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Examination of the effectiveness of the operation process of a radar system

K e y w o r d s

Servicing process, system modelling, expert system, artificial neural network, knowledge base, diagnostic information.

S ł o w a k l u c z o w e

Proces obsługiwania, modelowanie systemów, systemy ekspertowe, sztuczne sieci neuronowe, bazy wiedzy, informacja diagnostyczna.

S u m m a r y

This paper presents a method to investigate the effectiveness of an operation process with a servicing expert system including an artificial neural network. A method of simulation testing with the use of computer technology is described. The theoretical bases are presented of the modelling of an operation process of objects in the form of the following models: mathematical (analytical), graphical and descriptional. For the tests, a model was developed of an organisation of a servicing system of those technical objects that require short shutdown times (aircraft, radiolocation systems, etc.). The requirements are presented and described for simulation tests, which is the development of a test plan, the preparation of data to describe the performance of an object, and the development of models for an operation process of a technical object, which express the investigated aspects of this process. The results are presented of the simulation tests of a repairable technical object.

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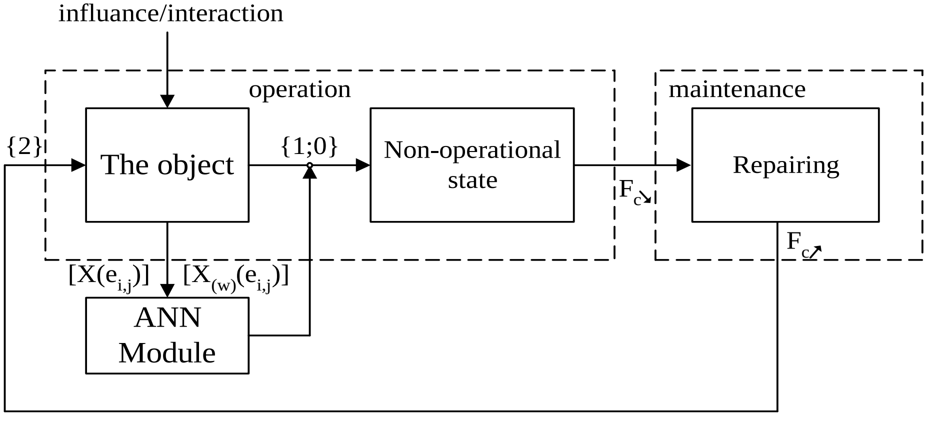
1. Introduction

Technical objects used in the process of operation may be found in specific states (operation or servicing) [1, 2, 10, 11, 12]. During operation, a technical object is exposed to various reactions, there are ageing changes, and the functional elements of the object wear. The changes of the physical properties of the object in relation to their nominal values result in the lowering value of the quality of functioning, thus the lowering value of the object's operational function during its operation. Then, the technical object passes to a shutdown state in the operation process (Fig. 1), which is determined by the states of non-operation or incomplete operation states.

In the shutdown state, the objects do not realise their foreseen operational functions. In order to counteract random changes of the object's quality of operation and to maximise it, the object's technical servicing is organised through planned and unplanned servicing.

Operation of technical (and other) objects is connected with the costs of operation. The user of a given technical object makes efforts to optimise the costs of operation and these issues are complex. In order to do so, one needs to establish the indices that characterise the operation process of a technical object, establish the performance of a given object (how to operate this object effectively, in which conditions it is to be operated, when servicing is to be organised and how to optimise this process, etc.), and also conduct tests of the operation process in the perspective of its effectiveness [1, 2, 3, 7, 8, 10, 11, 12].



where: $X(e_{i,j})$ – diagnostic signal in jth element of ith set; $X_{(w)}(e_{i,j})$ – model signal for $X(e_{i,j})$ signal; F_C – function of the use of the object, $W(\varepsilon(e_{i,j}) = \{2, 1, 0\})$ – diagnostic information-value of state assessment logics for element „j" within „i" module of the object.

Fig. 1. Diagram of operation process for technical object utilising artificial neural network
Rys. 1. Schemat procesu eksploatacji wykorzystującego sztuczną sieć neuronową

2. Indices which characterize the operation process of a technical object

From the set presented in the literature [11, 12] of those indices which characterise the operation process of a technical object, the quantity which best reflects the operation process is availability factor K_g and availability function $K_g(t)$. The calculation process of availability function $K_g(t)$ is usually simplified when it is calculated for the boundary value at $t \to \infty$. This quantity has a close relation with the stationary characteristics of the process of damages and servicing. For this reason, availability factor K_g is the most suitable measure to express the effectiveness of the operation process, which combines at the same time the object's performance and economic properties.

