Journal of
Marine Science and Engineering

MDPI

Article

Failure Rate Assessment for Onshore and Floating Offshore Wind Turbines

He Li [1], Weiwen Peng [2], Cheng-Geng Huang [2] and C. Guedes Soares [1,*]

[1] Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisbon, Portugal
[2] School of Intelligent Systems Engineering, Sun Yat-Sen University, Guangzhou 510275, China
* Correspondence: c.guedes.soares@centec.tecnico.ulisboa.pt

Abstract: A detailed analysis is performed on a dataset of failure and maintenance records from various onshore wind farms located in different geographical areas for the safety, risk, reliability, availability, and maintainability characterization of wind turbines. Specifically, characteristics related to failures, including the criticality of failure modes, failure frequencies, failure rates, and lifetime distributions of components, are analyzed to support the failure identification and failure prevention of wind turbines. Additionally, characteristics of maintenance, including typical maintenance measures of failures, policies for spare components, delayed maintenance, as well as related times such as reaction time, travelling time, and mean time to repair, are provided to support the maintenance management of wind farms. Based on the operational data analysis results, a reliability influence factor-based failure data correction approach is presented to transfer the onshore data to floating offshore turbines by modeling the differences in failure occurrences based on experts' judgment. A comprehensive comparison with existing studies validates the performance of the proposed approach.

Keywords: wind energy; wind turbine; failure rate correction; failure data; maintenance data

check for updates

Citation: Li, H.; Peng, W.; Huang, C.-G.; Guedes Soares, C. Failure Rate Assessment for Onshore and Floating Offshore Wind Turbines. *J. Mar. Sci. Eng.* **2022**, *10*, 1965. https://doi.org/10.3390/jmse10121965

Academic Editor: Vengatesan Venugopal

Received: 2 November 2022
Accepted: 7 December 2022
Published: 10 December 2022

1. Introduction

Wind energy, including floating offshore wind, is taking over the market share compared to traditional energies [1–4]. The ever-decreasing levelized cost of energy [5] and progressive advancement of modern technologies [5–7], together with rapidly accumulating domain knowledge and experiences [8–10], have contributed to speeding up the development of wind energy in the last several decades [11,12]. At present, the economic performance of onshore wind energy competes with traditional energy sources despite the drawbacks of seasonally variable output and environmental problems such as bird crashes and sound pollution [2,3,13]. However, the electricity produced from offshore wind is still expensive [14,15]. For instance, the power generation cost of a 2 MW offshore wind turbine operating at 50% efficiency and for 60% of the available time is about 135 GBP/MWh, which is obviously higher than that of onshore wind turbines at a power generation cost of 100 GBP/MWh [16].

The Operation and Maintenance (O&M) cost of wind turbines takes up to 20% of the overall energy cost, and such a proportion becomes bigger when referring to floating offshore wind [17,18]. Wind farm developers, operators, and users are trying to reduce the O&M costs of wind projects by understanding the failure features of wind turbines, improving the capability of maintenance resource management, and finding feasible measures to prevent the equipment from undergoing unexpected failures. However, the above aspects have been restricted by insufficient O&M data, primarily due to confidential issues among wind farms, operators, manufacturers, and other stakeholders [19–21].

To enrich the data on the failure, risk, reliability, availability, maintainability, and economic applications of wind turbines, the industry has established several databases, as listed in Table 1.

Table 1. Databases of wind turbines.

Country	Names of Databases	Number of WTs	Years
Germany	WindStats Germany, LWK, WMEP	6428	1989–2006
Denmark	WindStats Denmark	2345	1994–2004
Finland	VTT	72	1996–2008
Sweden	Sweden	723	1997–2005
Spain	CIRCE	4300	~2013
USA	CREW	800–900	2011–2015
India	India	15	2000–2004
China	Huadian, East China, SE China	1555	2009–2013
UK	Round 1 UK *, SPARTA *, Strathclyde	1516	2004–2016
Netherlands	NoordzeeWind	36	2007–2009
——	LGS-Onshore **	76	2018–2020

*: offshore wind; **: this paper; LWK: Landwirtschaftskammer Schleswig-Holstein; WMEP: Wissenschaftliches Mess- und Evaluierungsprogramm; VTT: Technical Research Centre of Finland; CIRCE: Universidad de Zaragoza; CREW: Continuous Reliability Enhancement for Wind; SPARTA: System Performance, Availability and Reliability Trend Analysis.

The mentioned datasets include the following main parameters:

- Failure rates from the WindStats Germany [22] and the Swedish [23] databases;
- Downtimes from the WMEP [24] and the VTT [25] databases;
- Productivity based on the VTT database [25];
- Stop rates (not limited to failures) from the NoordzeeWind database [26];
- The monthly number of repairs based on the SPARTA database [17];
- Failure and repair classifications based on the Strathclyde database [27].

However, the feasibility of such published information depends on the completeness of collected data and the comprehensiveness of analyses. Integrated analysis of multiple databases benefits the comprehensiveness of the analysis and the robustness of the results extracted. Failure rates of wind turbines based on a combination of several databases have been reported in [19,20,28].

The released databases of wind turbines installed from 1986 to 2016 indicate that the most recent populations are more than five years old and have, thus, passed the warranty period. However, the advancements in materials, manufacturing, design concepts, and O&M tools have led to a technical revolution in wind energy, especially in wind turbine applications [29–31]. The above indicates that the old datasets represent the properties of the previous wind turbines but may not apply to the recent ones. Hence, reporting new and more recent operation data with a comprehensive analysis can provide stakeholders and practitioners in the wind energy sector with urgently needed information on wind turbines' failure and maintenance features.

Floating offshore wind turbines, representing the next step in the wind energy market, are new concepts with limited installations [3,4]. Failure, risk, reliability, availability, and maintainability investigations of such equipment are restricted by unavailable failure and operation data. Reported onshore-data-based analyses such as reliability analysis [18,32], failure rate assessment [33], mean time to failure prediction [18,34], and maintenance strategy planning [30,35] cannot be applied to floating offshore wind facilities without pre-treatments. To this end, the construction and application of the failure rate correction approach to transfer the fruitful accumulated operation data of onshore wind turbines to the corresponding components of floating offshore structures would enrich the database of floating offshore wind turbines at an early stage of operation under the situation of unavailable operation data.

Stress factor-based and reliability influence factor-based (RIF-based) methods are applied to the failure rate correction/prediction of similar products [33]. Stress factor-based approaches reflect differences between the failure rates of new components of a product and those of similar ones using environmental and power utilization stress factors. For instance, Santos et al. [36] predicted failure rates of offshore wind turbines' components according to the operation data of onshore structures with the assistance of a stress factor model. Theoretically, however, the method requires extensive environmental and operation data collection, restricted to model applications.

RIF-based failure rate correction methods map the differences between the RIFs of components so that the failure rates of new (sometimes unknown) elements can be corrected/predicted. For instance, based on a similar topside system, Rahimi et al. [37] assigned weights to the RIFs of components of a subsea system to infer the failure properties of the system with the assistance of the scaling factor and boundary values designed. To upgrade the above deterministic model, Bhardwaj et al. [38] proposed a failure rate prediction model using Bayesian networks to represent the uncertainty of RIFs. The Bayesian network-based failure correction model was validated by analyzing a subsea processing system. Brissaud et al. [39] constructed an influencing reference coefficient of RIFs for failure rate assessment, which predicts the failure rates of components as an interval (considering uncertainties of RIFs) rather than a single value as existing methods did.

However, the approaches we have already mentioned are complicated, and they either require extensive data collection or additional indicators (or both simultaneously). With these restrictions, more recently, Li et al. [33] proposed a risk-RIF-based failure rate correction model to transform the failure data of onshore and bottom-fixed offshore wind turbines to a comparable level of floating equipment. The method requires fewer inputs but has better accuracy. However, it is pointed out that the risk-RIF-based failure rate correction model calculates a general indicator to reflect the overall differences of RIFs between various types of wind turbines and cannot map the discrepancies between each component. From a failure mechanism point of view, the harsh and complicated sea conditions introduce more fragility and initiate more failures in components exposed to them, such as floating foundations, mooring, towers, and blades, compared with those installed in nacelles, such as gearboxes, generators, and convertors. Hence, the failure rate correction should reflect the specific failure properties of each component.

Accordingly, following the risk-RIF-based failure rate correction model in [33], this paper proposes a failure rate correction approach for mapping the failure data of new products in their infantile stage, such as floating offshore wind turbines, from similar maturely operated equipment such as onshore wind turbines. The novel contributions of this paper are as follows:

(i) A new operation dataset of wind turbines is opened, which is the most up-to-date and can better reflect the failure and maintenance properties of recent wind turbines and strengthen the database of the wind energy sector.
(ii) A failure rate correction approach is proposed to transfer well-accumulated onshore wind turbines to supplement the insufficient operation data of the floating offshore wind sector. This extends the model in [33], in which the failure rate correction calculates a general indicator to reflect the overall differences between onshore and floating offshore wind turbines, and cannot reflect the discrepancies between each component. Meanwhile, in the present paper, the failure rate correction model is constructed using a bottom-up approach from elements to components until the wind turbine level is reached, to examine the failure rate differences of all the components.

The proposed failure rate correction approach can be applied to all scenarios of approximately inferring the failure rates of new products from maturely operated ones with sufficient operation data or knowledge, and it is not limited to the wind energy sector.

The rest of this paper is arranged as follows. Section 2 presents the particulars of the dataset. Section 3 analyzes the failure data of wind turbines. Section 4 provides maintenance information. Section 5 introduces the failure rate correction approach. The results, comparisons, validations, and discussions are listed in Section 6. The conclusions are provided in Section 7.

2. Features of the Dataset

This analysis includes 423 failures of 76 multi-MW (Megawatt) collected from wind turbines operating in four wind farms in China, see Figure 1. The observation consists of about 1.44 million operation hours or more than 164 turbine years. Different manufacturers make wind turbines with five configurations. For confidentiality reasons, the types of wind turbines and the power, rotor diameter, blade size, manufacturers, and operators of the wind turbines are not mentioned here. The wind turbines are less than three years old and are operated by users, but the manufacturers carry out maintenance as the wind turbines are in their warranty period.

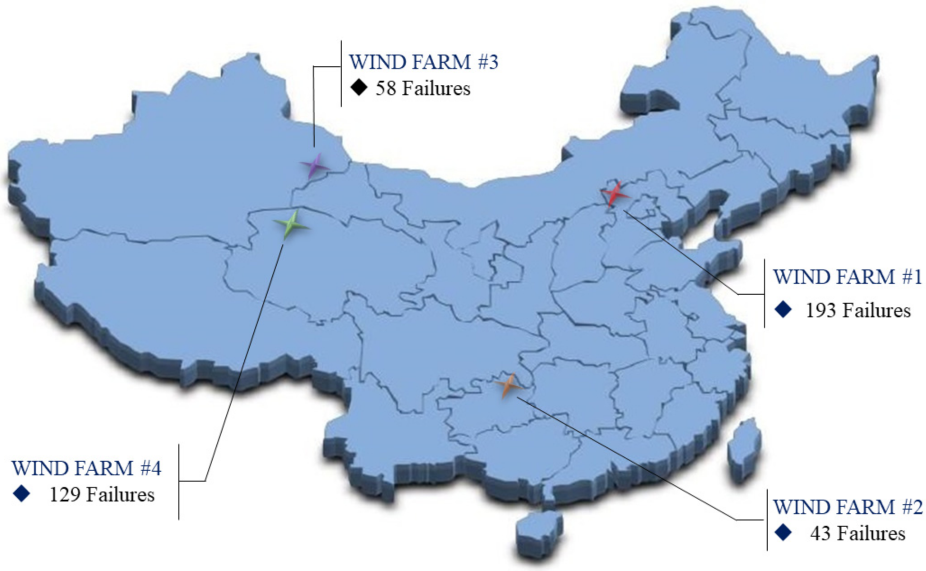

Figure 1. Wind farm locations in China.

