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Editorial

Assessment of the Reliability of Wind Farm Device on the Basis of Modeling Its Operation Process

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Abstract: The evaluation and analysis of the procedures for determining the dependability of WF wind farm equipment employed in a few publications are this article's main problems. The publications chosen for review specifically mention investigations into the dependability of WF wind farm machinery. The following topics were the authors' main areas of analysis: description and review of the techniques used to represent how technical items operate and the selection of the weight of the theoretical ideas of reliability that were used to gauge the dependability of the wind farm equipment under study. The authors of the studied works set out to address a number of significant problems pertaining to the modernization of the management of the WF equipment renewal process. The subjects of the studied works suggest that the established models of the technical object's operational process are particularly significant in both the theory and practice of the reliability of technical objects. Using Kolmogorov–Chapman equations, models of the WFD operating process that are based on the idea of Markov processes are very helpful for simulation studies.

Keywords: wind power plant; reliability; simulation testing; intelligent systems; servicing process; Markov processes; expert system

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1. Introduction

Complex technical infrastructure, such as wind farm equipment, when employed, loses its functional qualities throughout its operation, and its capacity to carry out the necessary functions (their intended tasks) declines. In the literature, the issue of defining usable capacity is referred to as a functional resource. The diminishing reliability of technical objects, including WF wind farm equipment, is likewise closely related to decreasing useful capacity. Age-related changes and the damaging impacts of internal (temperature, pressure, etc.) and external elements are the main causes of technical items' decreasing reliability. As a result, the issue of making continuous and current measurements and assessments of the equipment reliability of wind farms arises. The organization of the renewal of the functional qualities of complicated technological equipment can be made based on knowledge of the existing the reliability of wind farm equipment. The issue is highly complex for technological instruments that continuously carry out their functions and without the option of being taken out of service; these instruments include wind farm equipment, electricity systems, medical systems, and others. The primary research goal stated in the studied articles is now to understand how reliable wind farm equipment is. The following publications [1–4] present the current level of reliability of in-service equipment of wind farms (WFs) and other sophisticated technical facilities, which is an ongoing research issue.

1. Assessment of the Operation Process of Wind Power Plant's Equipment with the Use of an Artificial Neural Network. *Energies*, 2020, 13, 2437;
2. Reliability Testing of Wind Power Plant Devices with the Use of an Intelligent Diagnostic System. *Energies* 2022, 15, 3583.
3. Assessment of the Reliability of Wind Farm Devices in the Operation Process. *Energies* 2022, 15, 3860.
4. Organization and Reliability Testing of Wind Farm Device in its Operation Process. *Energies* 2022, *15*, 6255.

The challenges of modeling technical objects themselves and their operation processes are of special importance in reliability studies of complex technical objects, including WF equipment. The reliability of wind farm equipment is a significant research question. The works present issues with graphical and analytical modeling for assessing the dependability of technical products. Models of the operation of technical items based on the idea of Markov processes are particularly crucial in the theory and practice of the reliability of technical objects. Kolmogorov–Chapman equations that analytically describe the related (created) model of the exploitation process are utilized for the non-reliability assessment of technical items in these models. This article also presents this kind of study methodology.

By applying reliability studies, it is possible to estimate the value of the quantity used in the study describing the reliability of the wind farm equipment in operation. Large bodies of data indicating the precise conditions of a certain facility's operation procedure are the most valuable. The testing period, which was excessive in this study, prevents it from being very effective. As a result, simulation studies of the reliability of equipment on the operational wind farm are documented in the literature in the research practice on this topic. The models were created to describe the operational process of wind farm equipment. The adoption of a specific theoretical reliability magnitude to evaluate the reliability of wind farm equipment in use, and the presentation of a method to describe and evaluate the resource for further use of wind farm equipment, are the factors that are considered to be of the utmost importance in these studies.

In this paper, the problems with a simulated assessment of the reliability of WF equipment in operation are highlighted. Testing the process of exploitation of intricate technological items, such as the WF and TWG electrical subsystems, is a substantial cognitive challenge (Main Power Supply Point). Since WF users must understand how to handle the organizational and technological processes that renew WFs in a technical service system, this issue is very important. A well-designed WF renewal system is the only way to save money and make sure that these facilities work as efficiently as possible while saving money.

This article's review and description of the used materials chosen from significant publications [5–9] expressly displaying the dependability of WF research are related to these issues. The article will discuss topics such as modeling the level of dependability of in-service wind farm equipment, describing the theoretical reliability quantities used to measure that reliability, and describing the evaluation of the resource for more wind farm equipment use.

The following structure and organization of the work were adopted in order to address the main aim of this article, which the authors set out to address in the form of knowing the reliability of the equipment of the wind farm based on the publication.

Reliability analysis of WF equipment is presented in Section 2, "Assessment of the Operation Process of Wind Power Plant's Equipment with the Use of an Artificial Neural Network". The reliability of WF equipment was studied through simulation using the following models of the operational process. This article presents three of its models for simulation testing of the wind farm operation process.

- *Model A*: an operation process of a wind power plant that uses an intelligent maintenance system with an artificial neural network.
- *Model B*: an operation process of the object that uses information in bivalent logic: a model with a maintenance system organized by planning its optimal prevention activities.
- *Model C*: an operation process of a wind power plant with a maintenance system that is classically organized without any examination of the state in the assessment process: a strategy for the maintenance of the object with the period of prevention activities being planned.

An important aspect of the reliability studies presented in this work is the demonstration of the impact of changes in the time and conditions of renewal of WF equipment on its reliability, including

1. The regeneration of the object in the designed intelligent maintenance system that uses the information from an artificial neural network;
2. A traditional manner of the organization of the maintenance system (model C);
3. Defined strategies of prevention activities in relation to the quality of the operation process;
4. An assessment of the quality of the operation process of the wind power plant with a traditional method of the organization of the maintenance system;
5. The conducting of a qualitative assessment of the strategies adopted to maintain the fitness of the WPP for the quality of the operation process.

