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RESEARCH ARTICLE

Dynamic Reliability and Availability Allocation of Wind Turbine Subassemblies Through Importance Measures

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ABSTRACT This paper illustrates the impact of wind turbine (WT) subassemblies' availability on WTs' performance. Complete and detailed reliability, availability, and maintainability (RAM) analysis of various subassemblies of WTs utilizing the Weibull probability density function (PDF) is also introduced. A modified dynamic important measures-based reliability and availability are presented to show the significant impact of various WT subassemblies on the overall system performance. This method is mainly utilized to rank the WT subassemblies regarding their impact on the system reliability and availability, identifying the subassemblies that the planned maintenance should focus on. Dynamic ranking of WT subassemblies is obtained to achieve the desired level of reliability and availability. The obtained results demonstrate the effectiveness and efficiency of the proposed approach that achieves the system's secure operation and improves system reliability and availability.

INDEX TERMS Dynamic availability importance measures, maintainability, reliability, wind turbine.

NOMENCLATURE

DAIM	Dynamic Availability Importance Measure
DRIM	Dynamic Reliability Importance Measure
DT	Drive Train
EC	Electrical Control
ES	Electrical System
GB	Gearbox
GE	Generator
HC	Hydraulic Control
IM	Importance Measure
MB	Mechanical Break
MTBF	Mean Time between Failures
MTTR	Mean Time to Repair
PDF	Probability Density Function
PS	Pitch System
RAM	Reliability, Availability, and Maintainability
RB	Rotor Blades
RH	Rotor Hub
WF	Wind Farm
WT	Wind Turbine
A_i	Availability of subassembly i
A_s	Availability of system
$A_{s,Parallel}$	Availability of system that contains m-independent subassemblies connected in parallel
$A_{s,Series}$	Availability of system that contains m-independent subassemblies connected in series
β	Weibull shape parameter
η	Weibull life parameter
i	Subassembly number
I_A^i	Dynamic availability importance measure of a subassembly

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$I^i_{A,MTBF_i}$	Dynamic availability importance measure for Mean Time between Failures
$I^i_{A,MTTR_i}$	Dynamic availability importance measure for Mean Time to Repair
I^i_R	Dynamic reliability importance measure of a subassembly
$f(t)$	Probability density function
λ	Failure rate
m	Number of connected subassemblies in the system
μ	Repair rate
$R(t)$	Reliability function
R_i	Reliability of subassembly i
R_s	Reliability of system
t	Specific time

I. INTRODUCTION

Wind energy sectors significantly dominate universal energy produced by clean and renewable energy sources. The worldwide installed capacity of wind energy generation systems reached approximately 651 GW by 2019. Fig. 1 shows the global wind power capacity, 2009-2019. The global installed wind energy capacities are expected to attain about 2000 GW by 2030. The increasing growth rate of wind energy worldwide has grabbed the stakeholders' attention to the financial loss, which may be occurring due to the unforeseen subassemblies' failures for the prolonged periods of downtime. Consequently, there is an increasing need for more efforts to ensure that the required and predicted energy is generated from wind energy systems. Thus, reliability and availability assessments are performed for such systems in the planning stage to ensure the accurate prediction of wind energy production [1].

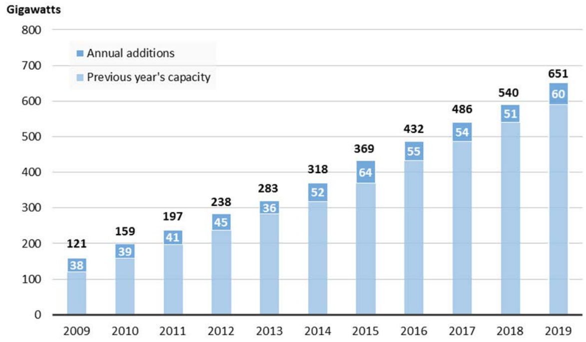


FIGURE 1. Wind power global capacity, 2009-2019 [1].

Two fault categories may lead to loss of energy production from wind energy conversion systems; wear-out failures and temporary random faults. Wear-out failures are described as permanent or long-term events. In these types of failures, repairing or replacing failed subassemblies at a specific time is needed. These actions need additional costs; however, they are critical in the operational stage. If the failed subassembly isn't identified accurately and repaired or replaced in time, other subassemblies or the whole system may be affected.

On the other hand, temporary random faults are defined as temporary and short-term events caused by external factors. Temporarily shutting down and restarting the faulty subassemblies or even the whole system may be the appropriate action to clear these faults [2]. Unfortunately, in the case of permanent faults, repairing or replacing the defective subassemblies cannot be performed for an extended period due to inaccessibility issues. Thus, some subassemblies' failure rates become more critical, making the developers select systems with lower failure rates [3].

System reliability is expressed as the probability of successful operation of a system, subsystem, or subassembly to perform the required function acceptably for an intended period. Reliability represents the wind energy systems' crucial issue in the planning and operational stages, which enables predicting the system behavior over its operating lifetime and contributes to setting appropriate maintenance strategies. As a result, reliability may be used to control the revenue losses [4], [5], [6]. On the other hand, the availability of a system can be defined as the percentage of time that the system remains available to achieve its required function. Therefore, the system's availability depends on more factors than reliability [4], [7], [8], [9]. Thus, the availability study is necessary for assessing the system performance, especially when accessibility is considered.

In the last decade, the reliability and availability of wind energy conversion systems and their improvements represent a main point of interest for many research and articles on reliability and availability [4].

Reliability and availability are considered good indicators for evaluating a system's performance. Their values depend on the reliability/availability of the subassembly and also on the system structure. Of course, these values decrease with increasing the subassembly ages [10]. Therefore, the main requirements for operating complex systems are availability and reliability. For the design stage, these requirements are also very important to specify the appropriate subassemblies' availability and reliability [11]. Some issues must be resolved during both the design and operation phases to improve the performance/availability of such systems. The effect of improvements on the whole system availability after identifying the system's weak points represents the most important issue among them. More investigations have been performed in availability studies about the problem of availability allocation using various approaches [11], [12], [13], [14], [15]. At the subassembly level, it is substantial to consider the critical characteristics of reliability and maintainability for the system to deal with the availability allocation.

Therefore, it is very important to point out that the important measures based on reliability and maintainability must be considered to improve the existing availability characteristics. According to the concept of importance measures (IMs), some subassemblies have more importance than others in providing a particular system. The subassembly importance analysis, which represents the essential part