The four wind farms are located in different areas with significant geographical and climatic discrepancies. Specifically, wind farms #1, #3, and #4 are located in flatlands with a more than 40 °C temperature difference between summer and winter (below 0 °C). However, wind farm #2 is situated on a mountain with a comparatively small temperature difference between winter and summer. The wind speed in wind farms #3 and #4 is higher than in the other wind farms, but sand content in the air is higher than in wind farm #1 and significantly higher than in wind farm #2.

3. Failure Data Analysis

3.1. Failure Definition

There is no standardized document issued to define wind turbine failures. Hence, researchers have defined wind turbine failures from different viewpoints based on the available data. Based on the downtime data, Wilkinson et al. [40] defined a failure as an event with downtime longer than one hour and requiring at least a manual restart of the wind turbines. Based on the operational data, Carroll et al. [27] defined a failure as an unscheduled visit to a wind turbine in which materials (elements or components) are consumed to enable the wind turbines to function.

This analysis based on maintenance records, including corrective and preventive maintenance, defines a failure as (i) an event that causes wind turbine stoppage; (ii) the triggering of Supervisory Control and Data Acquisition System (SCADA) or Condition Monitoring System (CMS) alarms due to a dangerous operational state; (iii) harmful states of components identified in predetermined inspections, such as the iron element (Fe) content of lubricating oil exceeding 200 mg/kg; or (iv) the predetermined periodical replacement of components.

3.2. Failure Properties

Overall, the observed wind turbines comprise 22 elements. A representative configuration of wind turbines is displayed in Figure 2. This analysis categorizes the 22 elements into seven units [12,41–43], including the Rotor (Blades, Hub, Main Bearing, and Main Shift), Generator, Gearbox, Electrical Facilities (Converter, Transformer, Monitoring and SCADA, Weather Unit, Power and Controller, and Other Electrical Facilities), Pitch & Yaw (Pitch System and Yaw System), Cooling & Hydraulics (Cooling System and Hydraulics), and Auxiliary (Crane, Climbing Aid, Brake, and Nacelle).

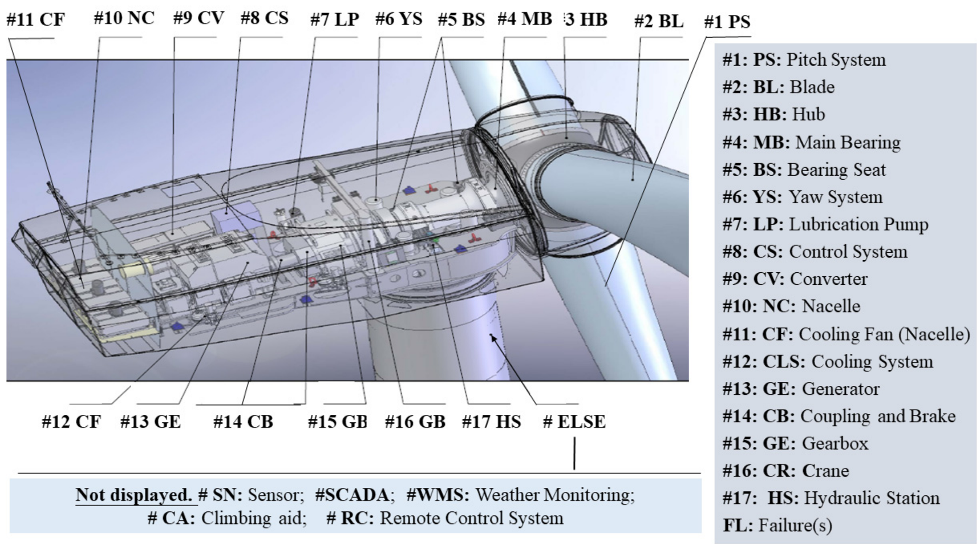

Figure 2. A representative configuration of a wind turbine.

3.2.1. Failure Mode and Failure Criticality

Failure modes are observable fault presentations, representing unhealthy working states of wind turbines. The collected 423 failures involved 112 failure modes, indicated in Appendix A Table A1. Electrical Facilities, Pitch & Yaw, and Cooling & Hydraulics process more than 71% (80 out of 112) failure modes of all the wind turbines. From a failure frequency point of view, the mentioned components contribute to over 67% of failures. The majority are functional failures rather than the structural failures of the Rotor, Generator, Gearbox, and Auxiliary (see Figure 3).

Electrical Facilities and Cooling & Hydraulics failures are common failures in wind farms #3 and #4. There is no evidence to illustrate the exact reasons, but the weather conditions may be a contributor. Specifically, air sand content and temperature differences (day and night, winter and summer) in these two wind farms are higher than in the others, which may introduce vulnerabilities to the wind turbines.

Failures mostly happen inside Nacelles, and a few are related to the SCADA, weather monitoring, and remote control systems. In addition, the majority of functional failures (79% of the total) require restarting or adjustment, while hard failures that require material consumption are a minority. Generally, most hard failures, such as anemometer damage, and several functional failures, such as wrong pitch angle, lead to severe consequences such as showdowns. For instance, 38% of failures of Rotors, 30% of failures of Electrical Facilities, and 24% of failures of Gearboxes made the wind turbines shut down, which is higher than for Cooling & Hydraulics (20%), Pitch & Yaw (15%), Generators (12%), and Auxiliary components (0%).

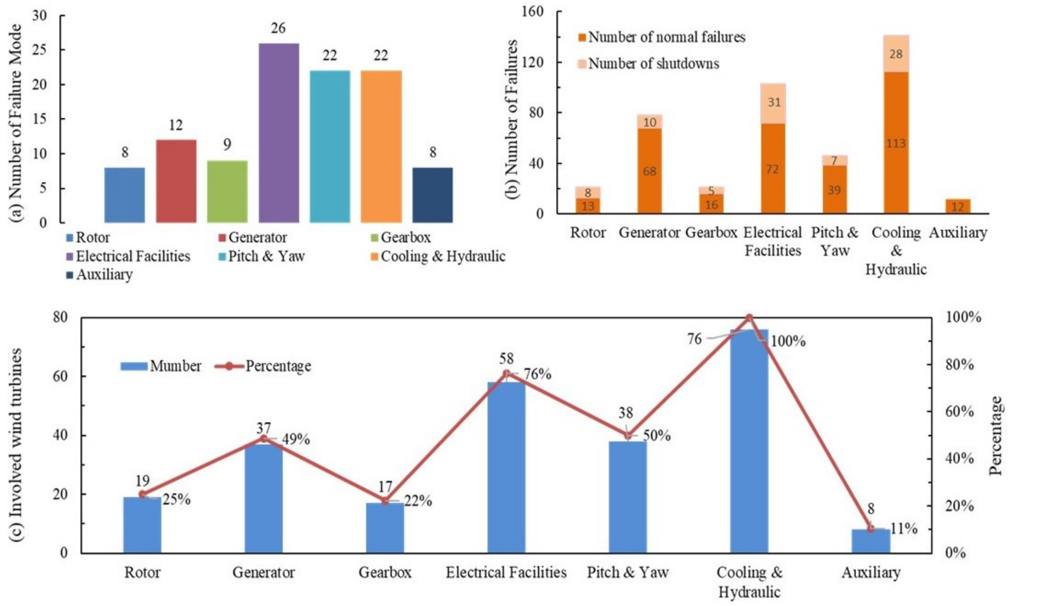

Figure 3. Failures of components. (**a**) Number of failure mode instances; (**b**) number of failures; and (**c**) involved wind turbines.

Additionally, a failure mode's severity depends on the damage to the wind turbines. For example, three out of 15 cabin brush failures caused the generator's shutdown due to heavy wear. In most cases, cabin brush wear can be identified and replaced according to the monitoring data and periodical inspections.

Cooling & Hydraulics failures happen commonly, indicating that the quality control of such a component is essential. Electrical Facilities failures happened in 58 wind turbines among the total 76 wind turbines, which is more than for Pitch & Yaw failures (38 wind turbines) and Generator failures (37 wind turbines).

It is worth pointing out that Gearbox failures mostly happened in 17 wind turbines of two types from one manufacturer. Hence, the manufacturing capability of manufacturers is a crucial factor in the quality of wind turbines. The above findings call for more attention from users (in wind turbine selection) and manufacturers (in supplier management and assembly capacity improvement).

The maintenance crew categorized failures into normal failures, critical failures, and extremely critical failures, as in Table 2. Normal failures can be fixed quickly and will not significantly reduce the productivity of wind turbines, while critical failures reduce availability and require timely maintenance. Extremely critical failures result in the stoppage of wind turbines and demand additional maintenance.

Table 2. Failure criticalities of components.

Component	Normal Failure	Critical Failure	Extremely Critical Failure
Rotor	17	3	1
Generator	49	22	7
Gearbox	14	5	2
Electrical Facilities	89	8	7
Pitch & Yaw	36	10	_
Cooling & Hydraulics	109	23	9
Auxiliary	11	1	_
Summary	(327 failures)	(82 failures)	(25 failures)

Overall, 77% of failures are normal ones and can be fixed by minor repair actions. Critical (82 failures) and extremely critical (25 failures) failures require additional materials or assistance from suppliers to finalize the maintenance. To be specific:

- From a component point of view, the Gearbox and Generator fail less in frequency but result in more critical consequences than the failure of Pitch & Yaw and Cooling & Hydraulics, followed by the Electrical Facilities, Rotor, and Auxiliary components; Electrical Facilities frequently fail, with limited impact on power generation. Failures of components that are directly involved in electricity generation, such as the Gearbox and Generator, are more critical than appendant ones such as Cooling & Hydraulics. No transformer failure was observed.
- From a wind turbine point of view, the component selection impacts the failure features of wind turbines. For instance, only a limited number of critical failures (including extremely critical ones) are observed in wind turbine models #1 and #4. The wind turbines in model #5 suffer more critical failures (see Table 3). The root reason can be traced to the component selection, supplier, and maintenance measures.
- From a wind farm point of view, the weather conditions significantly affect the failure features of wind turbines. For instance, most failures of wind farms #1 and #4 are normal failures, while the proportion of critical failures (including extremely critical failures) is markedly higher in the remaining wind farms. This indicates that the wind profile affects, to some extent, the failure criticalities of wind turbines. Generally, higher wind speed, longer uninterrupted working time (wind farm #1), and operation at higher altitudes (wind farm #4) introduce additional failure criticalities to wind turbines (see Table 4).

Table 3. Failure criticalities by type of wind turbine.

Wind Turbine Type	Wind Farm Installed	Normal Failure	Critical Failure	Extremely Critical Failure
Wind turbine model #1	#1	167	23	3
Wind turbine model #2	#3	30	9	11
Wind turbine model #3	#3	2	2	4
Wind turbine model #4	#4	104	22	3
Wind turbine model #5	#2	17	21	5

Table 4. Failure criticalities by wind farm.

Wind Farms	Normal Failure	Critical Failure	Extremely Critical Failure
Wind farm #1	167	23	3
Wind farm #2	17	21	5
Wind farm #3	32	11	15
Wind farm #4	104	22	3

The failure features of wind turbines are affected by, at least, the coupling of manufacturing, wind farm weather conditions, and continuous operating time. This analysis reveals the factors that influence the failure features of wind turbines. Still, the evidence is insufficient to distinguish the influence mechanisms of each factor and their couplings on wind turbines.

3.2.2. Failure Statistics

Failure Frequency

The failure frequency of the wind turbines is shown in Figure 4, and no satisfactory distribution is found to fit the failure frequencies of the wind turbines perfectly. Instead, a polynomial function is applied to show the failure frequency of the wind turbines. More than 36% of wind turbines fail less than three times; however, most wind turbines suffered five to nine failures during observation. The above conclusions may support wind farm maintenance scheduling and supplier management.

