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Analysis and assessment of the reliability of the operation process of a complex, diagnosed technical facility in 5-value logic

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Abstract

What the article talks about are the difficulties of figuring out how reliable the workings of a complicated technological object are, especially when using a five-valued logic-based diagnostic method. The foundation for conducting dependability studies on technological objects is the utilization of prepared models that depict operational processes. The present study aims to build and provide a comprehensive description of a five-state model that characterizes the operational process of the diagnosed facility. The operational states that hold significance are the states of the object being tested, as diagnosed within the framework of 5VL-value logic. The model of the exploitation process that was constructed was further validated using simulated experiments. The outcomes of these comparative tests yield the calculated probabilities of the tested thing existing in its distinct conditions. The estimated time frames of occurrence of the recognized states in the object were determined based on the probability of occurrence of the diagnostic states, which were derived from the reliability features of the tested object.

Keywords: artificial intelligence, knowledge bases, technical diagnostics

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1 Introduction

The literature on reliability highlights that reliability theory, similar to statistical quality control, is an academic discipline that relies on principles of probability and statistics. Its subject matter can be broadly categorized into three main areas: "reliability mathematics," "reliability engineering," and "reliability management." The focal point of this article is the utilization of "reliability mathematics" as a means of articulating and comprehending reliability. Reliability engineering is an established professional methodology including the domains of reliability design, production, testing, and verification, which holds significant practical implications.

In the writings about the energy distribution system, for instance, it is shown to be made up of many pieces of electrical equipment. If any of these parts break, the power could go out. When a system has many parts that are linked in series, and one of those parts fails, the whole system fails (Duer, 2020; Duer et al., 2022; Nakagawa, 2005; Nakagawa et al., 2000 s. 191-195). Most of the time, reliability is shown by how often and for how long system operations are interrupted each year, i.e., by counting how many hours of system operations are interrupted each year when everything works as it should. To find out how sensitive these metrics are to changes in parameters, we collect data on short-term and long-term system downtime, component failures, and downtime rates. Then, we use commercial software to calculate total system reliability metrics for each node in the system. From these data, we can choose the best electrical system design by taking cost and dependability into account (Wang et al., 2018; Epstein et al., 2008). So, if you use the traditional reliability-centric approach, you can get all of your departments to work together to find out why things fail, boost performance, and set the direction for safety, availability, and operational economics in "reliability management," which will help your programs reach their objectives.

One potential method for evaluating the dependability of technical items involves quantifying temporal factors within an actual operational context. Specifically, the cumulative distribution function and the probability density function are used to describe the variability of failure times in terms of the Weibull distribution. A novel concern in the field of reliability pertains to reverse actions, namely the estimation of the occurrence times of recognized states in an item based on the calculated probability of diagnostic states utilizing the reliability characteristics of such an object. The innovation of this paper is in the determination of the temporal occurrences of potential probabilities associated with individual states identified in the diagnosed object. Specifically, it focuses on calculating the timing of the occurrence of the state of unsuitability of the item. This approach presents novel prospects for the building and advancement of a fresh strategy aimed at rehabilitating the facility under examination, referred to in this study as the temporal occurrence-based strategy for addressing states of disrepair.

2 A five-state model of the operation process of a complex technical object diagnosed in 5VL logic

The functioning of a complicated technical object can be described as a stochastic process, denoted as S(t), where the elements (Si) are categorized into subsets representing the states of the object: usage and operation. Through a comprehensive analysis of all the operational scenarios that the object may encounter during every iteration, it becomes feasible to ascertain the many states of the item throughout the operational process. These states collectively form a set denoted as Z(t).

