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The effectiveness of fire detection with convolutional neural networks

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Abstract

Modeling the operation process of technical objects, especially complex and intelligent systems, is an important diagnostic problem. Such models are relevant when designing objects, making decisions regarding maintenance, and evaluating operation processes. A common assumption is that the model of the operation process can only record changes in states that occur over a finite period of time. In the traditional approach, when analyzing the number of possible different operating states of an object, a finite set of them is used. The model presented in this article allows analyzing a wide range of issues related to the operation process of complex technical objects. Using the probability functions of states and the readiness functions of a technical object, this model allows modeling the operation process at the initial design stage, assessing the compliance of the operation process of the object with the expected maintenance schedule, and assessing the potential results of the operation process of a complex technical object.

Keywords: object classification, technical diagnostics, artificial intelligence, diagnostic knowledge base

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1 INTRODUCTION

Research into increasing the reliability of objects and planning their failure-free operation period are the main tasks of reliability theory. To solve problems related to reliability theory, it is necessary to use modeling methods. One of the essential indicators of reliability is durability. A technical object is considered durable if it can withstand multiple repairs, which ensures its operation for longer periods of time. An important indicator when creating technical objects with maximum potential reliability in a given service interval are economic, technical, environmental and social factors [1-2].

The most accurate determination of the probable time of occurrence of changes in the properties of a complex technical object is possible using a multi-element classification. This can be achieved conceptually and mathematically and is aimed at timely prevention of failures of complex technical objects when solving technical diagnostics problems. The loss of properties of components included in a complex technical object as a result of damage to an interacting element is insufficiently represented in modern studies.

Thus, in study [3], a periodic check policy for the storage system by conducting regular tests is considered to maintain higher reliability. The system is repaired if the reliability falls below a predetermined value. In studies [4-6], improving the reliability of various technical systems is considered by updating the maintenance regime and adopting both predictive and proactive maintenance. The construction of reliability models is based on the theory of mathematical modeling [7]. In a number of modern studies, the uncertainty method is used in assessing reliability, which allows obtaining significant results [8-11].

This paper considers an example of systems and dependent components as a way to model the operation of a complex assembly element of a vehicle. The task of predicting the occurrence of changes in the states of the diagnosed object is presented in 5 states of the workflow model. An example is a hypothetical failure of one of the components of the internal combustion engine of a vehicle, which can affect the functionality of other systems or components in the engine. The novelty of this work in comparison with other works of this type [12-15] lies in the development of an analytical method for determining the onset times of selected states during 5VL diagnostics based on an assessment of the probability of the onset of selected technical states of individual elements of a complex object.

2 Interaction of elements of a complex technical object using the example of an internal combustion engine

The internal combustion engine is a typical type of mechanical drive used in vehicles with the architecture shown (Figure 1). A combustion engine converts the chemical energy contained in the fuel into mechanical energy. Moreover, the efficient operation of the engine depends on many systems, each of which is responsible for specific responsibilities. The operation of the engine is possible only thanks to the coordinated work of many units, components, elements.

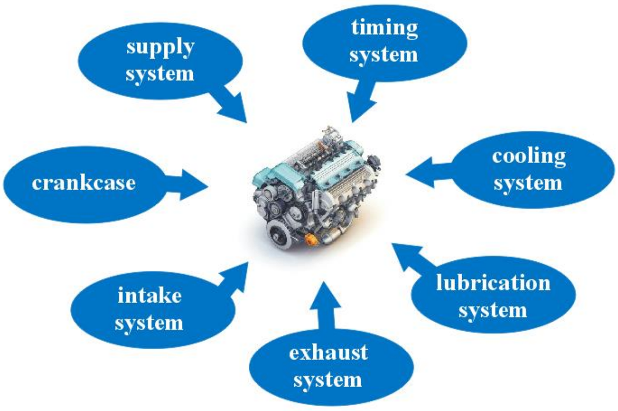

Fig. 1. *Engine architecture (source: own development)*

One of the elements that ensures efficient engine operation is the cooling system. The main component of the cooling system is the water pump (Figure 2). It ensures the circulation of the coolant in the system by creating the necessary pressure. During the circulation period, the liquid provides heat removal from the block and engine head. This helps maintain the required temperature of the vehicle's drive, which is from 90 to 95 degrees Celsius. This temperature is necessary to ensure long-term engine performance and optimize fuel consumption. A significant excess of temperature in the system leads to a catastrophic failure of the entire drive system.

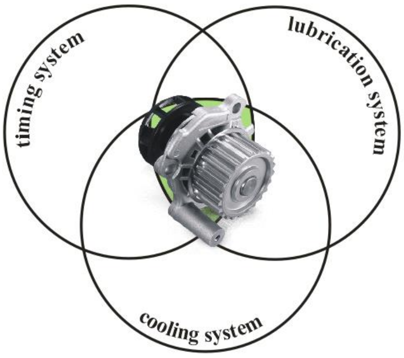

Fig. 2. *Element dependent on the work of three circuits (source: own development)*

Engine overheating occurs when the pump is unable to pump coolant efficiently. If the engine reaches excessively high temperatures, it may require costly repairs that involve replacing drive system components, which can be costly. In some cases, a crash may require replacing the entire drive. Changes in engine temperature, coolant leaks, noise coming from the area around the pump, and fluid stains under the vehicle are all signs of a faulty water pump.

In this regard, in addition to analyzing the causes of water pump failure, it is also necessary to identify the consequences of this failure and the possible impact on the deterioration of the properties and characteristics of other engine components interacting directly or indirectly with the system, a component of which is the water pump. From a diagnostic point of view, possession of such information makes it possible to predict the entire process of operation of a complex technical system – a drive engine. The creation of models that take into account all the factors of operation of a complex technical system with interrelations between elements is the main way to increase reliability. When initially creating mathematical models, graphical modeling is used, which is subsequently used to build an information database.

The article examines the relationships between three separate technical objects of the engine design: the cooling system, the timing system, and the lubrication system. Possible variants of dependencies of these elements in the engine system are shown in Figure 3. Each set represents a separate combination of the influence of the constituent elements on the internal combustion engine system. Figure 3 shows the dependencies of the internal combustion engine systems, where I is the cooling system, II is the lubrication system, III is the valve timing system.

