 2003 for onshore and offshore wind turbines [82]. Insurance companies does not require CMS for other wind turbine component (electrical and control system for instance), but wind turbine constructors do provide such solutions to monitor wind turbine sub-systems since guidelines and standards for wind turbines CMS were developed (ISO 13373-1 [83], IEC 61400-25-6 [84]).

Besides, Rolfes et al. describe in [76] that rotor-blade monitoring systems available on the market must be considered as being in a development stage, since high downtimes are always registered for this sub-system.

4.9. Failure Effects

Considering this FMEA analysis, failure effects exist in wind turbine sub-systems and may lead to failure propagation. The main components mounted in series inside the nacelle (main shaft, gearbox, generator) are highly influenced by their external environments. A vibration generated in the main shaft for instance can lead to a failure in gearbox bearings. This can conclude to the identification of dependencies between wind turbine components. This part was not developed in this paper and will be the object of our next research work.

5. Conclusions

In this study, we deal firstly with a system analysis to fix the main configuration of a generic 2–3 MW industrial wind turbine. The application of the hybrid cost-FMEA approach has been discussed and demonstrated for wind turbine system, this method used less data and proved to be as accurate as compared methods. The criticality assessment in the existent approaches was based on failure and occurrence probabilities and cost consequences of failures, whereas the proposed approach is based on failure rates, expected costs of failure and loss of production costs. No failure rates or occurrence probabilities were needed in this method. The reliability analysis proved that:

- Wear is the main and most common cause of failure in wind turbine systems. The system environment is the main reason for this issue. Wear can cause a variety of operational problems including misalignment and system vibrations. Abrasive and corrosive wear seem to be the most frequent wear type noticed, whereas fatigue influences more external components such as blades.
- Control and electric sub-systems have the highest failure rates in a wind energy system on the one hand. On the other hand, sub-systems such as gearboxes and rotor-blades have low failure rates, but cause high downtimes to the system.
- Expected failure costs were calculated for main wind turbine sub-systems. The study proved that gearboxes and rotor-blades are the critical sub-systems. A general overview of these sub-systems' reliability was presented
- Failure detection techniques were presented. CMS is accurate to prevent failures and minimize downtimes in wind turbine system.

Although the wind industry tries to handle the failure intensities of the different sub-systems, it is recommended that critical sub-systems such as gearboxes and blades should be tested more studiously than nowadays in order to avoid early failures. A suggestion is that wind turbine gearbox failures behaviors could be benchmarked with other gearbox failures in the industry.

This study was compared to others performed for wind turbine systems. The wind industry is in rapid growth and the wind technology is constantly improving. Updated FMEA analysis should be made not only to compare new wind turbine versions to old ones, but also to update reliability information about these systems. The reliability analysis presented in this paper is more concentrated on the design phases, no maintenance policy was introduced here. Thus, this study does not assess the wind turbine reliability through time.

The FMEA analysis also points out the influence of each component on the sub-system itself and its influence on the wind turbine. This will allow us in future research to determine the dependencies between wind turbine components. Such dependencies can affect the reliability analysis and the performance of the system. Future research will also focus on implementing maintenance in this FMEA model.

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Appendix A

Table A1. Sample of a 2 MW FMEA analysis.

Sub-System	Component	Failure Mode	Failure Causes	Failure Consequences	LWK Failure DATA	Failure Rate 134 Wind Turbines 1.5 MW	ISET Germany Failure DATA, 1500 WT aver 15 Years [9]	LWK Failure DATA, 5800 WT over 2 Years
Gearbox	Toothed shaft	Fatigue & fracture	Irregular grooving/welding defect/non alignment	Shaft cracks/non alignment	4%	3.26%	4%	8%
	Lubricant system	Loss of function	Presence of water or debris in the system/aged oil/ pump failure	Overheating/wear				
	Gears/gearing	accelerated wear/premature failure	Poor lubrication/presence of corrosive elements/presence of water in the lubricant oil/shocks	Damages in the system				
	Pipes	Leakage	Wear/excessive pressure in pipes	Loss of precision/Overheating				
Blade –rotor	Blades	Fouling	Climate/snow/hail/dust/ insects/environmental debris	Loss of aerodynamic properties/blades are not optimal for wind energy saving	7%	1%	7%	10%
	Hub	Fatigue/crack	Overload/delamination/ extreme wind conditions/lightening	Crack evolution/rotor stop	5%	3.25%	5%	5%

Swedish Power Plants Failure DATA, over 4 Years	WMEP FAILURE DATA, 1435 WT Over 2 Years	Windstats Denmark Failure DATA	Windstats Germany Failure DATA	EPRI California Failure DATA, 290 WT Over 2 Years	Reliawind RELEX Failure DATA	Failure Effects on the Sub-System	Failure Effects on the System	Failure Detection Methods
10%	5%	7%	3%	3%	5%	Main shaft vibration/Generator vibration Noise/Gearbox life time reduction	Emergency stop activation	Vibration sensors/Oil & heat sensors
13%	12%	8%	6%	7%	1%	Vibration/crack evolution/crack evolution on rotor	Emergency stop activation	Blade sensors/vibration sensors in hub/emergency stop activation/visual inspection in maintenance operations
-	2%	-	3.20%	3.40%	1.9%			Visual inspection/ rotor Sensors

Table A2. Data used to calculate the expected failure costs generated in a 2–3 MW wind turbine system.

Sub-System	Failure Rate (N/year) [21,63]	Annual Reliability	Average Replacement Cost (€) (Including Crane + Labor) [66–68]	Average Downtime per Hours [63,64]	Average Cost of Loss of Production; Selling Tariff 0.082 (€/kWh)			Expected Cost of Failure (€)	Criticality (€/kWh)
					2 MW	3 MW	Average		
Structure	0.09	0.913	682,386.00	97.00	4772.40	7158.60	5965.50	628,983.92	56,608.55
Gearbox	0.1	0.904	528,253.33	260.50	12,816.60	19,224.90	16,020.75	493,561.76	49,356.18
Rotor-blades	0.17	0.843	305,873.33	146.53	7209.44	10,814.16	9011.80	266,863.02	45,366.71
Main shaft	0.05	0.951	199,170.00	181.77	8942.92	13,414.38	11,178.65	200,589.32	10,029.47
Generator	0.1	0.904	189,908.00	126.13	6205.76	9308.64	7757.20	179,434.03	17,943.40
Yaw system	0.18	0.835	199,990.00	67.93	3342.32	5013.48	4177.90	171,169.55	30,810.52
Converter	0.24	0.786	81,272.00	90.00	4428.00	6642.00	5535.00	69,414.79	16,659.55
Electrical system	0.55	0.576	33,980.00	72.93	3588.32	5382.48	4485.40	24,057.88	13,231.83
Control system	0.41	0.663	28,388.00	55.20	2715.84	4073.76	3394.80	22,216.04	9108.58
Hydraulic system	0.23	0.794	23,300.00	41.47	2040.16	3060.24	2550.20	21,050.40	4841.59
Mechanical Brake	0.13	0.878	8560.00	65.60	3227.52	4841.28	4034.40	11,550.08	1504.51
Others	0.11	0.895	5000.00	105.60	5195.52	7793.28	6494.40	10,969.40	1206.63

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