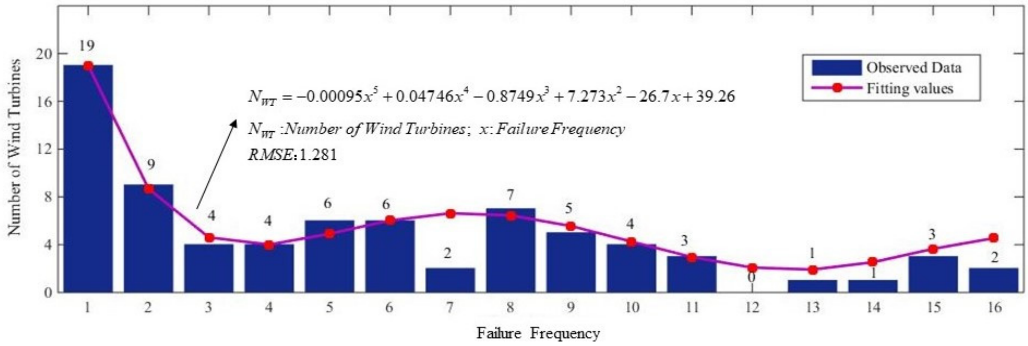

Figure 4. Failure frequency of wind turbines (RMSE: Root Mean Square Error).

Failure Criticality

The wind farm failure criticality categories are displayed in Figure 5 and Table 5. The statistics confirm that:

- The critical failure frequencies in wind farms #2 and #3 are relatively low. The manufacturer and maintenance measures contribute to this conclusion, as all the wind turbines in wind farm #2 and 7 out of 33 wind turbines installed in wind farm #3 are manufactured by one factory. On the contrary, similar wind turbines are not used in wind farms #1 and #4. Hence, the capability of manufacturers is a core factor in wind turbine quality.
- The distribution of (extremely) critical failures and critical failures in each wind farm is not even; moreover, the regular pattern of failure occurrence and the relationships between critical failures, extremely critical failures, and normal failures are not obvious.
- Wind turbines in wind farm #3 fail less, but their failures have severe consequences; for instance, 55% of wind turbines suffer only one failure during the observation period, of which 50% are extremely critical failures (6 failures) and critical failures (3 failures). Critical failures requiring complex maintenance, additional materials, or professional personnel would introduce additional downtime and maintenance costs and reduce wind turbines' availability and economic competitiveness. To this end, failure rates and failure criticalities should be considered in supplier management of wind projects.

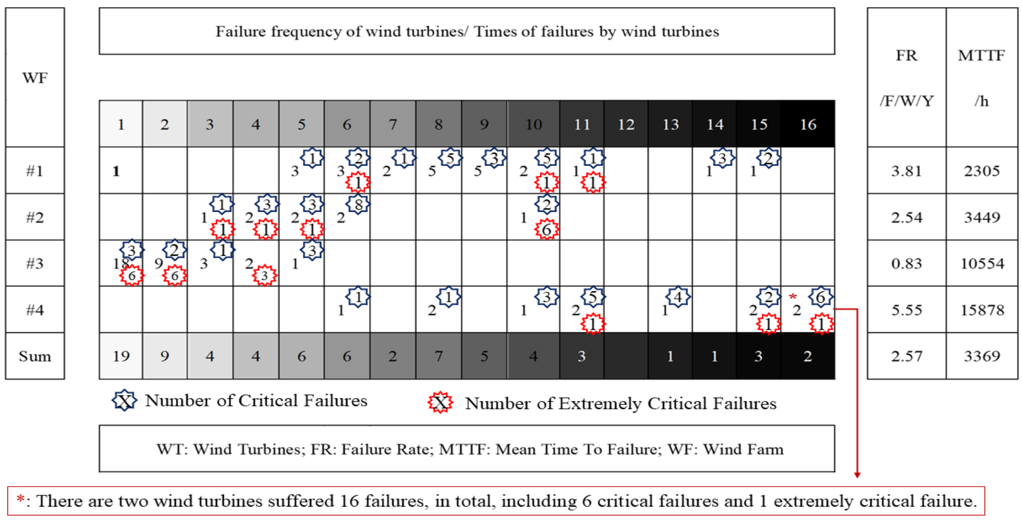

Figure 5. Failure criticality statistics by wind farm.

Table 5. The statistic of critical and extremely critical failures (per year).

Wind Farm	Wind Farm #1	Wind Farm #2	Wind Farm #3	Wind Farm #4	Average
CFR	11.9%	39.5%	15.5%	16.3%	20.8%
ECFR	1.2%	20.9%	25.9%	2.3%	12.6%
CFWT/MTTF	0.45/2.2	1/1	0.13/7.7	0.9/1.1	0.62/1.6
ECFWT/MTTF	0.06/16.7	0.53/1.9	0.31/3.2	0.13/7.7	0.34/2.9

(E)CFR: (extremely) critical failure rate; (E)CPWF: (extremely) critical failure per wind turbine per year; MTTF: mean time to failure.

Failure Rate

Failure rate represents the likelihood of failures within a unit of time. It indicates the wind turbines' inherent capability to resist failures under the coupling impacts of internal excitation such as strength degradation, and external excitation such as environmental conditions. The failure rate of the 76 wind turbines is 2.57 failures/turbine/year with an MTTF of 3409 h. The failure rates and MTTFs of the components are listed in Table 6.

Table 6. Failure rates and MTTFs of components.

Components	Subcomponents	MTTF/h	Failure Rate/Year
Rotor	Blades	50,563	0.1732
	Hub	126,407	0.0693
	Main Bearing	758,441	0.0116
	Main Shift	758,441	0.0116
Generator	Generator	9979	0.8778
Gearbox	Gearbox	26,153	0.3350
Electrical Facilities	Converter	12,641	0.6930
	Monitoring and SCADA	29,171	0.3003
	Weather Unit	68,949	0.1271
Pitch & Yaw	Pitch System	21,068	0.4158
	Yaw System	94,805	0.0924
Cooling & Hydraulics	Cooling System	10,835	0.8085
	Hydraulic	10,390	0.8431
Auxiliary	Crane	758,441	0.0116
	Climbing Aid	758,441	0.0116
	Brake	252,814	0.0346
	Nacelle	84,271	0.1040

The monthly failure rate of the wind turbines and their decomposition are displayed in Figure 6, which confirms that:

- Approximately 18 months is the inflexion point of the failure rate of wind turbines. The failure rate of the wind turbines changes irregularly before the inflexion point, and then, decreases obviously. Preventive maintenance supports the failure prevention of wind turbines, and carrying out preventive maintenance every six months is suitable according to the failure rate inflexion point of the wind turbines.
- The trends of failure rates of different types of wind turbines are similar. A total of 15 to 20 months of working is the limit for all types of wind turbines and wind farms, which almost always results from Cooling & Hydraulics failures. Hence, quality control for the Cooling & Hydraulics of wind turbines is essential. The quality of wind turbines varies a lot depending on their type; for instance, the failure rate of the wind turbines of type #1 is almost half of that of type #5, which encourages users and investors to pay close attention to their supplier selection.
- The trend of failure rate in terms of wind farms is similar to that concluded for the types of wind turbines. According to Figure 6c, flatland wind farms hold lower failure rates than those installed in mountains and desert areas. More specifically, wind

turbines in the mountains fail more in frequency than those operating in desert areas and, in turn, more than wind turbines that stand in flatland spaces.

- Cooling & Hydraulics failures are the decisive factors that increase the failure rate of wind turbines, especially over 15 to 20 months, considering that failures of wind turbines are dynamic processes that result from coupled components. Hence, dynamic, correlated, and real-time failure rate analyses of components benefit the O&M of wind turbines.

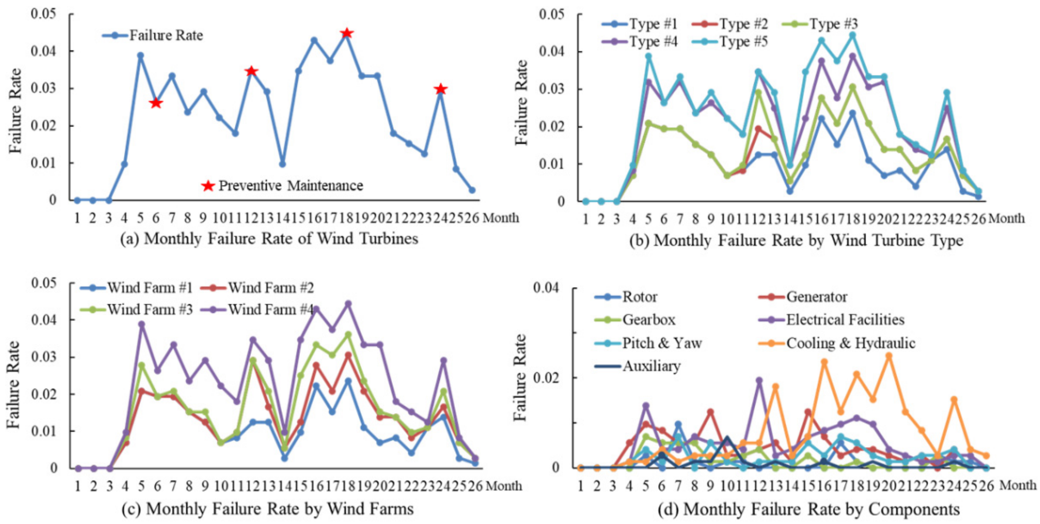

Figure 6. Failure rates: (**a**) of wind turbines as a whole; (**b**) by wind turbine type; (**c**) by wind farm; (**d**) by component.

This analysis found that the Weibull distribution satisfies the lifetimes fitting of some components better than others (see Table 7). The determination of working periods supports the maintenance scheduling and availability and productivity estimation of wind turbines, wind farms, and wind projects according to the bathtub curve concept of complex and repairable systems.

Table 7. Lifetime distribution of components (in the early failure period).

Integrated Components	Lifetime/ Weibull's Distribution	Integrated Components	Lifetime/ Weibull's Distribution
Rotor	SC (1321); SP (0.79)	Pitch & Yaw	SC (2144); SP (0.77)
Generator	SC (1894); SP (0.8)	Cooling & Hydraulics	SC (2793); SP (0.78)
Gearbox	SC (2449); SP (0.81)	Auxiliary	SC (759); SP (0.6)
Electrical Facilities	SC (2829); SP (0.83)	SC: scale parameter; SP: shape parameter	

This analysis determines that the wind turbines and their main components are in an early failure period as the fitted shape parameters of the Weibull distributions for all components are less than one. The evidence is insufficient to find the inflexion point of failure rate between the early failure and stable working periods; however, lifetime distributions of components confirm that the inflexion points of the failure rate of the components and wind turbines are later than 26 months.

4. Maintenance Data

4.1. Maintenance Measures

The maintenance crew includes onsite crew from manufacturers and offsite crew from suppliers. Eight maintenance measures are implemented (see Figure 7), including:

- Repaired: Repairing without replacement and no additional material is needed.
- Replaced: Repairing with replacement.

- Repaired and waiting for replacement: Repaired and waiting for additional materials for further replacement.
- Checked and waiting for replacement (operating): Checked without repair and waiting for additional materials for replacement. The failed wind turbine is operating.
- Checked and waiting for replacement (stopped): Checked without repair and waiting for additional materials for replacement. The failed wind turbine is stopped.
- Waiting for the supplier (operating): Waiting for the maintenance crew of suppliers. The failed wind turbine is operating.
- Waiting for the supplier (stopped): Waiting for the maintenance crew of suppliers. The failed wind turbine is stopped.
- Waiting for further instructions: The failure is unable to be repaired due to: (i) an unknow failure cause; (ii) a lack of maintenance experience; (iii) minor failures with limited impact; (iv) a problem beyond the authority of the maintenance crew; (v) huge and expensive structural failure.

