# Failure Rate and Repair Time Analysis of Offshore Wind Turbines

**Conference Paper** · September 2023

DOI: 10.1115/OMAE2023-101753



Luis Felipe Guarda Bräuning
University of São Paulo


Marcelo Ramos Martins
University of São Paulo

**Proceedings of the ASME 2023 42nd International Conference on Ocean, Offshore and Arctic Engineering**
**OMAE2023**
**June 11-16, 2023, Melbourne, Australia**



**OMAE2023-101753**

# FAILURE RATE AND REPAIR TIME ANALYSIS OF OFFSHORE WIND TURBINES

**Luis Felipe Guarda**
Analysis, Evaluation and Risk Management Laboratory – LabRisco, University of Sao Paulo, Brazil

**Leonardo Terra**
Analysis, Evaluation and Risk Management Laboratory – LabRisco, University of Sao Paulo, Brazil

**Marcelo Ramos Martins**
Analysis, Evaluation and Risk Management Laboratory – LabRisco, University of Sao Paulo, Brazil

## ABSTRACT

*Offshore wind turbines have several advantages over onshore turbines, such as greater efficiency and the ability to generate greater amounts of energy in a more constant manner. Despite this, the Levelized Cost of Energy of onshore wind turbines is still lower than for offshore wind turbines, and the main reason for this difference comes from the operating and maintenance costs. For this reason, optimize the operating and maintenance costs of offshore wind turbines represents one of the biggest opportunities to improve the offshore wind industry. However, the lack of failure rates and repair times for the new and bigger offshore turbines prevents the feasibility to develop new reliability analysis that could improve the offshore wind turbines costs. To tackle this problem, this work presents a comparison between the 7MW Levenmouth Demonstration Turbine and a theoretical wind turbine obtained from a literature review, contrasting in this way a data-based analysis against the information available in the literature. The obtained results show the feasibility of data-based analysis and Monte Carlo Simulation comparison to failure rates validation and transfer knowledge from the onshore to offshore wind turbine industry.*

Keywords: Offshore Wind Turbine, Reliability, Failure Rate, Repair Rate

## 1. INTRODUCTION

Offshore wind turbines (OWT) are more efficient, have a lower visual impact and less noise pollution than onshore wind turbines, as they are capable to generating higher and more constants amounts of energy than onshore wind turbines due to the higher speed of winds, greater consistency and lack of physical interference that the land or human-made objects can present [1]. Despite of this, the levelized cost of energy (LCOE) [2] for onshore wind turbines is still lower than for OWTs. The main reason for this difference is the higher operating and maintenance (O&M) costs of OWTs, which represents 23% of its LCOE, while it is 5% for onshore wind turbines [1].

In order to be able to analyze and improve the O&M costs of OWTs various information about the turbines and their components are required, such as failure rates and repair times.

Furthermore, as the offshore wind power industry only began to take more prominence in the last years, there is still a lack of failure rates and repair times for the new and bigger offshore wind turbines and their components, besides the absence of a common functional model assemble, in terms of which components are considered for each turbine (e.g., gearbox, yaw, blades, pitch) to analyze and compare the reliability, availability and maintenance of OWTs [3].

In [4], authors use fault tree analysis to evaluate the failure rate of a generic OWT considering eight major subsystems, however, partial failure information is collected from onshore wind turbines due to the lack of sufficient data. In [5], Carrol et al. considered ~350 OWT throughout Europe to provide failure rates and repair times for the overall wind turbine and its sub-assemblies, but it considers data from different types of OWT, different configurations and with a nominal power between 2 and 4 MW, which can be considered as small OWT nowadays.

To tackle the above-mentioned drawbacks and in order to analyze bigger OWT, this paper uses the 7MW Levenmouth Demonstration Turbine (LDT) database; the world's most advanced OWT dedicated to research, to obtain the failure rates and repair times of its components, to then compare it with the rates obtained from a bibliographic review of OWT. Since there is also an absence of a common functional model assemble, from the bibliographic review a model assembly of an OWT was defined. Failure rates and repair times of each common component from both LDT and the model assemble were compared. Finally, using a Monte Carlo Simulation (MCS) the technical and operational availability of the model assemble turbine were calculated and then compared with the values obtained from the LDT database, using the definitions from International Standard IEC 64400-26-1 for availability for wind energy generation systems [6].

## 2. MATERIALS AND METHODS

### 2.1 Levenmouth Demonstration Turbine Database

The Levenmouth Demonstration Turbine (LDT), is a 7MW Samsung turbine built at an experimental offshore wind turbine demonstration site at Fife Energy Park, Scotland. The turbine has a tower of 110 meters and has three blades, each 85 meters long and is owned by the Offshore Renewable Energy (ORE) Catapult.