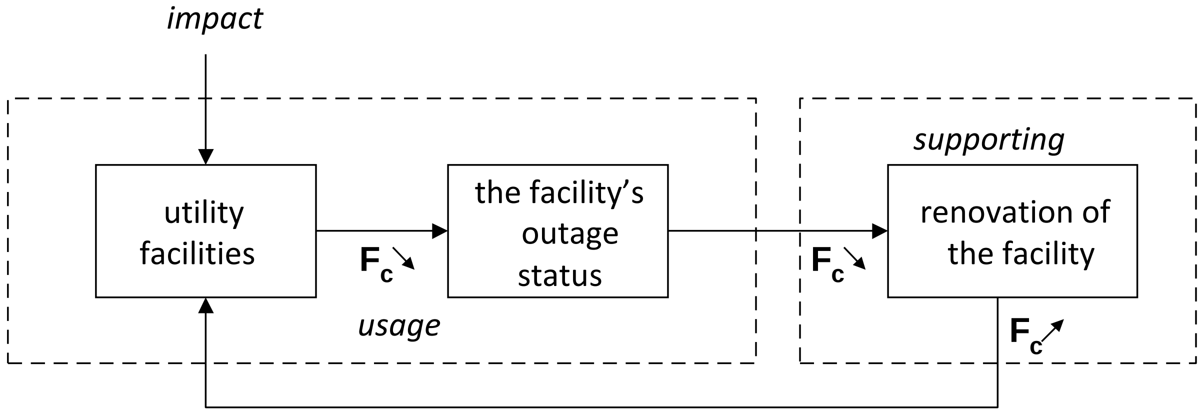

Figure 1: *Diagram of the technical facility operation process.*

The various potential states of an object during the operational process are identified through the diagnostic procedure. The collection of object states during the operation of an object, denoted as {S}, is contingent upon the chosen valence for state evaluation. This study assumes the division of the work into subsets denoted as {S0, S1, S2, S3, S4}. Specifically, {S0, S1, S2, S3} represents a subset of states related to fitness (usage), while {S1, S2, S3} represents a subset of states associated with incomplete availability. Nevertheless, it can be observed that the set {S4} is a subset of the state that is deemed inappropriate.

A state of use is a state in the operation of a technical object in which the object is employed for its intended purpose. The object performs its required functions in line with its intended purpose in the stage of usage (Dyduch et al., 2011; Siergiejczyk et al., 2016, s. 587-593) of the operating process {S0}. If an object is no longer in use because it no longer performs its needed tasks, it should be renewed as part of the maintenance process. The states found during the diagnosis process in which the item is not in use are part of the object's operating states {S0, S1, S2, S3}.

The following defines the state of use of a technical item in the process of operation of a technical object diagnosed in 5VL logic:

1. The diagnostic value of "4" in the 5VL logic indicates the facility's technical state, which is what the suitability status, denoted as {S0}, refers to. The state of an item is defined as the condition in which it operates according to its intended functions, on the assumption that the input signal features fall within the allowable range of changes denoted as X_j. Within the current state of the object, the values of the X_i signal features are situated within a range commonly referred to as the range of minor changes.
2. State of incomplete appropriateness {S1}: The technical condition of the facility is indicated by a diagnostic value of "3" in the 5VL logic. The state of an object with partial task performance capability is determined by the state of this object, provided that the input signals fall within the allowable range of changes in the properties of the signals X_j. In the present condition, it is necessary for the alteration in the value of at least one characteristic of the X_i signal to be confined to the range referred to as the significant change interval.
3. Critical airworthiness state {S2}: The technical condition of the facility, denoted by the value "2" in logic 5VL. This state specifies an object's state as the capacity to perform some, but not all, of its functions, given that the input signals are within the range of acceptable values for the signal characteristics X_j. In this state, the change in the value of at least one X_i signal feature must fall within an interval known as the critical change interval.
4. Pre-damage suitability status {S3}: The facility's technical condition, as indicated by the value "1" in the 5VL logic. This state defines the object's state as defined by its capacity to perform minor functions, given that the input signals are within the range of possible values for the signal characteristics X_j. In this scenario, the change in the value of at least one X_i signal feature must occur inside the pre-damage change interval.
5. State of unsuitability {S4}: The technical condition of the object, denoted by the value "0" in the 5VL logic. This state defines the state of an item that is fully incapable of fulfilling its functions, assuming that the input signals are within the range of unacceptable changes in the features of the signals X_j. In this state, the change in the value of at least one aspect of the signal X_i must fall within the range of undesirable alterations.

In practical operational scenarios, an operational procedure is employed that involves a diagnostic phase, which subsequently transitions into a utilization phase. Hence, the system has the capability to exist in any of the five states as seen in (Figure 2):

- state of airworthiness for use (S0),
- state of incomplete appropriateness (S1),
- critical airworthiness state (S2),
- pre-damage suitability status (S3).
- state of unsuitability (S4).