Section 3 includes a reliability assessment of WF equipment in terms of the impact of the intelligent diagnostic system WPPES on its reliability. The section is titled "Reliability Testing of Wind Power Plant Devices with the Use of an Intelligent Diagnostic System". The simulation research of the reliability of WF equipment included the following three models of the operational process, which were created for the purposes of the simulation testing because it would take too long to evaluate the actual operation process:

- *Model A*: the process by which intelligent systems in wind farm equipment assist in making decisions about the safety of their use (the model with the operating system with WPPES and an artificial neural network);
- *Model B*: Wind farm equipment without intelligent systems to support decisions on how safely to operate it (operating system model with WPPES and artificial neural network);
- *Model C*: Basic equipment operation procedure for wind farms.

The authors utilized a four-state model to explain the operation process of wind farm equipment in reliability studies in the fourth section, "Assessment of the dependability of wind farm devices in the operation process". The essay discusses a significant operational issue with the WF and how it affects the equipment reliability of wind farms. In their research, which is presented in this article, the writers looked at the following issue:

1. Testing and Evaluation of the Reliability of Wind Farm Devices in the Operation Process Due to the Decrease in the Value of the Repair Time.
2. Testing and Evaluation of the Reliability of Wind Farm Devices in the Operation Process Due to Changes in the Value of Time between Successive Failures of Wind Farm Devices.

The authors employed a five-state model to explain the operational process of wind farm equipment in their reliability studies in Section 5, "Organization and Reliability Testing of a Wind Farm Device in Its Operational Process". The five-state operating process model that was described, in our opinion, best captures the actual operation of the wind farm equipment in this context. In comparison to prior solutions in this field that were published in other papers, this aspect is where this work differs from others. The challenge of coordinating the replacement (repair) process of finding farm equipment using the SERV intelligent expert system is discussed in the paper, along with the effects of the suggested solutions on the degree of equipment reliability.

Review of the Literature

Complicated technical equipment used in the operational procedure performs worse than other equipment with a diagnostic system and its ability to complete the required (planned) responsibilities is compromised. In the literature, the utility problem is referred to as a functional resource [10,11]. The decrease in operating capacity is closely related to the decline in technical facility dependability, particularly that of WF equipment. The major reasons for the decline in the dependability of technical structures are aging and the negative effects of external variables. These factors make it more difficult to predict the current reliability of WF equipment and simulate the operation of sophisticated technological components. When it comes to medical devices, equipment for wind farms, and other products that always do what they are meant to do, the situation is very difficult.

As a result of the widespread adoption of modern technologies such as artificial intelligence and intelligent systems, current research supporting the creation of expert and advisory systems focuses on issues relating to the development of techniques for acquiring a person's specialized expertise. This topic has been covered in earlier works [12,13]. The challenges of monitoring the dependability of wind farm equipment when it is in use are depicted visually in Figure 1.

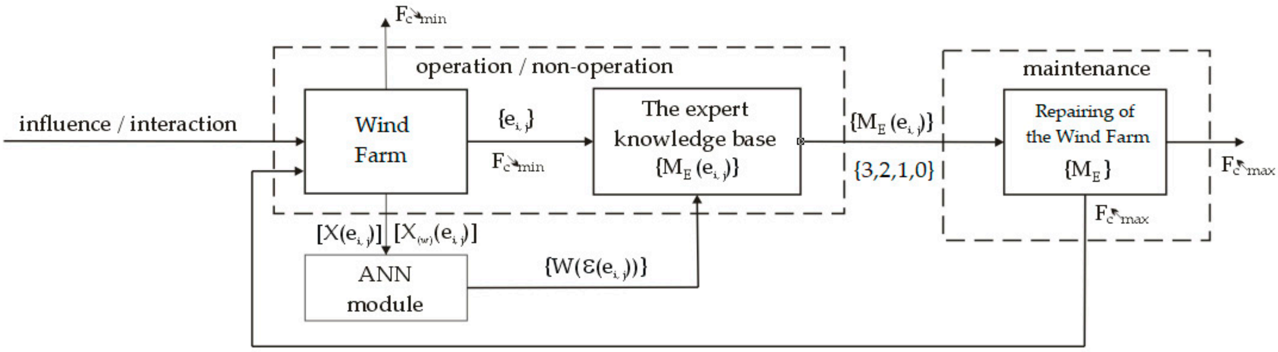

Figure 1. The use of an artificial neural network to exploit a technical object.

The fallowing is represented by labels in Figure 1:

- $X(e_{i,j})$ represents whether the diagnostic signal is the j-th element of the i-th set;
- $X_{(w)}(e_{i,j})$ is a benchmark signal. For $X(e_{i,j})$;
- F_C the minimum or maximum product use feature value;
- $\{M_E(e_{i,j})\}$ IS the knowledge foundation for customer service;
- $\{M_E\}$ is the system for upgrading technical infrastructure;
- $W(\varepsilon(e_{i,j}) = \{3, 2, 1, 0\})$ Item information value for the diagnostic state assessment logic "j" within the "i" object module.

This diagnosis makes it possible to ascertain the current level of equipment reliability employed by WFs and other highly developed technical facilities. In multi-valued logic, using inference (state recognition) to make a diagnosis is particularly beneficial [14]. Today's development of specialized diagnostic instruments has advanced significantly. These issues have been addressed in earlier studies [15–17]. These problems are glaringly evident in the diagnostics of medical devices, energy technology, etc. However, each one is unique to the entity being analyzed because they are diagnostic instruments. There is no diagnostic tool on the market with a wide variety of practical diagnostic uses. Per Duer and colleagues' research, diagnostic tools are a common and dependent sort of technical repair procedure. The functional components of this modular approach include measurement, diagnosis, and a diagnostic knowledge base. The only information bases, measuring systems, acquisition methods, etc. that can be used by a piece of technology or equipment are those that are related to measurement.