The database contains four datasets that correspond to the operational data of the 7MW LDT. The description of each dataset is as follows:

**1. LDT Alarm Log:** It consists of recording all the alarms that occurred during the operation of the LDT turbine. Each event in the log is an alarm that shows why the turbine was turned off and each log has a start and end time, in addition to a categorization of the reason for the alarm. The dataset has 14 variables and 34396 records, resulting in a dataset with 34396 lines and 14 rows. Data monitored from 20-02-2017 to 02-02-2020. The complete record of the LDT Alarm Log is contained in a single file that contains all the information.

**2. LDT Turbine SCADA-1sec:** Control Supervision and Data Acquisition (SCADA) data from the turbine consisting of 574 variables, including electrical, temperature and pressure readings and other physical variables from the different components and subsystems of the turbine. The sampling rate for all variables is 1 Hz. Data monitored from 2017-01-19 to 2020-01-31.

**3. LDT Met Mast SCADA-1sec:** Data from the meteorological measurement tower (Met Mast) from the LDT turbine site consisting of 11 sensors, including wind speed and direction at various heights. The sampling rate for all variables is 1 Hz. Data monitored from 2017-01-21 to 2020-01-31.

**4. LDT Substation SCADA-1sec**: Registration of electrical substation information from the LDT turbine site. It consists of 17 sensors, including power factor, reactive power, voltage and current. The sampling rate for all variables is 1 Hz. Data monitored between 2017-07-06 to 2020-01-31.

Additionally, the database includes an alarm list with additional information to the LDT Alarm Log database, which categorizes the different alarm codes and events contained in the database. This list is based on the international standard IEC 61400 26-1 Availability for wind power generation systems. The list includes 1265 event codes, which are divided into six categories. These categories are: Environment, Fault Events, Mains Interruptions/Errors, Technical Shutdown, Warning Events, and Requested Shutdown.

### 2.2 LDT and Literature Turbine Structure

This section presents the structure that was considered for the analysis of the LDT and the turbine considered from the literature.

The turbine considered from the literature review considers the seven subsystems listed below. Figure 1 presents the functional tree of the turbine from the literature review. It was considered the following subsystems:

1. Blades and hub
2. Yaw
3. Support structure
4. Pitch hydraulic system
5. Transmission and brake train
6. Generator
7. Electrical components.

Considering the seven above-mentioned subsystems, a Reliability, Availability and Maintainability (RAM) Analysis was performed employing a Monte Carlo Simulation (MCS)