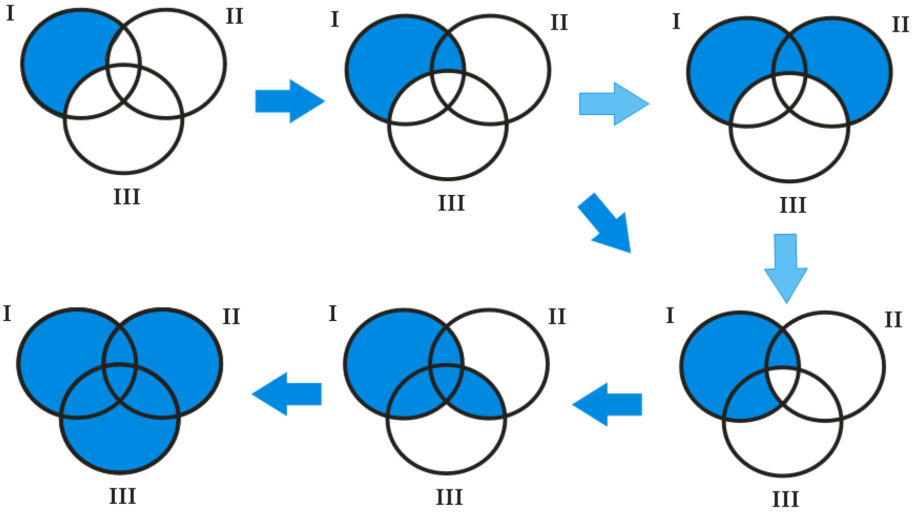

Fig. 3. *Example correlation of collections in different variants (source: own development)*

Depending on the state of the damaged system or its component, there is a direct or indirect impact on the operation, change in the characteristics of other systems and their components. It can be assumed that partial damage to one of the components of the cooling system, for example, a water pump, will not affect the interacting components and systems. In the case of a critical condition of the water pump, an impact on the components and systems interacting with the cooling system is possible or probable. In the event of a water pump failure, there is a possibility of visible changes in the characteristics of the components that are part of the systems interacting with the cooling system.

3 Five-state model of the internal combustion engine operating process

Technical objects are subject to constant adverse modifications during their operational life. The influence of these modifications includes the interaction of many internal and external elements with the object. These conditions cause a change in the state of the object, which is defined as the characteristic behavior of the object during use. As a result, technical objects must be constantly checked for their condition using diagnostic systems (Figure 4).

Thus, monitoring the condition of a technical object can be considered as two separate processes of continuous diagnostics. One of them consists of localizing the damage that occurs to the object, and the other one - in determining the period when the technical component returns to a working condition. To return the system to a working condition, stationary maintenance or repair in a specialized unit is required. As a result, determining the return of a technical object to its working condition is in practice less significant than identifying the source of damage.

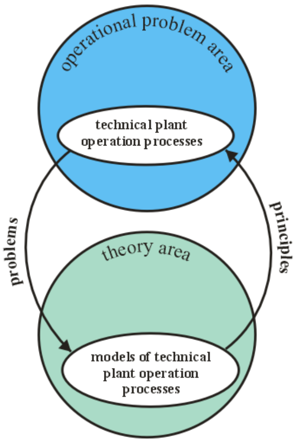

Fig. 4. *Diagnostic process (source: own elaboration)*

The operation of a complex technical object such as an internal combustion engine is often identified in the literature [13-14] as a stochastic process S(t). The elements in this process (Si) correspond to subsets of states in the object {S}: use and operation. The states of an object in operation process can be found by considering all potential operational scenarios in which the object may find itself after any number of transitions. The object diagnosis procedure helps to determine each of the several states of the object in operation process. In this study, it is assumed to be divided into subsets {S4, S3, S2, S1, S0}, where the subset {S4, S3, S2, S1} - is a subset of incomplete condition states. The subset {S0} is a subset of the unfit states.

When the engine is in operation its condition is {S4} fully functional and the operating mode is within the limits of compliance with the passport characteristics. Objects that are no longer used due to failure to perform their intended functions must be updated as part of the maintenance process. {S4, S3, S2, S1} (Figure 5) are the maintenance states of objects that are identified during the diagnostic process as being in a state where the object is not in use.

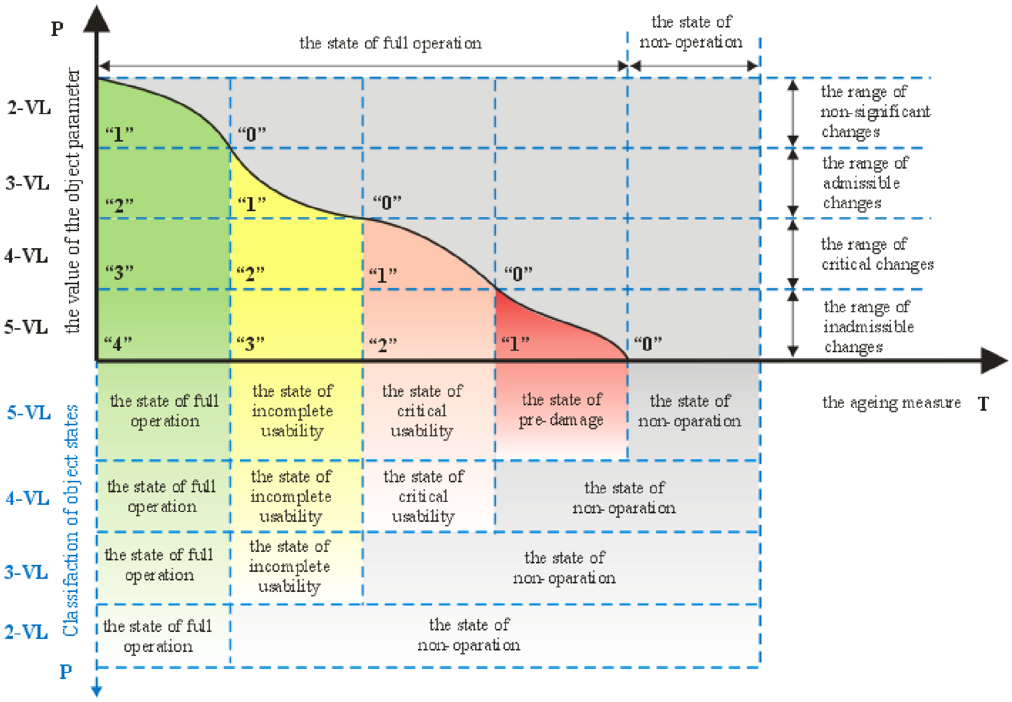

Fig. 5. *Classification scheme of object states in two-, three-, four- and five-valued logic (source: own elaboration)*