Minimizing the costs related to preventive measures is possible thanks to the proposed system of automatic facility performance regeneration. The expenditures related to organizing a facility maintenance system are completely minimized by this approach. When necessary, the object can be regenerated. This approach offers a facility-based artificial neural network-based intelligent diagnostic system; crucially, one that reliably recognizes the states of the facility for which preventive actions should be taken [18,19]. No loss and no expenses are incurred as a result of the inefficient use of the facility, which may happen during operation when the facility is not in use or is only partially efficient. The costs involved in performing regeneration of facility elements that have already been regenerated or are capable of doing so are eliminated by this method. The intelligent traffic maintenance system (which includes the intelligent diagnostic system) gives incomplete conditions of one or more of the internal (structural) parts of the object that need to be regenerated.

In the works by Kacalak et al. and others [20–23], a summary of the effective measuring system, a fundamental part of the diagnostic system structure, is provided. Theoretical foundations for developing a measuring system using a computer measurement card to create a measurement database for the diagnostic system are also provided. To aid in the inquiry, a sample database that tracks data for the individual in question was used. These studies [24] talk about how hard it is to make intelligent systems for diagnosing and testing technical components that combine human knowledge with automated technology.

The technical diagnostics of technological apparatus is a significant issue that promotes the coordination of technical tasks. The apparatus's diagnostic tests are designed to evaluate and characterize the technical condition of the structure that is being examined. For technical device diagnosis, state recognition in bivalent and trivalent logic is used. When deciding how to renovate a technical facility, the three-valued logical diagnoses of the diagnostician are the most important things to understand.

The authors included a variety of topics in their study, including the foundations and methods for developing simulations of complex technical infrastructures. The focus of this research is on the qualitative evaluation of such a structured traffic maintenance procedure, which is a topic covered by the authors of these works. To do this, our study offers simulation testing software. A description of the operational process models for the technical facilities must be included in the test program along with the choice of the test inputs, the service life of the technical facility, the total amount of time needed to regenerate (repair), the use of the facilities, and the establishment of qualitative indicators for the evaluation of the regeneration of the facility during the operational process. In order to help with the investigation, simulations were used to see what would happen if a technological object was put into an intelligent system with an artificial neural network.

The study by Dyduch and Siergiejczyk et al. describes reliability. There must be in-service investigations [25,26]. The electromagnetic compatibility of the electrical and electronic equipment used, albeit equally important, is not covered in this article. The impact of electromagnetic fields on the functionality of electronic equipment, however, cannot be disregarded [27–29]. Similar to dependability research, it is essential to model the technical object itself as well as its operational procedure. A key area for research is the reliability of wind farm equipment.

The problems with graphical and analytical modeling for the assessment of the dependability of technical facilities are illustrated in the works of Siergiejczyk and colleagues. Models of technical object exploitation processes based on Markov process theory are critical in the theory and practice of technological object reliability. These models use the Kolmogorov–Chapman equation to evaluate the reliability of technological goods. This study approach is also presented in this article.

Another field of reliability research is the use of Chapman–Kolmogorov equations in the operation of technical structures and systems. This is especially evident in the literature of Siergiejczyk and others [30]. The essay discusses the operational analysis and dependability of power supply systems in PSS transport telematics systems. The paper defines PSS in TTD and offers power supply system solutions from both primary and backup sources. This enables the identification of dependencies that demonstrate the probability that the system will continue to operate normally or experience a security emergency or security failure. After the PSS quality analysis in TTD was completed, an evaluation of the quality index's value for supply continuity was made. With the aid of this indicator, it is possible to show how the quality of continuity of the CQoPS power supply depends on more factors than only reliability. The example shows how to calculate CQoPS for both main and backup power using three observations, each of which affects quality. Other public facilities may take advantage of the variables provided by PSS's quality and reliability-in-service models (including critical infrastructure). Such a task is carried out by essential infrastructure.

Nakagawa et al. [31,32] discuss the modeling of the technical facility operation processes in their subsequent studies. The author's research is also significant. These publications outline the mathematical strategy used to duplicate this technique. Both the object's present states and any transitions (changes) that might have occurred during the exploitation process are evaluated by the author. An essential part of simulating the facility's operational process is the strategy for structural renewal that is displayed (or used) in the maintenance system. The author's research led to the development of a new method called "using the object's current state", which is also called "operating the object based on its state."

In works by Badrzadeh et al. and Pogaku et al. [33–38], it is discussed how electrical equipment is used and operated in wind farms. This study examines the modeling, programming, and construction of electrical machinery for wind farms.

A critical stage in simulating the operation of a complex technical structure is the development of a model of the process of updating the intelligent traffic maintenance system. Among other areas, publications have covered these topics. In Duer et al.'s and Buchanan et al.'s [39] research, the authors tackle issues with the definition of systems' maintenance models. The shape of the object matrix structure (dimension) is assumed as a result. It transforms into a matrix for maintaining objects. The elements of the holding matrix correspond to the basic parts of the object. The components of the structural maintenance matrix make it clear that certain subsets of these technical and technological operations must be completed in order to renew a given portion of the structure. The work of dividing up the structure's parts into tasks for the refurbishment that uses the appropriate materials and resources is challenging. These issues are consistently developed and improved throughout the author's publications.

It is crucial to understand the technical gadgets' design, performance, and incorrect diagnosis. Operational problems with wind farm infrastructure are discussed in a subsequent study.

Duer used analytical models that consider reliability dependencies to publish studies of the dependability of wind farm machinery in his publications. However, his findings indicate that applying this approach in simulation research is rather difficult. The planning, execution, and analysis of simulations conducted for the assessment of the efficiency of the maintenance system for wind power plant equipment are described in the study. Models of the operational procedures for wind farm equipment are very relevant to the reader. The organization of the building and the functioning of complex technical facilities are both covered. Three WF models of the equipment's operation were used in the simulation. An intelligent traffic maintenance system based on artificial neural networks is used in Model A, a wind power operational strategy. The second model, referred to as Model B, is an object operation method that makes use of bivalent logic and contains a maintenance system designed to identify the most effective preventive actions. The third method is Model C, which does not contain a status test during the evaluation phase but operates a maintenance system for a wind power plant with structured that are generally built. The building is maintained by manually drafting preventive measures and randomly selecting the operator to be in charge of them.

