UDC 681.3(07)

Ph.D. **Nazarenko A.A.** (SUITC)
Ph.D. **Banzak G.V.** (SUITC)
Ph.D. **Lenkov Y. S**. (min. of energy, Kyev)
Dr. Tech. Sci., **Banzak O.V.** (SUITC)

DOI: http://doi.org/10.17721/2519-481X/2024/85-06

DEVELOPMENT AND RESEARCH OF METHODS FOR OPTIMIZING MAINTENANCE PROCESSES

Complex technical objects are of exceptional importance in modern society. Such objects belong to the class of long-term, reusable objects. They are usually expensive and require significant costs for their operation. To ensure the required level of failure-free operation, technical maintenance (TM) is usually carried out, the essence of which is the timely preventive replacement of elements that are in a pre-failure state.

A characteristic feature of complex technical objects for special purposes is the presence in their composition of a large number (tens, hundreds of thousands) of different types components that have different levels of reliability, different patterns of their wear and aging processes. This feature requires a more subtle approach to the organization and planning of TM during their operation.

The problem is that when developing such objects, all issues related to maintainability and technical maintenance must be resolved at the early stages of the design of the object. If you do not provide in advance the necessary hardware and software for the built-in monitoring of the technical condition (TC) of the object, do not develop and "build" into the object the technology for carrying out maintenance, then it will not be possible to realize in the future the possible gain in the reliability of the object due to carrying out maintenance. Since all these issues should be resolved at the stage of creating the object (when the object does not yet exist), mathematical models of the maintenance process are needed, with the help of which it would be possible to calculate the possible gain in the level of reliability of the object due to carrying out maintenance, estimate the required costs for this. Then, based on such calculations, make a decision on the need to carry out maintenance for this type of objects and, if such a decision is made, develop the structure of the maintenance system, select the most acceptable maintenance strategy, determine its optimal parameters.

The article considers various methods for optimizing maintenance processes.

Keywords: components, built-in monitoring of the technical condition, reliability level

Introduction. Maintenance (MT) is a necessary component of the operation process a complex technical object intended for long-term operation. The scope, content and timing of MT should be fully determined by reliability properties of the object, the conditions and modes of its use. Effective execution of any MT operation is possible only if the design of the object provides for specially designed means (for measuring the determining parameters) and the availability and convenience of the operation are ensured. Determination and optimization of the parameters of the MT system are possible only on the basis of the application of mathematical models of the MT processes. Such models should be used in the design process at all stages as the composition, structure and design of the object are clarified. Known analytical MT models, unfortunately, are not very suitable for application to real complex technical objects. Therefore, the way out of situation is to develop a MT model based on the method of simulating statistical modeling.

Formation of the problem. Unfortunately, currently known mathematical models and methods for calculating the optimal parameters of maintenance processes are of little use for application to real technical objects. The main drawback of these models is that they either do not take into account the complex structure of the object at all, or only take into account some of the simplest structures [1, 2]. In [3], a comparative analysis of the problems arising in solving maintenance problems “by resource” and “by condition” is made. An overview of the latest works in the field of maintenance and repair of complex systems is given. In [4], a theoretical generalization of known mathematical models of maintenance processes is made. However, these models do not allow one to build methods suitable for practical use on their basis.

In our opinion, the situation is even worse with mathematical models of maintenance processes “by condition”. Only a small number of scientific papers are devoted to this area of research [5, 6].

Main part. Study of the influence variation coefficient on the value ν_i of the optimal maintenance level $u_{\text{то}i}$.

From simple physical considerations it is clear that the choice of optimal maintenance level $u_{\text{то}i}$ should depend on the statistical properties of the determining parameter of *i*-th element. It is obvious that the main characteristic on which the choice of optimal value depends $u_{\text{то}i}$ is the variation coefficient of the determining parameter ν_{ui}. The smaller the value ν_{ui}, greater optimal value should be $u_{\text{то}i}$.

In the developed ISM, *DN*-distribution is used as a model of failures of the serviced elements. A feature of *DN*-distribution is that the variation coefficient of the distribution ν_i is equal to the variation coefficient ν_{ui} of determining parameter of the element whose failures generate this *DN*-distribution [8]. This fact significantly simplifies the study of the properties of optimal maintenance levels $u^*_{\text{то}i}$. Let us study how the optimal value depends $u^*_{\text{то}i}$ on the variation coefficient of the serviced elements on average ν_i. The study will be carried out in TOC modeling mode with a constant monitoring frequency. For all serviced elements we will set the same values the coefficient of variation operating time before failure $\nu_i \equiv \nu$, and determine the same optimal value $u^*_{\text{то}i} \equiv u^*_{\text{то}}$. We will determine the optimal value $u^*_{\text{то}}$ according to the criterion

$$u^*_{\text{то}} : c_{\text{уд}}(E_{\text{то}}, u_{\text{то}}, T_{\text{к}}) \to \min_{u_{\text{то}}}, \qquad (1)$$

where the parameters $E_{\text{то}}$ and $T_{\text{к}}$ are fixed. The set $E_{\text{то}}$ is a characteristic of the object, the parameter $T_{\text{к}}$ will be varied in a certain range.

Special software has been developed to conduct the study, which allows us to obtain the dependence of indicator $c_{\text{уд}}(E_{\text{то}}, u_{\text{то}}, T_{\text{к}})$ on the parameters of interest to us. The calculation results are obtained in the form of corresponding graphs.