Availability factor K_g of an object is the probability of an event that consists in the fact that the object is in working order after a sufficiently long period of operation ($t \to \infty$). Availability factor K_g determines the average share of the operation periods of a technical object in the total period of its operation, which is presented with the following dependence:

$$K_g = \lim_{t \to \infty} K_g(t) = \lim_{t \to \infty} K_{gsr}(t) \qquad (1)$$

Where: K_{gsr} (t) – the average value of availability factor K_g.

The determination of availability factor K_g requires that the operation process of a given object be known exactly. While having the determined quantity that expresses the effectiveness of the operation process of an object of any class, one can determine the quality function of the operation process of the object.

The quality function of the object's operation process F_c is a dependence that characterises the object's operation process with respect to the effectiveness of the object's operation process in relation to the quantity of the input used during the total object's operation period, which is presented in the form of the following dependence:

$$F_c = \frac{K_g}{N_e} \qquad (2)$$

The quality function of the object's operation process expresses the effects obtained in the process of the object's operation in the form of availability factor K_g in relation to operation input N_e borne in a given time (t) of the object's operation.

3. Modelling of the operation process of a repairable technical object

The operation process of a complex technical object is a stochastic process Z(t), whose elements (Z_i) belong to the subsets of the object's states {Z}: operation and servicing. While analysing any possible operation situations in which the object could be found after any number of passes, one can determine the object's states in the operation process, which form a set of the object's states Z(t). Each of the possible object's states in the operation process that can occur is determined in the diagnosing process of the object [1, 2, 4, 5, 6, 9]. The set of the object's states in the object's operation process {Z}, depending of the accepted valence of the valuation of states, is divided into two or three subsets {Z_1, Z_2, Z_3}, where: Z_1 – subset of operation states, Z_2 - subset of non-operation states, Z_3 - subset of incomplete operation states. The subset of the states of the operation of the operation process is a single-element process of the states of use Z_1 of the object in the operation process.

The state in which the object is used in the operation process [1, 6] is such a state of the operation process Z_1 during which the object realises the required functions in compliance with its use. If the object is no longer operated because it is not realising its required functions, then it should be repaired in the process of servicing. The states distinguished in the diagnosing process, when the object is not use, belong to the subset of the object's servicing states {Z_2}. This subset is a multi-element set, to which the following states belong: Z_2, Z_3, Z_4 where: Z_2 – planned servicing; Z_3 - unplanned servicing; Z_4 – ineffective use (the shutdown state). Depending of the need of research in the literature [3, 4, 7, 11], various methods are used to present the operation process of a technical object. Most frequently, the model of the operation of the object is represented in a graphical form. A graph of the process is the graphical form of the realisation of the operation process of the object. An analytical form is another manner to present the realisation of the operation process of the object.

3.1. The servicing technical object-the radar system type Straight Flush Radar Vehicle

In order to design the servicing system for an analogue class technical object [11], in this case it was an air-defence radar device, it was needed to determine the internal structure of serviced object and the set of prophylaxis activities for the non-operational elements. The radar system-Straight Flush Radar Vehicle presented in Fig. 2 is a part of a surface–to–air–missile system (SA-6 "GAINFUL"). The purpose of the radar system is to fight air targets (aircraft, helicopters, rockets, drone vehicles), as well as ground and water targets in the range of the missiles. The radar system, Straight Flush Radar Vehicle, detects (determines the azimuth, distance and height) and controls the air fight. The antiaircraft set is adapted to work regardless of the time of the year and the day in temperatures from -40°C to +50°C, with a relative humidity of 90 per cent and the wind speed up to 20 m/s.