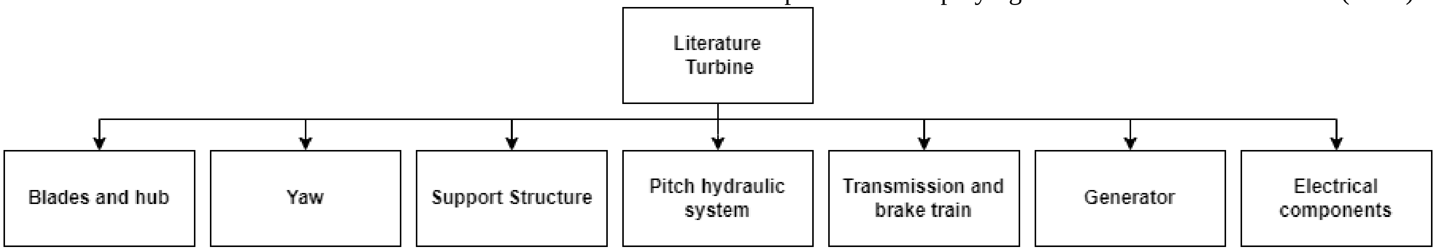


**FIGURE 1**: FUNCTIONAL TREE OF THE TURBINE OBTAINED FROM THE LITERATURE.

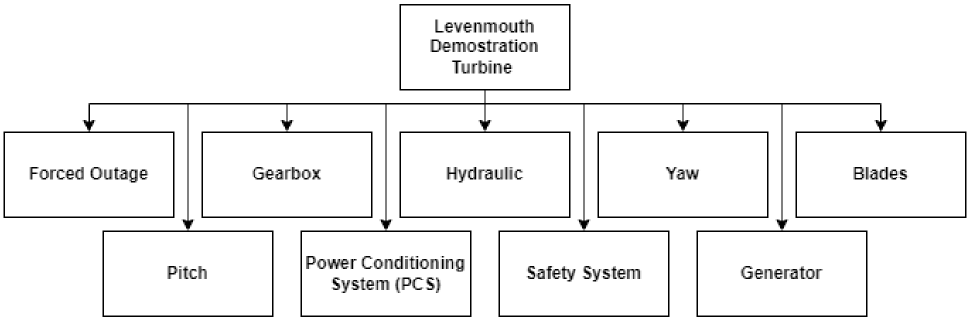


**FIGURE 2:** LDT FUNCTIONAL TREE.

[7],using as inputs the corresponding failure rates and repair rates obtained from the literature review. In this way, it was possible to obtain the Mean Time Between Failures (MTBF) and the Mean Time To Repair (MTTR) of each subsystem. Must be mentioned that for the MTTR, the Ram analysis includes three types of repairs, minor repair, major repair and replacement, following the information presented in [8]. TABLE 1 presents the failure rates and the total repair rates obtained from the literature review that were used to obtain the MTBF and MTTR.

**TABLE 1**: FAILURE RATE AND REPAIR RATE FOR EACH SUBSYSTEM CONSIDERED FROM THE LITERATURE REVIEW.

| | Failure rate [Failure/hour] | Minor Repair [Repair/hour] | Major Repair [Repair/hour] | Replace-ment [Repair/hour] |
|---|---|---|---|---|
| **Blades and hub** | 9.902E-05 | 1,28E-02 | 7,87E-04 | 3,41E-06 |
| **Yaw** | 4.865E-05 | 1,30E-02 | 3,00E-04 | 2,04E-05 |
| **Support structure** | 1.937E-04 | 3,57E-02 | 4,53E-03 | 2,78E-05 |
| **Pitch hydraulic system** | 2.121E-04 | 3,78E-02 | 4,85E-03 | 4,00E-05 |
| **Transmission and brake train** | 4.657E-05 | 2,94E-02 | 1,73E-03 | 6,67E-04 |
| **Generator** | 1.356E-04 | 2,63E-02 | 8,63E-03 | 1,17E-03 |
| **Electrical components** | 2.158E-04 | 1,52E-02 | 2,99E-03 | 4,62E-05 |

On the other hand, the structure of the LDT was inferred from the different subcomponents that are monitored in the database described in Section 2. In this sense, it should be mentioned that in the structure of the LDT, all subsystems that are monitored and that present at least one failure record were considered. Thus, the LDT is composed of the nine subsystems listed below. Figure 2 presents the LDT functional tree.

1. Forced Outage
2. Gearbox
3. Hydraulic
4. Yaw
5. Blades
6. Pitch
7. Power Conditioning System
8. Safety System
9. Generator

It should be mentioned that the LDT "Forced Outage" subsystem considers failures of several turbine subsystems, however, the failure record does not show exactly which subsystem failed, reason why it was discarded for the analysis.

By analyzing the two functional trees, it is possible to first establish which subsystems are common to both turbines, which subsystems are specific to one turbine or another, and, finally, which subsystems can be represented by the union of two or more turbine subsystems.

TABLE 2 presents a comparison between the subsystems of the two turbines studied, showing which subsystems of the turbine from the literature review have a correlate in the LDT, in addition to indicating whether the subsystem of the LDT presents sufficient failure and repair data to carry out a quantitative comparison of failure and repair rates.

**TABLE 2:** COMPARISON OF COMMON SUBSYSTEMS FOR BOTH TURBINES AND COMPATIBILITY FOR COMPARISON.

| Literature Turbine Subsystems | LDT Subsystem | Compatibility |
|---|---|---|
| Blades and hub | Blades | Comparable, but not enough data |
| Yaw | Yaw | Comparable |
| Support Structure | Nonexistent | Nonexistent in LDT |
| Pitch hydraulic system | I. Pitch<br>II. Hydraulic | Comparable |
| Transmission and brake system | Gearbox | Comparable |
| Generator | Generator | Comparable, but not enough data |
| Electrical Components | I. Safety System<br>II. Power Conditioning System | Comparable |

In this way, considering only the common subsystems that have sufficient failure and repair data in the LDT, four of the seven turbine subsystems present in the turbine from the literature review can have their reliability parameters compared with corresponding values obtained from the LDT database.

These subsystems are: "Yaw", "Pitch hydraulic system", "Electrical Components" and "Transmission and brake train".

The "Blades" and "Generator" systems that make up the literature turbine are also present in the LDT; however, the database does not have enough failure and repair records to perform the comparison of time to failure and repair time. The absence of failure records for these subsystems is justified by the magnitude of the time to failure and repair time for these systems.