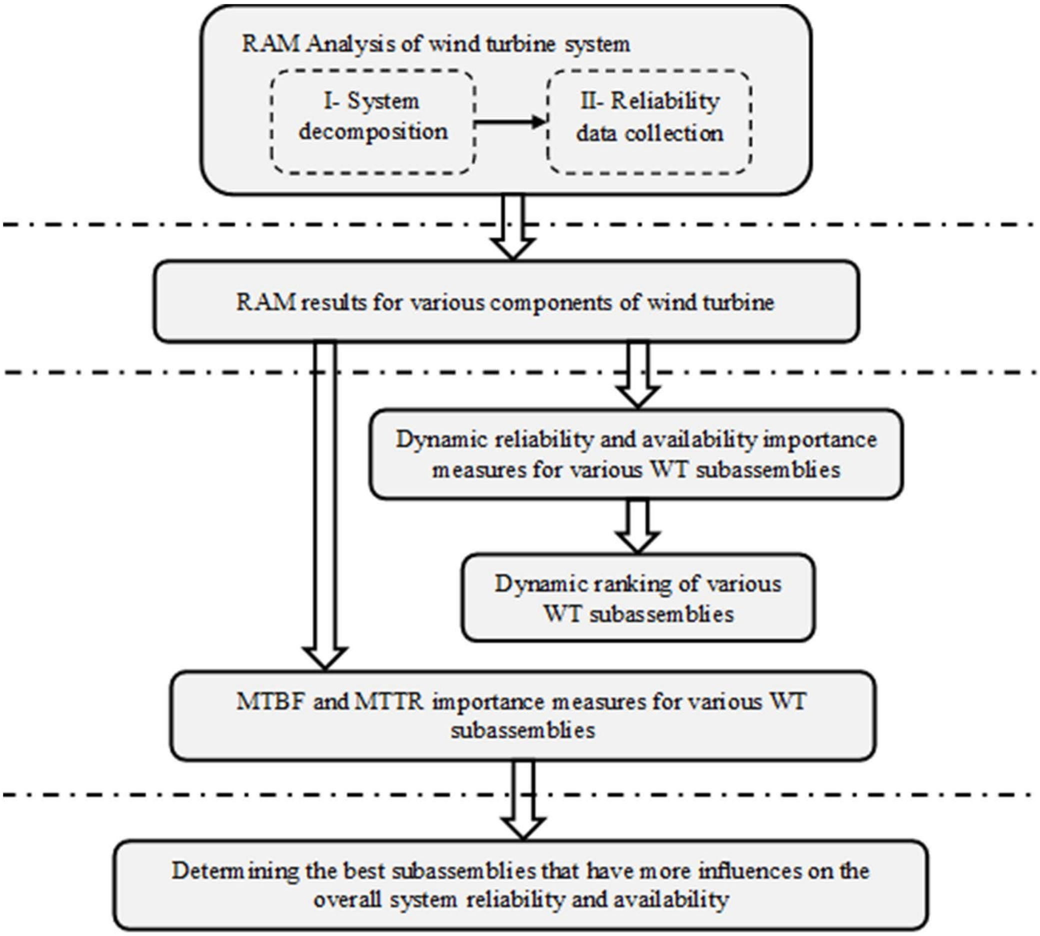


FIGURE 2. **Flowchart for the work steps of this paper.**

of the system reliability quantification process, identifies the system's weak subassemblies. It indicates the required modifications are shared to improve system reliability and maintainability [16]. The basic mathematical concept of the importance of measures-based reliability was introduced by Z. W. Birnbaum [17]. The IMs for various subassemblies of systems have been developed in reliability studies as in [18], [19], [20], [21], [22], [23], [24], and [25].

However, the studies dealing with the reliability and availability IMs give a static ranking of the subassemblies. The main reason behind this is that they considered that the failure and repair rates are constant; hence, the representation of the failure and repair events was exponential. Although the exponential representation of failure and repair events is valid with some subassemblies, it is not the best fit distribution with the wind turbine (WT) subassemblies, as discussed in section three. Instead, the Weibull probability density function (PDF) will be used in this paper, which plays a critical role in the statistical analysis of failure and repair events. Weibull PDF has no characteristic shape, and the selection of values for its parameters makes it extremely flexible, where various shapes attain through different values of β. The Weibull distribution is applicable to model decreasing, increasing, and constant failure rates to model various data and life characteristics. Thus, the utilizing of Weibull PDF is more general and practical than exponential PDF. Using the flexible Weibull PDF with the important measures will give the dynamic ranking of WT subassemblies that will be more realistic than the statistic ranking.

This paper presents a developed technique for reliability, availability, and maintainability (RAM) analysis of wind system subassemblies using a Weibull distribution. This paper's interests also extend to obtain the dynamic ranking of each subassembly of the wind energy system from the reliability and availability perspective based on reliability and availability IMs. Fig. 2 illustrates the work steps of this paper that are carried out using MATLAB. Table 1 lists a Comparison between the proposed work in this study and other related studies.

The rest of this paper is organized as follows. Section II introduces and explains the reliability and maintenance of WTs. Sections III and IV show the complete analysis and result of RAM of WT subassemblies. Dynamic reliability and availability IMs are proposed in section V. Results and discussions are offered in Section VI. Finally, Section VII provides the conclusions of this paper.

TABLE 1. Comparison Between the Proposed Work in This Study and Other Related Studies.

Item	This paper	[4]	[26]	[27]	[28]
The scope of the study	• RAM analysis • Dynamic reliability IMs • Dynamic availability IMs • Dynamic priority of various WT subassemblies.	• RAM analysis • Static priority of WT subsystems	• Reliability analysis only	• Reliability analysis only	• Reliability analysis only
The applied IM techniques	• Dynamic reliability IMs • Dynamic availability IMs	No IM techniques	No IM techniques	Reliability IM only	NA
The used PDF type of input data	• Weibull failures and repairs	• Exponential failure and repairs	• Weibull failures only	• Exponential failures only	• Weibull failure and repairs
Number of subassemblies or subsystems	10 subassemblies	15 subassemblies	15 subassemblies	4 subsystems	10 subassemblies
Ranking of subassemblies	Dynamic ranking of subassemblies	Static ranking of subsystems	Static ranking of subsystems using the FV technique	No ranking	No ranking

NA: Not available

II. WIND TURBINE RELIABILITY AND MAINTENANCE

There is an increasing need for complicated maintenance systems due to WTs' high machinery cost and infrastructure. This maintenance achieves high reliability, availability, maintainability, and safety [29]. Of course, this reflects on the cost of failure. For bearing failure as an example, the cost of repairing this failure or refurbishing the faulty item could be 5000 € in the case of detecting the failure. In comparison, this value could rise to more than 250.000 € if not detecting the failure due to collateral damage to other subassemblies [30].

Consequently, it is essential to point out that selecting the best maintenance systems represents the first step toward cost reduction. A significant improvement can be reached in the area of maintenance and repair strategies of WTs as a result of employing the supervisory control and data acquisition systems integrated with the condition monitoring techniques. Using fault detection algorithms or even fault detection and diagnosis methods and condition monitoring techniques is considered an early warning for mechanical, structural, and electrical defects, enabling the wind farms (WFs) operators to perform predictive maintenance to reduce the failure rates [31]. Smaller WTs require less preventive maintenance than larger ones [32]. In tandem with predictive maintenance, preventive maintenance is usually used. They have the same importance for offshore WTs because the maintenance personnel operate under the weather's mercy.

Fault prediction represents the main reason behind using these condition monitoring techniques, where they predict the fault before its occurrence with reasonable accuracy of 60 min [33]. Fig. 3 demonstrates the P–F curve in which the fault represents the consequences of the failure deterioration, as illustrated. The potential fault at point P is possibly detected. As shown in Fig. 3, the deterioration continues until it reaches functional failure at point F if the failure is not mitigated. The fault can be avoided through the time between P and F [34]. Due to high wear, some subassemblies have higher failure rates than others. These subassemblies are rotor blades, gearboxes, and generators.

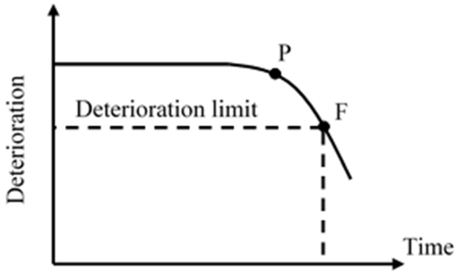


FIGURE 3. P-F curve.

There is an increasing need for complicated maintenance systems to achieve an acceptable level of reliability and availability. This maintenance system generally relies on setting a maintenance strategy for all subassemblies of the WT, which will increase the maintenance cost of the WT. Therefore, if we need to minimize this maintenance cost, we must determine the subassemblies that have the most significant impact on the reliability and availability of the WTs. In this case, the maintenance strategies will focus only on these subassemblies instead of all subassemblies. This maintenance will be achieved by the dynamic reliability and availability proposed in this paper.

III. RELIABILITY, AVAILABILITY, AND MAINTAINABILITY ANALYSIS OF WIND TURBINES

Three essential measures are used to estimate the effectiveness of system production. These measures, called RAM, are essential in the system's planning stage to ensure the accurate prediction of energy production. Two main factors are essentially used for the RAM analysis of any system. These factors are the Mean Time between Failure (MTBF) and Mean Time to Repair (MTTR). It is essential to point out that the MTBF is used to demonstrate reliability. In contrast, MTTR is used to demonstrate maintainability, and both MTBF and MTTR are used to demonstrate availability.

Reliability is the probability of a system performing its required function adequately for a specific time, t. The general reliability function $R(t)$ can be expressed as follows:

$$R(t) = \exp\left[-\int_0^t \lambda(t)\,dt\right] \tag{1}$$

Equation (1) is the general equation of the reliability function as a function of the hazard function $\lambda(t)$, and it's valid with all distributions. When the failure rate is constant and independent with time, the reliability function can be expressed by $R(t) = e^{-\lambda t}$.

In reliability engineering, the Weibull distribution is the most common distribution used in the statistical analysis of reliability data. This distribution can model decreasing, increasing, and constant failure rates to model various data and life characteristics. The best fittings of the Weibull distribution parameters grant extreme and flexible characteristics. The various shapes achieve through different values of the shape parameter. The 2-parameter Weibull PDF is given by:

$$f(t) = \frac{\beta}{\eta} \times \left({}^{t}\!/_{\eta}\right)^{\beta-1} \times \exp\left[-\left({}^{t}\!/_{\eta}\right)^{\beta}\right] \tag{2}$$

The Weibull reliability function is given by:

$$R(t) = \exp\left[-\left({}^{t}\!/_{\eta}\right)^{\beta}\right] \tag{3}$$

where η and β represent the life and shape parameters, respectively.