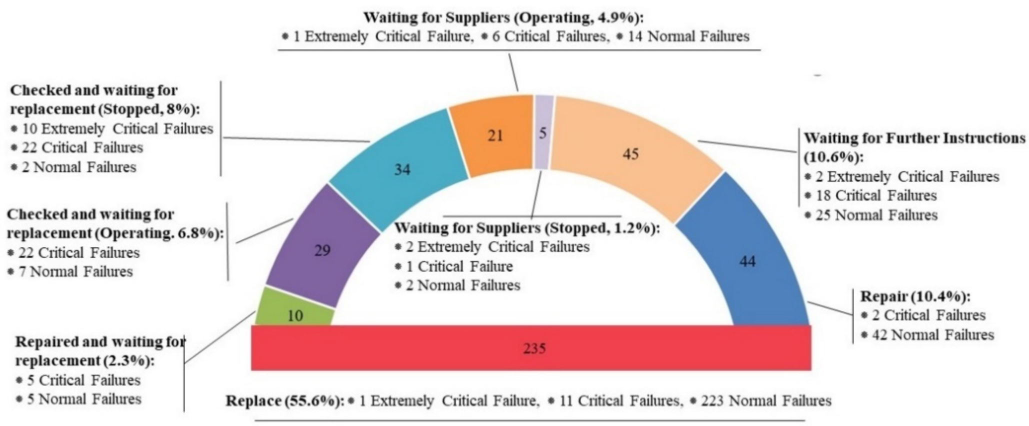

Figure 7. Maintenance measures.

The onsite maintenance crew handled the majority of failures (about 83%), and the offsite maintenance crew fixed only 6.1% of failures. However, failures fixed by the offsite maintenance crew are always difficult to repair and require additional materials that lack backup. Additionally, the remaining 11% of failures called for further negotiation between the onsite and offsite maintenance crews and would give rise to more delays in repairs.

The onsite maintenance crew repaired more normal failures (86%) than (extremely) critical failures, while the offsite maintenance crew mainly coped with complicated failures, more than 38% of which were critical ones. Overall, 66% of failures of the observed wind turbines were fixed so that they were good as new, which can be compared with about 25% of failures that were imperfectly fixed, leading to wind turbines operating with defects, and sometimes under the rated power.

4.2. Spare Parts

The non-optimized spare parts policy, which refers to components as a whole and their elements, delays wind turbine maintenance activity and plays a crucial role in wind farm management. The spare parts policy includes storeroom planning, elements distribution (into storerooms), and logistics. Two types of storerooms are established for wind farms (wind farm storerooms) and manufacturers (manufacturer storerooms).

The observed 423 failures involved more than 400 elements stored in wind farm storerooms (31%) and manufacturer storerooms (26%), and no backup elements made up the remaining proportion (43%). The wind farm storerooms contain fragile, low-value consumables such as lubricating oil and the manufacturer storerooms keep high-value elements. The time-consuming logistics give rise to longer maintenance delays. The elements without backup are always the ones that result in severe consequences and long downtimes; such elements are mostly from suppliers.

Overall, the 74 instances of delayed maintenance are consequences of lacking spare elements, involving almost all the key components of wind turbines (see Table 8), which indicates that feasible spare parts management contributes to the efficient maintenance of wind turbines and economic operations of wind farms. Additionally, the spare parts policy should also consider the health status assessment of components, economy-based storeroom optimization, and logistics.

Table 8. Delayed maintenance to failures.

Subcomponent	Elements	Number of Failures	Subcomponent	Elements	Number of Failures
Generator	Pump Motor	2	Hub	Steel Frame	3
	Screw Nut	1	Pitch System	Lubrication Oil	3
	Cooling Fan Slip Ring	1 6	Convertor	Cooling Fan Circuit Board	1 2
	Encoder Bearing	4 1	Gearbox	Pump Motor Lubrication Oil	4 2
	Water Pump Sensor	1 1	Nacelle	Sunroof Support Guardrail	2 1
Hydraulic	Storage tank Electromagnetic valve Oil Hose Switch Filter	1 1 1 1 1	Cooling System	Sensor Water Tank Pump Motor Cooling Fan Switch	2 1 3 1 4
Nacelle Cooling	Motor Fan	3 2	Control System	Cable Switch	3 1
Weather Unit	Anemometer	5	Yaw System	Brake	1
Climbing Aid	Control elements	1		Oil Hose	1

4.3. Maintenance Times

The time spent in maintenance is the basis of the availability, economy, and productivity estimation of wind turbines and wind farms. According to maintenance records, maintenance procedures for failures can be divided into three types, including Reaction Time (RT), Traveling Time (TT), and Time to Repair (TR) (see Figure 8).

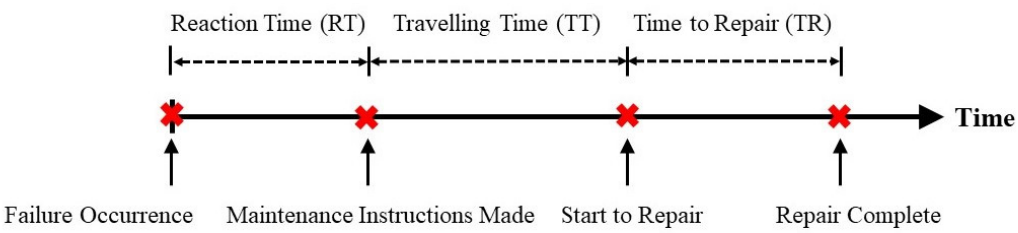

Figure 8. RT, TT, and TR of wind turbines.

4.3.1. Reaction Time

Reaction time is the period between failure and maintenance instructions being given. It includes failure identification based on the alarm of the SCADA and/or CMS systems, spare parts checking, and maintenance instruction determination. The maintenance instructions indicate failed components to the maintenance crew, and very few of them (less than 10%), can extend to element and root-failure-cause levels. As a consequence of incomplete records, 89% of the observed failures (375 RTs) were extracted from the maintenance records (see Figure 9).

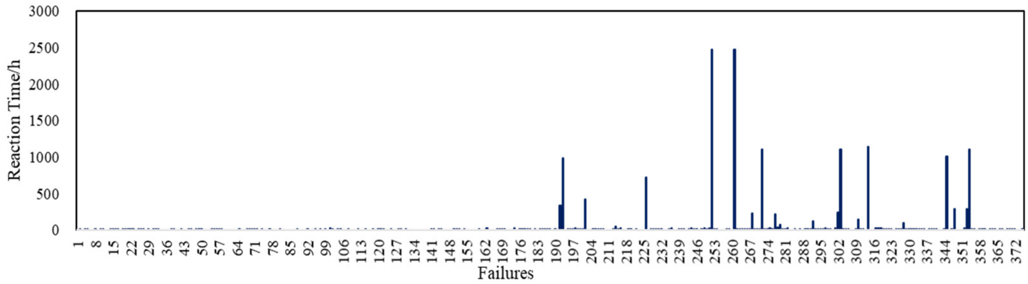

Figure 9. RTs of the maintenance of the 375 failures.

The average RT of the 375 failures is 41 h. However, 147 failures (nearly 40% of the total) with an RT of zero indicate that the maintenance instructions of some frequently occurring or difficult-to-repair failures can be made without any delay. Moreover, the average RT of the remaining 228 failures is 68 h. To be specific, the maintenance instructions of 200 failures (88% of the total) are made within a day, 212 failures (93%) within a week, and 220 failures (96%) within a month.

Eight generator, blade, and converter failures contribute an 86% RT to the total (see Figure 10). Logistics, spare parts, and complexity in maintenance are primary factors of RTs. Specifically, the bearing degradation (calling for replacement) of generators, the protective film peeling off the blades, and control circuit-board damage of the converter result in long RTs as there is no possibility of backing up such components in storerooms, for wind farms or for manufacturers. Moreover, the logistics with unpredictable risks, high costs, and complex maintenance require a longer waiting time for professional personnel, which further delays the RTs.

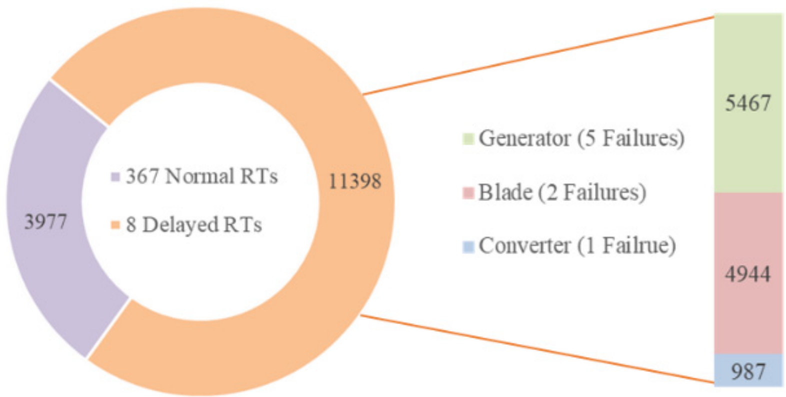

Figure 10. Delayed RTs/hour.

Except for the eight instances of delayed maintenance for failures with long RTs, the remaining 96% of failures had an average RT of 4.3 h. Thus, 4.3 h would be a robust benchmark for decision-making related to wind turbine maintenance. The RTs, except for delayed ones, are sorted by failure criticalities and maintenance measures in Table 9. More detailed information can be obtained by analyzing the data collected. However, further results are not demonstrated as they may not significantly contribute to the maintenance of wind turbines.

Table 9. RTs of maintenance sorted by failure criticality and maintenance measures/hours.

RTs of Maintenance/Hour (Average RT)	Extremely Critical Failures	Critical Failures	Normal Failures	RT Average
Repaired	—	12	6	6.3
Replaced	—	1	4	3.9
Repaired and waiting for replacement	—	1	2	1.5
Checked and waiting for replacement (operating)	—	4	1	3.2
Checked and waiting for replacement (stopped)	—	1	—	1
Waiting for Suppliers (operating)	—	1	1	1
Waiting for Suppliers (stopped)	—	0	25	16.7
Waiting for further instructions	13	1	1	1
RT Average	13	2.2	4	4.3

0: Less than one hour.

4.3.2. Traveling Time

Travelling Time (TT) is the period between maintenance instructions being formed and the maintenance being started. It mainly includes the transportation of personnel and components from storerooms or operation centers to wind farms. Overall, 338 (80%) travelling times were extracted from the maintenance records of the 76 wind turbines.

The average travelling time for the failures is 5.5 h (see Figure 11). Overall, the travelling time of 36% of failures is less than one hour, while 39% are over 12 h. The travelling times follow a bimodal distribution with mean values of 0.46 h and 12.51 h. It is concluded that gearboxes have the longest travelling time (24 h) due to their enormous size, lack of backups, and the necessity for special vehicles. Furthermore, there is no obvious evidence of the reason for the formation of bimodal distribution. However, the figure of 0.46 h is likely the travelling time to failed wind turbines without access to storerooms, and that of 12.51 h may include additional time to access the storerooms. The above conclusions indicate that enhancing the capability of the management of the operation centers, and the establishment of feasible and sufficient scheduling systems for spare parts, would contribute to the improvement of the economic operations of wind turbines.

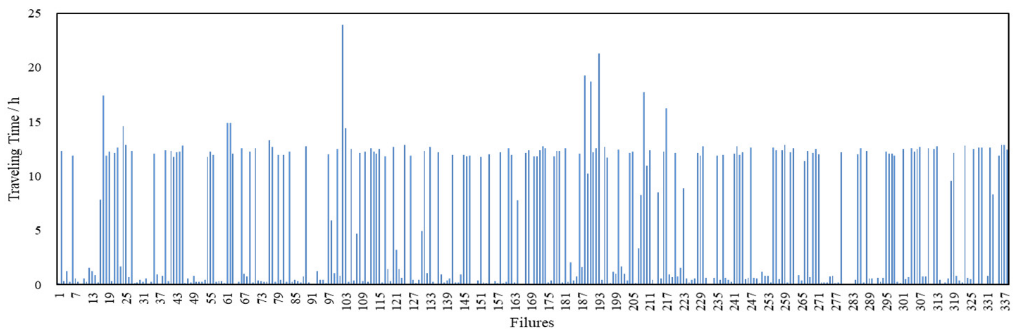

Figure 11. Travelling times of maintenance to the 338 failures.

The types of components and the location of the spare parts are decisive in the travelling times of maintenance, as: (i) the types of components determine the method of shipping, as the shipping of special components such as blades requires dedicated equipment and vehicles; (ii) the location of the spare parts (storerooms) affects the time of movement between storerooms and failed wind turbines. However, no robust evidence shows which factor is more crucial. Table 10 summarizes the travelling times of each component and is sorted by storeroom.