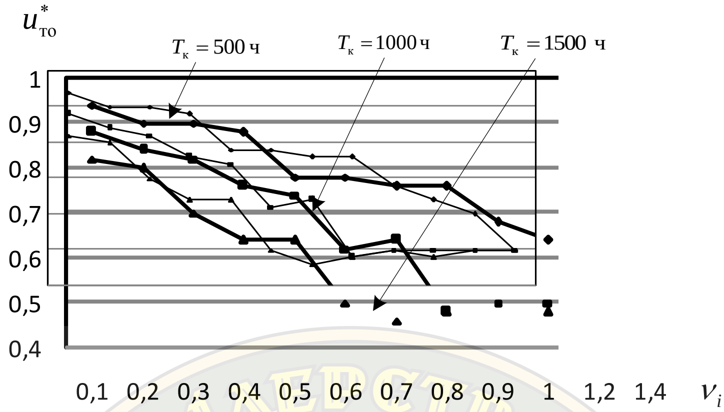
We will conduct the study using the example of the test object Test-1. In the DB for the Test-1 object, we will successively set different values of the coefficient of variation of the distribution of the operating time before failure of the lower-level structural elements. Then, for each value ν, we will perform calculations in order to determine the optimal value of the maintenance $u^*_{\text{то}}$ level according to criterion (1).

We will vary $u^*_{\text{то}}$ in the range [0.1; 0.96] with an interval of 0.02. We will perform calculations under the condition that set $E_{\text{то}}$ ={132, 12, 11111}, for three values of the inspection frequency $T_{\text{к}}$: 500 h, 1000 h and 1500 h.

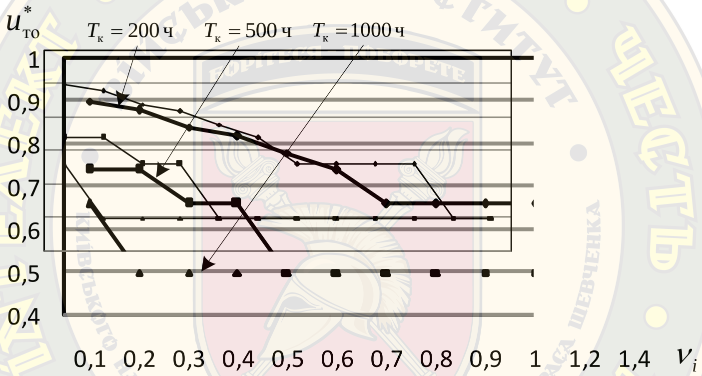
In fig. 1 shows graphs of the dependence of the specific operating cost $c_{\text{уд}}(E_{\text{то}}, u_{\text{то}}, T_{\text{к}})$ on

$u_{\text{то}}$ at $T_{\text{к}}$ = 1000 h for three values of the variation coefficient ν : 0.1; 0.5; 1.0.

The graphs in Fig. 1 are provided only to illustrate the type of results obtained. Based on the totality of all calculation results for the Test-1 object obtained in this study, the graphs shown in fig. 1a were constructed. Similar graphs were obtained for other test objects. In general, their nature is similar to the graphs for the Test-1 object. Fig. 1b shows the same graphs for the Test-4 object as an example.



a) object Test-1



b) object Test-4

Figure 1 – Graphs of the optimal maintenance $u^*_{\text{то}}$ level dependence on the variation ν_i coefficient value for different values of the inspection frequency $T_{\text{к}}$

In general, the following conclusions can be drawn from the results of the brief study:

The general idea that the smaller the value of the variation coefficient of the random operating time before failure of the serviced elements, the greater the optimal maintenance $u^*_{\text{то}}$ level value should be is confirmed;

Since the value of the variation coefficient for the serviced elements is usually significantly less than 1 (see table 1), the optimal maintenance $u^*_{\text{то}i}$ levels for different elements should be determined separately;

If the variation coefficients of the operating time before failure of the serviced elements are close to 1, the optimal maintenance level for them is $u^*_{\text{то}i}$ = 0.5.

Methodology for optimizing the parameters of the TOC strategy with a constant inspection frequency.

Problem (1) of optimizing the parameters of the TOC strategy with a constant inspection frequency, taking into account definition (2), can be represented as follows:

$$T_0(E^*_{\text{то}}, U^*_{\text{то}}, T^*_{\text{к}}) \geq T_0^{\text{тр}}; \quad (2\ \text{а})$$

$$c_{\text{уд}}(E^*_{\text{то}}, U^*_{\text{то}}, T^*_{\text{к}}) \to \min, \quad (2\ \text{б})$$

where $T_0^{\text{тр}}$ - is the specified required value of the mean time between failures of the object; , $E^*_{\text{то}}$, $U^*_{\text{то}}$ and $T^*_{\text{к}}$ - are the sought optimal values of the corresponding parameters.

It has already been noted above that this problem cannot be solved by strict analytical optimization methods; only an approximate solution to the problem is possible. Let us consider a method for an approximate solution to problem (2) based on the use of the IMS and the software implementing it (ISMPN program).

First, we will describe the method formally, present it as an algorithm that is implemented by the user (expert) in the dialogue mode with the PC. Later, we will consider the technology of using the software to solve the problem.

Technology for solving the problem.

The considered method is implemented by the user (expert) using ISMPN program. To apply the method, it is necessary, firstly, to create a DB for the object for which the problem is supposed to be solved, and, secondly, to perform a step-by-step search for a solution in accordance with the method considered above. At each (*k*-th) step, the user must perform the following actions (items):

1) add one element taken from set $E_{\text{то}}$ to the subset of serviced elements $E^+_{\text{то}}$ (initially empty);

2) perform simulation and find a conditionally optimal solution $\mathbf{STO}^+_S = \langle E^+_{\text{то}}, U^+_{\text{то}}, T^+_{\text{к}} \rangle$;

3) determine the achieved value of the mean time between failures T_0^+ and check the fulfillment of the requirement $T_0^+ \geq T_0^{\text{тр}}$. If the requirement is not fulfilled, return to step 1 and continue the search process. Otherwise, perform the next (final) step;

4) accept the resulting conditionally optimal solution $\mathbf{STO}^+_S$ as the optimal solution to the problem $\mathbf{STO}^*_S = \langle E^*_{\text{то}}, U^*_{\text{то}}, T^*_{\text{к}} \rangle$.