When a failed item of a given system restores its normal operating condition, this is known as maintainability. The maintainability of a system, subsystem, or even subassembly is the probability that it can be restored to a state in which it can perform its intended function within a given time. Maintainability engineering aims to increase the efficiency and safety of the system and reduce the cost of equipment maintenance when maintenance is performed under given conditions and using appropriate resources and procedures. Maintainability is the ability to perform successful actions of repairs within a given time. In other words, maintainability is a design parameter used to measure the ease and speed of restoring its operational status after a failure occurs. For instance, if the maintainability of an item is 90% in one hour, the probability that this item will be repaired is 90% within an hour. MTTR represents the random variable in maintainability, whereas MTBF is the random variable in reliability. The maintainability equation $M(t)$ for a system where its repair times follow the Weibull distribution can be written as:

$$M(t) = 1 - \exp\left[-\left({}^{t}\!/_{\eta}\right)^{\beta}\right] \tag{4}$$

Availability is the percentage of time that the system is available to perform its required function [35]. The time-dependent availability is expressed by:

$$A = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} \times \exp\left[-(\lambda + \mu)\,t\right] \tag{5}$$

where λ and μ represent the failure and repair rates, respectively.

RAM analysis of any complex system is executed through three steps. These steps are system decomposition, data collection, and modeling. The first step of RAM analysis decomposes the whole wind energy system into subassemblies according to their functions. The numbers of subassemblies vary according to the type and size of WT. The main subassembly of a typical WT is illustrated in Fig. 4. As shown in Fig. 4, the mechanical energy is transmitted by blades connected to the hub via a low-speed shaft to the gearbox's high-speed shaft. The main bearing supports the low-speed shaft, while the gearbox is used to adjust speed. The converter is utilized in some WTs to match the grid connection. The yaw system is mounted on a bedplate or foundation at the top of a tower. It is used to rotate the nacelle to control the alignment of the direction of the wind. The pitch system (PS) mounted in each blade acted as an aerodynamic brake and was used to control the power input to the WT. The yaw, the brake, and the PSs are controlled by a meteorological unit attached to provide weather data (e.g., wind speed and direction).

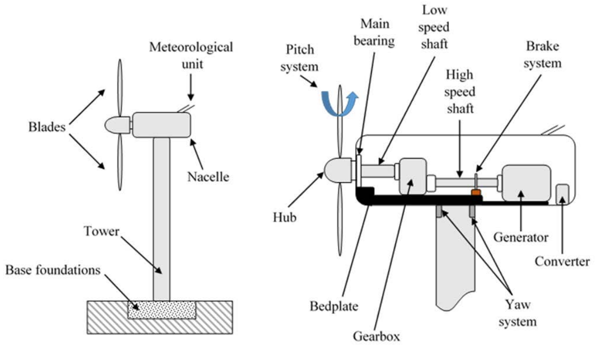


FIGURE 4. Wind turbine subassemblies.

According to the WTs' types and sizes, the costs of all of these subassemblies will vary. For instance, some WTs do not have a gearbox in some configurations. Therefore, depending on the configuration used, the costs of both generators and converters will differ. Anyway, Fig. 5 illustrates the distribution of the costs of the subassemblies for a typical 2 MW WT [34].

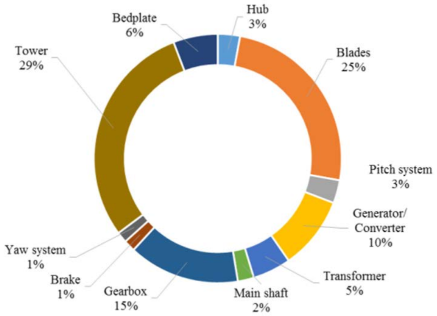


FIGURE 5. **Distribution of the costs of the subassemblies for a typical 2 MW wind turbine.**

The main reliability/availability assessment challenge is collecting accurate failure and repair rate data. The recorded data in some WFs are not available, and retrieving these data is too expensive. Even if field data were available, these usually don't satisfy the selected model's assumptions for analysis. Thus, some existing literature focuses only on the reliability assessment of vulnerable WT subassemblies considering only failure information and ignoring the repair interval. Although the repair interval is assumed to be very short in this literature, it will affect the system's operation and cannot be ignored. Thus, RAM analyses in this paper will conduct using both failure information and repair interval for most WT subassemblies such as electrical system (ES), electrical control (EC), hydraulic control (HC), yaw system (YS), rotor hub (RH), mechanical brake (MB), rotor blades (RB), gearbox (GB), generator (GE), and drive train (DT). The failure rates and downtime for these subassemblies have been computed by Ossai *et al.* [28] using several researchers [6], [7], [36], [37], [39], [39], [40] to estimate the variability of MTBF, MTTR using their maximum and minimum values (see Fig. 6). The technical data of the WTs used in this analysis are presented in Appendix. Maximum and minimum failure rates and downtime of the WT subassemblies shown in Fig. 6 are utilized to estimate the MTBF, MTTR, and Weibull parameters using a framework-based Monte Carlo simulation [28]. The results of the simulation run of the framework illustrated in Fig. 7 and Fig. 8 represent the input data for the RAM results.

IV. RAM RESULTS FOR WT SUBASSEMBLIES

The subassemblies' reliability was estimated by substituting the Weibull parameters of MTBF in Fig. 7b and Fig. 7c into Equation (3), and the subassemblies' reliability was estimated (see Fig. 9). It is clear from this figure that the yaw system and drive train have recorded the longest lifecycle duration. In contrast, the rotor hub and gearbox are expected to have the least lifecycle duration. Thus, due to their high proneness to failure, there is an increasing need for more frequent inspection of such subassemblies that fall within the lower limits of the lifecycle duration than others. Furthermore, monitoring these subassemblies more than others may decrease the downtime of the WT, as in the case of gearbox, as reported by many authors in literature [41], [42], [43]. The application of condition monitoring approaches can mitigate the reliability issues of the gearbox that are attributable to the design and manufacturing processes. Still, to minimize the downtime of WTs, the enhancement of design and manufacturing processes is imperative. Table 2 lists the percentage reliability of each subassembly after five and ten years of operation utilizing Weibull PDF.

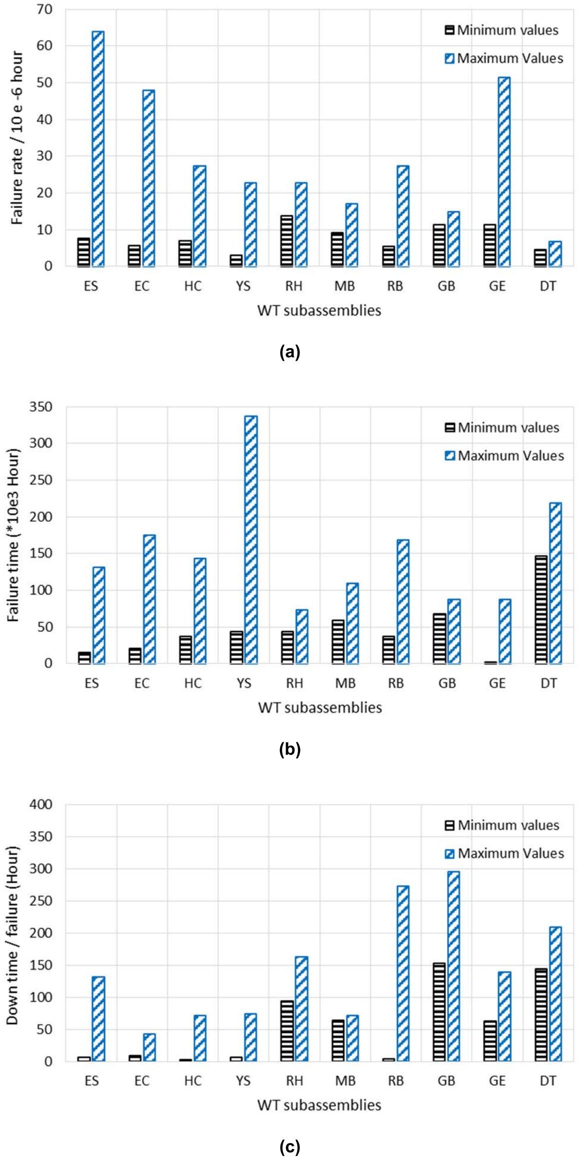


FIGURE 6. **Reliability data of WT subassemblies [32]. (a) minimum and maximum failure rates, (b) minimum and maximum failure time, and (c) minimum and maximum downtime/failure.**

Fig. 10 illustrates the probability density distribution of the MTBF. The gearbox and the rotor hubs have a higher failure probability because of their smaller variance than other subassemblies. Mechanical brakes come in the third of susceptible to failure level after rotor hub and gearbox in the cause of WF operation as shown in Fig. 10. Some literature concluded