Publications do a fantastic job of demonstrating the problems by describing and testing the various components that make up technical structures. There are no studies that fully describe the challenges of coordinating the operation of complex technical apparatuses for study, though. The goal of the paper is to mimic the operating reliability of the WF equipment as a result. For this assignment, the following research problems need to be solved: The first difficulty is comprehending and describing problems with WF device diagnosis. Another issue is determining and detailing how to operate and maintain the equipment used in wind farms. A major part of the study is the importance of understanding and describing the structure of the technical maintenance system when the tested structure is in use.

Technical equipment reliability assessments for wind farms using intelligent systems are rigorously prepared. The tested reliability values were obtained in the form of the capacity function (Kg(t)) for the stated operating process using the created WF model and analytical dependencies.

2. Assessment of the Operation Process of Wind Power Plant's Equipment with the Use of an Artificial Neural Network

Using Data from an Artificial Neural Network, the Planned Intelligent Maintenance System Will Let Objects Grow New Parts

Analysis of the research findings shown in (Figure 2) demonstrates that the readiness coefficient value for each of the three operation process models (A, B, and C models) grows as the value of time (T_p) increases toward time (T_a), as shown in the form of dependences. This conclusion appears to be accurate as well, because longer, more comprehensive preventive efforts are associated with longer-lasting maintenance activities. The maintenance system's complete regeneration of the object regenerates–restores the source (capacity) of the item to carry out its functions. As a result, the investigations' readiness function values (K_g(t)) rise as time (T_p) is increased. Among the three maintenance process models tested, Model A had the highest value of the readiness function (K_g(t)).

On the basis of these considerations, it can be said that the maintenance–regeneration system of wind power plants needs to be efficiently enhanced. Modern technologies such as neural networks and expert systems must be introduced and put to use in order to support the organization of the prevention systems of technical objects, which have a big impact on the effectiveness of their operation process.

From the analysis of the results obtained from the tests in relation to the input data (T/Ta = {ba}) and (Ta/Tp = {bb}) shown in Figure 2, performed during the research on the impact of the time of renewal activities (Tp) on the quality of the wind turbine operation process expressed by the value of the readiness function (Kg (t)), The highest value (Kg(t)) was obtained in model A(with renewal using the smart system) and was (Kg_A = 0.65), while the results in the other models were (Kg_B = 0.58, Kg_C = 0.037).

The subfigures (a, b, c and d) show the results of simulation studies assuming different variants of dependencies that the team under considered interesting in their research.

Analysis of the research findings reveals that an increment in the readiness function's value ($\Delta K_g = K_{gA} - K_{gB}$)), which represents the difference between value (K_g(t)) for value (T/T_a = 1) and (T_a/T_p = 1) in A and B models, is (ΛK_g = 0.21); this is obvious from the research findings. Taking these factors into account, we can say that the SERV computer program, when used with intelligent maintenance systems, is a modern and effective way to help with this process [4].