Let us consider the technology for performing each of these steps.

Formation of the set of serviced elements $E^+_{\text{то}}$.

Open the ISMPN program in the Database mode. On the Object Composition and Structure page (fig. 2), select the element to be included in set $E^+_{\text{то}}$ in the object's structural structure tree. Then, in the table that displays data on the selected object, in the PW column (recovery indicator), enter the value “in” (serviced element) for this element.

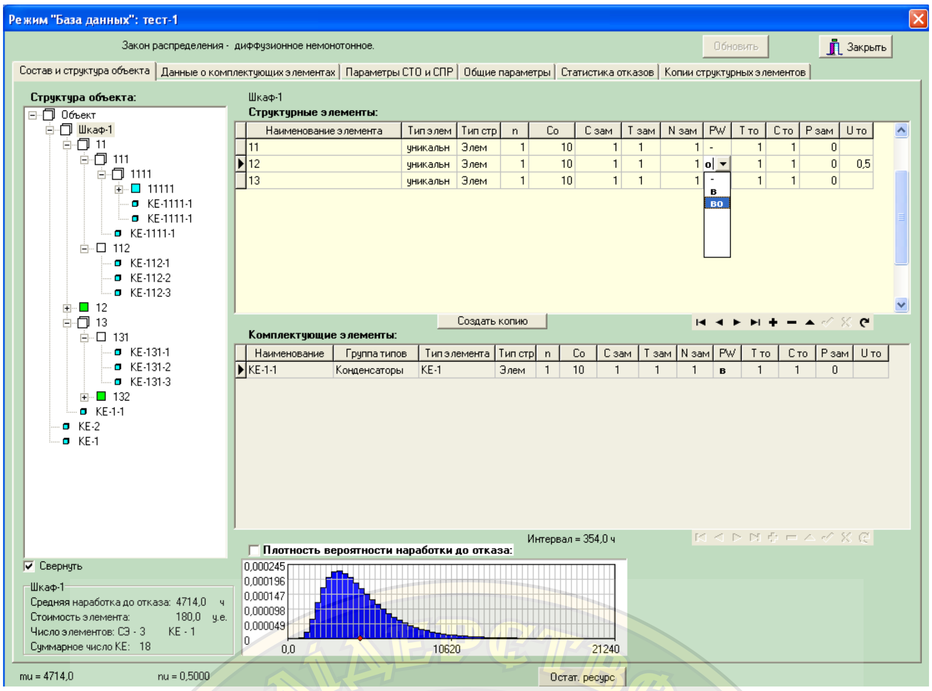


Figure 2 – Entering the “in” attribute for element “12”

All elements for which the “in” flag is set will be automatically included in the current set of serviced elements $E^{+}_{\text{то}}$.

The user defines the set of potentially serviced elements $E_{\text{то}}$ in advance, before starting calculations using this method.

2. Formation of a conditionally optimal solution $\mathbf{STO}^{+}_{S}$.

Calculations to determine a conditionally optimal solution are performed in the following sequence:

- open the ISMPN program in the TO Research | Uto+Tk variation mode. (figure 2 shows PC screen after completing the calculations);

- enter the boundaries and intervals of variation $T_{\text{к}}$ inspection frequency and the maintenance level $u_{\text{то}k}$. The parameters of variation frequency $T_{\text{к}}$ are selected in such a way as to find the minimum of the function $c^{+}_{\text{уд}}(T_{\text{к}})$ with sufficient accuracy. It is recommended to set $u_{\text{то}k}$ the variation range to [0.1; 0.9], the variation interval to 0.05;

- click the Start and perform simulation button.

After the simulation is complete, graphs of the functions $u^{+}_{\text{то}k}(T_{\text{к}})$, $c^{+}_{\text{уд}}(T_{\text{к}})$, $T^{+}_{0}(T_{\text{к}})$ and $K^{+}_{\text{ти}}(T_{\text{к}})$ will be displayed, as shown in figure 3. T_{0} and $K_{\text{ти}}$, are functions of the corresponding indicators and , obtained with the optimal vector . If it turns out that the function $c^{+}_{\text{уд}}(T_{\text{к}})$ does not have a pronounced minimum (the minimum is obtained at the edge of the range $[T_{\text{к}1}, T_{\text{к}2}]$), it is necessary to change the boundaries and accordingly, $T_{\text{к}1}$ and $T_{\text{к}2}$ re-run the simulation.

The found optimal value $T^{+}_{\text{к}}$ and the corresponding values $u^{++}_{\text{то}k}$, $c^{+}_{\text{уд}}$, T^{+}_{0} and $K^{+}_{\text{ти}}(T_{\text{к}})$ are displayed on the right, next to graphs.

The obtained values $U^{+}_{\text{то}}$ and $T^{+}_{\text{к}}$ are accepted as the values of the corresponding parameters of the conditionally optimal solution: $\mathbf{STO}^{+}_{S} = \left\langle E^{+}_{\text{то}}, U^{+}_{\text{то}}, T^{+}_{\text{к}} \right\rangle$.