In summary, the viable comparison (given enough data) to make is as follows:

$$Yaw_{Literature\ turbine} = Yaw_{LDT} \tag{1}$$

$$Pitch\ and\ hydraulic_{Literature\ turbine} = Pitch_{LDT} + Hydraulic_{LDT} \tag{2}$$

$$Electrical\ Components\ _{Literature\ turbine} = Power\ Conditioning\ System_{LDT} + Safety\ System_{LDT} \tag{3}$$

$$Transmission\ and\ brake\ train_{Literature\ turbine} = Generator_{LDT} \tag{4}$$

### 2.3 IEC 61400-26-1: Availability for wind energy generation systems

This section presents the main guidelines from the international standard IEC 61400-26-1: Availability for wind energy generation systems used to develop this work. The IEC 61400-26-1 standard has two definitions of time-based availability, operational and technical. To define both availabilities, the standard defines 12 categories for classifying the state of the turbine. Depending on the desired availability, some categories are used and others are not (The corresponding equations are presented later in the text). The categories are the following: [6]:

**1) Full Performance (IAOSFP):** the turbine is operational and functioning according to the design specifications, without restrictions or technical limitations other than those specified in the design specifications.

**2) Partial Performance (IAOSPP):** the turbine is operating with lower performance than expected due to internal or external conditions.

**3) Ready Standby (IAOSRS):** The turbine is ready to respond to a predefined event.

**4) Technical standby (IAOOSTS):** periods in which the turbine is temporarily inoperative due to the performance of autonomous tasks necessary to maintain the intended functions.

**5) Out of environmental specification (IAOOSEN):** the turbine is ready to operate, but it is not working due to the environmental conditions not meeting the project specifications.

**6) Requested shutdown (IAOOSRS):** the turbine is operational, but it is not working, as it was stopped by request.

**7) Out of electrical specification (IAOOSEL):** the turbine is ready to operate, but it is not working, due to the electrical parameters of the turbine. This can be caused by network parameters that exceed operational specifications.

**8) Scheduled maintenance (IANOSM):** The turbine is in this state during the scheduled maintenance of turbine elements, preventing the turbine from performing the intended functions.

**9) Planned Corrective Action (IANOPCA):** The turbine is in this state during actions required to maintain, restore or improve intended turbine functions when these actions are not part of normal scheduled maintenance.

**10) Forced Outage (IANOFO):** The turbine is in this state when some damage, failure or alarm disables the turbine. This can be detected manually or automatically.

**11) Suspended (IANOS):** The turbine is in this state in all situations in which the activities in SCHEDULED MAINTENANCE, PLANNED CORRECTIVE ACTION and FORCED OUTAGE must be interrupted or cannot be started due to conditions that compromise personal safety or integrity of the equipment.

**12) Force Majeure (IAFM):** The FORCE MAJEURE category is applied to all situations in which an extraordinary event or circumstance, beyond the control of the parties involved, prevents the parties from fulfilling their obligations.

Using these 12 categories listed above, the operational and technical availability is calculated according to Equations (5) and (6) respectively:

Based on these states, it is defined:

• **Operational availability:** Portion of the time the system is operating and/or able to operate, compared to the total time. According to this definition, the period in which the turbine is in the categories: full performance (IAOSFP) and partial performance (IAOSPP) is considered as available times. On the other hand, the period that the turbine is in one of the other defined categories is considered as unavailable times for the calculation.

• **Technical availability:** Fraction of a given period of time that a turbine is operating according to the technical specifications for which it was designed. According to this definition, the periods of time in which the turbine is in one of the following categories are considered as available times: full performance (IAOSFP), partial performance (IAOSPP), technical standby (IAOOSTS), requested shutdown (IAOOSRS), out of environmental specification (IAOOSEN) and out of electrical specification (IAOOSEL). On the other hand, periods of time in which the turbine is in one of the following categories are considered as unavailable times for the calculation: planned corrective action (IANOPCA) and forced outage (IANOFO). Finally, the categories: suspended (IANOS) and scheduled maintenance (IANOSM), are excluded from the calculation.