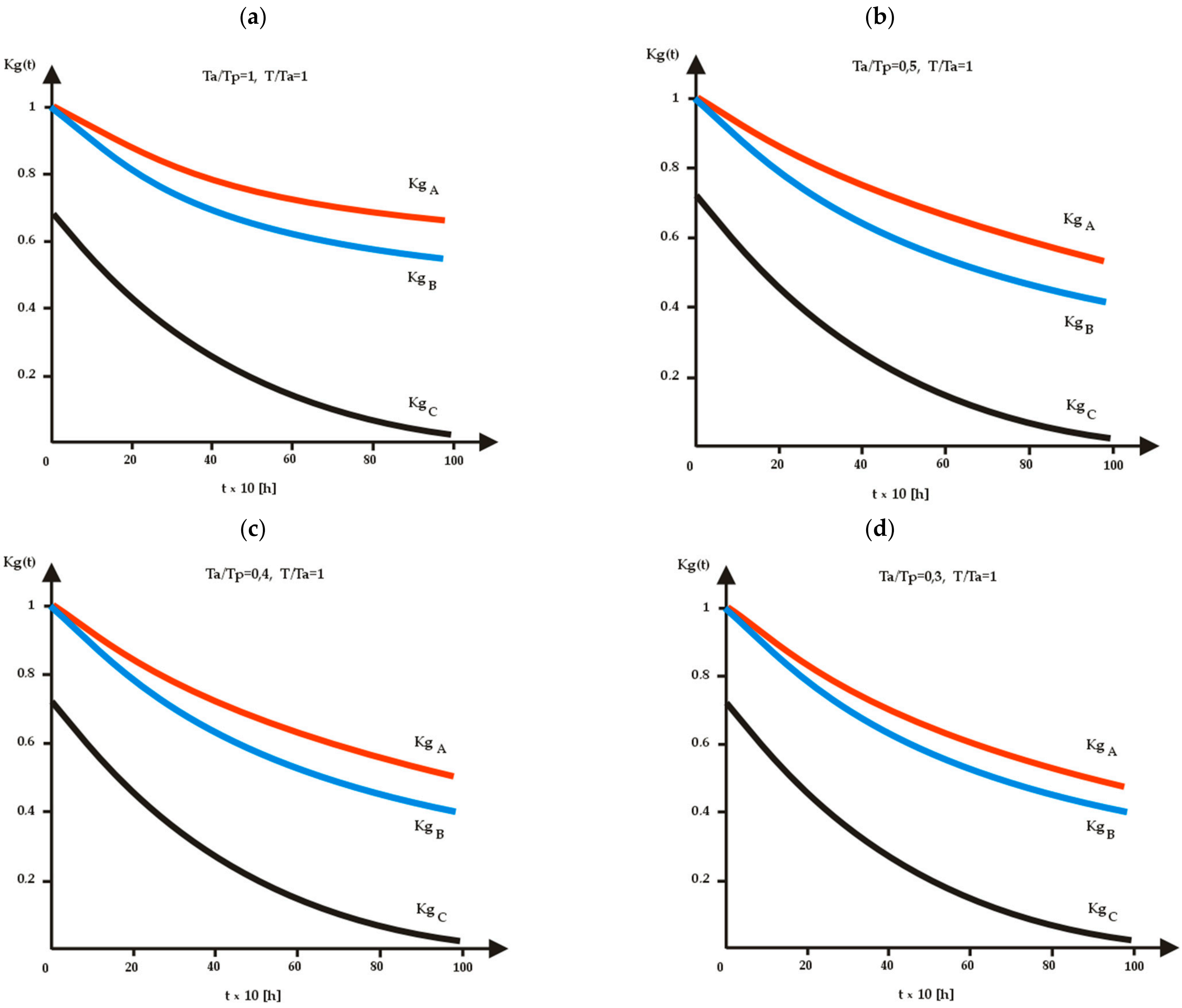

Figure 2. Courses for the readiness function Kg(t) of a wind power plant's operation process that employs several forms of condition monitoring systems T/Ta = 1. Figure 2's symbol represents: K_g(t): availability capability; t: operating period; T_a: time for immediate repairs; T_P: the average length of planned repairs to wind power plants.

3. Reliability Testing of Wind Power Plant Devices with the Use of an Intelligent Diagnostic System

Assessment of the Reliability of Wind Farm Equipment on the Basis of the Readiness Function

Three different models of facility operation processes were examined to see how reliable the facility was after renovations to the maintenance system (models A, B, and C). The outcomes discovered are represented visually in (Figure 3). The simulation tests looked at the dependability indicators for the operation of wind farm equipment when utilizing the WPPES expert system, an artificial neural network (model A), and FW without the WPPES system (models B and C). The reliability assessment of the object's availability factor Kg and non-availability factor Fch were examined in the simulation analysis. Charts display the test findings that were achieved (Figure 3).

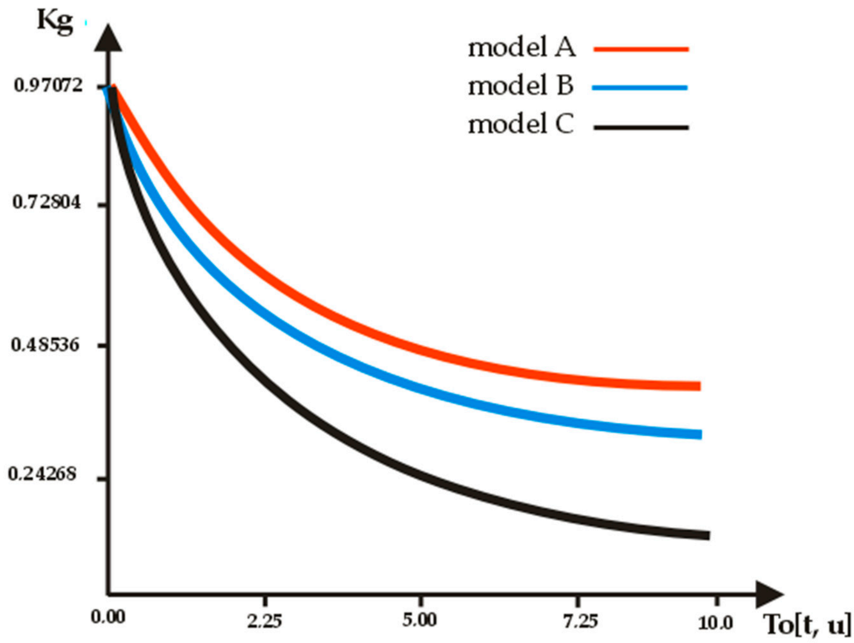

Figure 3. The graph of the $K_g(t)$ readiness function for the tested wind farm equipment models (A, B, and C) throughout the operation, where: T_o is the object's simulation test time and t, u is the process's operational time units.

The method for testing and evaluating the reliability characteristics of wind farm equipment during operation is presented in this study. Additionally, the facility operation process quality function (Fc(t)) and operation process absorption (non-readiness) function (Fch(t)) were offered as two new quantities for the reliability testing of the tested object. The reliability of how wind farm equipment works is shown by these two metrics, whose values are new and have not yet been published.

Research, analysis, and observation of the real operating process were used to provide the foundation for how the simulation tests of the wind farm devices were organized and the input data for the tests were determined. The literature is continually developing on the subject of evaluating the dependability of complicated technology. Three models of the wind farm operation process were created for the research study's simulation in the article.

Model A, which explains how wind farm equipment equipped with intelligent technologies supports decision-making on the safety of its use, is the first of the models created. Model B, the second model created, describes the operation of wind farm equipment without the assistance of any intelligent WPPES systems for decision-making on the safety of its use. The third model, model C, is a straightforward (theoretical) operation method for wind farm machinery. The article discusses and covers the following topics with regard to planning simulation tests:

1. Models (A, B, and C) depict how the wind farm's machinery operates.
2. A test strategy is created.
3. Preparation: information is entered about the tested object's functionality, such as its use time (T), working life (TNA), time to remove unfitness (TNP), and planned repair time (TNP).
4. The operation process (use and maintenance) of the wind farm equipment is understood and described.

It is challenging to assess the equipment's reliability characteristics while it is operating, a problem that is discussed in the article. This finding's complexity is a result of the difficulty in gathering study input data. Over a lengthy period, one can gather numerical data explaining how the Wind Farm's machinery functions. The actual operation procedure of the wind farm equipment's observation time (measurement of downtime and service life) is typically expressed in years during its "life." A simulation test is the sole sensible (reasonable) method for carrying out this kind of study. This kind of research calls for an understanding of the real operational process of wind farm equipment, a description of it, and the selection of trustworthy input data. A solid testing strategy (how to test the wind farm equipment) is at the heart of each study. The organization of the operation process is modeled, and this structure serves as the foundation for the simulation research of the operation process of wind farm devices.