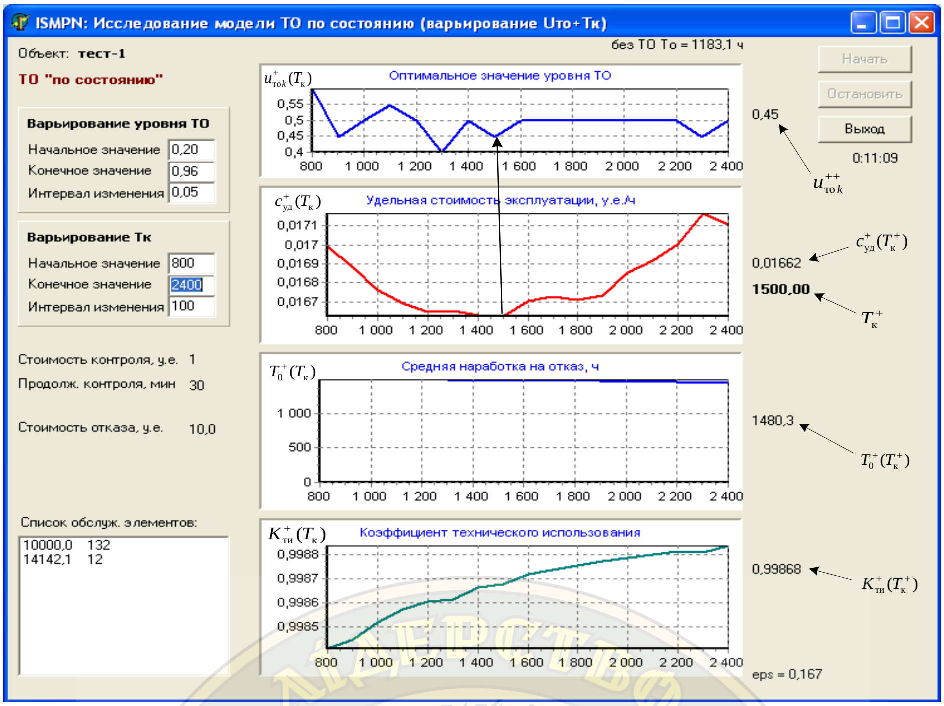


Figure 3 – PC screen view with function graphs $u^{+}_{\text{то}}(T_{\text{к}})$, $c^{+}_{\text{уд}}(T_{\text{к}})$, $T^{+}_{0}(T_{\text{к}})$ and $K^{+}_{\text{ти}}(T_{\text{к}})$

Evaluation of the obtained results at *k*-th step of solving the problem.

Based on the value of mean time between failures obtained in current step $T^{+}_{0} = T_{0}(\mathbf{STO}^{+}_{S})$, the condition is checked $T^{+}_{0} \geq T^{\text{тр}}_{0}$.

If the condition is satisfied, then the obtained conditionally optimal solution $\mathbf{STO}^{+}_{S}$ is accepted as the final solution to the problem:

$$\mathbf{STO}^{*}_{S} := \mathbf{STO}^{+}_{S}.$$

The process of finding a solution in this case is complete.

Otherwise, if $T^{+}_{0} < T^{\text{тр}}_{0}$, it is necessary to return to point 1, add another serviced element to the set $E^{+}_{\text{ТО}}$ and repeat the calculations.

We will illustrate the application of the technique using the example of the test object Test- The object has 15 recoverable elements. For example, we will set that the 5 least reliable elements among them are potentially serviced, the data on which are given in table 1. Since all elements are connected (in terms of reliability) in series, the coefficient of variation of the distribution of the mean time before failure of the serviced elements is the same as for the lower-level elements, i.e. $\nu_i = 1$.

Table 1

Characteristics of potentially serviceable elements of Test-1 object

Element number	Element name	Mean time to failure $T_{\text{срi}}$, h
1	132	10000
2	12	14142
3	11111	14142

4	КЕ-131-1	20000
5	КЕ-131-2	20000

For modeling, we set the following parameters:

$T_э$ = 20 years; $c_п^0$ = 10 c.u./h; $\varepsilon^{тр}$ = 0.2; N_I^{max} = 500;

We will perform the calculations in sequence in accordance with the considered technology.

At 1-st step, we will include $E_{то}^+$ element 132 in the set: $E_{то}^+$ = {132}.

1. Open the ISMPN program in Research TO | Variation Uто+Tк mode and set the following variation parameters:

- for $u_{то}$: $u_{то} \in$ [0,1; 0,9]; $\Delta u_{то}$ = 0,05;
- for $T_к$: $[T_{к1}, T_{к2}]$ = [800 ч, 2400 h]; $\Delta T_к$ = 100 h.

After this, we will perform the modeling. fig. 4 shows the obtained modeling results.

Using the function graph $c_{уд}^+(T_к)$, we find its minimum and the corresponding conditionally optimal value $T_к^+$. Then, using the graph $u_{то1}^+(T_к)$, we find the conditionally optimal value . As a result, we obtain:

$$T_к^+ = 1300 \text{ h}; \; u_{то1}^{++} = 0{,}5.$$

$u_{то1}^{++} = u_{то1}^+(T_к^+)$. According to the graph, we determine the achieved value of the mean time between failures T_0^+ = 1343 h.

As a result of the calculations performed at step 1, we obtain the following conditionally optimal solution:

$$\mathbf{STO}_S^+ = \langle E_{то}^+, U_{то}^+, T_к^+ \rangle = \langle \{132\}, \{0{,}5\}, 1300\,ч \rangle.$$

Taking into account that specified requirement for reliability of the object $T_0^+ \geq T_0^{тр}$ =1500 h with the received TOS parameters is not met, it is necessary to perform the next search step.