Using the categories listed above, it is possible to define technical availability and operational availability as follows:

$$Operational\ Availability = 1 - \frac{\begin{pmatrix} \text{IAOOSTS} + \text{IAOOSEN} + \text{IAOOSRS} + \\ \text{IAOOSEL} + \text{IANOSM} + \text{IANOPCA} + \\ \text{IANOFO} + \text{IANOS} + \text{IAFM} \end{pmatrix}}{\begin{pmatrix} IAOSFP + IAOSPP + IAOSRS + \\ + IAOOSTS + IAOOSEN + \\ IAOOSRS + IAOOSEL + IANOSM + \\ IANOPCA + IANOFO + IANOS + IAFM \end{pmatrix}} \quad (5)$$

$$Technical\ Availability = 1 - \frac{(IANOPCA + IANOFO)}{\begin{pmatrix} IAOSFP + IAOSPP + IAOSRS + \\ IAOOSTS + IAOOSEN + IAOOSRS + \\ IAOOSEL + IANOPCA + IANOFO \end{pmatrix}} \quad (6)$$

## 3. RESULTS AND DISCUSSION

This section presents the results of comparing the failure and repair rates of each common subsystem between the turbine considered from the literature review and the LDT according to the subsystems which were identified as comparable in section 2.2 The operational and technical availability values for the two turbines are also presented and compared according to equations 5 and 6 respectively.

In order to be able to make a fair comparison between the two turbines. Given that, the LDT database considers in the alarm log any type of turbine shutdown, including automatic and manual resets (refering to shutdowns lasting no longer than three hours) of the turbine, the following assumptions were taken into account:

I. The following definition of failure was used [5]: visit to a turbine, outside of a scheduled operation, in which some material is consumed. Faults resolved through remote, automatic, or manual resets are not covered by this fault definition.

II. Travel time and delivery time are not included. Estimating costs with this consideration means that repair costs are independent of distance from shore [5].

III. It was considered that both failure and repair rates follow exponential distributions.

Furthermore, due to the large number of records corresponding to automatic or manual resets in the LDT database, it was decided to filter the turbine shutdowns depending on their duration in order not to contaminate the values of MTBF and MTTR. The time intervals to perform the filtering were based on the values presented in [8]. Defining so, all shutdowns with a duration equal or less to 3 hours were considered as manual resets, all shutdowns with duration intervals between 3-7.5 and 7.5-26 hours, where considered as minor repair and major repairs respectively. Finally, all shutdowns with a duration greater than 26 hours were considered as replacements. TABLE 3 presents the time values used.

**TABLE 3:** TIME VALUES USED TO FILTER LDT SHUTDOWNS.

| | Manual Reset | Minor Repair | Major Repair | Replacement |
|---|---|---|---|---|
| **Repair Time** | 3 hours | 7.5 hours | 26 hours | >26 hours |

Yaw subsystem was the first submitted to comparison. TABLE 4 includes MTBF and MTTR values obtained for Yaw subsystem from literature turbine. On the other hand, TABLE 5 presents the MTBF and MTTR of Yaw from LDT for different time filters.

When analyzing the two above-mentioned tables, it is evident that in case of MTBF, when using the 7.5-hour filter in the LDT, a value of the same order of magnitude is obtained as for the value obtained from the turbine form the literature (25759.9 and 19651.0 hours). In this sense, the 7.5-hour filter guarantees the consideration of turbine shutdowns only due to faults, thus avoiding the consideration of shutdowns related to automatic and manual turbine restorations.

On the other hand, when observing the MTTR of the two turbines, it is possible to infer that, considering the same filter, there is a substantial difference between the value obtained from the turbine from the literature when compared to that verified from the LDT database, 95,0 and 8.7 hours, respectively. However, the MTTR value obtained from the turbine from the literature also considers component replacements. Thus, as first instance it must be mentioned that, the LDT database contained data only for the first three years of the turbine operation, where are no records of Yaw replacements. In this way, when comparing the LDT MTTR value with the expected value for realization from the small repair used in the RAM analysis, presented in TABLE 6, it is perceived that the MTTR of the Yaw for the two turbines is in the same order of magnitude, 14 and 8.7 hours, respectively.

**TABLE 4:** LITERATURE TURBINE YAW MTBF AND MTTR.

| MTBF [hours] | MTTR [hours] |
|---|---|
| 19651 | 95 |

**TABLE 5:** LDT'S YAW MTBF AND MTTR FOR DIFFERENT TIME FILTERS.

| Time filter | MTBF [hours] | MTTR [hours] |
|---|---|---|
| **None** | 57.3 | 0.1 |
| **3 hours** | 6439.9 | 5.2 |
| **7.5 hours** | 25759.9 | 8.7 |

**TABLE 6:** EXPECTED TIMES FOR DIFFERENT YAW REPAIR TYPES USED FOR THE LITERATURE TURBINE.

| Minor Repair [hours] | Major Repair [hours] | Replacement [hours] | Total [hours] |
|---|---|---|---|
| 14 | 20 | 49 | 83 |

Second subsystem submitted to comparison was Pitch and hydraulic. TABLE 7 presents the MTBF and MTTR values obtained for the Pitch and Hydraulic obtained from the literature review. in case of TABLE 8 it shows MTBF and MTTR values obtained by combining the fault records of the Pitch subsystem and the Hydraulic subsystem from the LDT database.