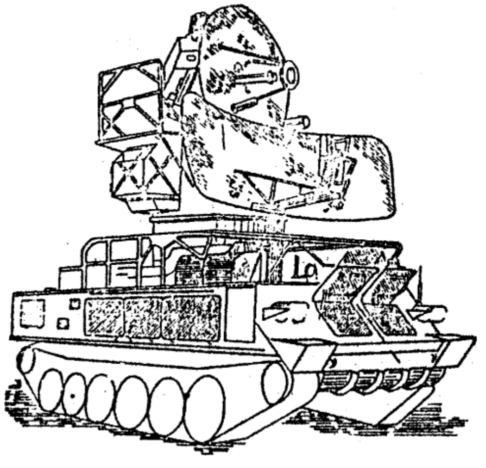
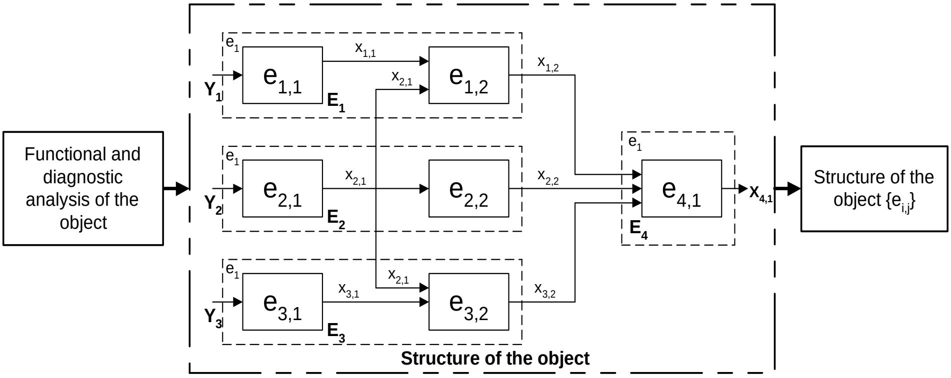


Fig. 2. The picture of an air-defence radar device of (SA-6) system
Rys. 2. Widok zestawu stacji radiolokacyjnej wykrywania i naprowadzania systemu (SA-6)

The radar system, Straight Flush Radar Vehicle, is characterised by a high resistance to climactic and natural factors. The (SA-6) system can be operated fully automatically as regards detection, identification, tracking, and raking of targets. The set is adapted to cooperation and coupling with four sources of external information. The radar can rake at the same time 1 target with 1 or 2 rockets fired within a span of 5 seconds from one or two launchers.

3.1. Modelling of the servicing object of a radar system, Straight Flush Radar Vehicle

The technical object used for tests in the present study is a reparable complex technical object of an analogue class. While preparing a diagnostic model of this class of an object, its internal structure was divided into four levels of the maintenance structure (Fig. 3): level one – object, level two – assemblies (in object), level three – subassemblies (in each assembly $\{E_i\}$), and level four – modules-basic elements (in each subassembly, of each assembly of the object). The first level of the maintenance structure of the object is constituted by the object itself. It is a set of functional assemblies $\{E_i\}$.



where: E_i - ijth functional assembly in the object,
e_i - j jth subassembly or functional element in a given assembly, $Y_{1,2,3}$ – input signals in the object.

Fig. 3. Functional and diagnostic model of the object
Rys. 3. Model funkcjonalno-diagnostyczny obiektu technicznego

Each functional subassembly of the object consists of basic elements, which are the smallest and indivisible functional element in the object. It was assumed in the paper that such an element is understood as a basic element in the object where there is an output (diagnostic) signal on its output. If object has been divided into *i* structural levels, and in each of them, there are *j* basic elements, then each of the object's structural levels constitutes a set of operating elements $\{e_{i,j}\}$, which was presented in the form of the following dependence:

$$\{O\} \Rightarrow (\{E_i\} \Rightarrow \{e_j\}) = \{e_{i,j}\} \tag{3}$$

Where: {O} – object's internal structure, $\Rightarrow$ – relation of result (division), E_i – ith functional assembly of the object, e_j – jth subassembly in ith assembly of the object, $\{e_{i,j}\}$ – set of basic elements in the object (structure of the object).

The division of the object's internal structure $\{e_{i,j}\}$ accepted in this paper defines explicitly the depth of penetration into this structure. The accepted division is considered to be sufficient if we distinguish the basic module-element in the structure of the object. One of the purposes of the functional-diagnostic analysis is the determination of the state of the object. The object's state is determined on the basis of an examination of the set of output (diagnostic) signals $\{X(e_{i,j})\}$(Table 1) [1-11]. The set of its functional elements $\{e_{i,j}\}$ determined during a diagnostic study of the object constitutes the basis for the list included in the table of a set of diagnostic signals (Table 1).