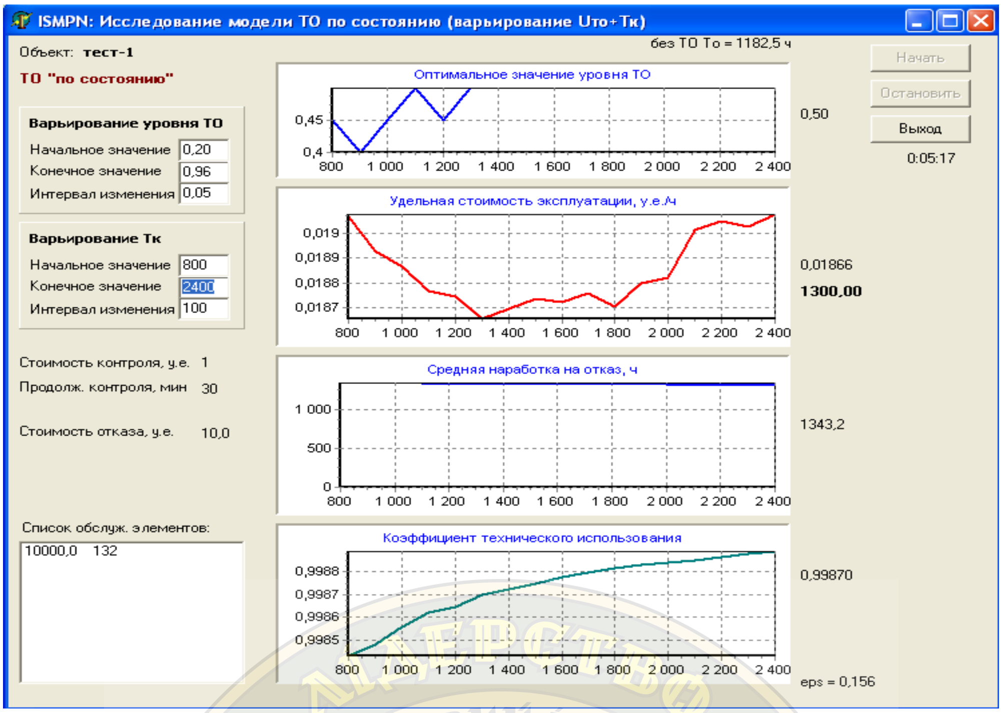


Figure 4 – Function graphs $u^{+}_{\text{то}}(T_{\text{к}})$, $c^{+}_{\text{уд}}(T_{\text{к}})$, $T^{+}_{0}(T_{\text{к}})$ and $K^{+}_{\text{ти}}(T_{\text{к}})$ for $E^{+}_{\text{то}}$ ={132} ($v_i = 1$)

But before that, it is necessary to open DB and enter the conditionally optimal value of the maintenance $u^{++}_{\text{то}1}$ level obtained for element 132. The value $u^{++}_{\text{то}1}$ = 0.5 must be entered in the Uto column for element 132, as shown in fig. 5.

After that, the next (2-nd) step of finding a solution can be performed.

1. At 2-nd step, we add element 12 to the set $E^{+}_{\text{то}}$. As a result, we obtain set $E^{+}_{\text{то}}$ ={132, 12}.

2. We open the ISMPN program in Maintenance Research | Uto+Tk variation mode and perform calculations in accordance with the technology discussed above. After the calculations at the 2nd step, we obtain the following conditionally optimal solution:

$$\mathbf{STO}^{+}_{S} = \left\langle E^{+}_{\text{то}}, U^{+}_{\text{то}}, T^{+}_{\text{к}} \right\rangle = \left\langle \{132,12\};\ \{0{,}5;0{,}4\}, 1300\,\text{ч} \right\rangle .$$

3. At the 2nd step, we obtain the value of the average time between failures T^{+}_{0} = 1485 h. If this value $T^{\text{тр}}_{0}$ does not satisfy the specified requirement, then the next step is performed.

In the table. 2 shows the results of calculations obtained in 5 search steps performed for all serviced elements present in the set $E_{\text{то}}$ (see table 1).

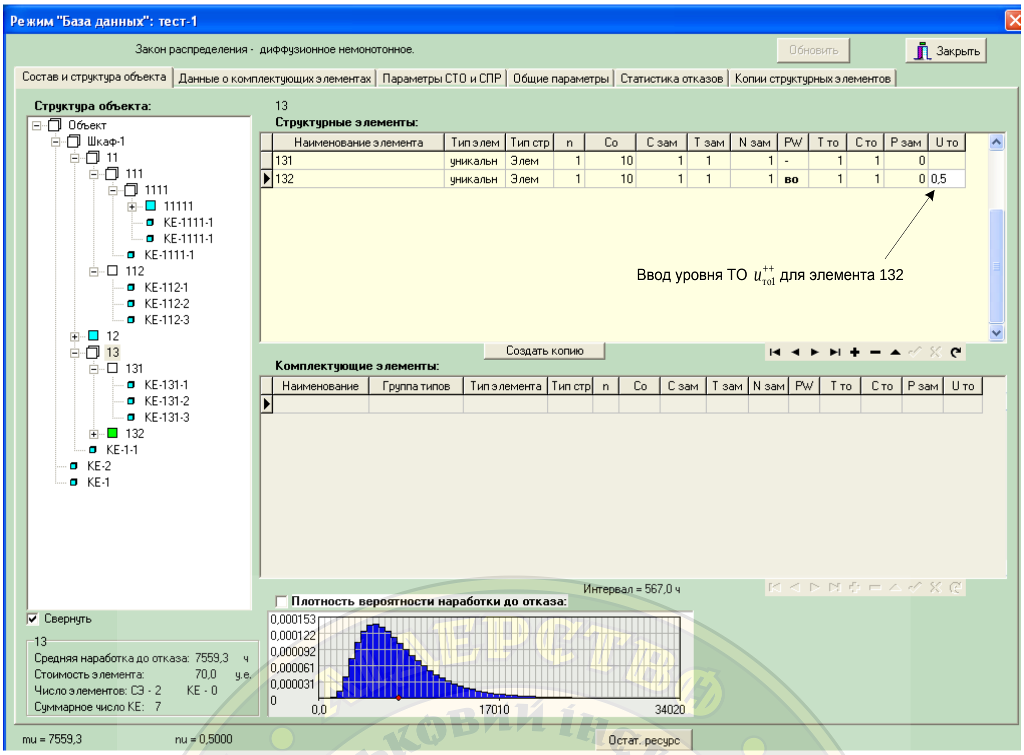


Figure 5 – Entering TO $u_{\text{то}k}^{++}$ level for element 132

Table 2

Results of calculations of conditionally optimal TOC parameters for Test-1 object ($\nu_i = 1$)