In simulation tests, the following reliability values were looked at to figure out how reliable the wind farm device would be while it was running:

- Model (A, B, and C) coefficient (K_g) value. The value tested in the model is (K_{gA} = 0.7508). On the other hand, this value is as follows for the remaining models: K_{gC} is equal to 0.2332 and K_{gB} = 0.4931, respectively. The arrangement of the utilization of wind farm equipment in the operational process in Model (A) is therefore the most effective system.
- The purpose of wind farm equipment's operational process quality (F_C) in models A, B, and C). The model (A), where F_{CA} = 0.2239, has the highest standard of equipment utilization in the operation of a wind farm (F_C). For models B and C, these values, which add up to (F_{CB} = 0.1979 and F_{CC} = 0.0959), are, however, lower.
- Equipment in wind farms that is unreliable during operation (F_{ch}). This is the highest number (F_{chC} = 0.9750) that was considered for model C. This value (F_{chA} = 0.7508) for model A is the smallest value. Additionally, we can draw the conclusion that the equipment set for the Wind Farm is capable of operating during the analyzed operational period (t = T) for time (t = 3/4T) in model C.

4. Assessment of the Reliability of Wind Farm Devices in the Operational Process

Using the Availability Factor as a Basis for Reliability Analysis of Wind Farm Equipment

The service elements are renewed at the appropriate level based on their present status from the "3, 2, 1, 0" set, using data from the SERV system. The implementation of the renewal process (the use of technical and technological activities) is then also the best course of action. To fully refresh the components of the WF devices, only those technological operations (renewing service elements) are carried out that are necessary and developed by the SERV system. As a result, the organization and implementation issues with the wind farm equipment renewal process will lead to a shorter turnaround time for repairs. Figure 3 shows what was learned from testing and evaluating the reliability of wind farm equipment while it was running because maintenance time was cut down.

The assumed average repair time of 0.3 indicates that the renewal time of FW devices was reduced to 70% in the maintenance system based on information from the SERV system compared to the average value of the renewal time of wind farm devices implemented in the maintenance system organized traditionally (classic). The study confirmed (through testing) that the effect of the typical repair time is equal to the test value (1.0) suitable for replacing wind farm devices in the traditionally arranged maintenance system (without support from the use of intelligent systems). The determined reliability of wind farm equipment renewed in the maintenance process, expressed as the availability factor K_g (2), is 0.99943517 for the mean repair time value of (1.0) (Figure 4).

Figure 5 shows the reliability of FW equipment in the form of readiness factor (Kg) as a function of changes in average repair time. Changes in the average repair time of FW equipment are supposed to occur in such an operation process in which an intelligent SERV renewal system is used. The SERV system is a computer program that realizes (determines) a set of renewal information based on the determined diagnostic information. Figure 5 shows the reducing changes in WF repair time resulting from the efficiency of the SERV system compared to the renewal process organized without the SERV system.

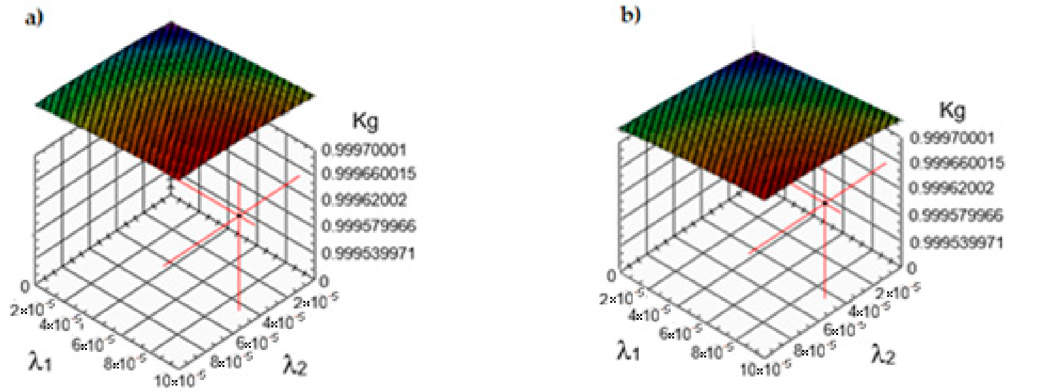

Figure 4. The Kg availability coefficient graphs show how the reliability of wind farm equipment is tested by varying the average repair time for constant parameters, such as type I mean service time = 0.8 (h), type II mean operating time = 1.3 (h), and mean time between successive failures = 1200 (h), where: (**a**) mean repair time = 0.3 (h) and (**b**) average repair time = 0.4 (h).

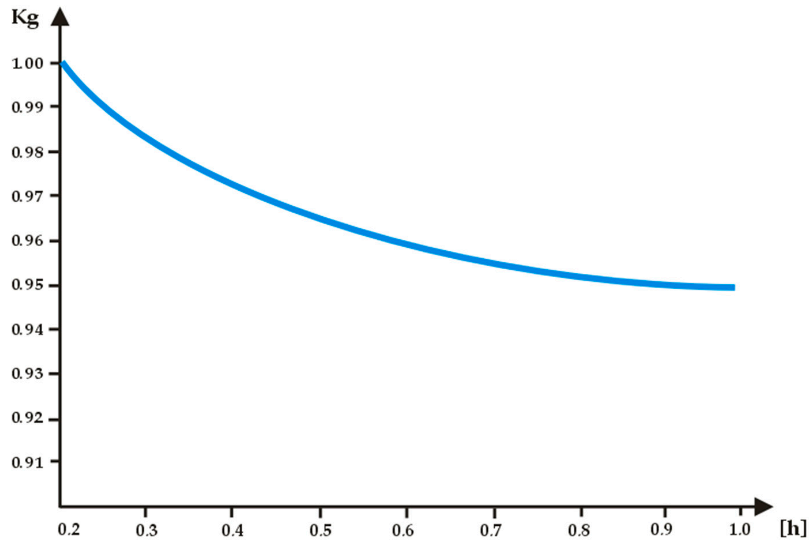

Figure 5. A graph showing how repair time affects the wind farm equipment's operational reliability.