After evaluating these two tables, it can be concluded that for the MTBF of the LDT when using a 7.5-hour filter, a value of the same order of magnitude is obtained as for the value obtained from the literature turbine (1404.8 and 4658.0 hours). As verified for the Yaw subsystem, the 7.5-hour filter guarantees the consideration of turbine shutdowns only due to faults, thus avoiding the consideration of shutdowns related to automatic and manual turbine resets.

Further, comparing the MTTR of Pitch and hydraulic obtained from the literature turbine with the MTTR value obtained by combining the two subsystems of Pitch and Hydraulic from the LDT database, a greater difference is verified (6.4 and 47 hours). However, making the same consideration that was mentioned for the MTTR of the Yaw system regarding the time range covered by the LDT database, and considering that the database also does not present substitutions for either the Pitch or the Hydraulic subsystem, it is possible to compare the MTTR value obtained from the LDT database with the expected value for the small repair used in the RAM analysis, shown in TABLE 9. Thus, it is observed that the MTTR set of the Pitch and Hydraulic subsystems of the LDT is closest to the MTTR value obtained from the literature turbine, 6.4 and 26.0 hours, respectively. Although the value is not exactly in the same order of magnitude, it should be mentioned that, for comparing the subsystems of both turbines it was required to combine two subsystems of the LDT. For this reason, some differences may arise due to the fact that the Hydraulic subsystem of the LDT is also suppling all the elements that are activated by a hydraulic system and not just the Pitch subsystem. Thus, the simplest elements of the turbine have shorter repair times than Pitch, so by covering these simpler elements first, along with Pitch, the overall expected repair time will decrease.

**TABLE 7:** LITERATURE TURBINE PITCH AND HYDRAULIC MTBF AND MTTR.

| MTBF [hours] | MTTR [hours] |
|---|---|
| 4658 | 47 |

**TABLE 8:** LDT'S COMBINED PITCH AND HYDRAULIC MTBF AND MTTR FOR DIFFERENT TIME FILTERS.

| Time filter | MTBF [hours] | MTTR [hours] |
|---|---|---|
| **None** | 12.16 | 0.2 |
| **3 hours** | 787.7 | 5.1 |
| **7.5 hours** | 1404.8 | 6.4 |

**TABLE 9:** EXPECTED TIMES FOR DIFFERENT PITCH AND HYDRAULIC REPAIR TYPES USED FOR THE LITERATURE TURBINE.

| Minor Repair [hours] | Major Repair [hours] | Replacement [hours] | Total [hours] |
|---|---|---|---|
| 26 | 19 | 25 | 70 |

Next subsystem compared was Electrical components. TABLE 10 presents the MTBF and MTTR values obtained for Electrical Components for the literature turbine. whereas, TABLE 11 presents the MTBF and MTTR values obtained by combining the Power conditioning subsystem and the Safety system subsystem of LDT.

Considering TABLE 10 and is possible to determine, it is observed that for the MTBF of the LDT, when using a filter of 7.5 hours, has a value in the same order of magnitude to the one obtained for the literature turbine, 1984 and 4771 hours, respectively. Thus, in the same way as verified for the Yaw and Pitch and Hydraulic subsystems, the 7.5-hour filter guarantees the consideration of turbine shutdowns only due to faults, thus avoiding the consideration of shutdowns related to automatic and manual turbine restorations.

On the other hand, the MTTR for the Electrical Components subsystem obtained for the literature turbine and the MTTR value obtained by combining the Power conditioning system and Safety system of the LDT have a clear difference in the order of magnitude (136 and 6,11 hours) However, when analyzing TABLE 12 with the average times for different types of repair, it is possible to observe that the MTTR value of the LDT and the values used in the RAM analysis, for the small repairs category, are in the same order of magnitude.

**TABLE 10:** LITERATURE TURBINE ELECTRICAL COMPONENTS MTBF AND MTTR.

| MTBF [hours] | MTTR [hours] |
|---|---|
| 4771 | 136 |

**TABLE 11:** LDT'S ELECTRICAL COMPONENTS MTBF AND MTTR FOR DIFFERENT TIME FILTERS.

| Time filter | MTBF [hours] | MTTR [hours] |
|---|---|---|
| **None** | 60.6 | 0.4 |
| **3 hours** | 101.9 | 4.7 |
| **7.5 hours** | 1948.4 | 6.11 |

**TABLE 12:** EXPECTED TIMES FOR DIFFERENT ELECTRICAL COMPONENTS REPAIR TYPES USED FOR THE LITERATURE TURBINE.

| Minor Repair [hours] | Major Repair [hours] | Replacement [hours] | Total [hours] |
|---|---|---|---|
| 12 | 14 | 18 | 44 |

Finally, Transmission and Brake subsystem was compared. TABLE 13 presents the MTBF and MTTR values obtained for the Transmission and Brake for the literature turbine TABLE 14 shows the MTBF and MTTR of the Gearbox from LDT for different time filters.