Table 1. Table of the input diagnostic signals of the object
Tablica 1. Tablica sygnałów diagnostycznych obiektu

Object	Level of object E_i	Vector of initial diagnostic signals $\{X(e_{i,j})\}$				
		$X(e_{1,1})$	...	$X(e_{i,j})$	...	$X(e_{i,J})$
O	E_1	$X(e_{1,1})$	...	$X(e_{1,j})$	...	$X(e_{1,J})$
	⋮	⋮	...	⋮	...	⋮
	E_i	$X(e_{i,1})$	...	$X(e_{i,j})$	...	$X(e_{i,J})$
	⋮	⋮	...	⋮	...	⋮
	E_I	$X(e_{I,1})$	...	$X(e_{I,j})$	...	$X(e_{I,J})$

Where: $X(e_{i,j})$ – diagnostic signal of j^{th} element in i^{th} assembly.

3.2. Model of an expert servicing system with an artificial neural network of a radar system

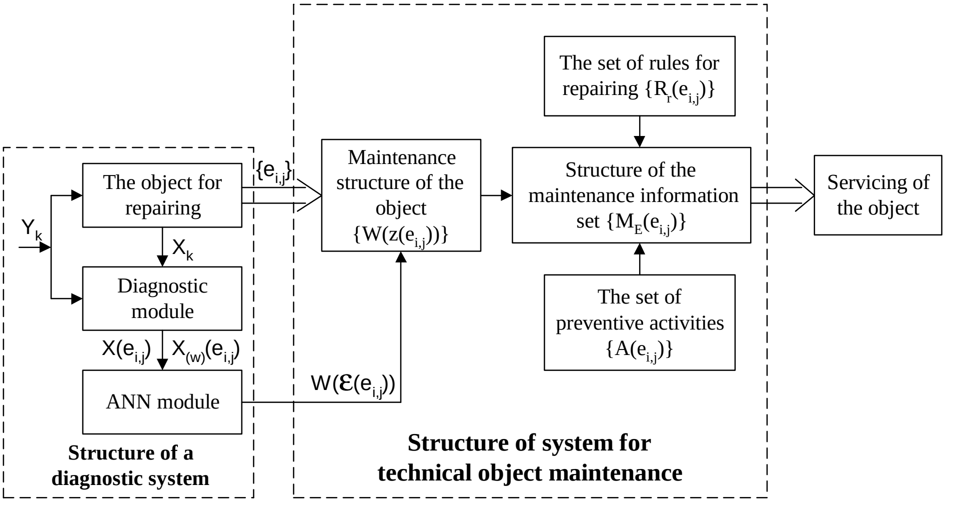
A particularly important element of the maintenance system is the knowledge base (Fig. 4). It can be defined as a specialised set of the object's maintenance information, which is determined by the following: the maintenance structure of the object $\{W_z(e_{i,j})\}$, the set of rules for maintenance (repairing) $\{R_r\}$, and the set of preventive activities $\{A(e_{i,j})\}$.

The quality of the use of an object can be measured with two quantities: the use function of the object $F_C(t)$ and F_C index of the use function of the object. The values of function $F_C(t)$ are determined by the divergence between the actual state of the object in the space of the use features (ω), and the state of the usability in the nominal space of usability features (M_E) (Fig. 1). The nominal space of usability features (M_E) is determined by elementary nominal vectors of the object's usability function $F_C(e_{i,j})$.

It is evident from the analysis (Fig. 4) that the process of the renovation of an object in an analytical approach consists in the transfer of the object's usability features from the level of the plane of the current use (ω) to the level of the plane of nominal usability features (M_E). The function that renovates the object in the servicing system is presented in the form of the following dependence:

$$M_E(e_{i,j}) = f\left(W\left(z\left(e_{i,j}\right)\right); A_l\left(e_{i,j}\right); R_r\left(e_{i,j}\right)\right) \tag{4}$$

Where: $\{W_z(e_{i,j})$ – the maintenance structure of the object $\}$, $\{R_r(e_{i,j})\}$ – the set of rules for maintenance (repairing), $\{A(e_{i,j})\}$ – the set of preventive activities, $\{M_E(e_{i,j})\}$ – the maintenance system produces a set of maintenance information.