Table 10. Travelling times of maintenance to components, sorted by storeroom/hours.

STS of Components/h (Number of Failures/Average TT)	Spare parts in Wind Farm Storeroom	Spare Parts in Manufacturer Storeroom	TT Average
Rotor	—	9/1.6	1.6
Generator	8/3	14/5.3	4.5
Gearbox	4/3	10/6	5.1
Electrical Facilities	20/3.9	22/7.7	5.9
Pitch & Yaw System	13/6.9	7/8	7.3
Cooling & Hydraulics	55/6.2	25/3.6	5.4
Auxiliary	2/12.5	1/1	8.7
Average	5.6	5.3	5.5

4.3.3. Time to Repair

Time to Repair (TR) is a period between the start of maintenance and its completion, representing the capability and productivity of the maintenance crew. The mean Time to Repair (MTTR) was used as an index to rate the capacity of a system or equipment recovery from failures with the intervention of maintenance personnel. Overall, the MTTRs of 266 failures of wind turbines were extracted, the average of which was 3.6 h, with a maximum of 23 h and a minimum of less than one hour (see Figure 12).

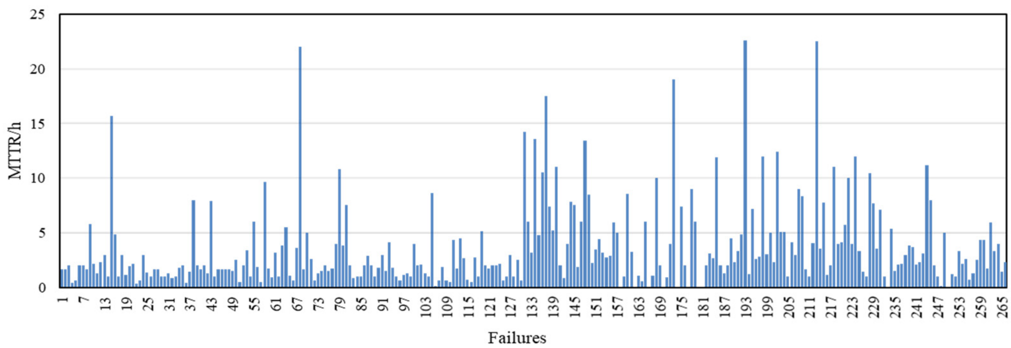

Figure 12. MTTRs of the 266 failures.

Very few failures need long-time maintenance that exceeds 20 h, including converter cable replacement (22.5 h) and monitoring and control system repair (23 h). Lacking experience in maintenance is the root reason for longer maintenance times, which calls for strict training for the maintenance crew on the repair of some infrequent failures, such as cable failures. This can prevent the maintenance crew from staying inside the wind turbines for a long time, which endangers the personnel. Overall, there were 15 failures with MTTRs of less than one hour, including nine easy-to-repair failures fixed via restarting/resetting and six unhandled failures.

The MTTRs of components are sorted by maintenance measure in Appendix A Table A2. Most wind turbine failures can be repaired within 5 h or replaced within 3.4 h, while the remaining 8% of failures cannot be fixed as soon as the maintenance crew arrives and in one visit. The maintenance of Electrical Facilities such as weather units and Monitoring, and SCADA and machinal elements such as Brakes and Nacelles takes longer. However, the frequencies of those failures are low. The maintenance crew's capability for repair the converter, generator, and hydraulics should be enhanced, as these elements fail more frequently and require a relatively longer Time to Repair. To conclude, Appendix A Table A3 shows a summarization of the RTs, TTs, and MTTRs of components that wind farms sort.

5. The Proposed Failure Rate Correction Methodology

This section proposes a developed failure rate correction approach to infer the failure rates of floating offshore wind turbine components according to sufficiently accumulated onshore data. Failure rate correction is a modification procedure of the absolute value of onshore wind turbine failure rates; it infers the failure rate of floating offshore wind turbines so that it can reflect the failure properties of floating offshore wind turbines. The constructed model in this paper is an extended version of that proposed in Ref. [33], and aims to find a transformation factor reflecting differences between the failure properties of onshore and floating offshore wind turbines' components based on evaluations by experts. To remove the limitation of the earlier method only being applicable to the wind turbine's level, this paper constructed a localized methodology to map such differences at all levels of wind turbines, including components and elements. The proposed model in this paper can provide practitioners with a better, deeper, and more detailed understanding of the failure properties of the components and elements of floating offshore wind turbines, as well as their differences from onshore ones.

The developed schedule is demonstrated in Figure 13 and comprises the following steps:

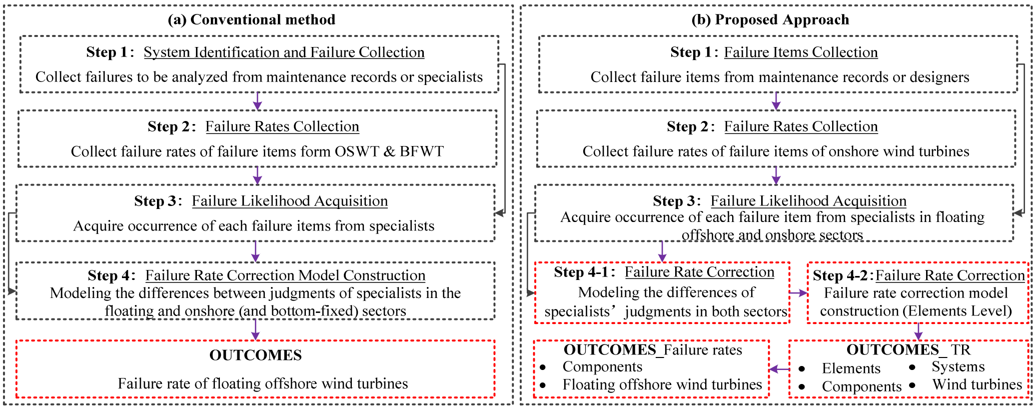

Figure 13. The framework of the proposed failure rate correction approach/conventional method is referenced from [33]. OSWT: onshore wind turbine; BFWT: bottom-fixed wind turbine; TR: transformation factor.

Step 1: Failure item collection. Collect the failure items of floating offshore wind turbines from the maintenance records of onshore wind turbines or the designers of floating offshore wind turbines.

Step 2: Failure rate collection. Collect the failure rates of the failure items of onshore wind turbines.

Step 3: Failure likelihood acquisition. Determine the occurrence of each failure item from specialists in both the floating offshore and onshore sectors, according to the benchmark in Table 11.

Table 11. The rating guidance of occurrence [10,12,33].

Rating	Occurrence		Rating	Occurrence	
	Probability (P)	Description		Probability (P)	Description
1	$P < 10^{-5}$	Extremely low	6	$2 \times 10^{-3} < P < 1 \times 10^{-2}$	Moderate
2	$P = 10^{-5}$	Remote	7	$10^{-2} < P < 4 \times 10^{-2}$	Frequent
3	$P = 10^{-5}$	Very slight	8	$4 \times 10^{-3} < P < 0.2$	High
4	$10^{-5} < P < 4 \times 10^{-4}$	Slight	9	$0.2 < P<0.33$	Very high
5	$4 \times 10^{-4} < P < 2 \times 10^{-3}$	Occasional	10	$P > 0.33$	Extremely high

Step 4: Failure rate correction. Numerically compare the differences between the occurrence values given by onshore and offshore specialists and infer the failure rates of the floating offshore wind turbine components (see Section 3.1).

The proposed failure rate correction approach aims to map the differences in failure rates based on the corresponding differential features of failure occurrences that are easy to obtain, knowing that failure rates and failure occurrences represent the same physical meaning, that is, failure likelihood. First, collect the occurrences of the components and define the occurrence matrix as:

$$\mathbf{O} = \begin{bmatrix} \mathbf{O}^1 & \mathbf{O}^2 & \cdots & \mathbf{O}^{\mathbf{i}} & \cdots & \mathbf{O}^{\mathbf{v}} \end{bmatrix}^{\mathbf{T}} \tag{1}$$

where $\mathbf{O}$ is the occurrence matrix of the whole system and $\mathbf{O}^{\mathbf{i}}$ denotes the occurrence matrix of component i. Accordingly, the occurrence matrix of the floating offshore wind turbine with v components is arranged as:

$$\mathbf{O} = \begin{bmatrix} O_1^1 & O_2^1 & \cdots & O_i^1 & \cdots & O_q^1 \\ O_1^2 & O_2^2 & \cdots & O_i^2 & \cdots & O_q^2 \\ \vdots & \vdots & & \vdots & & \vdots \\ O_1^w & O_2^w & \cdots & O_i^w & \cdots & O_q^w \\ \vdots & \vdots & & \vdots & & \vdots \\ O_1^v & O_2^v & \cdots & O_i^v & \cdots & O_q^v \end{bmatrix} \tag{2}$$

where O_i^w is the occurrence of the failure item i of the component w. Additionally, the maximum number of failure items for each component is q.

Hence, the occurrences of failure items in the component w given by both offshore (**WO**) and onshore (**O**) specialists are arranged as follows:

$$\mathbf{O} = \begin{bmatrix} \frac{1}{v}\sum\limits_{w=1}^{v} O_1^w & \frac{1}{v}\sum\limits_{w=1}^{v} O_2^w & \cdots & \frac{1}{v}\sum\limits_{w=1}^{v} O_i^w & \cdots & \frac{1}{v}\sum\limits_{w=1}^{v} O_q^w \end{bmatrix} = \begin{bmatrix} O_1 & O_2 & \cdots & O_i & \cdots & O_q \end{bmatrix} \tag{3}$$

$$\mathbf{WO} = \begin{bmatrix} \frac{1}{r}\sum\limits_{w=1}^{r} WO_1^w & \frac{1}{r}\sum\limits_{w=1}^{r} WO_2^w & \cdots & \frac{1}{r}\sum\limits_{w=1}^{r} WO_i^w & \cdots & \frac{1}{r}\sum\limits_{w=1}^{r} WO_q^w \end{bmatrix} = \begin{bmatrix} WO_1^w & WO_2^w & \cdots & WO_i^w & \cdots & WO_q^w \end{bmatrix} \tag{4}$$

Select the first m failure items in **O** and **WO** as the benchmark to balance the differences in specialist groups (the floating and onshore sectors) as in [33], for which the comparison matrix of the selected failure items is defined as:

$$\boldsymbol{\xi} = \begin{bmatrix} \frac{WO_1}{O_1} & \frac{WO_2}{O_2} & \cdots & \frac{WO_i}{O_i} & \cdots & \frac{WO_q}{O_q} \end{bmatrix} \tag{5}$$

Subsequently, define a factor α_i for each component as:

$$\alpha_i = \sum_{i=1}^{q} \frac{O_i}{WO_i} \tag{6}$$

where k is the number of failure items (failure mode or cause) of the component w.

The overall factor (α) of the floating offshore wind turbines is computed as follows:

$$\alpha = \frac{1}{v}\sum_{i=1}^{v} \alpha_i \tag{7}$$

With the factor (α_i), define a transformation matrix $\mathbf{O}^{Adjust}$ for the remaining $q - m + 1$ failure items of the component i, as:

$$\mathbf{O}_i^{Adjust} = \alpha_i \times \mathbf{O} = \begin{bmatrix} \alpha_w O_{m+1} & \alpha_w O_{m+2} & \cdots & \alpha_w O_{m+i} & \cdots & \alpha_w O_q \end{bmatrix} \tag{8}$$

Accordingly, the transformation factor (Δ_i) of the component i is computed as follows:

$$\Delta_i = \frac{\sum \mathbf{WO}_i}{\sum \mathbf{O}_i^{Adjust}} \tag{9}$$

Hence, the failure rates of the remaining $q - m + 1$ failure items of the component w are computed as follows:

$$\bar{\boldsymbol{\lambda}}_{q-m+1} = \Delta_i \times \boldsymbol{\lambda}_{q-m+1} \tag{10}$$

where $\bar{\boldsymbol{\lambda}}_{q-m+1}$ is the failure rates of the items, except for those of the support structures, and λ_{m+i} represents the failure rate of the failure item $m + i$ (in **O** and **WO**) in both floating offshore and onshore wind turbines.