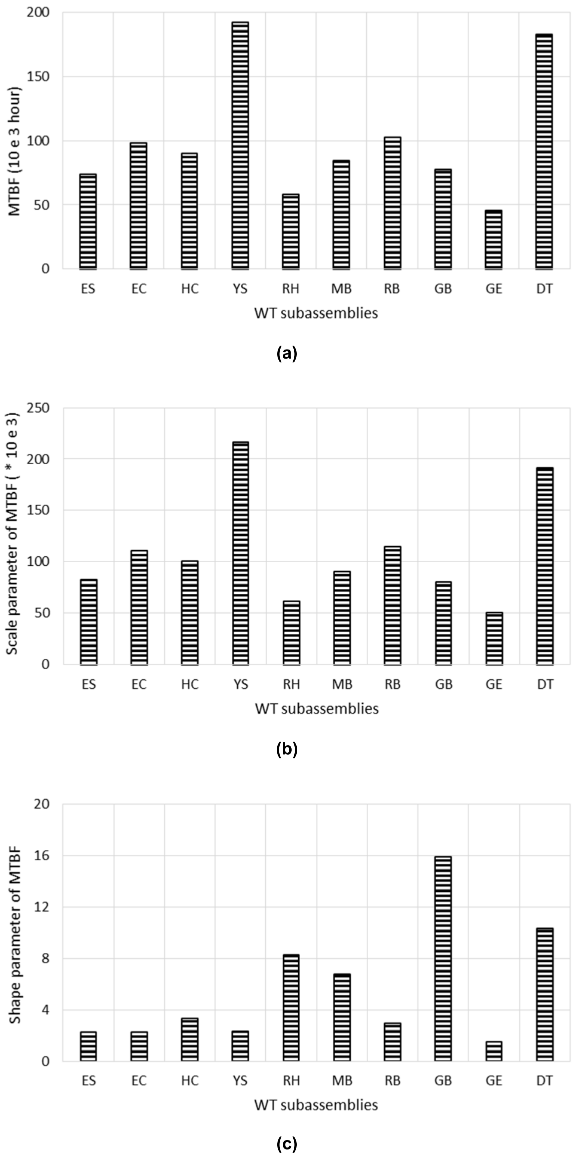


FIGURE 7. Failure duration Weibull parameters of WT subassemblies [32]. (a) MTBF, (b) scale parameter of MTBF, and (c) shape parameter of MTBF.

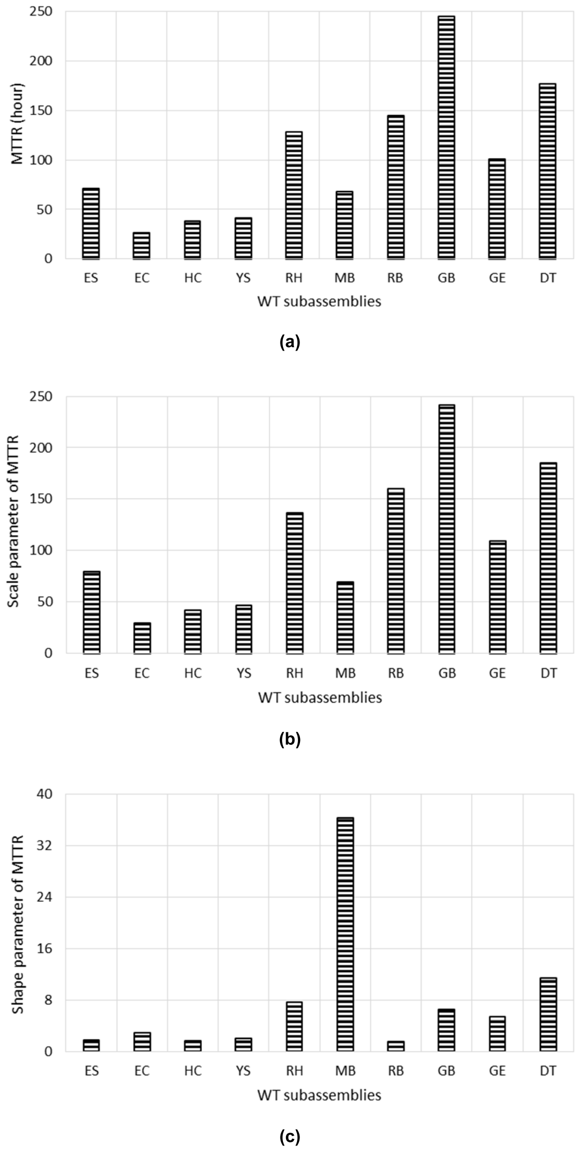


FIGURE 8. Downtime duration Weibull parameters of WT subassemblies [32]. (a) MTTR, (b) scale parameter of MTTR, and (c) shape parameter of MTTR.

that the mechanical subsystem, including subassemblies such as hydraulic, yaw, gearbox, brake pads, and blades, records about 79% of failures in WTs [7], [44]. This paper concluded that the hydraulic controls recorded a median range of the subassemblies' failure rates, and the yaw system doesn't expect to pose any downtime problems to WTs.

By substituting the Weibull parameters of MTTR in Fig. 8b and Fig. 8c into Equation (4), the subassemblies' maintainability was estimated (see Fig. 11). It is clear from this figure that the rotor blades and gearbox have recorded the longest maintainability. In contrast, the electrical controls and mechanical brakes are expected to have the least maintainability. By substituting the Weibull parameters of MTBF and MTTR, Fig. 7a and Fig. 8a, into Equation (10), the availability of various subassemblies of WT was estimated (see Fig. 12). It is illustrated from this figure that the yaw system is the most extended availability, followed by the electrical controls. In contrast, the gearbox and the generator are expected to have the least availability.

Table 3 lists the percentage availability of each subassembly after five and ten years of operation utilizing Weibull PDF.

V. DYNAMIC RELIABILITY AND AVAILABILITY ALLOCATION

Reliability allocation should execute in the initial stages of systems design, which relates to setting the reliability objectives for the subsystems and/or subassemblies to achieve the desired overall system reliability. The overall mission requirements of the system are the basis of determining the value of the system's reliability. There is an increasing need for a proper method to determine the subassemblies' reliability value to obtain the system reliability. As mentioned before, the predicted failure probability or the reliability of the subassemblies can be derived from its failure data analysis. On the other hand, the availability allocation is the process that encompasses each subjective judgment, such as stakeholders' decisions and the philosophies related to operational and maintenance, and objective judgments, such as subassembly performance of the system. The availability problem is dealt with the criticality of reliability and maintainability characteristics at the subassembly level of the system. Thus, IMs' reliability and maintainability are critical to improving the system's availability characteristics.

There are two categories of reliability and availability allocation methods; optimal allocation techniques and the weighting factor approach. The optimal allocation methods help enhance system reliability, availability, and cost. These methods rely on proper mathematical programming techniques to obtain the best possible combination of subassemblies' reliability and availability. The weighting factor methods are based on historical observations and provide reasonable allocations. This paper uses a modified optimal allocation method because all subassemblies are statistically independent, and failure rates are not constant. Due to these considerations, the Weibull PDF represented the best fit for the failure distribution of various WT subassemblies instead of the exponential PDF which is valid only if the failure rate is constant. Furthermore, due to utilizing the Weibull PDF with the mentioned method, the obtained results from the allocation method will be dynamic.

Recently, the IMs are considered a guideline for improving the system strategy [45]. They can identify the weakest subassemblies and indicate the appropriate modifications to improve system reliability and availability. Concentrating on improving those subassemblies will achieve the maximum improvement in the overall system reliability and availability. This paper will use dynamic reliability IMs (DRIMs) and dynamic availability IMs (DAIMs). Generally, DRIMs and DAIMs of each subassembly are specified by a numerical value between 0 and 1. DRIM is a function of only MTBF/failure rate, whereas DAIM is a function of MTBF/failure rate and MTTR/repair rate. The values 0 and 1 signify the lowest and the highest level of importance. The DRIM and the DAIM of a subassembly in a system that contains m subassemblies can be calculated by:

$$I_R^i = \partial R_s / \partial R_i \tag{6}$$

$$I_A^i = \partial A_s / \partial A_i \tag{7}$$

where R_i is the subassembly reliability, R_s is the system reliability, A_i is the subassembly availability, and A_s is the system availability.