Where: $X(e_{i,j})$ – diagnostic signal in j^{th} element of i^{th} set; $X_{(w)}(e_{i,j})$ – model signal for $X(e_{i,j})$ signal; F_C – function of the use of the object.

Fig. 4. Diagram of a servicing system with an artificial neural network
Rys. 4. Schemat procesu obsługiwania obiektu technicznego wykorzystującego sztuczną sieć neuronową

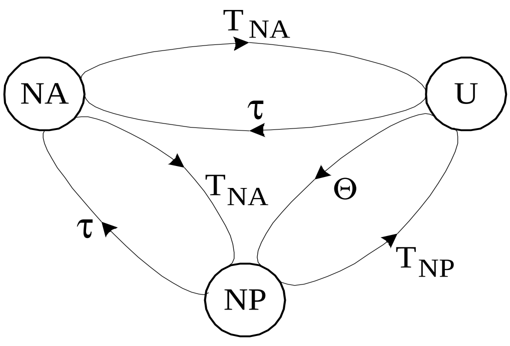
As a result, the maintenance system produces a set of maintenance information $\{M_E(e_{i,j})\}$, which will be used for the organisation of the object's rational (optimised) maintenance system.

A set of the servicing information of the object, which constitutes the basis in the process of designing of the structure of the servicing system, is presented in the form of the following dependence:

$$M_E\left(e_{i,j}\right)=\left\{M\left(e_{i,j}\right),W\left(z\left(e_{i,j}\right)\right)A_l, R_r\right\} \tag{5}$$

3.3. Modelling of the operation process of a technical object

Every operation process of any object consists of a subset of the operation state and a subset of the servicing state (Fig. 5). The description of passes between the distinguished states of an object's operation process tested, and relations between them constitutes a difficult task and requires that the real operation process is known exactly.



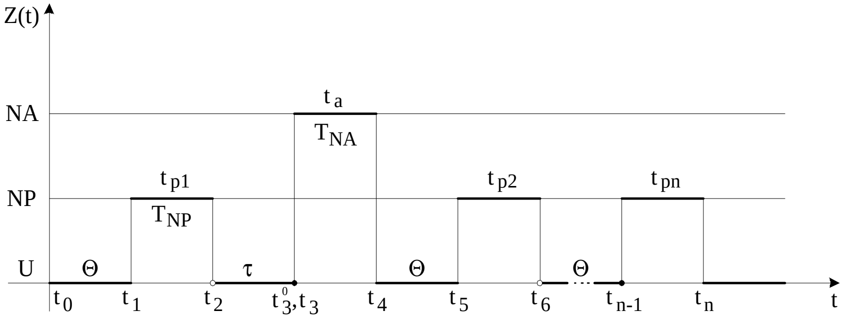
Where: T_{NA} – duration of unplanned repair; T_{NP} – duration of planned repair; Θ – periodicity of the object's planned repair, τ – intensity of damages.

Fig. 5. Graph of a model of an object's operation process with a servicing system which uses an artificial neural network which processes diagnostic information expressed in the values of the three–values {2, 1, 0} of the states
Rys. 5. Graf modelu procesu eksploatacji obiektu z systemem obsługiwania wykorzystującym sztuczną sieć neuronową wypracowującą informację diagnostyczną wyrazaną w trójwartościowej ocenie stanów

Only when it is known, a model of the operation process of the object can be developed while one of the ways are used for this purpose to present a given structure of the object's operation process. In each operation process of the object described, the most difficult tasks are as follows: the development of the model of the structure of the object's operation, as well as establishing and describing a possible subset of the state of the technical object's operation.

While having a constructed servicing system (Fig. 5) and knowing the relations between operation states, one can begin to develop a model of the object's operation process under investigation. Its practical realisation is presented in Fig. 5. In order to understand the idea of the operation process model developed, one needs to analyse the mechanism of the change of the states (the way in which passes between the states occur). A practical manner of the organisation of a pass between the distinguished operation states of the object in its developed model is presented in Fig. 6.

An analysis of the ways of the change of the states of the object operated in compliance with the model described demonstrates that this object can be found in of the following states:
– Z_1 – operation U;
– Z_2 – scheduled servicing (prophylactic repair);
– Z_3 – unplanned repair NA (emergency).



Where: • – moments of object’s damages; ° – moments of object’s repairs.