Considering the aforementioned points, the model for system operation process may be described as a structured sequence of three distinct formats.

$M = \langle SE, RE, FR \rangle$

where:

SE = {S0, S1, S2, S3, S4}

SE refers to a collection of operational states within the transport telematics system, which can be interpreted as follows:

- S0 – airworthiness status for use,
- S1 – state of incomplete appropriateness,
- S2 – critical airworthiness state,
- S3 – pre-damage suitability status,
- S4 – state of unsuitability

The stages encompassed by the SE set should be understood as the states of: complete serviceability, partial repairability, crucial serviceability, pre-damage serviceability, and repair following the incidence of unsuitability (damage) to the item.

The second component, denoted as RE, within an ordered triple M, consists of a collection of pairs, whereby the elements possess the subsequent interpretation:

- (S0, S1) informs of system state transition potential S0 to the state S1,
- (S1, S0) informs of system state transition potential S1 to the state S0,
- (S0, S2) informs of system state transition potential S0 to the state S2,
- (S2, S0) informs of system state transition potential S2 to the state S0,
- (S2, S3) informs of system state transition potential S2 to the state S3,
- (S3, S0) informs of system state transition potential S3 to the state S0,
- (S2, S4) informs of system state transition potential S2 to the state S4,
- (S4, S0) informs of system state transition potential S4 to the state S0.

Thus:

RE = {(S0, S1), (S1, S0), (S0, S2), (S2, S0), (S2, S3), (S3, S0), (S2, S4), (S4, S0)}

That is:

$RE \subset S \times S$

It is assumed that the FR element comprises a collection of functions, each of which is defined on the set RE and maps to the set of positive real numbers, denoted as R^+. The functions λ and μ exhibit a specific form, namely:

$$\lambda : RE \longrightarrow R^+$$

$$\mu : RE \longrightarrow R^+$$

Accordingly, an integer value is allocated to each element in the RE set from the R^+ set, in accordance with the interpretation of the transition intensity. Figure 2 illustrates a graphical representation of the situation described previously.

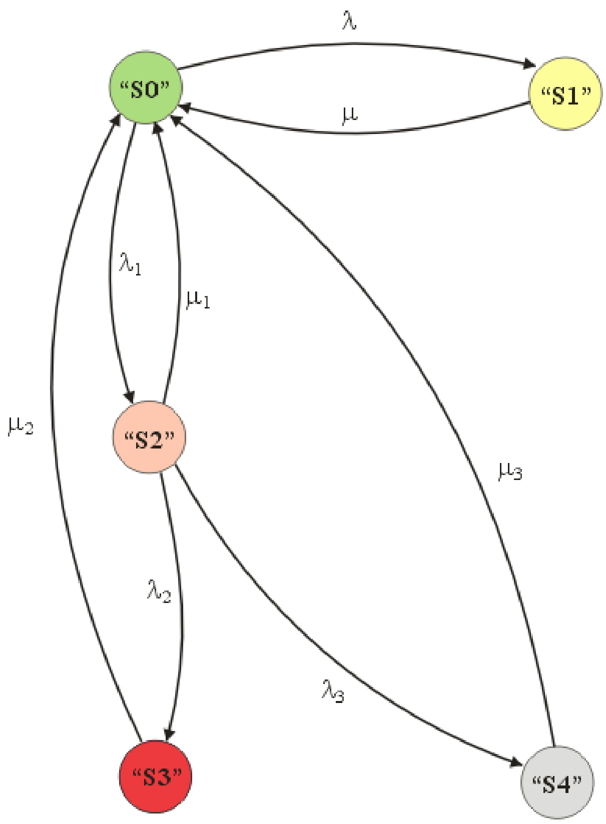

Figure 2. *Model of the operation process of a complex technical object being diagnosed in five-valued logic 5-VL (source: own work).*

Markings in Figure 2:

λ - the intensity of the system's transition from state to state S0 to the state S1,

μ - system transitions between states S1 to the state S0,

λ_1 - the intensity of the system's transition from state to state S0 to the state S2,

μ_1 - system transitions between states S2 to the state S0,

λ_2 - the intensity of the system's transition from state to state S2 to the state S3,

μ_2 - system transitions between states S3 to the state S0,

λ_3 - the intensity of the system's transition from state to state S2 to the state S4,

μ_3 - system transitions between states S4 to the state S0.