From TABLE 13 and TABLE 14 is possible to infer that the MTBF of the LDT when using a filter of 7.5 hours, the value is not in the same order of magnitude of the corresponding value of the literature turbine. However, when using the next filter, 26 hours, both values, LDT and literature turbine MTBF are in the same order of magnitude, 26031 and 21470 hours, respectively. In this case a bigger filter is needed as the LDT's Gearbox presents several reset stops that have a duration longer than 7.5 hours, reason why it is necessary to apply the 26 hours filter.

On the other hand, when comparing the MTTR for the Transmission and Brake subsystem obtained from the literature turbine and the MTTR value obtained for the LDT Gearbox, it is realized a difference in the order of magnitude even using the 26 hours filter, 245 and 43,52 respectively. However, when analyzing TABLE 15 with the average times for different types of repairs, it is observed that the MTTR value for the LDT Gearbox is almost equal to the combined repair times for minor and major repairs. In this way, as for the MTBF, as the Gearbox have a smaller failure rate and the LDT database only have records for the first three years, no catastrophic failures that need a replacement are recorded on the LDT database. In this way, when considering only minor and major repairs, the MTTR for both analyzed turbines are in the same order of magnitude.

**TABLE 13:** LITERATURE TURBINE TRANSMISSION AND BRAKE MTBF AND MTTR.

| MTBF [hours] | MTTR [hours] |
|---|---|
| 21470 | 245 |

**TABLE 14:** LDT'S GEARBOX MTBF AND MTTR FOR DIFFERENT TIME FILTERS.

| Time filter | MTBF [hours] | MTTR [hours] |
|---|---|---|
| **None** | 2.27 | 0.1 |
| **3 hours** | 837.7 | 8.8 |
| **7.5 hours** | 2002.4 | 13.3 |
| **26 hours** | 26031 | 43.5 |

**TABLE 15:** EXPECTED TIMES FOR DIFFERENT GEARBOX REPAIR TYPES USED FOR THE LITERATURE TURBINE.

| Minor Repair [hours] | Major Repair [hours] | Replacement [hours] | Total [hours] |
|---|---|---|---|
| 15 | 22 | 231 | 268 |

After comparing the time to failure and repair time of each of the common subsystems for the literature turbine and LDT, the technical and operational availability of both turbines was compared, following equations (5) and (6) defined in the IEC 61400-26-1. The purpose of generating this comparison is to explore the impact that the differences in the values of time to failure and repair time of the analyzed subsystems can have on the total availability of the turbine, in addition to seeing the impact of the different configurations considered for each turbine. TABLE 16 shows the comparison of the technical and operational availability obtained from the LDT database and the literature turbine considering the reliability parameters obtained from the literature.

**TABLE 16:** TECHNICAL AND OPERATIONAL AVAILABILITY COMPARISSON BETWEEN LDT AND LITERATURE TURBINE.

| | LDT [%] | Literature Turbine [%] | Difference |
|---|---|---|---|
| **Technical Availability** | 88.9 | 90.49 | 1.8% |
| **Technical Unavailability** | 11.11 | 9.51 | |
| **Operational Availability** | 74.71 | 75.9 | 1.6% |
| **Operational Unavailability** | 25.28 | 24.1 | |

When analyzing TABLE 16, it can be seen that both for technical availability and for operational availability, the difference in values obtained for each of the analyzes carried out does not exceed 2% (1.8% and 1.6% respectively).

In this sense, considering that for each of the compared subsystems, the MTBF of both turbines always reached values in the same order of magnitude, it can be concluded that times to failure of both turbines are similar and comparable despite differences in size or power both turbines may have. conversely, the differences found in repair times for some subsystems were justified by the fact that the LDT database only contains a time range corresponding to three years. However, when comparing the value obtained from the LDT database with the expected value for the time to carry out small repairs in the systems, compatibility between the values was verified.

It should be mentioned that although the LDT database contains real data collected from an offshore wind turbine, it only covers a period of almost three years. This means that for certain subsystems, such as the Gearbox, adjustments must be made in order to make a fair comparison between the LDT and the literature turbine. Some failures, such as substitutions, are not typically expected within the first three years of the turbine's operation, and a reanalysis of the database would be necessary once more data has been collected. However, the use of pre-defined categorization of types of repairs enables a fair comparison between the two analyzed turbines. This is especially valuable given that the offshore wind turbine industry is relatively new and lacks vast amounts of data.