IMs are utilized to specify the effect of each subassembly reliability and availability of a system on the overall system reliability and availability, respectively. The subassembly that records the largest value of the IM is that it has the greatest effect on the whole system's reliability and availability. Consequently, it is essential to determine the value of the IM of each subassembly of a system before taking any action toward improving system reliability and availability. This is to obtain the optimal results from improving the system reliability, availability and determine which subassembly needs to be improved, hence obtaining the optimal results from improving the system reliability and availability. The improvement efforts should be concentrated on improving the subassemblies that have the largest effect on system reliability and availability if each of those values needs more improvement.

Sets of IMs can also be specified with the DAIMs according to the relation between MTBF/MTTR and the system availability as follows:

- DAIMs of MTBF or failure rate; and
- DAIMs of MTTR or repair rate.

The MTBF/failure rate of a certain subassembly on the overall system availability can be represented by the DAIMs of MTBF/failure rate. The subassembly with the largest value of DAIMs of MTBF/failure rate has the most significant effect on the system's availability. It can be calculated by:

$$I_{A,MTBF_i}^i = \frac{\partial A_s}{\partial MTBF_i} = \frac{\partial A_s}{\partial A_i} \times \frac{\partial A_i}{\partial MTBF_i} \tag{8}$$

However, the DAIMs of MTTR/repair rate is an indicator of the MTTR/repair rate of a subassembly effect on the overall system availability. The high value of DAIMs of MTTR/repair rate means a high effect on the system's availability. It is calculated as follows:

$$I_{A,MTTR_i}^i = -\frac{\partial A_s}{\partial MTTR_i} = -\frac{\partial A_s}{\partial A_i} \times \frac{\partial A_i}{\partial MTTR_i} \tag{9}$$

From the reliability theory point of view, the steady-state availability of a system that contains m-independent subassemblies connected in series can be written as:

$$A_{s,Series} = \prod\nolimits_{i=1}^{m} A_i = \prod\nolimits_{i=1}^{m} \frac{MTBF_i}{MTBF_i + MTTR_i} \tag{10}$$

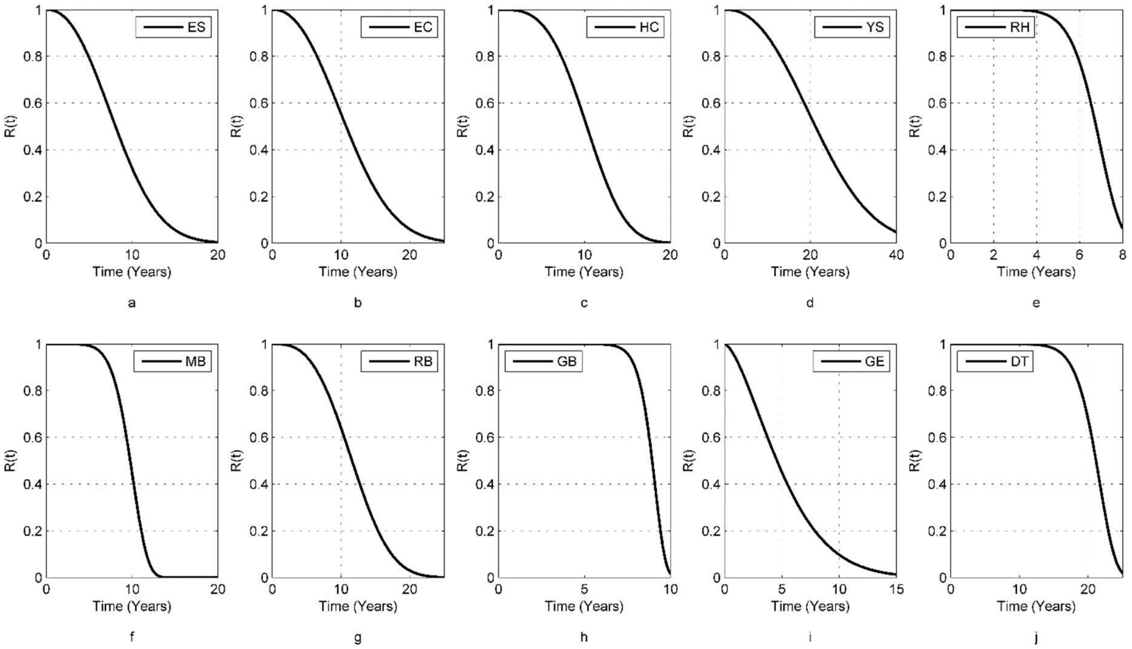
The DAIMs of specific subassembly i in a series system can be expressed as:

$$I_{A,Series}^i = \frac{\partial A_s}{\partial A_i} = \prod\nolimits_{\substack{K=1\\K\neq i}}^{m} A_K \tag{11}$$

The DAIMs of a specific subassembly is affected by all subassemblies' availability except that subassembly. The subassembly that records the minimum availability estimate should greatly prioritize increasing the whole system's availability. According to the availability characteristics of a system, various DAIMs types can be calculated by the following equations:

$$I_{A,MTBF_i,Series}^i = A_s \times \frac{MTTR_i}{MTBF_i\,(MTTR_i + MTBF_i)} \tag{12}$$

$$I_{A,MTTR_i,Series}^i = A_s \times \frac{1}{MTTR_i + MTBF_i} \tag{13}$$



a b c d e

f g h i j

FIGURE 9. Reliability results for WT subassemblies.

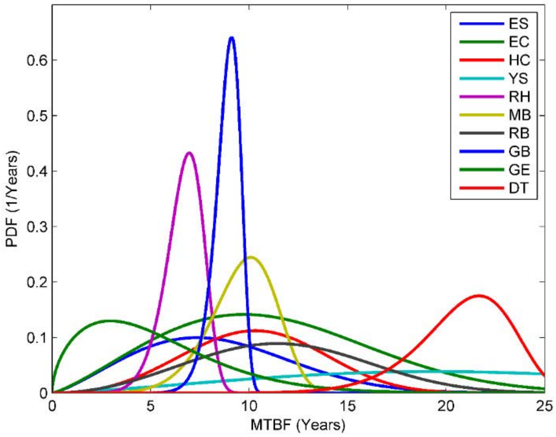


FIGURE 10. PDF of MTBF of various WT subassemblies.

The steady-state availability of a system that contains m-independent subassemblies connected in parallel can be expressed as:

$$A_{s,Parallel} = 1 - \prod_{i=1}^{m} \left(1 - \frac{MTBF_i}{MTBF_i + MTTR_i}\right) \quad (14)$$

The DAIMs of specific subassembly i in a parallel system can be expressed as:

$$I^{i}_{A,Parallel} = \frac{\partial A_s}{\partial A_i} = 1 - \prod_{\substack{K=1\\K\neq i}}^{m} (1 - A_K) \quad (15)$$

The DAIMs of a specific subassembly is affected by the availability of all subassemblies in the system except subassembly. According to the availability characteristics of a system, various DAIMs types can be calculated by the following equations.

$$I^{i}_{A,MTBF_i,Parallel} = 1 - \prod_{\substack{K=1\\K\neq i}}^{m} (1 - A_K) \times A_i \times \frac{MTTR_i}{MTBF_i\,(MTTR_i + MTBF_i)} \quad (16)$$

$$I^{i}_{A,MTTR_i,Parallel} = 1 - \prod_{\substack{K=1\\K\neq i}}^{m} (1 - A_K) \times A_i \times \frac{1}{MTTR_i + MTBF_i} \quad (17)$$

VI. RESULTS AND DISCUSSION

The dynamic reliability and availability important measures suggested in section V are utilized to find the weakest subassembly that affects the overall system reliability and availability. Fig. 13 shows the subassemblies' reliability and availability collected together, representing the IMs stage's input. The IMs stage's output representing the subassemblies' ranking according to their influence on the overall system reliability and availability is shown in Fig. 14 and Fig. 15, respectively. It is found that the ranking of subassemblies according to the impact on the overall performance of the WT is a dynamic ranking. This means that this ranking varied (not fixed) through the expected lifetime of the WT.

The main reason behind this is using the flexible Weibull PDF, which combines the permanent and intermittent faults that make the availability vary through the lifetime of the WT. Therefore, the priority of the subassemblies to enhance the overall system performance is very short (each year). As shown in Fig. 14, the generator has the greatest impact on the overall reliability among the WT subassemblies for the

TABLE 2. Percentage reliability of wind turbine subassemblies after five and ten years of operation.