Accordingly, the failure rates of floating offshore wind turbines' failure items are:

$$\bar{\boldsymbol{\lambda}} = \begin{bmatrix} \boldsymbol{\lambda}_{\text{FOWT}} & \bar{\boldsymbol{\lambda}}_{q-m+1} \end{bmatrix} \tag{11}$$

where $\bar{\boldsymbol{\lambda}}_{q-m+1}$ is the corrected failure rates of the floating offshore wind turbine, and $\boldsymbol{\lambda}_{\text{FOWT}}$ is the failure rates of the components of the floating offshore wind turbines. The failure rate of the unique components designed for floating offshore wind turbines, such as support structures, can be inferred via field data collection or the failure rate approximation model presented in [33].

Hence, the failure rate of the entire floating offshore wind turbine (λ) is calculated by Equation (12) under the series system assumption.

$$\lambda = \sum \bar{\boldsymbol{\lambda}} = \sum_{i=1}^{m} \lambda_{FOWT}^{i} + \sum_{i=m+1}^{v} \bar{\lambda}_{q-m+i} \tag{12}$$

It is worth mentioning that, unlike the previous globalized model published in [33], this paper proposes a localized failure rate correction approach to infer the failure rates of the components of floating offshore wind turbines. However, it is also applicable to infer the same characteristics of the entire system (see Equations (7) and (12)). Moreover, the parameters at the whole system level can be used to validate the performance of the proposed approach (see Section 6).

6. Results, Comparisons, Validations, and Discussions

6.1. Results

This paper focuses on the failure and maintenance data of onshore and floating offshore wind turbines. The maintenance data of onshore and floating offshore wind turbines are comparable, as: (i) The maintenance actions for components inside the Nacelles of both types of wind turbines are similar, and are less affected by sea conditions due to the protection from Nacelles. However, the accessibility of offshore wind farms is lower. (ii) The maintenance actions for the remaining components mainly refer to support structures, which require specific technologies that are not involved in the maintenance and operation of onshore wind turbines. Accordingly, this paper does not correct the summarized maintenance data, including maintenance measures, spare parts, and especially maintenance times (RT, TT, MTTR), as in most cases, these data can be applied to floating offshore wind turbines directly.

The experts' judgments used in this study are the same as those collected in [33]. Overall, the failure rate correction model is bottom-up and consists of the following procedure, taking the Gearbox as an example:

Frist, collect and arrange the occurrence of the 10 failure causes of the Gearbox from the onshore and floating offshore sectors, as in Equation (3) (onshore) and Equation (4) (offshore):

$$\mathbf{O} = \begin{bmatrix} 3.96 & 3.16 & 2.57 & 1.78 & 3.16 & 3.96 & 3.56 & 3.76 & 3.76 & 3.16 \end{bmatrix} \tag{13}$$

$$\mathbf{WO} = \begin{bmatrix} 5.86 & 5.00 & 4.43 & 4.00 & 5.71 & 5.71 & 5.71 & 4.57 & 6.14 & 4.00 \end{bmatrix} \tag{14}$$

Second, determine the overall factor (α) of floating offshore wind turbines according to Equations (5)–(7), and accordingly, α is equal to 1.26. Adjust the occurrences in **O** as follows:

$$\mathbf{O}^{Adjust} = 1.26 \times \mathbf{O} = \begin{bmatrix} 4.99 & 3.98 & 3.24 & 2.14 & 3.92 & 4.96 & 4.49 & 4.74 & 4.74 & 3.98 \end{bmatrix} \quad (15)$$

Determine the transformation factor of the Gearbox of the floating offshore wind turbine according to Equation (8):

$$\Delta = \frac{\sum \mathbf{O}_i^{WO}}{\sum \mathbf{O}_i^{\text{Adjust}}} = 1.232 \quad (16)$$

Step 3: Transfer the failure rate of the floating offshore wind turbine Gearbox based on that of the same component of onshore wind turbines (0.335 failures/turbine/year) and the transformation factor as follows:

$$\overline{\lambda}_{Offshore} = \Delta \times \lambda_{onshore} = 1.232 \times 0.335 = 0.413 \quad (17)$$

The proposed failure rate correction approach deepens the failure rate correction from the entire wind turbine level to the component level. However, the same can be achieved the subcomponent level by repeating the same analytical procedure, and the results are listed in Table 12. According to the results, the failure rates of the Main Bearing and Yaw System assessed in onshore wind turbines are slightly higher than those of the floating offshore structures. The reason is that Nacelles isolate the impacts of harsh environmental conditions on the components inside them. A more detailed analysis at the subcomponent level is not performed in this paper, as it may not provide a cutting-edge understanding of failures that would occur in different types of wind turbines and their items. The readers, however, can draw further conclusions according to the results listed in Table 12. The results at the component level are listed in Figure 14, which indicates that:

- The proposed method predicts higher failure rates of the components equipped in floating offshore wind turbines than for onshore devices, except for the Cooling & Hydraulics, Auxiliary, and Pitch & Yaw components. The failure rates of the Cooling & Hydraulics and Auxiliary components are not corrected due to insufficient expert judgment.
- The lower predicted failure rate of Pitch & Yaw confirms that the judgment of experts and the proposed approach reflect that: (i) the advances in materials, manufacturing, and operation and management would increase the robustness of components, and thus, reduce their failure rates; and (ii) the harmful sea conditions introduce additional fragility to floating offshore wind turbines and, in turn, increase the failure rates of several components. The final transformation factor of each component is a balance between at least the two aspects mentioned above.
- Failure rates of Electrical Facilities and of electromechanical components such as the Generator are higher than those of mechanical components such as the Rotor and Gearbox. This indicates that the harmful sea conditions introduce additional failures to fragile electrical, electromechanical, and hydraulic elements, and mechanical components are relatively robust in withstanding the environmental effects. The conclusions above suggest weak links to floating offshore wind turbine operation and maintenance.

Table 12. Failure rates and the corresponding transformation factors of subcomponents.

Components	Subcomponents	Transformation Factor		Failure Rates, Onshore	Failure Rates, Corrected
		Amount/Year	Rank		
Rotor	Blades	1.353	5	0.173	0.234
	Hub	1.224	7	0.069	0.085
	Main Bearing	0.909	10	0.012	0.011
	Main Shift	1.371	4	0.012	0.012
Generator	Generator	1.211	8	0.878	1.063
Gearbox	Gearbox	1.232	6	0.335	0.413
Electrical Facilities	Converter	1.531	3	0.693	1.060
	Transformer	1.555	2	0.042 **	0.066
	Monitoring and SCADA	—	—	0.300	0.300 *
	Weather Unit	—	—	0.127	0.127 *
	Electronics & Controller	1.688	1	0.730 **	1.235
Pitch & Yaw	Pitch System	0.906	11	0.416	0.377
	Yaw System	1.166	9	0.092	0.108
Cooling & Hydraulics	Cooling System	—	—	0.809	0.809 *
	Hydraulics	—	—	0.843	0.843 *
Auxiliary	Crane	—	—	0.012	0.012 *
	Climbing Aid	—	—	0.012	0.012 *
	Brake	—	—	0.035	0.035 *
	Nacelle	—	—	0.104	0.104 *

*: Failure rates without correction; **: failure rates computed based on those reported in [10] and [18]; failure rates in failures/year.

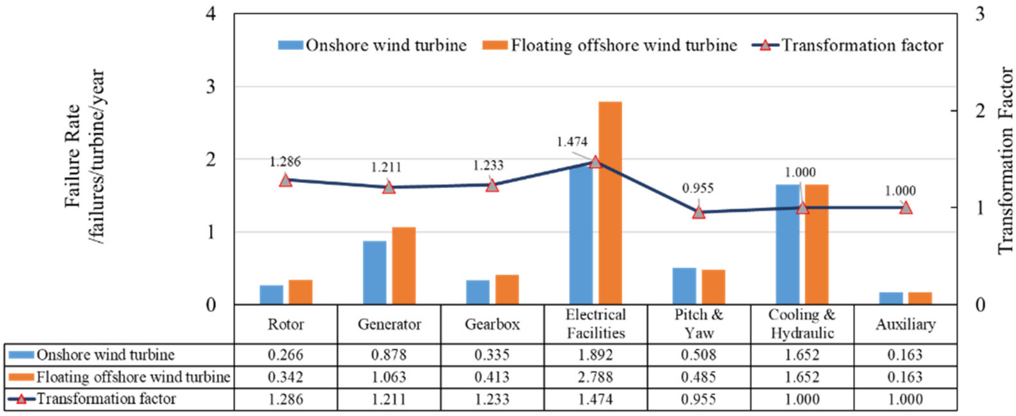

Figure 14. Failure rate transformation of components.

6.2. Comparisons, Validations, and Discussions

Overall, the proposed approach predicts that the failure rate of floating offshore wind turbines is 28.6% higher than that of onshore wind turbines. The predicted result is compared with existing models in Table 13. The failure rates corrected by the proposed approach were transferred to the corresponding components of the Bayesian network model constructed in [18] and [33] (see Figure 15 and Appendix A Table A4). The purpose of this was to access the failure rate and MTTF of floating offshore wind turbines in order to verify the performance of the proposed localized expert-judgement-based failure rate correction model (see Tables 13 and 14). This analysis reveals that a floating offshore wind turbine suffers 8.37 failures per year with an MTTF of 1046 h. The comparative results in Tables 13 and 14 confirm that:

- From a holistic point of view, failure rate correction/prediction models agree that the failure rate of floating offshore wind turbines is higher than that of onshore devices. RIF-based models predict that the failure rate disparity with onshore wind turbines is less than 30%; this can be compared with the result of the stress factor-based model, which computed 75% differences between the two types of wind turbines.

The evidence is insufficient to select the model that can best provide convincing and precise results. However, it should be mentioned that the model selection should follow the features of the methods. Specifically, stress factor-based methods correct failure rates via global factors related to environmental and power utilization aspects. However, the RIF-based method produces a cluster map of the disparity of wind turbines according to the failure features of detailed failure cases of components.

- RIF and subjective data-based failure rate correction models, including the localized model presented in this paper and the globalized model published in [33], and the stress factor-based model [31] predict higher failure rates of floating offshore wind turbines than the others. Considering that the larger and more complex structures assembled, and further and deeper wind farms, resulted in insufficient maintenance and accessibility, floating equipment tended to fail more frequently than other types. Accordingly, the aforementioned method, including the proposed approach, corrected the failure rate in the right way.
- The relative error of the predicted failure rate from a holistic wind turbine point of view is less than 1% compared with the RIF- and risk-based models [33] (more than 1%) and the stress factor-based model (more than 2%). According to the results in Table 14, the relative error of the proposed method is not the lowest. However, it is worth adding that the primary contribution of the presented approach is that the approach extends the globalized RIF-and-subjective data-based models so that the failure rate correction can extend to component and element levels; this is the foundation of failure, risk, reliability, availability, and operation and maintenance investigations of floating offshore wind turbines with insufficient data.

Table 13. Comparison of failure rates of elements assessed using failure correction models.

Models	Failure Rate Disparity with Onshore Devices		
	Amount *	Higher/Lower	Model Features
[33]	26%	Higher	RIF- and subjective data-based models—Globalized
[36]	75%	Higher	Stress factor-based model
[37]	3.3%	Higher	RIF- and risk-based models
[38]	19%	Higher	RIF- and uncertainty-based models
[39]	18% **	Higher	RIF interval-based model
[Present]	28.6%	Higher	RIF- and subjective data-based model—Localized

*: The average of all elements; **: compared with the mean value.

Table 14. Assessed failure features of the floating offshore wind turbine.