Finally, it have to be quoted that to obtain the technical and operational availability of the LDT, it was necessary to develop a code made in the Python programming language, which allowed analyzing the LDT Alarm Log database and associating the state of the turbine, each instant of time, to one of the categories presented in the IEC 61400-26-1 standard: Wind power generation systems - Availability for wind power generation systems.

## 4. CONCLUSIONS

This paper presents a comparison of failure and repair rates between the subsystems of two turbines, the 7MW LDT and a theoretical turbine obtained from a literature review. Additionally, using the corresponding failure and repair rates for each turbine, a MCS was carried out to evaluate the operational and technical availability for both turbines according to the IEC 64400-26-1 for availability for wind energy generation systems. The obtained results show the feasibility of data-driven analysis and comparison of Monte Carlo simulation for validation of failure rates and knowledge transfer from onshore to offshore wind turbine industry.

Future work could focus on the economic implications of the results presented in this paper, while also addressing the uncertainty of the dataset used. The failure and repair rates obtained can provide valuable information for decision-makers in the offshore wind industry, as they can impact the overall cost of energy generation. For example, a higher failure rate for a particular subsystem could lead to more frequent maintenance or replacement, increasing the operational costs of the turbine. On the other hand, a shorter repair time could result in less downtime and revenue loss, improving the profitability of the turbine. Therefore, a cost-benefit analysis considering the failure and repair rates of different subsystems could be carried out to optimize the design and operation of offshore wind turbines, while also accounting for the uncertainty of the data. Additionally, the use of data-driven analysis and Monte Carlo simulation demonstrated in this paper could be extended to other areas of the offshore wind industry, such as forecasting energy production and estimating lifetime costs, leading to further economic benefits and sustainability.

## ACKNOWLEDGMENT

This work was developed in cooperation with the research project entitled "Research and Development on Deep Water Floating Offshore Wind Turbines" conducted by the University of São Paulo. Authors would like to thank Petrobras for financing the aforementioned project and the Brazilian National Petroleum Agency (ANP) for providing the regulations for its execution. Prof. Marcelo Martins also acknowledges his support from the Brazilian National Council for Scientific and Technological Development (CNPq) through grant 308712/2019-6

## REFERENCES

[1] Z. Ren, A. S. Verma, Y. Li, J. J. E. Teuwen, and Z. Jiang, “Offshore wind turbine operations and maintenance: A state-of-the-art review,” *Renew. Sustain. Energy Rev.*, vol. 144, no. January, 2021, doi: 10.1016/j.rser.2021.110886.

[2] J. Aldersey-Williams and T. Rubert, “Levelised cost of energy – A theoretical justification and critical assessment,” *Energy Policy*, vol. 124, no. September 2018, pp. 169–179, 2019, doi: 10.1016/j.enpol.2018.10.004.

[3] G. Herzig, “Global Offshore Wind Report 2021,” *Glob. Wind Energy Counc.*, no. February, pp. 1–8, 2022, [Online]. Available: https://gwec.net/wp-content/uploads/2021/03/GWEC-Global-Wind-Report-2021.pdf.

[4] J. Kang, L. Sun, and C. Guedes Soares, “Fault Tree Analysis of floating offshore wind turbines,” *Renew. Energy*, vol. 133, pp. 1455–1467, 2019, doi: 10.1016/j.renene.2018.08.097.

[5] J. Carroll, A. McDonald, and D. McMillan, “Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines,” *Wind Energy*, vol. 19, no. 6, pp. 1107–1119, 2016, doi: 10.1002/we.1887.

[6] I. S. O. 14026, “International Standard International Standard,” 2014.

[7] M. V. Clavijo, A. M. Schleder, E. L. Droguett, and M. R. Martins, “RAM analysis of dynamic positioning system: An approach taking into account uncertainties and criticality equipment ratings,” *Proc. Inst. Mech. Eng. Part O J. Risk Reliab.*, vol. 236, no. 6, pp. 1104–1134, 2022, doi: 10.1177/1748006X211051805.

[8] I. Dinwoodie, O. E. Endrerud, M. Hofmann, R. Martin, and I. Sperstad, “Reference cases for verification of operation and maintenance simulation models for offshore wind farms,” *Wind Eng.*, vol. 39, no. 1, pp. 1–14, 2015, doi: 10.1260/0309-524X.39.1.1.