The operational states of the internal combustion engine that are diagnosed using 5VL logic are shown below (Figure 5):

- S4, the state of operability, represents the technical state of the internal combustion engine designated by the value "4" in the 5VL logic. When the values of the input signal characteristics are within the permissible deviations Xj, the internal combustion engine is considered to be in a state where it performs its functions in accordance with the technical characteristics. When the internal combustion engine is in this state, the values of its signal characteristics Xi are within the established limits of permissible variations.
- State of partial operability {S3}: the technical state of the internal combustion engine designated by the value "3" in the 5VL logic. Under these conditions, the engine is considered to be partially operative, provided that the input signals are within the permissible ranges for the signal characteristics Xj. In this case, the interval of significant change is the range of values within which at least one characteristic of the signal Xi can change.
- S2, the critical state of operability, represented by the number "2" in the 5VL logic, is the technical state of the engine. If we assume that the input signals are within the range of change of the permissible values of the characteristics of the signal Xj, then this state determines the ability of the engine to partially perform its functions. In this case, the key interval of change is the range of values within which at least one characteristic of the signal Xi can change.
- The technical state of an internal combustion engine, represented by the number '1' in 5VL logic, is the pre-fault performance state {S1}. If the input signals are within the range of permissible variations in the signal characteristic X_j, then the internal combustion engine is said to be in this state, defined by its ability to perform minor functions. In this case, the range of change before failure is the range of values within which at least one signal characteristic X_i can change.
- Faulty state of object {S0}: Technical state of the internal combustion engine, represented by the value "0" in the logical diagnostics 5VL. In this state, it is assumed that the input signals are outside the ranges of change of the permissible values of the signal characteristic Xj and corresponds to the complete inability of the internal combustion engine to perform its function. In this state, at least one value of the signal characteristic Xi may be in the inadmissible range of parameter change.

4 Definition of damage model in five-state classification of internal combustion engine operation process

When the engine is running at a working temperature of 90 to 100 degrees C0, its performance is at its maximum while minimizing the fuel combustion process (Figure 6). Excessive or insufficient engine heating is a consequence of a mechanical failure or natural wear of a cooling system component, which leads to failure. Fluid leakage is also a common type of cooling system failure. A possible cause of cooling system failure may be a faulty thermostat, radiator, or fan. However, a faulty liquid pump is the most serious engine failure. It stops the flow of coolant, which leads to fairly rapid engine heating with subsequent failure.

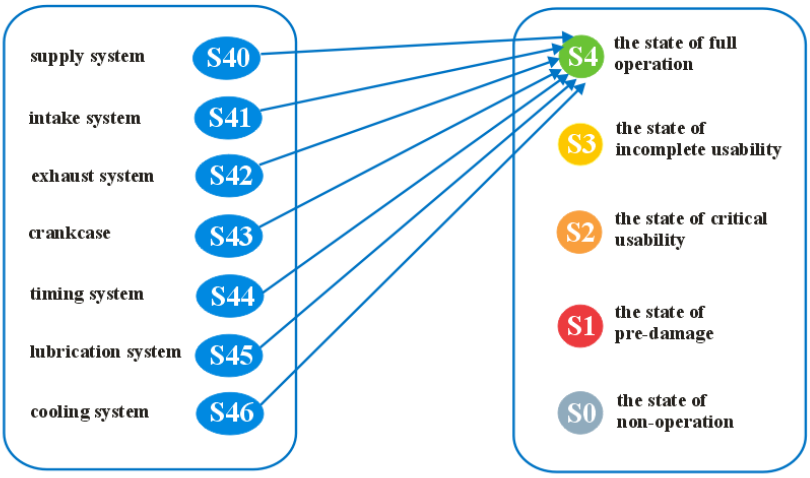

Fig 6. *Correct engine operation (source: own development)*

Figure 7 shows the relationship between damages and the current state of the engine during its operation.

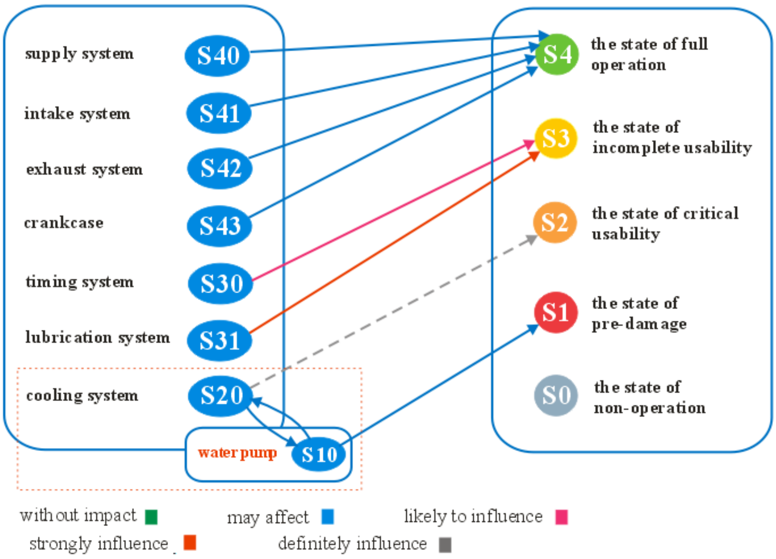

Fig. 7. *Engine operation with a defective pump (source: own development)*

A coolant pump failure occurs in the event of wear of the bearings, timing gear, failure of the electrical module (if the pump is powered on new vehicles), improper installation of the pump, breakage of the timing belt or chain (depending on the design), or changes in the properties of the coolant during operation.

5 Model of the internal combustion engine operation process

In the actual operation of a complex technical object, diagnostic systems are used to ensure control of its transition to various states. In this way, the object under test can be in one of five states. Figure 8 shows the five possible states of the object:

- the state of full operation (S4),
- the state of incomplete usability (S3),
- the state of critical usability (S2),
- the state of pre-damage (S1).
- the state of non-operation (S0).