The investigation assumed that changes in the mean value of the interval between successive lesions may occur within the range of 1000 ÷ 3000 (h). Figure 6 shows the results of testing the average time between failures of wind farm equipment to see how reliable it is while it is running. The effect of the average duration between successive failures on the caliber of the service process as well as the influence on the degree of dependability of WF devices was evaluated for this value in the range of 1000 ÷ 3000 (h) (Figure 6).

The analysis is based on the idea that the reliability of wind farm equipment is good enough if the average time between failures is 1000 h.

The publication does a particularly good job of presenting the issues raised in this paper in reliability evaluations of the operation of the WF wind farm equipment. This paper examines the reliability testing of wind farm equipment in order to help the system operator's decision making in the safe monitoring of its use. Three operational process models were created in this study, and they are as follows:

- *Model A*, reporting the functioning of wind power projects with intelligent decision-supporting systems;
- *Model B*, explaining how to run wind farm equipment that does not have smart support systems or use the WPPES system
- *Model C*, describing a straightforward (ideal) procedure for running the equipment at a wind farm.

The reliability of the wind farm device in the process of operation with changes was examined in the simulation tests using the following reliability values. The reliability value in the form of the K_g (1) readiness coefficient determined in the test is the highest and amounts to 0.99979371. The reliability value of the mean time between successive failures (3000 (h)) is the highest and amounts to 0.99942755. The reliability value of the average repair time equal to (0.3) (h) is the highest and amounts to 0.99942755.

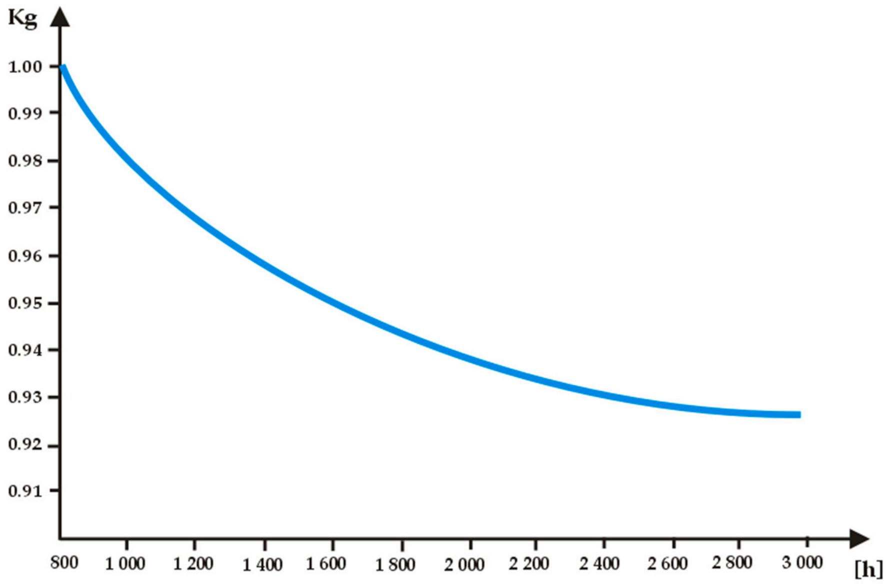

Figure 6. A graph showing the reliability of wind farm equipment in terms of time between breakdowns during operation.

5. Organization and Reliability Testing of Wind Farm Device in Its Operation Process

Testing of Wind Power Plant Equipment Reliability during Operation

Using the inverse Laplace transform, we can obtain the probabilities of the test system being in each phase of operation for an exponential distribution. The WFD system test took a year (Figure 7).

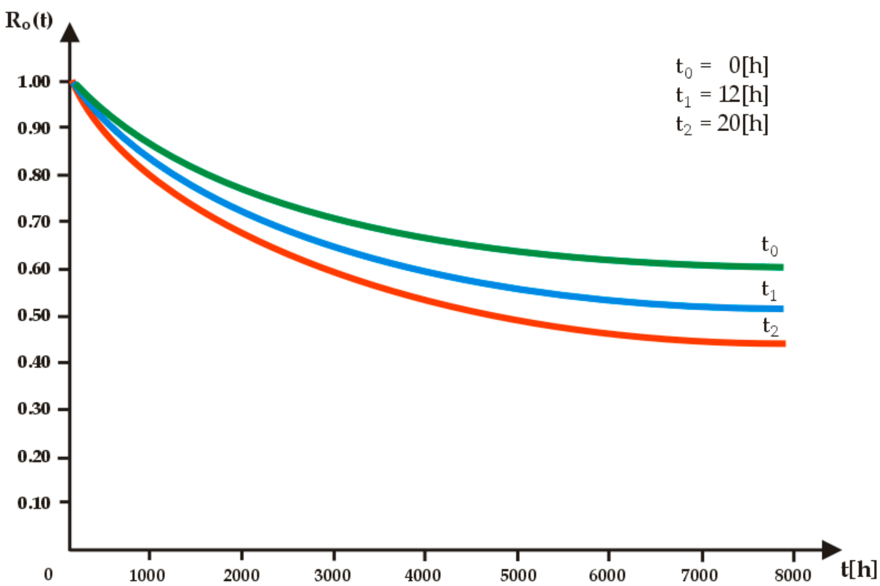

Figure 7. Own study: graph showing changes in the likelihood that the WFD system's evaluated value will continue to be in the condition of full fitness S1 over time.

Results of the Reliability Function Simulation Test ($R_o(t)$) can be used to evaluate the WFD system's capability to carry out the necessary activities. This study's primary goal was to find these solutions. The use of the five-state WFD model in research is novel compared to earlier papers of this type. Models of the operational process in the form of two-, three-, and four-state models have been accepted for testing in the work. According to the findings of this study (Figures 7 and 8), the five-state model of WFD is the one that best captures the operation of wind frames. This study's primary goal was to find these solutions. The use of the five-state WFD model in research is novel compared to earlier papers of this type.