Step number k	Conditionally optimal parameters $\mathbf{STO}_S^+$			Values of indicators obtained with conditionally optimal parameters $\mathbf{STO}_S^+$			
	$E_{\text{ТО}}^+$	$u_{\text{то}k}^{++}$	$T_{\text{к}}^+$, h	T_0^+, h	$c_{\text{уд}}^+$, c.u./h	$K_{\text{ти}}^+$	ε
1	{132}	0,5	1300	1343	0,01866	0,99870	0,156
2	{132, 12}	0,4	1300	1485	0,01663	0,99861	0,171
3	{132, 12, 11111}	0,5	1200	1660	0,01461	0,99851	0,180
4	{132, 12, 11111, KE-131-1}	0,65	1300	1808	0,01361	0,99850	0,182
5	{132, 12, 11111, KE-131-1, KE-131-2}	0,65	1200	1988	0,01266	0,99847	0,198

Let the requirement for the reliability level for Test-1 object be $T_0^{\text{тр}}$ =1500 h. Then, based on the data obtained, we determine the following optimal TOS parameters:

$$\mathbf{STO}_S^* = \mathbf{STO}_S^+ = \langle \{132, 12, 11111\};\ \{0{,}5; 0{,}4; 0{,}5\}, 1200\,\text{ч} \rangle.$$

With the obtained optimal parameters, following values of the indicators will be provided:

$T_0(\mathbf{STO}_S^*)$ = 1660 h;

$c_{уд}(\mathbf{STO}_S^*)$ = 0,01461 c.u./h;

$K_{ти}(\mathbf{STO}_S^*)$ = 0,99851.

The relative error of simulation results, at which these results were obtained, is ε = 0.180.

This solution was obtained under the condition that the coefficient of variation of the random time to failure ν_i for all elements of the object is the same and equal to 1. An interesting question is: how will the optimal parameters of the TOC change in the case of smaller values of ν_i. This question is important because many elements of real technical objects are characterized by a distribution of time to failure with a coefficient of variation that is significantly less than 1 (see Table 1). To study this issue, we will perform calculations for the Test-1 object, obtained under the condition that the coefficient of variation ν_i for all elements is 0.5.

Fig. 6 shows the graphs of the functions $u_{то}^+(T_к)$, $c_{уд}^+(T_к)$, $T_0^+(T_к)$ and $K_{ти}^+(T_к)$, obtained at the first step of calculations for the set $E_{то}^+$ = {132} at ν_i = 0.5.

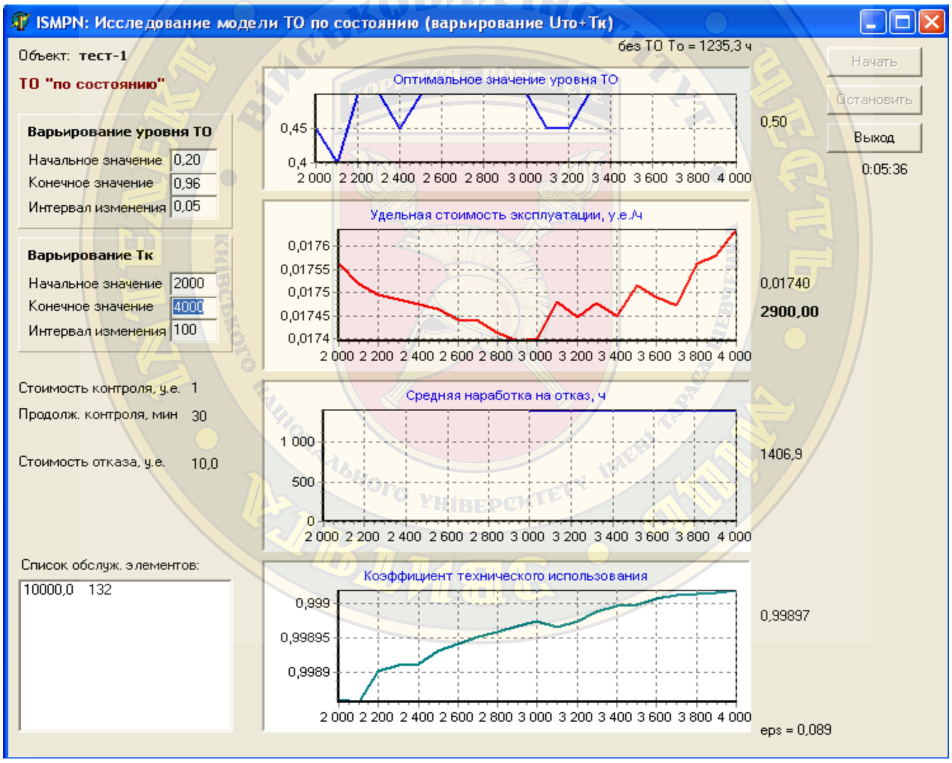


Figure 6 – Graphs of functions $u_{то}^+(T_к)$, $c_{уд}^+(T_к)$, $T_0^+(T_к)$ and $K_{ти}^+(T_к)$ for $E_{то}^+$ ={132} ($\nu_i = 0{,}5$)

Tab. 3 shows the obtained conditionally optimal parameters of TOC $\mathbf{STO}_S^+$ and the corresponding values of the indicators T_O^+, $c_{уд}^+$ and $K_{ти}^+$.