With this in mind, the operational process model of the system is an ordered triad of the form:

$$\mathbf{M = \langle SE, RE, FR \rangle}$$

where:

$$\mathbf{SE = \{S0, S1, S2, S3, S4\}}$$

Using this interpretation (SE), a number of alternative states of a technical object can be characterised:

- S0 - state of unfitness,
- S1 - state before failure,
- S2 - state of critical serviceability,
- S3 - state of incomplete serviceability,
- S4 - state of full serviceability.

The SE set consists of the states of full serviceability, incomplete repairability, critical serviceability, pre-damage and repair when the component becomes unserviceable (damaged). The second element of the ordered triple M, RE, is formed by a set of pairs containing components with the following interpretation:

- λ is the intensity with which the system transitions from state S4 to state S0, hence λ(S4,S0) is a measure of this transition,
- μ is the intensity with which the system transitions from state S0 to state S4, hence μ(S0,S4) is a measure of this transition,
- λ_1 is the intensity with which the system transitions from state S4 to state S3, hence λ_1(S4,S3) is a measure of this transition,
- μ_1 is the intensity with which the system transitions from state S3 to state S4, hence μ_1(S3,S4) is a measure of this transition,
- λ_2 is the intensity with which the system transitions from state S3 to state S2, hence λ_2(S3,S2) is a measure of this transition,
- μ_2 is the intensity with which the system transitions from state S1 to state S4, hence μ_2(S1,S4) is a measure of this transition,
- λ_3 is the intensity with which the system transitions from state S2 to state S1, hence λ_3(S2,S1) is a measure of this transition,
- μ_3 is the intensity with which the system transitions from state S2 to state S4, hence μ_3(S2,S4) is a measure of this transition,
- λ_4 is the intensity with which the system transitions from state S1 to state S0, hence λ_4(S1,S0) is a measure of this transition,
- μ_4 is the intensity with which the system transitions from state S2 to state S3, hence μ_4(S2,S3) is a measure of this transition,
- λ_5 is the intensity with which the system transitions from state S3 to state S0, hence λ_5(S3,S0) is a measure of this transition,
- μ_5 is the intensity with which the system transitions from state S1 to state S2, hence μ_5(S1,S2) is a measure of this transition,
- λ_6 is the intensity with which the system transitions from state S2 to state S0, hence λ_6(S2,S0) is a measure of this transition,
- μ_6 is the intensity with which the system transitions from state S0 to state S1, hence μ_6(S0,S1) is a measure of this transition,
- λ_7 is the intensity with which the system transitions from state S4 to state S1, hence λ_7(S4,S1) is a measure of this transition,
- μ_7 is the intensity with which the system transitions from state S0 to state S2, hence μ_7(S0,S2) is a measure of this transition,
- μ_8 is the intensity with which the system transitions from state S0 to state S3, hence μ_8(S0,S3) is a measure of this transition,

- μ_9 is the intensity with which the system transitions from state S1 to state S3, hence μ_9(S1,S3) is a measure of this transition,

thus:

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

This is:

$$\mathbf{RE} \subset \mathbf{SxS}$$

Assuming that R^+ is the set of positive real numbers, one defines FR as the set of functions defined on RE that take values from R^+. The functions, in particular μ, have the following form:

$$\lambda : \mathbf{RE} \longrightarrow R^+$$

$$\mu : \mathbf{RE} \longrightarrow R^+$$

In this way, the transition intensity can be interpreted and each element of the RE set can be assigned a number from the R+ set. As shown in Figure 8, the scenario described above is represented graphically.

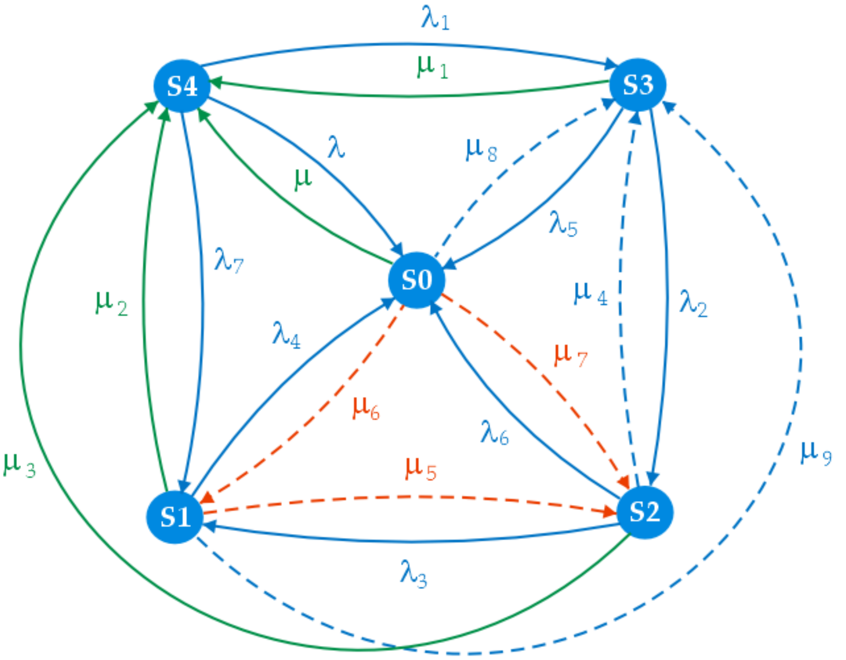

Fig. 8. *Application of the designated technical element in the 5-VL logic procedure (source: own elaboration)*

When describing the transition network (Figure 8), a number of equations were used to obtain the probabilities of the system being in the selected states (Kolmogorov-Chapman):

$$s * R_o - \lambda = = -\mu_6 * R_o + \lambda_4 * Ps_1 - \mu_7 * R_o + \lambda_6 * Ps_2 - \mu_8 * R_o + \lambda_5 * Ps_3 - \mu * R_o + \lambda * Ps_4 \quad (1)$$

$$s * Ps_1 = = \mu_6 * R_o - \lambda_4 * Ps_1 - \mu_2 * Ps_1 + \lambda_7 * Ps_4 - \mu_5 * Ps_1 + \lambda_3 * Ps_2 - \mu_9 * Ps_1 \quad (2)$$

$$s * Ps_2 = = \mu_7 * R_o - \lambda_6 * Ps_2 + \mu_5 * Ps_1 - \lambda_3 * Ps_2 - \mu_4 * Ps_2 + \lambda_2 * Ps_3 - \mu_3 * Ps_2 \quad (3)$$