Fig. 6. Example of the realisation of the object’s operation process model with a servicing system using an artificial neural network which develops diagnostic information expressed in the values of the three-values {2, 1, 0} of the states
Rys. 6. Przykład realizacji modelu procesu eksploatacji obiektu z systemem obsługiwania wykorzystującym sztuczną sieć neuronową wypracowującą informację diagnostyczną wyrażaną w trójwartościowej ocenie stanów {2, 1, 0}

From among the operation indices presented above, the availability factor was considered to be the most dependant, from the changes of the operation process quality, and which is described with the following dependence:

$$K_g(\Theta) = \frac{\int_0^{\Theta} R(t)dt}{\int_0^{\Theta} R(t)dt + T_{NP} \cdot F(\Theta)} \tag{6}$$

Where: T_{NP} – mean duration of the object’s scheduled repair; F(Θ) = P{ł < Θ} – value of the distribution function of time until damage in moment t = Θ; R(Θ) = P{ł ≥ Θ} = 1 – F(Θ) – value of survival function in moment t = Θ.

It is evident from an analysis of dependence (6) that availability factor K_g can be determined when value Θ is known which determines the periodicity of the realisation of the object’s scheduled repair. If $\lambda(\Theta^*) = \Theta^*$ is a function constant in time, then dependence (6) accepts the following form:

$$K_g = \frac{T}{1 + (T_a - T_p) \cdot \Theta^*} \tag{7}$$

Where: T – operation time, T_a – emergency repair time, T_p – prophylaxis time, Θ^* – optimal periodicity of prophylactic servicing.

Considering the need to relate future results of the research in a comparative analysis of the models of operation processes, a model must be developed of an operation process of a real object with a traditional servicing system.

4. Simulation test of the effectiveness of a radar system's operation process

An investigation of the operation process of an object, and all the more a simulation investigation, requires input data which characterises the real operation process of a selected class of an object and its simulation models. The results of simulation tests obtained for the accepted duration of the investigation T_o are presented in (Figs. 7 and 8).

An investigation of the real operation process of an object constitutes the basis for obtaining data for a simulation investigation of the models of processes. The following quantities constitute the required input data for tests:

- Duration of the use of the object T (time when the object is in the operation state);
- Duration of the removal of the object's non-operation state T_a;
- Duration of prophylactic repair T_p;
- The period of forecast (optimal) prophylaxis θ^*; and,
- The period of planned prophylaxis θ.

The operating quantities used for the purpose of a simulation examination of the object's models of operation processes were determined on the basis of observations and an examination of the technical and operating documentation of the device tested of the same class [11]. The input data accepted for the investigations are as follows:

- The average time of the removal of the non-operation state (T_a) is determined from (T/T_a) relation for given values included in set {B}, where $T/T_a = \{B\}$; for the examinations, values {B = 1, 2, 4, 8} were accepted; and,
- The average time of a prophylactic repair (T_p) is determined from (T/T_p) relation for simulation examinations; a constant value (5) was accepted, where: $(T/T_p) = 5$; the average period of the planning of a prophylactic repair was determined in the diagnostic experiment in the way of forecasting of the time of further preventive treatment, and this time amounts to $\theta^* = 115$ [h - time units] [11].

The source of the data mentioned above may be an observation of real operation processes as well as a suitably prepared and conducted simulation experiment.

The simulation investigations were carried out for constant inputs for prophylaxis in the whole period of operation (a simulation time of the use of the object: T_o). As an evaluation of a real operation process is too time consuming, three operation process models were developed for the purpose of investigations:

1. Model A: an object's operation process using information in trivalent logic (a model with an expert system, with artificial neural network),
2. Model B: an object's operation process using information in divalent logic,
3. Model C: an operation process of an object organised in a classical manner, i.e. without an investigation of the state.

In the investigations, the following were evaluated: the indices which characterise the operation process of technical objects, availability factor K_g and the quality function of the operation of the object process F_c. The determination of the value of availability factor K_g and the quality function of the object's operation process requires that the properties of the operation process of the technical object used are known exactly: the characteristics of the damage and servicing processes (T – time of use and T_a – time of servicing).