Specifically, Figure 2 visually represents the transitions between the states that are emphasized, which are depicted through the arcs connecting them:

- λ(S0,S1), hence λ has an interpretation of the system's intensity of transition from state to state stanu S0 to the state S1,
- μ(S1,S0), hence μ has an interpretation of the system's intensity of transition from state to state S1 to the state S0,
- λ(S0,S2), hence λ_1 has an interpretation of the system's intensity of transition from state to state S0 to the state S2,
- μ(S2,S0), hence μ_1 has an interpretation of the system's intensity of transition from state to state S2 to the state S0,
- λ(S2,S3), hence λ_2 has an interpretation of the system's intensity of transition from state to state S2 to the state S3,

- μ(S3,S0), hence μ_2 has an interpretation of the system's intensity of transition from state to state S3 to the state S0,
- λ(S2,S4), hence λ_3 has an interpretation of the system's intensity of transition from state to state S2 to the state S4,
- μ(S4,S0), hence μ_3 has an interpretation of the system's intensity of transition from state to state S4 to the state S0.

The literature employs diverse methodologies to present a model of the operational process of a technical facility, depending on the research requirements (Stawowy et al., 2021; Siergiejczyk et al., 2014, s. 14-19; Stawowy et al., 2021; Paś et al., 2020). The graphical representation is commonly utilized to depict the model of the facility operation process. The visual representation of the execution of the facility operation process is commonly referred to as a process graph. An alternative method frequently employed to illustrate the execution of the facility operation process is using an analytical format. Occasionally, one may encounter a scenario in which the aforementioned models of facility operation processes coexist and mutually enhance one another. The practical implementation of the exploitation process model is most effectively demonstrated through its graphical representation.

The object exploitation process graph is a visual representation that illustrates the many states involved in the object exploitation process. In this graph, the states are represented by highlighted vertices, while the transitions between states are depicted by arcs connecting the vertices. The graph depicting the exploitation process has been constructed in such a manner that it may be adapted to various forms, such as analytical, based on the specific study objectives. When formulating a conceptual framework for the operational procedures of a certain facility, it is imperative to adhere to the prescribed approach.

It is assumed that the modeling of the operation process entails the determination of the probabilities associated with the transport telematics system being in distinct states, namely S0, S1, S2, S3, and S4. Consequently, it becomes imperative to ascertain these probabilities:

- the probability function of the system being in a state S0,
- the probability function of the system being in a state S1,
- the probability function of the system being in a state S2,
- the probability function of the system being in a state S3.

the probability function of the system being in a state S4.

3 Analysis and assessment of the reliability of the operation process of a complex technical object diagnosed in 5-value logic

In order to ascertain the probabilities associated with certain states of interest within the system, it is necessary to describe the network of transitions depicted in Figure 2 using the following equations:

$$\begin{gathered}
-\lambda \cdot P_0 + \mu \cdot P_1 - \lambda_1 \cdot P_0 + \mu_1 \cdot P_2 + \mu_2 \cdot P_3 + \mu_3 \cdot P_4 = 0 \\
\lambda \cdot P_0 - \mu \cdot P_1 = 0 \\
-\lambda_1 \cdot P_2 - \lambda_2 \cdot P_2 - \mu_1 \cdot P_2 + \lambda_1 \cdot P_0 = 0 \\
\lambda_2 \cdot P_2 - \mu_2 \cdot P_3 = 0 \\
\lambda_3 \cdot P_3 - \mu_3 \cdot P_4 = 0
\end{gathered} \tag{1}$$

The matrices can be represented in matrix notation as follows:

$$\begin{bmatrix} -(\lambda+\lambda_2) & \mu & \mu_1 & \mu_2 & \mu_3 \\ \lambda & -\mu & 0 & 0 & 0 \\ \lambda_1 & 0 & -(\lambda_2+\lambda_3+\lambda_1) & 0 & 0 \\ 0 & 0 & \lambda_2 & -\mu_2 & 0 \\ 0 & 0 & \lambda_3 & 0 & -\mu_3 \end{bmatrix} \cdot \begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