$$s * Ps_3 = = \mu_8 * R_o - \lambda_5 * Ps_3 + \mu_4 * Ps_2 - \lambda_2 * Ps_3 - \mu_1 * Ps_3 + \lambda_1 * Ps_4 + \mu_9 * Ps_1 \quad (4)$$

$$s * Ps_4 = = \mu * R_o - \lambda * Ps_4 + \mu_2 * Ps_1 - \lambda_7 * Ps_4 + \mu_1 * Ps_3 - \lambda_1 * Ps_4 + \mu_3 * Ps_2 \tag{5}$$

$$\{R_o, Ps_1, Ps_2, Ps_3, Ps_4\} \tag{6}$$

Assuming initial conditions:

$$\begin{gathered} R_o\,(0) = 1 \\ Ps_1(0) = Ps_2(0) = Ps_3(0) = Ps_4(0) = 0 \end{gathered} \tag{7}$$

Thus, taking into account the obtained equations, it is possible to determine the probability of the state of use of the technical object under consideration, which can be considered as a numerical equivalent of the value of the readiness index.

The change of various operational and reliability indicators affects the change of the index values describing the states of the diagnostic system. The correlation of this dependence was analyzed using computer modeling methods. Table 1 shows the intensity of repair and damage to the system used for the analysis.

To determine the required values, operational data obtained from repair enterprises in the industrial and energy sectors, as well as failure rates given in [10-12] are used.

Table 1. Parameters for system reliability

Parameter	Value [1/h]
λ	0.00015
λ_1	0.000025
λ_2	0.000021
λ_3	0.0000316
λ_4	0.00023
λ_5	0.000022
λ_6	0.000225
λ_7	0.0000187
λ_8	0.0000165
λ_9	0.0000137
μ	0.0108
μ_1	0.0316
μ_2	0.0108
μ_3	0.0341
μ_4	0.0416
μ_5	0.0208
μ_6	0.0116
μ_7	0.0216
μ_8	0.0216
μ_9	0.0116

$$R_o \rightarrow -((7.54509 \times 10^{-38} + 5.09138 \times 10^{-34}\, s + 4.08974 \times 10^{-32}\, s^2 + 1.17885 \times 10^{-30}\, s^3 + 1.44099 \times 10^{-29}\, s^4 + 6.34433 \times 10^{-29}\, s^5) / (0. - 3.31304 \times 10^{-35}\, s - 3.18224 \times 10^{-33}\, s^2 - 1.18104 \times 10^{-31}\, s^3 - 2.12353 \times 10^{-30}\, s^4 - 1.85718 \times 10^{-29}\, s^5 - 6.34433 \times 10^{-29}\, s^6)) \tag{8}$$

$$Ps_1 \rightarrow -((2.11178 \times 10^{-55} + 8.51264 \times 10^{-52}\ s + 1.05097 \times 10^{-49}\ s^2 + 5.30234 \times 10^{-48}\ s^3 + 1.38455 \times 10^{-46}\ s^4 + 1.97053 \times 10^{-45}\ s^5 + 1.45153 \times 10^{-44}\ s^6 + 4.33507 \times 10^{-44}\ s^7) / (6.15077 \times 10^{-18} + 4.16974 \times 10^{-16}\ s + 8.89811 \times 10^{-15}\ s^2 + 5.8905 \times 10^{-14}\ s^3) \times (0. - 3.31304 \times 10^{-35}\ s - 3.18224 \times 10^{-33}\ s^2 - 1.18104 \times 10^{-31}\ s^3 - 2.12353 \times 10^{-30}\ s^4 - 1.85718 \times 10^{-29}\ s^5 - 6.34433 \times 10^{-29}\ s^6))) \tag{9}$$

$$Ps_2 \rightarrow -((-5.93459 \times 10^{-66} - 3.54134 \times 10^{-62}\ s - 5.02918 \times 10^{-60}\ s^2 - 3.01714 \times 10^{-58}\ s^3 - 9.8419 \times 10^{-57}\ s^4 - 1.88351 \times 10^{-55}\ s^5 - 2.11574 \times 10^{-54}\ s^6 - 1.293 \times 10^{-53}\ s^7 - 3.3209 \times 10^{-53}\ s^8) / ((-3.12374 \times 10^{-11} - 4.114 \times 10^{-10}\ s) \times (6.15077 \times 10^{-18} + 4.16974 \times 10^{-16}\ s + 8.89811 \times 10^{-15}\ s^2 + 5.8905 \times 10^{-14}\ s^3) \times (0. - 3.31304 \times 10^{-35}\ s - 3.18224 \times 10^{-33}\ s^2 - 1.18104 \times 10^{-31}\ s^3 - 2.12353 \times 10^{-30}\ s^4 - 1.85718 \times 10^{-29}\ s^5 - 6.34433 \times 10^{-29}\ s^6))) \tag{10}$$

$$Ps_3 \rightarrow -((-2.06151 \times 10^{-65} - 1.23328 \times 10^{-61}\ s - 1.48431 \times 10^{-59}\ s^2 - 7.49643 \times 10^{-58}\ s^3 - 2.05048 \times 10^{-56}\ s^4 - 3.28117 \times 10^{-55}\ s^5 - 3.07384 \times 10^{-54}\ s^6 - 1.56184 \times 10^{-53}\ s^7 - 3.3209 \times 10^{-53}\ s^8) / ((-3.12374 \times 10^{-11} - 4.114 \times 10^{-10}\ s) \times (6.15077 \times 10^{-18} + 4.16974 \times 10^{-16}\ s + 8.89811 \times 10^{-15}\ s^2 + 5.8905 \times 10^{-14}\ s^3) \times (0. - 3.31304 \times 10^{-35}\ s - 3.18224 \times 10^{-33}\ s^2 - 1.18104 \times 10^{-31}\ s^3 - 2.12353 \times 10^{-30}\ s^4 - 1.85718 \times 10^{-29}\ s^5 - 6.34433 \times 10^{-29}\ s^6))) \tag{11}$$

$$Ps_4 \rightarrow -((-6.31783 \times 10^{-63} - 8.42364 \times 10^{-61}\ s - 4.77683 \times 10^{-59}\ s^2 - 1.50565 \times 10^{-57}\ s^3 - 2.88506 \times 10^{-56}\ s^4 - 3.43856 \times 10^{-55}\ s^5 - 2.48446 \times 10^{-54}\ s^6 - 9.91202 \times 10^{-54}\ s^7 - 1.66045 \times 10^{-53}\ s^8) / ((-3.12374 \times 10^{-11} - 4.114 \times 10^{-10}\ s) \times (6.15077 \times 10^{-18} + 4.16974 \times 10^{-16}\ s + 8.89811 \times 10^{-15}\ s^2 + 5.8905 \times 10^{-14}\ s^3) \times (0. - 3.31304 \times 10^{-35}\ s - 3.18224 \times 10^{-33}\ s^2 - 1.18104 \times 10^{-31}\ s^3 - 2.12353 \times 10^{-30}\ s^4 - 1.85718 \times 10^{-29}\ s^5 - 6.34433 \times 10^{-29}\ s^6))) \tag{12}$$