There are the following conclusions from the analysis (Figs. 7 and 8) of dependencies (K_g) and (F_C) expressed in the function of test duration (T_o) – conventional units of the test duration:

1. The results of the investigation of quantities (K_g) (Fig. 7) for the model (A and B) are decreasing, and the largest value of (K_g) is for model A, and it is (K_{gA} = 0.7508). For the remaining models, this quantity is as follows: (K_{gB} = 0.4931 and (K_{gC} = 0.2332).
2. The quantity investigated (K_g) has also a practical aspect: it refers to the effectiveness of the organisation of a given servicing system. We may find from the definition of this quantity: dependence (1) of quantity (K_g) [1 -11] that this factor determines the availability of the object to be used as it is intended for use in the period of use (T). Therefore, the organisation system of prophylaxis is the most effective presented in model (A), as value (K_{gA} = 0.7508) is the maximum value.
3. The tested function of the operation process quality (F_C) in models (A, B, and C), that is graphically represented in (Fig. 8) is also expressed in the accepted time of the test (T_o). It is evident from the definition of quantity (F_C): dependence (2) that the input borne in the object's servicing system organisation in a given model has a large impact on this quantity.
4. The quantity of inputs for models (A, B, and C) and a constant expressed with a linear function were accepted for the tests. It is evident from the analysis (Fig. 8) that the best quality of operation process (F_C) is for model (B), where: (F_{CB} = 0.2239), while for model (A) it is (F_{CA} = 0.1979). It can be supposed that the organisation of the servicing system in model (A) is more cost consuming, and this is a more technologically advanced servicing system.

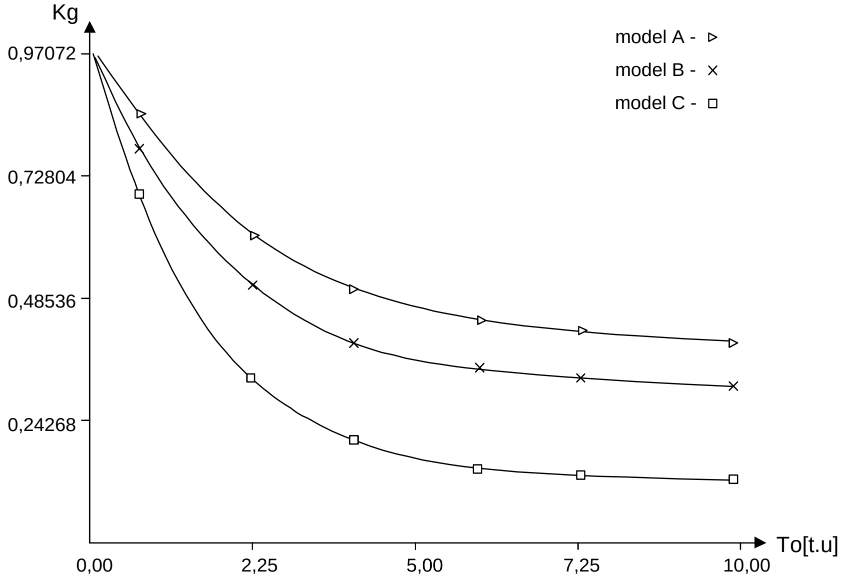


Fig. 7. Availability function $K_g(t)$ of operation process models tested (for linear functions of expenditures) for T/Ta = 2 and $N/T_o = 1$
Rys. 7. Funkcja gotowości $K_g(t)$ badanych modeli procesu eksploatacji (dla liniowej funkcji nakładów dla T/Ta = 2 and $N/T_o = 1$