Reliability	ES	EC	HC	YS	RH	MB	RB	GB	GE	DT
After five years	79.3446	88.3634	93.8955	97.5854	94.4406	99.2681	94.4750	99.9933	45.0758	100.000
After ten years	32.1705	55.3538	53.1011	88.4954	0.00000	44.6193	63.9312	1.58810	9.7405	99.9702

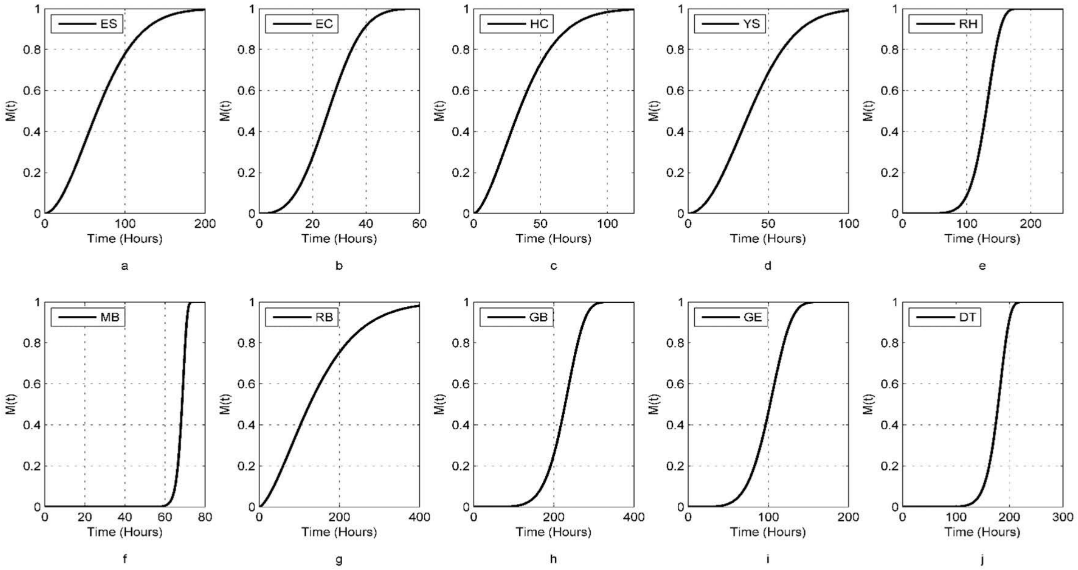


FIGURE 11. Maintainability results for WT subassemblies.

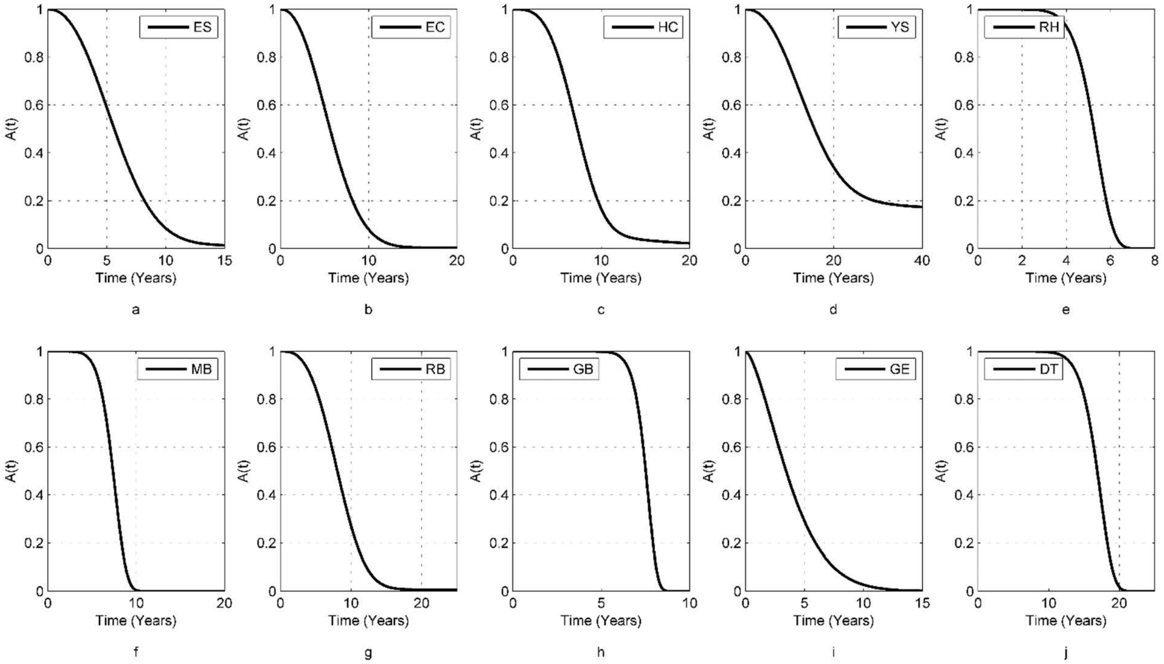
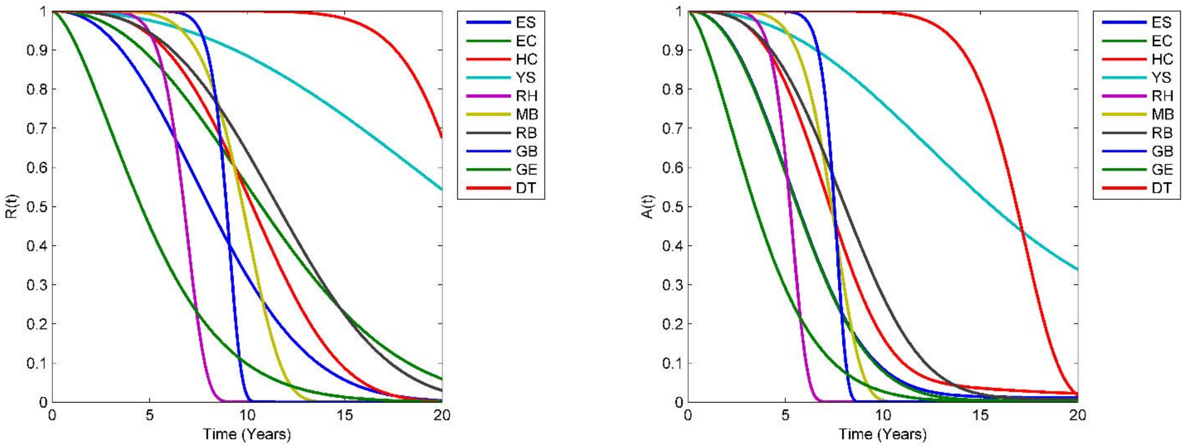


FIGURE 12. Availability results for WT subassemblies.

first seven years. At the same time, rotor hub subassembly recorded the first priority between all subassemblies from year eight to year twelve. From year thirteen to year fifteen, the gearbox represents the first priority. For the last five years, the rotor hub has been the strongest influence on the overall system reliability among all subassemblies of WT.

TABLE 3. Percentage availability of wind turbine subassemblies after five and ten years of operation.

AVAILABILITY	ES	EC	HC	YS	RH	MB	RB	GB	GE	DT
AFTER FIVE YEARS OF OPERATION	59.0391	58.6174	81.5273	94.5430	62.3663	95.1416	84.4957	99.8932	29.1438	99.9998
AFTER TEN YEARS OF OPERATION	8.55670	7.95910	16.5147	76.3270	0.00000	0.4207	27.0524	0.0000	2.7232	99.6914



(a) (b)

FIGURE 13. Collected (a) reliability and (b) availability of WT subassemblies.

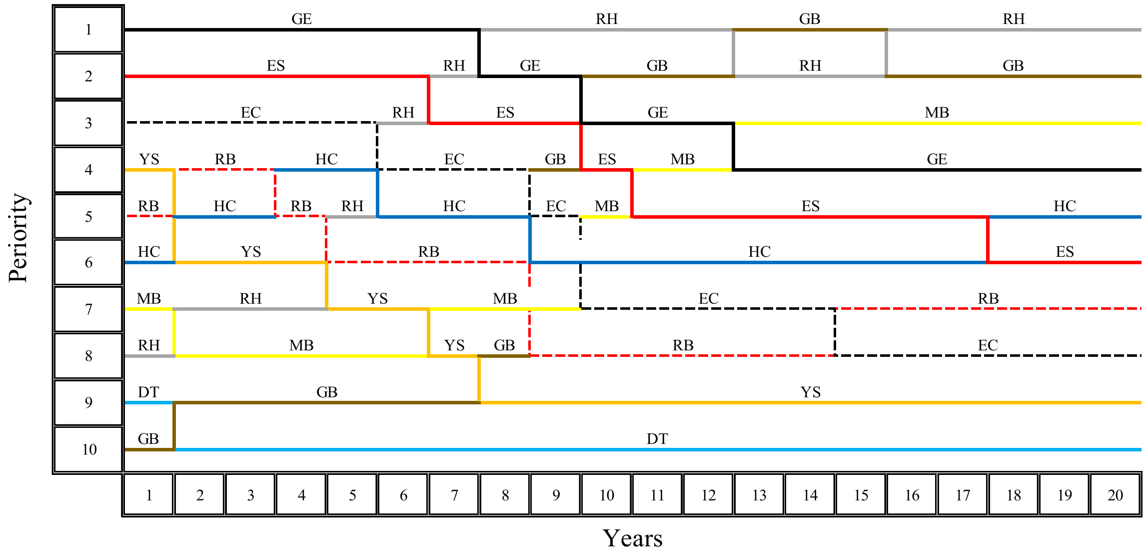


FIGURE 14. Dynamic ranking of subassemblies according to reliability.