6 Results of the study

In the simulation study of an internal combustion engine, expressions (1-7) are used, from which the probability of failure of various engine components during its operation is determined. The value of the probability of operability of any technical object in terms of reliability is called the reliability function. Numerically, for a given time value, it is equal to the value of the readiness index. The study of the reliability of an internal combustion engine during its operation allows for the prompt determination of the effect of changes in various reliability indicators on the values of the parameters characterizing the states of the analyzed diagnostic system.

Using the inverse Laplace transform and the values in Table 1, the following probabilities of the system under study being in each operating state were obtained for an exponential distribution:

- the duration of the internal combustion engine test was - 1 year: t = 8760 [h].
- probability of remaining in fully recoverable condition S4 for 1 year: $Rs_0(t) = 0{,}98783$
- probability of becoming partially airworthy S3 in 1 year: $Ps_1(t) = 0{,}0004901$
- probability of becoming critical S2 in 1 year: $Ps_2(t) = 0{,}0004697$
- probability of progression to S1 in 1 year: $Ps_3(t) = 0{,}0001890$
- probability of S0 becoming unserviceable in 1 year: $Ps_4(t) = 8{,}32593 \cdot 10\text{-}6$

The authors' scientific task was to carry out a diagnostic study of a complex technical object in order to determine the current state of its structural components and the condition of the object. In further reliability studies, a model of the technical object's operating process was developed. In the model, the identified technical states were used as operating states of the object, in which the combustion engine can be located as a result of transitions between states in the model. In the next step, the graphical model of the exploitation process was described by the Kolmogorov-Chapman equations of state. As a result of solving the system of differential equations of state describing the analytical model of the exploitation process, the reliability function Ro(t) (Figure 5) of the internal combustion engine in this process was determined. The final stage of the research was a simulation reliability study, which was carried out in a simulation manner for the assumed operating time of the facility, i.e. the 1-year cycle time of the facility, which is (t = 8760 [h]). In the reliability study of the internal combustion engine, the simulation determined the probabilities of the tested internal combustion engine being in one of the states contained in the set of states {S4,S3,S2,S1,S0}.

The novelty of the article is the combination of the results of diagnostic tests (specified states of the object) with the study of the reliability of the internal combustion engine. The result of these tests is the determined reliability function Ro(t) and the probability of the object being in each state. The objective of the first stage of reliability testing was to calculate the value of the reliability function Ro(t) of the internal combustion engine during the operation process. In addition, the values of the probability of this object staying in one of the states (states of use) after any number of transitions between states were determined. In the second stage of the study, the failure function Ro(t) was plotted as a function of time (t = 8760 [h]). In the next stage, the values of the probabilities of occurrence of the recognised states in the studied object were plotted on the chart of the Ro(t) characteristic. The marked probability values of the distinguished states on the Ro(t) characteristic unambiguously determine the corresponding time intervals on the Ro(t) characteristic (Figs. 9 and 10).

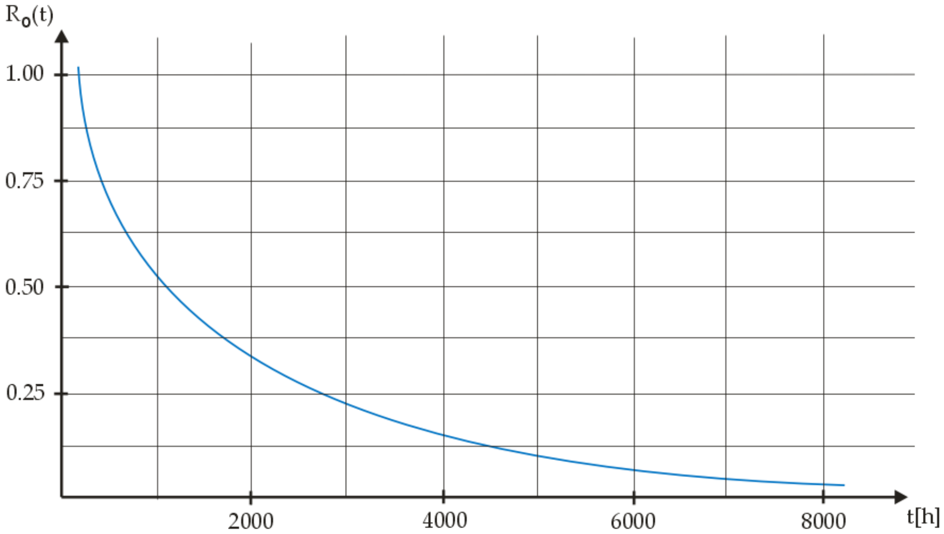

Fig. 9. *Reliability function diagram for the operation of an internal combustion engine over a period of one year* $\{R_o, Ps_1, Ps_2, Ps_3, Ps_4\}$