Failure Rate Correction Models	Failure Rate/ Failure/Turbine/Year		MTTF/Hour		Relative Error / in %
	Onshore	Offshore *	Onshore	Offshore *	
[Present]	8.3	8.37	1055	1046	−0.85
[33]		8.34		1050	−0.47
[36]		8.49		1031	−2.27
[37]		8.21		1066	1.04
[38]		8.25		1061	0.57
[39]		8.24		1063	0.76

* offshore wind.

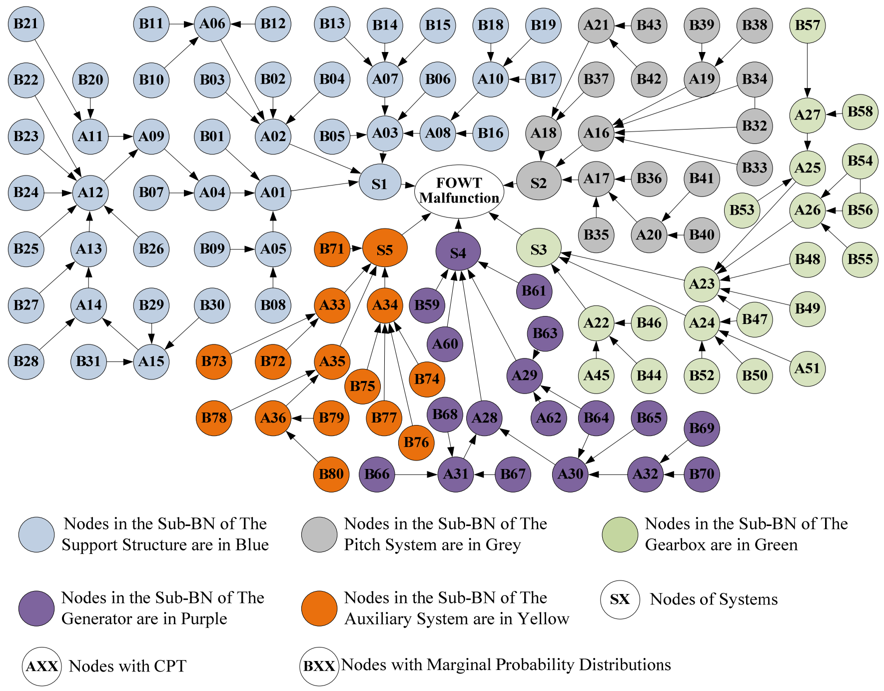

Figure 15. The BN model of the floating offshore wind turbine [18,33] (see Appendix A).

7. Conclusions

This paper provides detailed failure and maintenance data analysis for wind turbine safety, risk, reliability, availability, and maintainability investigations. Overall, wind turbine failure features, including the critical failure, failure frequencies, failure rates, and lifetime distributions of primary components, are specified. Maintenance properties such as maintenance measures, spare policies, and three reference times related to maintenance are also provided.

A reliability influence factor-based (RIF-based) data transformation approach is presented with the assistance of subjective specialists' judgment to transfer the onshore data to the floating offshore wind turbines; these are a new concept, and very few been installed. The proposed approach can infer the failure rates of the components of floating offshore wind turbines at the element level to provide more comprehensive and detailed information to practitioners in the field. Overall, this paper provides a new dataset for the wind energy sector with up-to-date data, and a comprehensive analysis tool to transfer the failure data to the floating offshore wind sector. The outcomes of this paper contribute to the design and operation of wind turbines and the management of wind farms and will strengthen the database of the wind energy sector.

Author Contributions: Conceptualization, H.L. and C.G.S.; methodology, H.L., C.-G.H. and W.P.; writing—original draft preparation, H.L. and C.G.S.; writing—review and editing, C.G.S.; supervision, C.G.S.; project administration, C.G.S.; All authors have read and agreed to the published version of the manuscript.

Funding: The first author was funded by the project ARCWIND–Adaptation and implementation of floating wind energy conversion technology for the Atlantic region—which is co-financed by the European Regional Development Fund through the Interreg Atlantic Area Programme under contract EAPA 344/2016. This work contributes to the Strategic Research Plan of the Centre for Marine Technology and Ocean Engineering (CENTEC), which is financed by the Portuguese Foundation for Science and Technology (Fundação para a Ciência e Tecnologia—FCT) under contract UIDB/UIDP/00134/2020.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Failure modes of main components.

Components	Subcomponents	Failure Descriptions
Rotor	Hub Main bearing Blade	Hub broken Bearing overheating; bearing seat failure Cracked; comes off; delamination; wear with Hub; replaced for a new standard
Generator	Generator	Carbon brush failure *; slip ring failure *; cooling water pump failure *; generator elastic support failure; lubrication pump motor failure; cooling water tank failure; cooling fan failure; generator encoder failure; bearing failure; insufficient bearing grease; cable failure; generator converter short circuit.
Gearbox	Components Lubrication	Temperature control valve failure; abnormal gear wear; gearbox respirator Fe content exceeded; leak; lubrication pump filter failure *; lubrication pump motor failure *; seal damage; cooling water pump failure
Electrical Facilities	Converter SCADA Control System Weather Units & Sensors	Cooling failure; cable failure; contactor damage; fuse is blown; breaker failure; power failure *; circuit failure *; reactor damaged *; crowbar board failure *; current transformer failure *; communication module failure SCADA reports unknown data Yaw fuse failure; yaw contactor failure *; communication module; fiber damage *; yaw starter failure; unknown failure *; cooling fan; cable failure; shutdown The wrong temperature reported *; pressure sensor damage; brake sensor failure; anemometer damage *; anemometer failure
Pitch & Yaw	Gearbox & Motor Electric & Controller Yaw	Wrong pitch angle *; Fe exceeding standard; leak, encoder damage *, malfunction Fuse blown *; motor damage *; cable failure; power failure; blockage; pump damaged; pitch reducer leak, capacitor damage *; contactor damage; power overload *; cable failure; fuse blown; limit switch triggered by mistake *; slip rings * Leak; structural damage; yaw reducer broken tooth
Cooling & Hydraulics	Internal Cooling External Colling Hydraulic Units	Water cooling pump failure *; lubrication pump motor failure *; cooling water tank failure; seal damage *; water cooling switch *; water pump seal failure; air cooler failure; lubrication pump filter failure Motor failure *; blade failure *; cover failure; fan failure Storage tank damage; storage tank leak gas and oil*; improper maintenance; electromagnetic valve damage *; storage tank low pressure (unknown reasons); periodical replacement of filter (half a year) **; hydraulic tubing leaks; brake pressure switch failure; hydraulic motor failure; filter failure
Auxiliary	Auxiliary Components	Lightning protection belt broken; water leak; sunroof support rod damage; guardrail damage; shroud broken; beam crack; brake wear; climbing aid control element failure

*: Failures resulted in wind turbine shutdown; **: replacement without failure.

Table A2. The MTTRs of components by maintenance measures/hour.

Components	Subcomponents	RP	RPA	RWR	CWRO	CWRS	WSO	WSS	WFI	MTTR Average
Rotor	Blade	—	8/4.5	—	—	—	3/0	—	—	3.3
	Hub	—	—	—	1/2	—	—	—	—	2
	Main Bearing	—	2/0.6	—	—	—	—	—	—	0.6
Generator	Generator	6/2.3	28/3.3	1/10	—	1/6	—	1/11	—	3.6
Gearbox	Gearbox	—	12/2.7	—	—	—	—	—	—	2.7
Electrical Facilities	Converter	8/5	41/3.4	1/1	—	—	—	—	—	3.6
	Monitoring and SCADA	7/6.8	9/3.2	—	—	—	—	—	1/1	4.4
	Weather Unit	2/7.8	2/7	—	—	—	—	—	—	7.3
Pitch & Yaw	Pitch System	6/3.8	18/3.3	—	—	—	—	—	—	3.4
	Yaw System	—	4/4.2	1/0	1/0	—	—	—	—	2.8
Cooling & Hydraulics	Cooling System	1/1	35/4	3/5.2	1/2	1/4	—	—	—	3.8
	Hydraulics	3/3.9	53/3.2	1/0	—	—	—	—	—	3.2
Auxiliary	Brake	1/19	2/1	—	—	—	—	—	—	7
	Sensor	—	1/2	—	—	—	—	—	—	2
	Nacelle	—	—	—	—	—	—	1/7	—	7
MTTR Average		5	3.4	3.8	1.3	5	0	9	1	3.6

RP: repaired; RPA: replaced; RWR: repaired and waiting for replacement; CWRO: checked and waiting for replacement (operating); CWRS: checked and waiting for replacement (Stopped); WSO: waiting for suppliers (operating); WSS: waiting for suppliers (stopped); WFI: waiting for further instructions; 0: less than one hour; A/B: number of instances of maintenance/MTTR (in hour).

Table A3. RT, TT, and MTTR of components by wind farm/hour.

Components	Subcomponents	Wind Farm #1			Wind Farm #2			Wind Farm #3			Wind Farm #4		
		RT	**TT**	**MTTR**	**RT**	**TT**	**MTTR**	**RT**	**TT**	**MTTR**	**RT**	**TT**	**MTTR**
Rotor	Blade	—	—	—	1236	—	0	—	—	—	0	2	4.5
	Hub	0	—	2	—	—	—	—	—	—	1	0	—
	Main Bearing	0	7	0.6	—	—	—	—	—	—	—	—	—
Generator	Generator	0	3	2.4	5	10	4.3	8	0	9.8	280	6	4.4
Gearbox	Gearbox	1	5	2.3	0	—	—	3	12	4.7	1	—	2.6
Electrical Facilities	Converter	1	6	2	—	—	—	467	0	9.8	6	5	4.7
	Monitoring and SCADA	1	8	1	12	—	6	4	9	4.2	3	10	7
	Sensor	—	—	—	—	—	—	—	—	—	0	13	2
	Weather Unit	—	—	—	13	—	9	0	4	5	3	0	7.8
Pitch & Yaw	Pitch System	2	9	3.6	—	—	—	—	—	—	7	7	3.2
	Yaw System	0	0	4.2	0	—	0	0	—	—	—	—	—
Cooling & Hydraulic	Cooling System	2	2	2.4	2	5	9	69	6.5	6.8	70	5	4.5
	Hydraulic	0	5	2.6	8	6	1.7	63	7	5.9	1	5	4.2
Auxiliary	Brake	—	—	—	14	12	9.5	—	—	—	—	13	2
	Nacelle	0	1	—	3	—	7	—	—	—	0	7	—
	Climbing Aid	—	—	—	1	—	—	—		—	—	—	—
	Crane	—	—	—	—	—	—	—	—	—	0	0	—
Average		1	5	2.5	4	7	3.4	50	6	6.2	67	5	4.4

0: Less than one hour.

Table A4. Node definition of the BN model.