Thus, the importance or focus of one subassembly along the total lifetime of the system and the consideration that its improvement will enhance the overall system reliability must be changed according to these findings.

Similarly, as shown in Fig. 15, the generator has the greatest impact on the overall availability among the WT subassemblies for the first five years. At the same time, rotor hub subassembly recorded the first priority between all subassemblies from year six to year nine. From year ten to year twelve, the gearbox represents the first priority. For the last eight years, the mechanical brake has been the greatest influence on the overall system availability among all subassemblies of WT. Thus, the importance or focus of one subassembly along the system's total lifetime and the consideration that its improvement will enhance the overall system availability must be changed according to these findings. It is very important to point out that the proposed dynamic reliability and availability IMs will generate another dynamic ranking

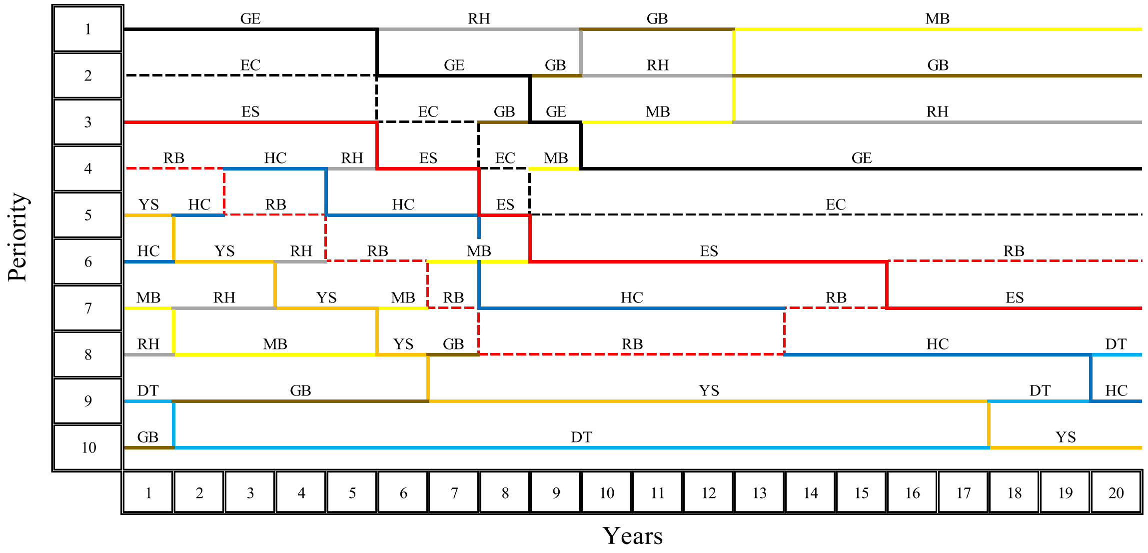


FIGURE 15. Dynamic ranking of subassemblies according to availability.

TABLE 4. Dynamic MTBF-IMs for various WT subassemblies.

Subassemblies	ES	EC	HC	YS	RH	MB	RB	GB	GE	DT
After 1 year	1.15E-08	2.39E-09	4.08E-09	9.79E-10	3.29E-08	8.35E-09	1.2E-08	3.56E-08	4.23E-08	4.63E-09
After 2 years	8.3E-09	1.73E-09	2.95E-09	7.07E-10	2.37E-08	6.03E-09	8.67E-09	2.57E-08	3.06E-08	3.34E-09
After 3 years	4.87E-09	1.01E-09	1.73E-09	4.15E-10	1.39E-08	3.54E-09	5.09E-09	1.51E-08	1.79E-08	1.96E-09
After 4 years	2.14E-09	4.44E-10	7.58E-10	1.82E-10	6.1E-09	1.55E-09	2.23E-09	6.61E-09	7.86E-09	8.6E-10
After 5 years	5.11E-10	1.06E-10	1.82E-10	4.36E-11	1.46E-09	3.72E-10	5.34E-10	1.58E-09	1.88E-09	2.06E-10
After 6 years	2.41E-11	5.02E-12	8.56E-12	2.05E-12	6.89E-11	1.75E-11	2.52E-11	7.46E-11	8.88E-11	9.71E-12
After 7 years	1.29E-14	2.68E-15	4.56E-15	1.1E-15	3.68E-14	9.34E-15	1.34E-14	3.98E-14	4.73E-14	5.18E-15
After 8 years	8.67E-23	1.8E-23	3.08E-23	7.38E-24	2.48E-22	6.3E-23	9.06E-23	2.68E-22	3.19E-22	3.49E-23
After 9 years	3.13E-29	6.5E-30	1.11E-29	2.66E-30	8.93E-29	2.27E-29	3.27E-29	9.67E-29	1.15E-28	1.26E-29
After 10 years	3.41E-36	7.1E-37	1.21E-36	2.91E-37	9.75E-36	2.48E-36	3.57E-36	1.06E-35	1.26E-35	1.37E-36
After 11 years	6.62E-40	1.38E-40	2.35E-40	5.64E-41	1.89E-39	4.81E-40	6.92E-40	2.05E-39	2.44E-39	2.67E-40
After 12 years	4.3E-45	8.94E-46	1.52E-45	3.66E-46	1.23E-44	3.12E-45	4.49E-45	1.33E-44	1.58E-44	1.73E-45
After 13 years	1.86E-52	3.87E-53	6.6E-53	1.58E-53	5.31E-52	1.35E-52	1.94E-52	5.75E-52	6.84E-52	7.49E-53
After 14 years	5.44E-63	1.13E-63	1.93E-63	4.63E-64	1.55E-62	3.95E-63	5.68E-63	1.68E-62	2E-62	2.19E-63
After 15 years	1.95E-65	4.06E-66	6.92E-66	1.66E-66	5.57E-65	1.42E-65	2.04E-65	6.03E-65	7.18E-65	7.86E-66
After 16 years	1.11E-65	2.3E-66	3.93E-66	9.42E-67	3.16E-65	8.04E-66	1.16E-65	3.42E-65	4.07E-65	4.46E-66
After 17 years	6.93E-66	1.44E-66	2.46E-66	5.9E-67	1.98E-65	5.03E-66	7.24E-66	2.14E-65	2.55E-65	2.79E-66
After 18 years	4.11E-66	8.55E-67	1.46E-66	3.5E-67	1.17E-65	2.99E-66	4.29E-66	1.27E-65	1.51E-65	1.66E-66
After 19 years	1.95E-66	4.05E-67	6.91E-67	1.66E-67	5.56E-66	1.41E-66	2.03E-66	6.02E-66	7.16E-66	7.84E-67
After 20 years	5.92E-67	1.23E-67	2.1E-67	5.04E-68	1.69E-66	4.3E-67	6.19E-67	1.83E-66	2.18E-66	2.39E-67

if the number of the subassemblies differs from the number introduced in this work. This means that it is critically important in the planning stage of the WFs to collect reliability data (failure and repair rates) of each subassembly from WFs that have the same operating characteristics and construct the guide ranking of the subassemblies as in Fig. 14 and Fig. 15. This will help the operators and the developers of the WF to identify the critical subassemblies that the maintenance will be focused on.

As mentioned before, the system's availability depends on more factors than reliability. Thus, availability improvement is necessary for assessing the overall system performance. System availability improvement will be excited by either improving the MTBF or MTTR for the subassemblies that have priority one in Fig. 15. Therefore, DAIMs for MTBF and MTTR will be determined utilizing Equations (12) and (13). Table 4 and Table 5 list the results of the dynamic IMs for MTBF and MTTR of various WT subassemblies,

TABLE 5. Dynamic MTTR-IMs for various WT subassemblies.