Transforming, we get:

$$\begin{gathered} P_1 = \frac{\lambda}{\mu} \cdot P_0 \\ P_2 = \frac{\lambda_2}{\lambda_1+\lambda_2+\mu_1} \cdot P_0 \\ P_3 = \frac{\lambda_2}{\mu_2} \cdot P_2 \\ P_4 = \frac{\lambda_3}{\mu_3} \cdot P_2 \end{gathered} \tag{2}$$

Of course:

$$P_0 + P_1 + P_2 + P_3 + P_4 = 1 \tag{3}$$

Therefore:

$$P_0 \cdot \left(1 + \frac{\lambda}{\mu} + \frac{\lambda_2}{\lambda_2+\lambda_3+\mu_1} + \frac{\lambda_2}{\mu_2} \cdot \frac{\lambda_1}{\lambda_2+\lambda_3+\mu_1} + \frac{\lambda_3}{\mu_3} \cdot \frac{\lambda_1}{\lambda_2+\lambda_3+\mu_1}\right) = 1 \tag{4}$$

$$P_0 = \frac{1}{\left(1 + \frac{\lambda}{\mu} + \frac{\lambda_2}{\lambda_2+\lambda_3+\mu_1} + \frac{\lambda_2}{\mu_2} \cdot \frac{\lambda_1}{\lambda_2+\lambda_3+\mu_1} + \frac{\lambda_3}{\mu_3} \cdot \frac{\lambda_1}{\lambda_2+\lambda_3+\mu_1}\right)} \tag{5}$$

$$P_0 = \frac{\mu \cdot \mu_2 \cdot \mu_3 \cdot (\lambda_2+\lambda_3+\mu_1)}{\begin{gathered}\mu \cdot \mu_2 \cdot \mu_3 \cdot (\lambda_2+\lambda_3+\mu_1) + \lambda \cdot \mu_2 \cdot \mu_3 \cdot (\lambda_2+\lambda_3+\mu_1) \\ +\mu \cdot \mu_2 \cdot \mu_3 \cdot \lambda_1 + \mu \cdot \mu_3 \cdot \lambda_2 \cdot \lambda_1 + \mu \cdot \mu_2 \cdot \lambda_3 \cdot \lambda_1\end{gathered}} \tag{6}$$

Hence, utilizing equation (7), we may ascertain the likelihood value denoting the utilization of the transport telematics system. In terms of numerical representation, it is equivalent to the value of the readiness indicator.

The utilization of computer simulation has facilitated the expeditious assessment of the effects of modifications in different reliability and operational metrics on the indicators that characterize the conditions of the diagnostic system under analysis. The analysis focused on the intensities of repairs and system damage as indicated in Table 1. The values of adoption were determined by the utilization of academic sources (Dhillon, 2006) as well as operational data acquired from energy corporations.

Table 1. System reliability parameters.

Parameter	Value [1/h]
λ	0.00001
λ_1	0.00002
λ_2	0.000025
λ_3	0.000004167
μ	0.0208
μ_1	0.0416
μ_2	0.0208
μ_3	0.0416

Based on equations 3–7 and employing the inverse Laplace transform with the data provided in Table 1, we are able to derive the probabilities associated with the several operational states of the tested system for the exponential distribution.

- duration of the railway monitoring system test – 1 year:

$$t = 8760(h) \tag{7}$$

- the probability of the tested diagnostic system remaining in a state of full S0 suitability for a period of 1 year:

$$P_0(t) = 0{,}9988319222061706 \tag{8}$$

- the probability of the tested diagnostic system remaining in the state of partial S1 suitability for a period of 1 year:

$$P_1(t) = 0{,}00048014975066258263 \tag{9}$$

- the probability of the tested diagnostic system remaining in the S2 critical state for a period of 1 year:

$$P_2(t) = 0{,}00047974636032957274 \tag{10}$$

- the probability of the tested diagnostic system remaining in the S3 pre-failure state for a period of 1 year:

$$P_3(t) = 0{,}00019985575200001795 \tag{11}$$

- the probability of the tested diagnostic system remaining in a state of unusability S4 for a period of 1 year:

$$P_4(t) = 8{,}32593 \cdot 10^{-6} = 0{,}0000083259308375034 15 \tag{12}$$

The assessment of the probability of diagnostic states has emerged as a novel way in addressing the challenge of testing the reliability of intricate technical systems. To achieve this objective, it is necessary to ascertain the inability function $P_0(t)$ of the object being tested in order to determine the duration of the test. Furthermore, it is necessary to establish a linear trendline to represent the frequency of the distinct states. Subsequently, it is necessary to indicate the values of the occurrence probabilities of the states on the $P_0(t)$ characteristic. The probability values assigned to the distinct states unambiguously establish their corresponding time intervals on the $P_0(t)$ characteristic.