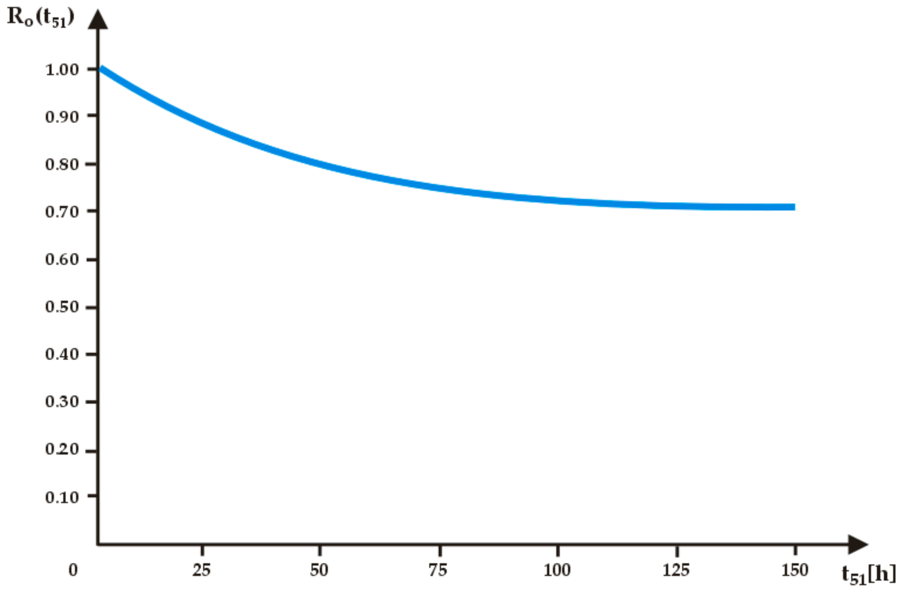

Figure 8. Dependence between the likelihood that the examined WFD system will continue to be fully fit after being restored—own study.

Considering that the time required to return the studied system to its optimal state (μ_{51} = $t_{51} - 1$ (h)) is constrained to a small window $(t_{51} \in \langle 12; 178\rangle (h))$. This means that the WFD system that was looked at is likely to be fully fit within 1 to 7 days, as shown in Figure 7.

Models of the operational process in the form of two-, three-, and four-state models have been accepted for testing in this work. According to the findings of this study (Figures 7 and 8), the five-state model of WFD is the one that best captures the operation of a wind farm. Two components of the reliability function (Ro(t)) of the WFD simulation test were carried out:

- The first step involved looking at the reliability function ($R_o(t)$) of the WFD in use.
- The second part of the WFD simulation study was the time-flow current (t_{51}) of the WFD's residency in the state (S_5) during the important technological activity of renewing the WFD.

The reliability function (Ro(t)) in the operation of the WFD was evaluated as the foundational simulation test. Figures 7 and 8 displays the outcomes of this investigation. The time (t) at which the test would be run at a year's interval, which corresponds to the time (t = 8760 (h)), was a crucial presumption for simulation testing. It is evident from the reliability function's ($R_o(t)$) graph for the WFD in Figure 7 that the reliability function has a value of ($R_o(t)$) = 0.84985 for an operating life normalized at (t = 4000 (h)). The reliability function value ($R_o(t)$) of the WFD is acceptable. In terms of practical interpretation, the dependability function's value directly translates into the value of the necessary function (F_C) (Figure 7), which assesses the WFD's ability to carry out its duties, namely to generate energy. As a result, ($F_C = 0.84985 < 1$) is the function's value needed for WFD. Although it does not have a consistent value, it is nevertheless acceptable at a high level.

6. Conclusions

An ongoing cognitive tool for evaluating the viability (resource) of WF equipment's continued usage is the issue of testing and analyzing its reliability. In the publications under review, the authors talked about a number of important concerns about modernizing and reorganizing the procedure for replacing WF equipment. The following reliability challenges are particularly crucial to research and assessment:

- Using data from an artificial neural network, in which the planned intelligent maintenance system will let objects grow new parts,
- Assessment of the reliability of wind farm equipment on the basis of the readiness function,
- Using the availability factor as a basis for reliability analysis of wind farm equipment,
- Testing of wind power plant equipment reliability during operation.

Because the study was conducted at the same time as simulation studies, reliability assessments of wind farms and other complicated technical items are possible. The simulation studies discussed in the studied works were carried out using a model of how technical things operate. A selection of fundamental quantities of reliability concepts was established in order to assess the WFDs' level of reliability. The dependability quantities chosen for the reliability analysis can be viewed as exemplary. The subjects of the studied works show that the produced models of the process of operation of technical objects are particularly significant in the theory and practice of the reliability of technical objects. Simulations built on the Markov process theory are particularly helpful in simulation research. The authors of the aforementioned works used two-, three-, four-, and five-state models to describe the operation of wind farm equipment. The five-state model of the operating process is very significant and can be viewed as a novelty in reliability studies of wind farm equipment.

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Symbols and Initialisms

$X\ (e_{i,j})$	diagnostic signal in the jth element of the ith set,
$X_{(w)}\ (e_{i,j})$	model signal for $X\ (e_{i,j})$ signal,
$F_{C\ max}$	max. value of the function of the use of the object,
$W\ (\varepsilon(e_{i,j})) = \{2, 1, 0\})$	valued of state assessment logics for jth element within ith module (from the set of the accepted three-value logic of states' assessment)
$R_0(t)$	probability function for a WFD system in the state of full fitness S_1
$Q_2(t)$	probability function for a WFD system in the state of partial fitness S_2
$Q_3(t)$	probability function for a WFD system in the state of partial fitness S_3
$Q_4(t)$	probability function for a WFD system in the state of partial unfitness S_4
$Q_5(t)$	probability function for a WFD system in the state of full unfitness S_5
λ	damage intensity

T_o	simulation test time of the object
μ	repair intensity
λ_1	intensity of type I inspections
μ_1	type I operational maintenance intensity
λ_2	intensity of type II inspections
μ_2	type II operational maintenance intensity
$\{M_E(e_{i,j})\}$	service knowledge base
$\{M_E\}$	technical facility renovation system
WFD	wind farm device
WPPES	Wind Power Plant Expert System
SERV	intelligent operating system
DIAG	intelligent diagnostic system

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