Table 3

Results of calculations conditionally optimal parameters of TOC for Test-1 object ($\nu_i = 0{,}5$)

Step number k	Conditionally optimal parameters $\mathbf{STO}_S^+$			Values of indicators obtained with conditionally optimal parameters $\mathbf{STO}_S^+$			
	$E_{\text{то}}^+$	$u_{\text{то}k}^{++}$	$T_{\text{к}}^+$, h	T_0^+, h	$c_{\text{уд}}^+$, c.u./h	$K_{\text{ти}}^+$	ε
1	{132}	0,5	2900	1405	0,01740	0,99897	0,089
2	{132, 12}	0,5	2900	1553	0,01541	0,99892	0,099
3	{132, 12, 11111}	0,5	3000	1738	0,01340	0,99888	0,100
4	{132, 12, 11111, КЕ-131-1}	0,65	2700	1896	0,01248	0,99884	0,107
5	{132, 12, 11111, КЕ-131-1, КЕ-131-2}	0,45	2900	2086	0,01154	0,99881	0,113

Based on the data obtained in table 3, and taking into account that $T_0^{\text{тр}}$ = 1500 h, for the case ν_i = 0.5 we obtain the following solution to problem (1):

$$\mathbf{STO}_S^* = \mathbf{STO}_S^+ = \langle \{132{,}12\};\ \{0{,}5;0{,}5\}, 2900\,\text{ч} \rangle .$$

This results in the following values of the indicators:

$T_0(\mathbf{STO}_S^*)$ = 1553 h;

$c_{\text{уд}}(\mathbf{STO}_S^*)$ = 0,01541 c.u./h;

$K_{\text{ти}}(\mathbf{STO}_S^*)$ = 0,99892 (ε = 0,099).

The following conclusions can be drawn from the obtained results:

1. The optimal number of serviced elements has decreased. Instead of 3 elements that should be serviced at ν_i = 1, now, if ν_i = 0.5, it is sufficient to service only 2 elements;

2. The optimal inspection frequency has increased significantly $T_{\text{к}}^*$ (instead of $T_{\text{к}}^*$=1200 h, the value obtained is $T_{\text{к}}^*$ = 2900 h).

Figure 1.7 shows the graphs of the function indicators T_0^+ and $c_{\text{уд}}^+$ depending on the number of serviced elements $n(E_{\text{то}}^+)$. The graphs clearly illustrate the tendency for the indicators to improve even T_0^+ and $c_{\text{уд}}^+$ decrease in the variation coefficient ν_i.

Using the example of the test object Test-1, let us consider another question: what is TOC process in the case of a strategy with a constant inspection frequency, and what are the characteristics of this process.

Obviously, this is a random process occurring at discrete moments in time that are multiples of the inspection frequency $T_{\text{к}}$. At each of these moments in time, TO of i-th element from the set $E_{\text{то}}^*$ is performed with probability $p_{\text{то}i}$.

For research purposes, ISMPN program has built-in procedures that allow accumulating statistics on the number and frequency of maintenance various elements over a given period of operation of the object. Based on the accumulated statistics, following indicator estimates are calculated:

$\overline{T}_{\text{то}i}$ - average frequency of maintenance *i*-th element;

$\nu_{\text{то}i}$ - coefficient of variation the random frequency of maintenance *i*-th element;

$\overline{n}_{\text{то}i}$ - average number of maintenance of *i*-th element, which is performed during a given period of operation objects.

Table 1.4 presents the estimates of these indicators obtained in the considered modeling example for the Test-1 object.

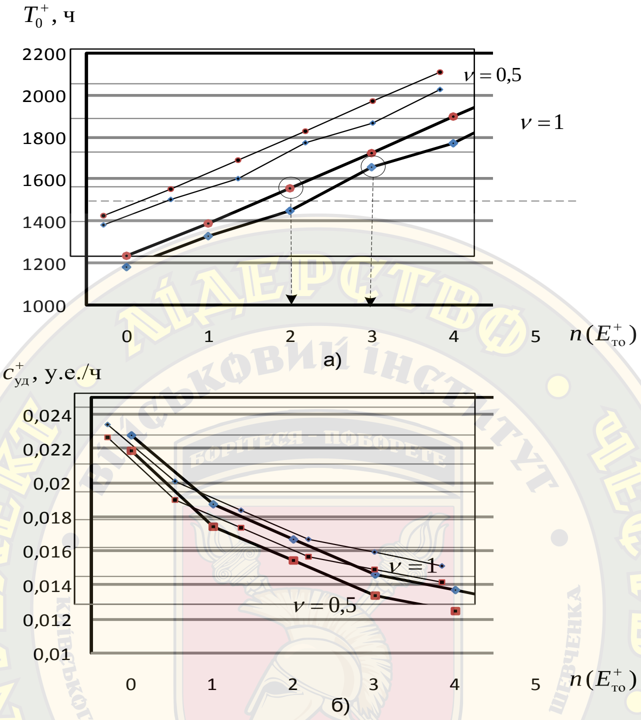


Figure 7 – Graphs of the dependence indicators T_0^+ and $c_{\text{уд}}^+$ on the number of serviced elements $n(E_{\text{то}}^+)$ for different values ν_i

Table 4

Characteristics of the random TOC process of Test-1 object with optimal parameters of TR strategy **STO**$_S^*$

Serviced elements	$\nu_i = 1$			$\nu_i = 0,5$		
	$\overline{T}_{\text{то}i}$, h	$\nu_{\text{то}i}$	$\overline{n}_{\text{то}i}$	$\overline{T}_{\text{то}i}$, h	$\nu_{\text{то}i}$	$\overline{n}_{\text{то}i}$
132	5533	0,83	30,2	6480	0,40	25,9
12	7447	0,86	22,2	8501	0,41	19,7
11111	7420	0,86	22,3	-	-	-

Conclusions. The best strategy in terms of mean time between failures T_0 and specific operating cost $c_{\text{уд}}$ is the “adaptive maintenance” strategy. Then comes the “condition-based maintenance” strategy. The worst strategy is the “lifetime-based maintenance” strategy. A maintenance strategy is considered the best if the function graph T_0^+ is located above (for the function $c_{уд}^{+}$ – below) in relation to the corresponding graph for the compared strategy. The maintenance strategy that is the best in terms of the indicator T_0^{+} is usually the best in terms of the indicator $c_{уд}^{+}$, and vice versa.