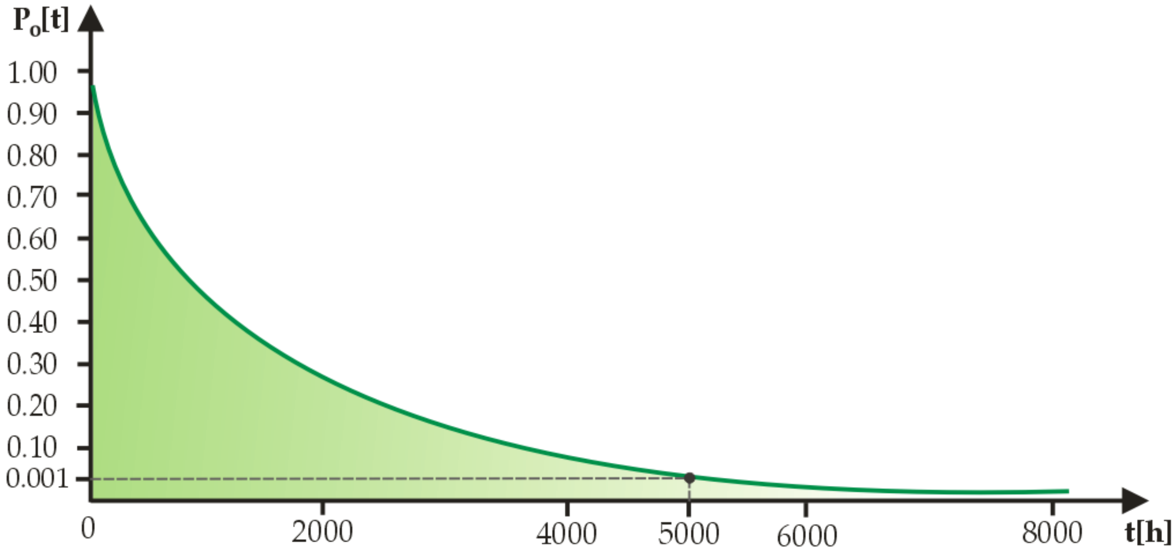

Figure 3. *Graph of changes in the probability of the analyzed system remaining in a state of full S1 serviceability for a period of 1 year (source: own work).*

Determining the anticipated occurrence of a specific state is accomplished by the graphical representation of a comprehensive characteristic function, denoted as $P_0(t)$. This methodology is employed in the field of diagnostics and is distinguished by its utilization of 5VL logic. The examination of the $P_0(t)$ characteristic depicted in Figure 3 reveals that the computed probabilities of the specified set of states {S1, S2, S3, S4} in the 5VL logic are situated in the lower region of the $P_0(t)$ characteristic illustrated in Figure 3. Hence, the $P_0(t)$ characteristic is depicted in Figure 4, illustrating a range of variations in its value below 0.001.