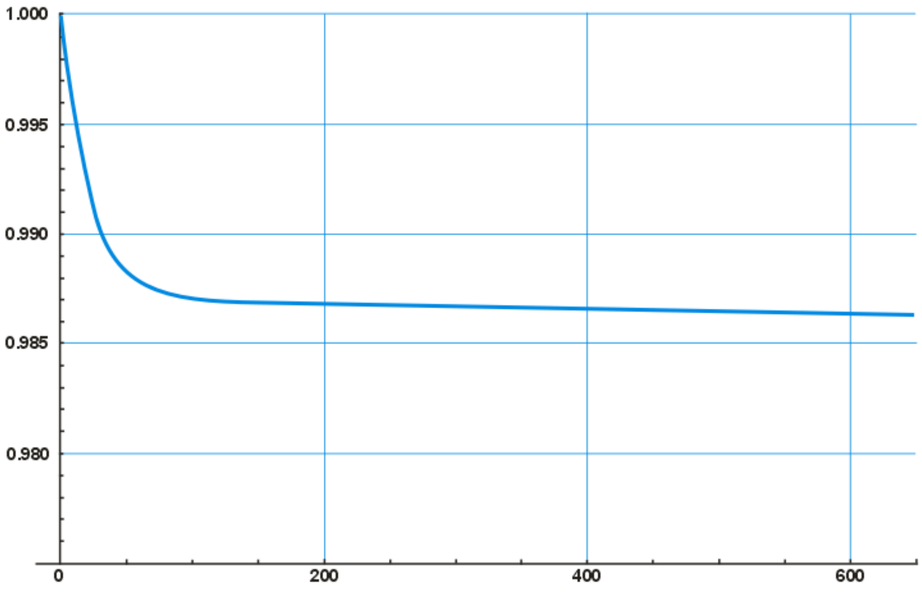

Fig. 10. *Graph of the reliability function in the initial phase of operation of a test internal combustion engine in transport vehicles over a period of 1 year* $_{\{R_o\}}$.

7 Research of reliability of technological process of internal combustion engine

The construction of a complex characteristic Ro(t) is necessary to assess the time of occurrence of the probability of the onset of a condition detected during diagnostics (Figure 11).

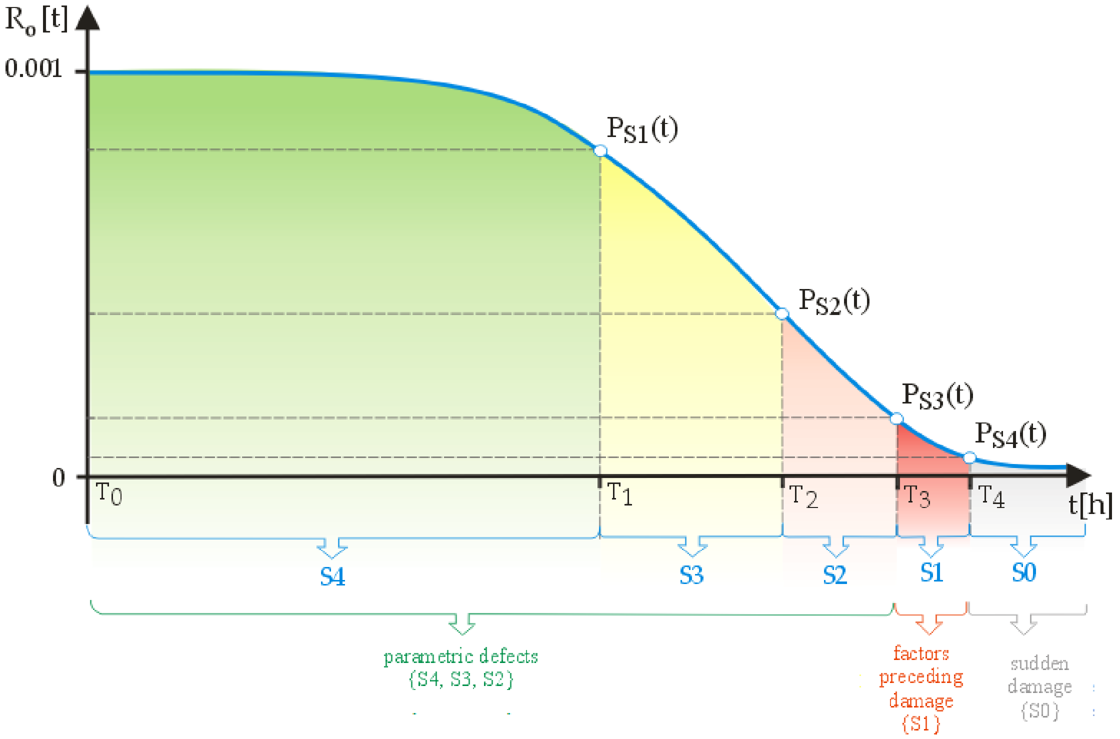

Fig. 11. *Comprehensive reliability function for the operation of an internal combustion engine over period T* $_{\{Ps_1,Ps_2,Ps_3,Ps_4\}}$*(source: own elaboration)*

Depending on the research task, the model of the process of functioning of technical objects is considered using various approaches [10-12]. Traditionally, it is more convenient to represent the model of the process of functioning of the object graphically (Figure 12).

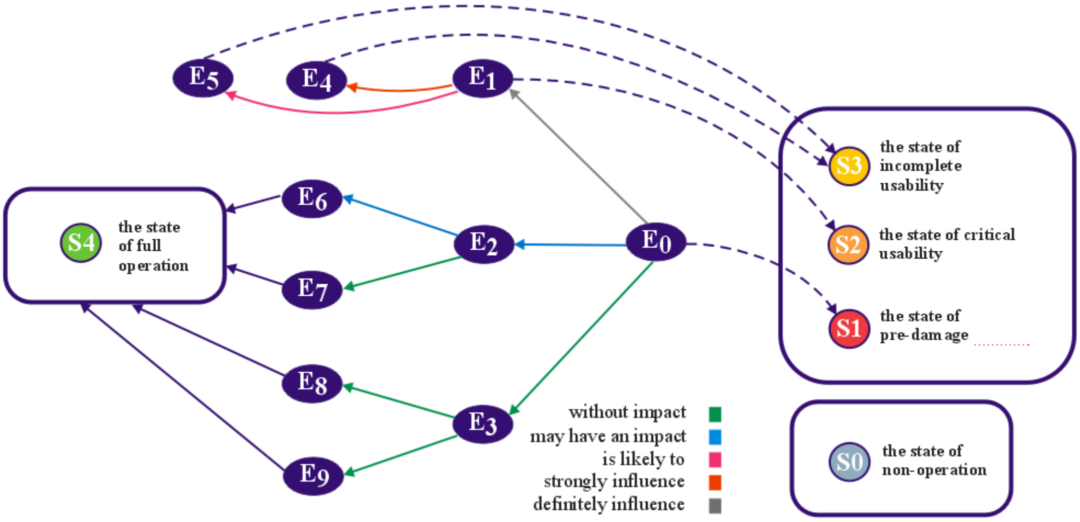

Fig. 12. *Graphic model of the facility operation process (source: own elaboration)*

The analytical form offers another approach to demonstrating the implementation of the operation process of an internal combustion engine. In some cases, both types of operation process models are used.