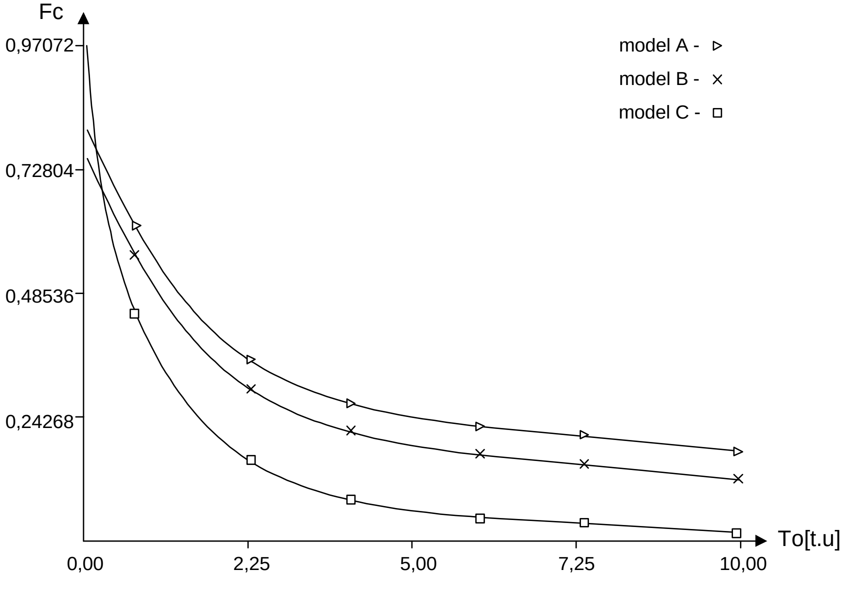


Fig. 8. Quality function of object's operation process F_c of operation process models tested (for linear functions of expenditures) for T/Ta = 2 and $N/T_o = 1$
Rys. 8. Funkcja jakości procesu eksploatacji obiektu F_c badanych modeli procesu eksploatacji (dla liniowej funkcji nakładów dla T/Ta = 2 and $N/T_o = 1$

The results of the investigations conducted serve to confirm the justifiability of the accepted concept of the organisation (designing) of the servicing system of repairable technical objects with the required short shutdown time.

In the organisation process of every servicing system, the costs constitute the factor that determines this process. The results obtained in the research indicate that an optimisation of the costs of the prophylaxis of technical objects can be achieved in two ways. The first one of them indicates that only those elements of an object should be renovated which require that these are elements in the state of an incomplete operation and in the non-operation state (therefore, there is a problem of the designing of the structure of the servicing system). According to the second manner of decreasing the costs of regeneration, the object's elements need to be regenerated in a selective manner by performing not all of the regeneration activities but only prophylactic activities as selected by an expert (an expert knowledge base), which are suitable for the state in which a given element is of an object of a given class of the servicing element.

The issues of the modelling of operation processes of technical objects are complex. They are related to many fields of science, such as mathematics, theory of operation, reliability theory, technical diagnostics, theory of systems modelling, information technology, etc. Each of these fields is intensively being developed at present.

5. Conclusions

This study covers a method of a simulation testing of the models of the organisation of servicing of technical objects with the required short time of their shutdown (aeroplanes, radiolocation systems, etc.). The issues presented in the study concerning the testing of the performance of technical objects during operation present a difficult task. This difficulty is the result of the length of the time for testing in the real process of the object's operation (this is the time of the "life" of the object), which is practically expressed in decades of years. The only reasonable approach for this type of research is simulation testing. However, this requires the real operation process of a given technical object to be known, on the basis of which the following needs to be prepared: the model of the operation process of a given technical object, plan of testing, input data for the test to describe the performance of a given object, such as the object's use time T - the time when the object is in the operation state, T_a – time of the removal of the object's non-operation state, T_p – time required for the performance of a prophylactic repair, the specific nature of the prophylaxis of this class of objects.

The models of the servicing system organisation constitute the basis of a simulation testing of the operation process of a technical object. The study presents the idea of one example model of the operation process with the servicing system tested, which makes use of diagnoses in a trivalent logic. The model presented in the article of the organisation of a servicing system which makes use of diagnoses in a trivalent logic is an innovative and interesting solution.

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Badanie efektywności procesu eksploatacji zestawu stacji radiolokacyjnej

S t r e s z c z e n i e

W pracy zaprezentowano metodę badania efektywności procesu eksploatacji, w którym występuje obsługowy system ekspertowy, ze sztuczną siecią neuronową. Opisano sposób badania symulacyjnego z wykorzystaniem techniki komputerowej. Przedstawiono podstawy teoretyczne modelowania procesu eksploatacji obiektów w postaci modelu: matematycznego (analitycznego), graficznego i opisowego. Na potrzeby badań opracowano model organizacji systemu obsługiwania obiektów technicznych wymagających krótkiego czasu ich przestojów (samoloty, systemy radiolokacyjne itp.). Przedstawiono i opisano wymagania do badania symulacyjnego, którymi są: opracowanie planu badania, przygotowania danych opisujących właściwości użytkowe obiektu oraz opracowanie modeli procesu eksploatacji obiektu technicznego wyrażających badane aspekty tego procesu. Przedstawiono wyniki badania symulacyjnego naprawialnego obiektu technicznego.