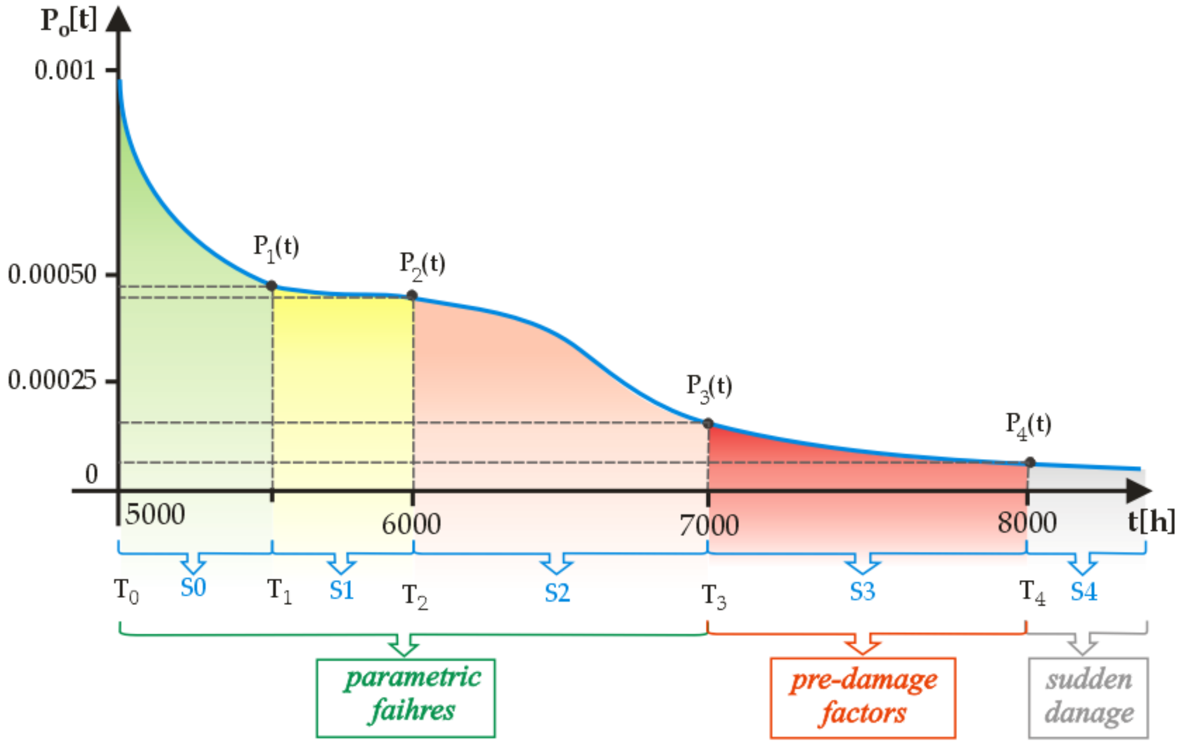

Figure 4. *Detailed graph of changes in the probability of the analyzed system remaining in a state of full S1 serviceability for a period of 1 year (source: own work).*

Figure 4 displays the estimated probabilities of the determined object states. Next, the probabilities of individual states occurring (P_i (t)) were indicated on the $P_0(t)$ characteristic.

The intervals for the occurrence periods of the individual probability predicted in the graph (Figure 4) are as follows::

- $P_o = 0{,}99883 \rightarrow \langle 0 \div 5500 \rangle$ [h]
- $P_1 = 0{,}0004801 \rightarrow \langle 5500 \div 6000 \rangle$ [h]
- $P_2 = 0{,}0004797 \rightarrow \langle 6000 \div 7000 \rangle$ [h]
- $P_3 = 0{,}000199 \rightarrow \langle 7000 \div 8000 \rangle$ [h]
- $P_4 = 8{,}32593 \cdot 10^{-6} \rightarrow \langle \text{powyżej } 8000 \rangle$ [h]

4 Summary

This article discusses the challenges associated with analyzing and assessing the reliability of a technical object diagnosed in 5VL logic throughout its functioning. In order to achieve the intended objective, a conceptual framework outlining the operational process of the facility, incorporating 5VL diagnostics, was established and explicated through graphical and analytical representations. The several stages of the exploitation process model are evidently connected to the technical states of the facility that are identified in the 5VL diagnostics. The operational process model of the tested object comprises subsets and a subset of user states represented by suitability states (S0), incomplete suitability states (S1), crucial suitability states (S2), and pre-damage suitability states (S3). The set of serviceable states consists solely of one element, namely the state S4, which is characterized as being unusable. The primary contribution of this study, in comparison to similar works, lies in the establishment of an analytical approach for ascertaining the occurrence periods of distinct states identified in 5VL diagnostics. This method is founded on the computed probability of occurrence for the technical states that are distinguished inside the item. The uniqueness of this research is in the determination of the temporal occurrences of potential probability for specific states. The identification of the point at which an object becomes unsuitable presents novel prospects for the formulation of a fresh approach towards the refurbishment of said thing.

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