The problem of determining the times of occurrence of the probability of a given state identified in the diagnostics requires the plotting of a detailed characteristic $R_o(t)$. The analysis of the characteristic ($R_o(t)$) in Fig. 5 shows that the determined values of the calculated probabilities of the distinguished set of states {S0, S1, S2, S3, S4} lie in the lower part of the characteristic $R_o(t)$. Thus, the characteristic ($R_o(t)$) is submitted for further study (Fig. 11) with a range of variation of its values below 0.001. Fig. 11 shows the estimated probability values of the object's steady states. Points are then marked on the $R_o(t)$ characteristic, which are the probabilities of occurrence of each state (Ps(t)). The estimated intervals ($R_o(t)$) on the plot (Fig. 11) of the individual probabilities of occurrence of each state are:

$R_o = 0.98783 \rightarrow \langle 0 \div 560 \rangle$ [h]

$Ps_1 = 0.0004901 \rightarrow \langle 1270 \div 3820 \rangle$ [h]

$Ps_2 = 0.0004697 \rightarrow \langle 3820 \div 5570 \rangle$ [h]

$Ps_3 = 0.000189 \rightarrow \langle 5570 \div 6991 \rangle$ [h]

$Ps_4 = 8.32593 \cdot 10^{-6} \rightarrow \langle t > 6991 \rangle$ [h]

The intervals thus determined between the indicated time of occurrence of state Ps are also the intervals of the technical object's residence times in the various possible technical states.

8 Analysis of results

The reliability function Ro(t), the graphs of which are shown in Figures 9 and 11, was used in the reliability simulation studies carried out on the combustion engine under study. The following conclusions can be drawn from the analysis of the Ro values: (t) characteristics and values of the probabilities (Ps(t)) of the occurrence of possible states at the expected time of use:

1. at time T_0 (T_0 = 560[h]), the occurrence of state S4 - the matching state - was determined. Thus, in the time interval <0; 560[h]> the combustion engine under test is in state S4 - fit state. In this state, the internal combustion engine performs its tasks fully and to the required extent.
2. in the following time interval, the determined time T_1 denoting the occurrence of the state S3 - state of incomplete fitness has the value (T_1 = 1270[h]). Thus, in the time interval <560[h]; 1270[h]> the combustion engine under test is in S4 - state of fitness. In this state, the internal combustion engine is fully operational.

3. at the next time interval T_2, denoting the occurrence of the S2 - critical efficiency state, it takes the value (T_2 = 3820[h]). In the time interval <1270[h]; 3820[h]> the combustion engine under test is in the S-state.
4. the internal combustion engine under test is in the S3 state - state of inefficiency. In this state, the internal combustion engine performs to a limited extent.
5. the next tested time T_3, indicating the occurrence of state S1 - pre-damaged state, time T_3 has the value (T_3 = 5570[h]). Thus, in the time interval <3820[h]; 5570[h]>, the combustion engine under test is in state S2 - critical performance state. In the S2 state, the combustion engine under test performs minimally.
6. the next time interval under test, T_4, denoting the occurrence of the S0 - unserviceable state, has the value (T_4 = 6991[h]). Thus, in the time interval <5570[h]; 6991[h]>, the combustion engine under test is in the S1 - pre-failure state. In state S1, the internal combustion engine under test performs minimally.
7. in the time interval above <6991[h]>, the combustion engine under test is in state S0 - unserviceable state. In this state, the internal combustion engine ceases to perform its task and is damaged.

During operation of the internal combustion engine shown in Fig. 11, it is affected by external and internal conditions, which, together with wear and aging processes, cause engine damage. Damage caused to the engine can be minor (non-critical) or significant (critical). Each damage caused to the object negatively affects its efficiency and further use. Based on research data, damage caused to a technical object can be presented as follows:

- Damage is a condition occurring in an internal combustion engine , in which the ability of the object to perform the required functions is lost (the object ceases to fulfil its sentences). Damage by its nature can be divided into critical and non-critical.
- Critical damage is damage that results in the internal combustion engine being in an unusable condition - the "0" condition. In this state, there is a sudden complete loss of the facility's ability to perform the required function. A critical failure may involve significant property damage or other dangerous events to the facility itself and the personnel operating the facility.
- A non-critical failure is a damage that gradually occurs in an internal combustion engine during its service life due to changes associated with aging, exposure to internal factors (e.g. temperature, pressure, etc.) present in the structural elements of the object, and others.

In an internal combustion engine, a gradual (parametric) continuous decrease in the level of its operational characteristics occurs during its service life. A gradual parametric decrease in the ability of the object to perform the required functions also occurs. A non-critical failure does not necessarily entail material losses or emergency events for the object itself and the personnel operating the object. The obtained results of studies of the reliability of an internal combustion engine are relevant for assessing the quality of use of the entire object. This allows us to develop a qualitative characteristic of the entire period of operation of an internal combustion engine, which requires: possible (predicted) states during its operation and the time of occurrence of the probability values Ps of each state, as shown in Figure 11.

9 Conclusions

This paper presents the problem of analysis and reliability assessment of a technical object diagnosed in the operation process with 5VL logic. For this purpose, a model of the exploitation process of the object with 5VL diagnostics was developed and described in graphic and analytical form. The distinguished states of the exploitation process model are uniquely related to the technical states of the object distinguished with 5VL diagnostics. The operating process model of the test object contains subsets of operating states in the form of serviceability states (S4), incomplete serviceability state (S3), critical serviceability state (S2) and pre-failure serviceability state (S1).

The subset of operability states is a single-element subset - the state of inoperability (S4). Determining the time of occurrence of the inoperable state of the object provides new opportunities for developing a new strategy for updating the object under study. When implementing the proposed strategy for updating a technical object, the category of the technical object is certainly important. The most responsible of the known in practice categories of technical objects are objects of continuous operation in passenger aircraft and ships, energy systems, medical devices, etc. For these categories of technical objects, the approach to applying the strategy for updating a technical object proposed by the authors, called "strategy for known states of technical objects", is most relevant.

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