SUBASSEMBLIES	ES	EC	HC	YS	RH	MB	RB	GB	GE	DT
AFTER 1 YEAR	0.000844	0.000234	0.000368	0.000188	0.00192	0.000705	0.001231	0.002757	0.001931	0.000846
AFTER 2 YEARS	0.00061	0.000169	0.000266	0.000136	0.001386	0.000509	0.000889	0.00199	0.001394	0.000611
AFTER 3 YEARS	0.000358	9.92E-05	0.000156	7.96E-05	0.000813	0.000299	0.000521	0.001167	0.000818	0.000358
AFTER 4 YEARS	0.000157	4.35E-05	6.83E-05	3.49E-05	0.000357	0.000131	0.000229	0.000512	0.000359	0.000157
AFTER 5 YEARS	3.76E-05	1.04E-05	1.64E-05	8.36E-06	8.54E-05	3.14E-05	5.48E-05	0.000123	8.59E-05	3.76E-05
AFTER 6 YEARS	1.77E-06	4.91E-07	7.72E-07	3.94E-07	4.03E-06	1.48E-06	2.58E-06	5.78E-06	4.05E-06	1.77E-06
AFTER 7 YEARS	9.45E-10	2.62E-10	4.12E-10	2.1E-10	2.15E-09	7.89E-10	1.38E-09	3.08E-09	2.16E-09	9.47E-10
AFTER 8 YEARS	6.37E-18	1.77E-18	2.77E-18	1.42E-18	1.45E-17	5.32E-18	9.28E-18	2.08E-17	1.46E-17	6.38E-18
AFTER 9 YEARS	2.3E-24	6.37E-25	1E-24	5.11E-25	5.22E-24	1.92E-24	3.35E-24	7.49E-24	5.25E-24	2.3E-24
AFTER 10 YEARS	2.51E-31	6.95E-32	1.09E-31	5.58E-32	5.7E-31	2.09E-31	3.65E-31	8.18E-31	5.73E-31	2.51E-31
AFTER 11 YEARS	4.86E-35	1.35E-35	2.12E-35	1.08E-35	1.11E-34	4.06E-35	7.09E-35	1.59E-34	1.11E-34	4.87E-35
AFTER 12 YEARS	3.16E-40	8.75E-41	1.38E-40	7.02E-41	7.17E-40	2.64E-40	4.6E-40	1.03E-39	7.22E-40	3.16E-40
AFTER 13 YEARS	1.37E-47	3.79E-48	5.95E-48	3.04E-48	3.1E-47	1.14E-47	1.99E-47	4.46E-47	3.12E-47	1.37E-47
AFTER 14 YEARS	3.99E-58	1.11E-58	1.74E-58	8.89E-59	9.08E-58	3.34E-58	5.82E-58	1.3E-57	9.13E-58	4E-58
AFTER 15 YEARS	1.43E-60	3.97E-61	6.24E-61	3.19E-61	3.26E-60	1.2E-60	2.09E-60	4.67E-60	3.27E-60	1.43E-60
AFTER 16 YEARS	8.12E-61	2.25E-61	3.54E-61	1.81E-61	1.85E-60	6.79E-61	1.18E-60	2.65E-60	1.86E-60	8.14E-61
AFTER 17 YEARS	5.09E-61	1.41E-61	2.22E-61	1.13E-61	1.16E-60	4.25E-61	7.42E-61	1.66E-60	1.16E-60	5.1E-61
AFTER 18 YEARS	3.02E-61	8.37E-62	1.32E-61	6.72E-62	6.86E-61	2.52E-61	4.4E-61	9.85E-61	6.9E-61	3.02E-61
AFTER 19 YEARS	1.43E-61	3.97E-62	6.23E-62	3.18E-62	3.25E-61	1.19E-61	2.08E-61	4.67E-61	3.27E-61	1.43E-61
AFTER 20 YEARS	4.35E-62	1.21E-62	1.89E-62	9.67E-63	9.88E-62	3.63E-62	6.34E-62	1.42E-61	9.94E-62	4.36E-62

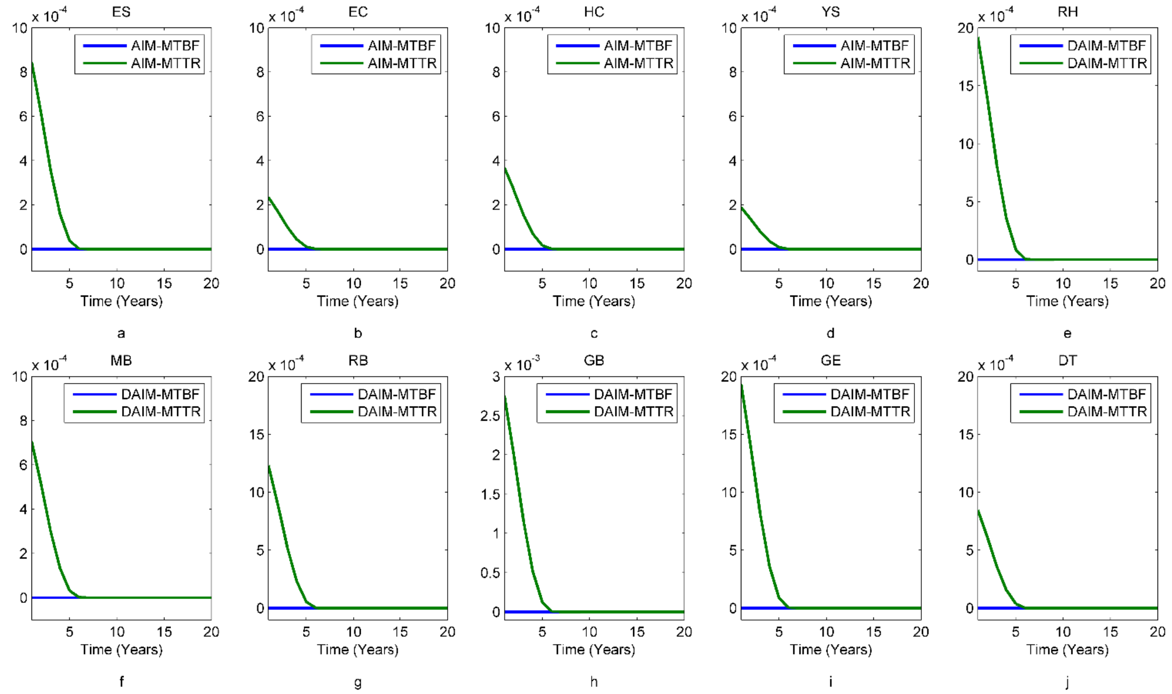


FIGURE 16. Effect of the dynamic MTBF-IMs and MTTR-IMs of various WT subassemblies to improve overall system availability.

respectively. Fig. 16 illustrates the effect of the dynamic MTBF-IMs and MTTR-IMs of various WT subassemblies to improve overall system availability.

Comparing the IMs of MTBF and MTTR of each subassembly can determine whether the MTBF or MTTR of that subassembly has more influence on the WT availability.

According to the analysis (Fig. 15), if the WT availability needs to be improved, the efforts should be concentrated on increasing the availability of the subassemblies that have the first ranking (GE, RH, GB, and MB). Furthermore, it is better to pay more attention to MTTR for those subassemblies; their MTTR on the overall system availability is greater than the corresponding effect of the MTTF of those subassemblies, as indicated by a comparison of dynamic MTBF-IMs and MTTR-IMs.

VII. CONCLUSION

This paper has carried out a complete and detailed RAM analysis of various wind turbine subassemblies utilizing the Weibull PDF. Moreover, the dynamic important measures-based reliability and availability method has been proposed and utilized as a modified tool for identifying the subassembly that has the most significant impact on the whole system's reliability and availability. It has been observed that the ranking of subassemblies according to the impact on the overall performance of the WT is a dynamic ranking. This means that this ranking varied (not fixed) through the expected lifetime of the WT. The main reason behind this is using the flexible Weibull PDF, which combines the permanent and intermittent faults that make the availability vary through the lifetime of the WT. From the availability point of view, the ranking of the most critical subassemblies is derived: GE, RH, GB, and MB. The better insight intends by this work to the wind system operator and its designer to predict and select the optimal operating point in dynamic situations and select the appropriate maintenance strategy of each subassembly to improve the system reliability and availability.

APPENDIX

The following table gives the technical data of the WTs that used in this analysis.

TABLE 6. Wind turbines subassemblies.

Reference	WT type	Technology used	Rating
[7]	NA	Asynchronous dual speed generator coupled with gear.	3.735 MW wind farm contains 15 WT, each one rated 225 kW.
[37]	V44-600kW	Wound-rotor asynchronous generator and "OptiSlip" technology for RCC	600 kW
	V90-2MW system	DFIG and partially rated converter	2 MW
[38]	723 Sweden WT	DFIG-PRC	NA
[39]	NA	WRIG	2 MW
[40]	Danish designs	NA	1.5 to 2 MW DOWEC project: 5 MW (100 WTs)

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