Code	Failures	Code	Failures
	S1—Support Structure		
A01	Mooring subsystem failure	B09	Insufficient emergency measurement
A02	Tower failure	B10	Strong waves
A03	Floating foundation failure	B11	Lightning Strike
A04	Device failure	B12	Storm
A05	Extreme sea conditions	B13	Typhoon
A06	Collapse due to environment	B14	Plane crash
A07	Hit by dropped objects	B15	Biological collision
A08	Watertightness fault	B16	Inefficient detection
A09	Other devise failures	B17	Pipe joint corrosion
A10	Pipe joint failure	B18	Pipe joint weld defect
A11	Fairlead failure	B19	Pipe joint fatigue
A12	Mooring lines broken	B20	Fairlead corrosion
A13	Mooring line breakage	B21	Fairlead fatigue
A14	Mooring line wear	B22	Transitional chain wear
A15	Accumulating wear	B23	Friction chain wear
B01	Human Error	B24	Mooring winch failure
B02	Resonance	B25	Buoy friction chain wear
B03	Faulty welding	B26	Anchor pickup device damage
B04	Material fatigue	B27	Abnormal stress
B05	Pillar damage	B28	Invalid maintenance
B06	Capsizing	B29	Mooring line wear
B07	Anchor failure	B30	Mooring line fatigue
B08	Poor operation environment	B31	Mooring line corrosion
	S2—Pitch System		
A16	Hydraulic system failure	B35	Lighting protection failure
A17	Alarm facility failure	B36	Limit switch failure
A18	Wrong pitch angle	B37	Abnormal vibration
A19	Hydraulic oil failure	B38	Oil leakage
A20	Power failure	B39	Filter failure
A21	Meteorological unit failure	B40	Power 1 failure (the main power)
B32	Hydraulic motor failure	B41	Power 2 failure (the backup power)
B33	Overpressure	B42	Vane damage
B34	Accumulator failure	B43	Anemometer damage

Table A4. *Cont.*

Code	Failures	Code	Failures
	S3—Gearbox		
A22	Lubrication failure	B49	Pitting (gear)
A23	Abnormal gear	B50	Corrosion of pins
A24	Bearing fault	B51	Abrasive wear
A25	Tooth wear (gears)	B52	Pitting (gear bearing)
A26	Cracks in gears	B53	Gear tooth deterioration
A27	The offset of tooth gears	B54	Excessive pressure
B44	Abnormal filter	B55	Excess temperature
B45	Poor-quality lubrication oil	B56	Fatigue (gear)
B46	Dirty lubrication oil	B57	Poor design of tooth gears
B47	Abnormal vibration (GB)	B58	Tooth surface defects
B48	Glued		
	S4—Generator		
A28	Rotor and stator failure	B63	Structural deficiency
A29	Bearing failure	B64	Abnormal vibration (GE)
A30	Abnormal signals	B65	Abnormal instrument reading
A31	No centricity generation	B66	Failure to synchronize
A32	Overheating	B67	Broken bars
B59	Measurement facility failure	B68	Failure to start on demand
B60	Wire fault	B69	Sensor failure
B61	Leak	B70	Temperature above limitation
B62	Asymmetry		
	S5—Auxiliary System		
A33	Speed train failure	B74	Controller failure
A34	Electric component failure	B75	Transformer failure
A35	Blade failure	B76	Sensor failure
A36	Rotor failure	B77	Converter failure
B71	Yaw subsystem failure	B78	Blade structure failure
B72	Drive train failure	B79	Hub failure
B73	Brake failure	B80	Bearing failure

References

1. Sadorsky, P. Wind energy for sustainable development: Driving factors and future outlook. *J. Clean. Prod.* **2021**, *289*, 125779. [CrossRef]
2. Willis, D.J.; Niezrecki, C.; Kuchma, D.; Hines, E.; Arwade, S.R.; Barthelmie, R.J.; DiPaola, M.; Drane, P.J.; Hansen, C.J.; Inalpolat, M.; et al. Wind energy research: State-of-the-art and future research directions. *Renew. Energy* **2018**, *125*, 133–154. [CrossRef]
3. Díaz, H.; Guedes Soares, C. Review of the current status, technology and future trends of offshore wind farms. *Ocean Eng.* **2020**, *209*, 107381. [CrossRef]
4. Díaz, H.; Serna, J.; Nieto, J.; Guedes Soares, C. Market needs, opportunities and barriers for the floating wind industry. *J. Mar. Sci. Eng.* **2022**, *10*, 934. [CrossRef]
5. Johnston, B.; Foley, A.; Doran, J.; Littler, T. Levelised cost of energy, A challenge for offshore wind. *Renew. Energy* **2020**, *160*, 876–885. [CrossRef]
6. Hussain, W.; Khan, S.; Mover, A.H. Development of quality, environment, health, and safety (QEHS) management system and its integration in operation and maintenance (O&M) of onshore wind energy industries. *Renew. Energy* **2022**, *196*, 220–233.
7. Li, H.; Huang, C.G. Guedes Soares, C. A real-time inspection and opportunistic maintenance strategies for floating offshore wind turbines. *Ocean Eng.* **2022**, *256*, 111433. [CrossRef]
8. Castro-Santos, L.; Bento, A.R.; Silva, D.; Salvação, N.; Guedes Soares, C. Economic feasibility of floating offshore wind farms in the north of Spain. *J. Mar. Sci. Eng.* **2020**, *8*, 58. [CrossRef]
9. Scheu, M.N.; Tremps, L.; Smolka, U.; Kolios, A.; Brennan, F. A systematic Failure Mode Effects and Criticality Analysis for offshore wind turbine systems towards integrated condition based maintenance strategies. *Ocean Eng.* **2019**, *176*, 118–133. [CrossRef]
10. Li, H.; Díaz, H.; Guedes Soares, C. A failure analysis of floating offshore wind turbines using AHP-FMEA methodology. *Ocean Eng.* **2021**, *234*, 109261. [CrossRef]
11. Castro-Santos, L.; Silva, D.; Bento, A.R.; Salvacao, N.; Guedes Soares, C. Economic feasibility of floating offshore wind farms in Portugal. *Ocean Eng.* **2020**, *207*, 107393. [CrossRef]
12. Li, H.; Diaz, H.; Guedes Soares, C. A developed failure mode and effect analysis for floating offshore wind turbine support structures. *Renew. Energy* **2021**, *164*, 133–145. [CrossRef]
13. Li, H.; Teixeira, A.P.; Guedes Soares, C. A two-stage Failure Mode and Effect Analysis of offshore wind turbines. *Renew. Energy* **2020**, *162*, 1438–1461. [CrossRef]

14. Bento, N.; Fontes, M. Emergence of floating offshore wind energy: Technology and industry. *Renew. Sustain. Energy Rev.* **2019**, *99*, 66–82. [CrossRef]
15. Li, H.; Teixeira, A.P.; Guedes Soares, C. An Improved Failure Mode and Effect Analysis of Floating Offshore Wind Turbines. *J. Mar. Sci. Eng.* **2022**, *10*, 1616. [CrossRef]
16. Sinha, Y.; Steel, J.A. A progressive study into offshore wind farm maintenance optimisation using risk based failure analysis. *Renew. Sustain. Energy Rev.* **2015**, *42*, 735–742. [CrossRef]
17. Martinez, A.; Iglesias, G. Mapping of the levelised cost of energy for floating offshore wind in the European Atlantic. *Renew. Sustain. Energy Rev.* **2022**, *154*, 111889. [CrossRef]
18. Li, H.; Guedes Soares, C.; Huang, H.Z. Reliability analysis of a floating offshore wind turbine using Bayesian Networks. *Ocean Eng.* **2020**, *217*, 107827. [CrossRef]
19. Dao, C.; Kazemtabrizi, B.; Crabtree, C. Wind turbine reliability data review and impacts on levelised cost of energy. *Wind Energy* **2019**, *22*, 1848–1871. [CrossRef]
20. Santos, F.P.; Teixeira, A.P.; Guedes Soares, C. Review of wind turbine accident and failure data. In *Renewable Energies Offshore*; Guedes Soares, C., Ed.; Taylor & Francis Group: London, UK, 2015; pp. 953–959.
21. Carroll, J.; McDonald, A.; Dinwoodie, I.; McMillan, D.; Revie, M.; Lazakis, I. Availability, operation and maintenance costs of offshore wind turbines with different drive train configurations. *Wind Energy* **2017**, *20*, 361–378. [CrossRef]
22. Tavner, P.J.; Xiang, J.; Spinato, F. Reliability analysis for wind turbines. *Wind Energy* **2007**, *10*, 1–18. [CrossRef]
23. Ribrant, J.; Bertling, L. Survey of failures in wind power systems with focus on Swedish wind power plants during 1997–2005. In Proceedings of the 2007 IEEE Power Engineering Society General Meeting, Tampa, FL, USA, 24–28 June 2007; pp. 1–8. [CrossRef]
24. Faulstich, S.; Hahn, B.; Tavner, P.J. Wind turbine downtime and its importance for offshore deployment. *Wind Energy* **2011**, *14*, 327–337. [CrossRef]
25. Stenberg, A.; Holttinen, H. Analysing failure statistics of wind turbines in Finland. In Proceedings of the 2010 European Wind Energy Conference and Exhibition, Warsaw, Poland, 20–23 April 2010; pp. 3985–3995.
26. Crabtree, C.J.; Zappalá, D.; Hogg, S.I. Wind energy: UK experiences and offshore operational challenges. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2015**, *229*, 727–746. [CrossRef]
27. Carroll, J.; McDonald, A.; McMillan, D. Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines. *Wind Energy* **2016**, *19*, 1107–1119.
28. Spinato, F.; Tavner, P.J.; Van Bussel, G.J.; Koutoulakos, E. Reliability of wind turbine subassemblies. *IET Renew. Power Gener.* **2009**, *3*, 387–401. [CrossRef]
29. Adedipe, T.; Shafiee, M.; Zio, E. Bayesian network modelling for the wind energy industry: An overview. *Reliab. Eng. Syst. Saf.* **2020**, *202*, 107053. [CrossRef]
30. Yeter, B.; Garbatov, Y.; Guedes Soares, C. Risk-based maintenance planning of offshore wind turbine farms. *Reliab. Eng. Syst. Saf.* **2020**, *202*, 107062. [CrossRef]
31. Yeter, B.; Garbatov, Y.; Guedes Soares, C. Life-extension classification of offshore wind assets using unsupervised machine learning. *Reliab. Eng. Syst. Saf.* **2022**, *219*, 108229. [CrossRef]
32. Eryilmaz, S. Reliability analysis of multi-state system with three-state components and its application to wind energy. *Reliab. Eng. Syst. Saf.* **2018**, *172*, 58–63. [CrossRef]
33. Li, H.; Guedes Soares, C. Assessment of failure rates and reliability of floating offshore wind turbines. *Reliab. Eng. Syst. Saf.* **2022**, *228*, 108777. [CrossRef]
34. Zhang, X.; Sun, L.; Sun, H.; Guo, Q.; Bai, X. Floating offshore wind turbine reliability analysis based on system grading and dynamic FTA. *J. Wind Eng. Ind. Aerodyn.* **2016**, *154*, 21–33. [CrossRef]
35. Kang, J.; Guedes Soares, C. An opportunistic maintenance policy for offshore wind farms. *Ocean Eng.* **2020**, *216*, 108075. [CrossRef]
36. Santos, F.P.; Teixeira, A.P.; Guedes Soares, C. An age-based preventive maintenance for offshore wind turbines. In *Safety and Reliability: Methodology and Applications*; Nowakowski, T., Mlynczak, M., Jodejko-Pietruczuk, A., Werbinska-Wojciechowska, S., Eds.; CRC Press: Boca Raton, FL, USA, 2014; pp. 1183–1192.
37. Rahimi, M.; Rausand, M. Prediction of failure rates for new subsea systems: A practical approach and an illustrative example. *Proc. Inst. Mech. Eng. Part O J. Risk Reliab.* **2013**, *227*, 629–640. [CrossRef]
38. Bhardwaj, U.; Teixeira, A.P.; Guedes Soares, C. Bayesian framework for reliability prediction of subsea processing systems accounting for influencing factors uncertainty. *Reliab. Eng. Syst. Saf.* **2022**, *218*, 108143. [CrossRef]
39. Brissaud, F.; Charpentier, D.; Fouladirad, M.; Barros, A.; Bérenguer, C. Failure rate evaluation with influencing factors. *J. Loss Prev. Process Ind.* **2010**, *23*, 187–193. [CrossRef]
40. Wilkinson, M.; Harman, K.; Hendriks, B.; Spinato, F.; van Delft, T. Measuring wind turbine reliability-results of the Reliawind project. In Proceedings of the 2011 EWEA Conference, Brussels, Belgium, 14–17, March 2011; pp. 1–8.
41. Santos, F.; Teixeira, A.P.; Guedes Soares, C. Modelling and simulation of the operation and maintenance of offshore wind turbines. *Proc. Inst. Mech. Eng. Part O J. Risk Reliab.* **2015**, *229*, 385–393. [CrossRef]
42. Kang, J.; Sun, L.; Guedes Soares, C. Fault Tree Analysis of floating offshore wind turbines. *Renew. Energy* **2019**, *133*, 1455–1467. [CrossRef]
43. Bhardwaj, U.; Teixeira, A.P.; Guedes Soares, C. Reliability prediction of an offshore wind turbine gearbox. *Renew. Energy* **2019**, *141*, 693–706. [CrossRef]