The "condition-based maintenance" and "adaptive maintenance" strategies are very close in terms of the indicators obtained. This is explained by their common essence – when performing maintenance, information about the actual current state of the object is used.

The effectiveness of various maintenance strategies significantly depends on the reliability and cost structure of the object. If the distribution of the cost restored (including serviced) elements closely correlates with the distribution of their reliability indicators, the difference in the effectiveness of various maintenance strategies is reduced. This is clearly seen in the example of the Test-2 object, for which the least reliable elements are also the most expensive.

The optimal parameters of various maintenance strategies depend significantly on both the reliability-cost structure of the object and the specified requirement for level of failure-free operation of the object $T_0^{тр}$. The higher the specified value $T_0^{тр}$, the greater number of serviced elements should be included in the optimal maintenance strategy.

REFERENCES:

1. Sergey Lenkov, Konstantin Borjak, Gennady Banzak, Vadim Braun, ets. (2002) Forecasting to reliability complex object radio-electronic texnology and optimization parameter their technical usage with use the simulation statistical modelsю. Monograph in English. Odessa: Publishing house "VMV", 252 p.

2. Jason Brown, Lucas Mol (2017) On the roots of all-terminal reliability polynomials. Discrete Mathematics, Volume 340, Issue6, June, 1287-1299.

3. Lirong Cui, Yan Li, Jingyuan Shen, Cong Lin (2016) Reliability for discrete state systems with cyclic missions periods. Applied Mathematical Modtlling, Volumt 40, Issues 23-24, December, 10783-10799.

4. Iris Tien, Armen Der Kiureghian (2016) Algorithms for Bayesian network modeling and reliability assessment of infrastructure systems. Reability Engineering & System Safety, Volume 156, December, 134-147.

5. Volokh O.P. (2005) Methods of substantiation rational values operiodicity of maintenance of machines of engineering armament during operation. Collection of scientific works of Military Institute of Taras Shevchenko National University of Kyiv, 29-32.

6. Boryak K.F (2009) Faultlessness model of a complex recoverable object of electronic equipment. Collection of scientific works of Military Institute of Taras Shevchenko National University of Kyiv, 33-41.

7. Mikhalevich V.S., Volkovich V.L. (1982) Computational methods of research and design of complex systems. M.: Science, 286 p.

8. Braun V.O., Boryak K.F., Lantvoyt O.B., Tsytsarev V.N. (2008) Modeling of maintenance processes of complex reconstructed objects of radio-electronic equipment. News of the Engineering Academy of Ukraine. K., №1. 47 – 52.

9. Boryak K.F. (2008) Research of the process of maintenance complex renewable objects of electronic equipment with the help of simulation statistical model. Bulletin of the Engineering Academy of Ukraine. K., №2. 85 – 91.

10. Banzak H.V., Banzak O.V., Vozikova L.M. (2020) Simulation of technical maintenance process with adaptive change of control period. The 1st International scientific and practical conference "The world of science and innovation" Cognum Publishing House, London, United Kingdom. 10-14.

11. Banzak H.V., Boryak K.F., TSytsarev V.N. (2010) Reliability database of complex objects of radio-electronic equipment. Collection of scientific works of the Military Institute of Taras Shevchenko National University of Kyiv. № 27. 89 – 97.

12. Banzak O.V., Sieliykov O.V., Olenev M.V., Dobrovolskaya S.V., Konovalenko O.I. (2010) Research processes of gamma radiation detector for developing a portable digital spectrometer. Collection of scientific works of the Military Institute of Taras Shevchenko National University of Kyiv. № 69. 5 - 13.

13. Nataliya Lytvynenko, Serhii Lienkov, Olexander Lytvynenko, Hennadii Banzak, (2020)

Development of Geoinformation Technology for Monitoring Events on the Basis of Data from Unstructured Web Resource Text. International Journal of Innovative Technology and Exploring Engineering (IJITEE) ISSN: 2278-3075, Volume-9 Issue-5, 1160-1165

14. Oksana Banzak, Hennadii Banzak, Oleg Leshchenko, Antonina Gaber, (2024) Digital spectrometer gamma radiation for radiation in the field. The 8th International scientific and practical conference "European congress of scientific achievements" (August 12-14, 2024) Barca Academy Publishing, Barcelona, Spain. 64-69.

15. Oksana Banzak, Hennadii Banzak, Oleg Leshchenko, Nikita Khlevny, (2024) Optimization of parameters maintenance process of an electronic equipment facility. The 3rd International scientific and practical conference "Innovative development of science, technology and education" (December 14-16, 2023) Perfect Publishing, Vancouver, Canada. 2023. p. 409 – 415.

к.т.н., доц. Назаренко О.А., к.т.н., доц. Банзак Г.В.,
к.т.н., ст. досл. Лєнков Є.С., д.т.н., проф. Банзак О.В.

РОЗРОБКА ТА ДОСЛІДЖЕННЯ МЕТОДИК ОПТИМІЗАЦІЇ ПРОЦЕСІВ ТЕХНІЧНОГО ОБСЛУГОВУВАННЯ

Складні технічні об'єкти у суспільстві мають виключно важливе значення. Такі об'єкти належать до класу об'єктів, що відновлюються тривалого багаторазового застосування. Вони, як правило, є дорогими та потребують значних витрат на їх експлуатацію. Для забезпечення необхідного рівня безвідмовності в процесі їх експлуатації зазвичай проводиться технічне обслуговування (ТО), суть якого полягає у своєчасній запобіжній заміні елементів, що знаходяться в стані перед відмовою.

Характерною особливістю складних технічних об'єктів спеціального призначення є наявність у їхньому складі великої кількості (десятки, сотні тисяч) різнотипних елементів, що комплектуються, що мають різний рівень надійності, різні закономірності процесів їхнього зносу та старіння. Ця особливість вимагає більш тонкого підходу до організації та планування ТО у процесі їх експлуатації.

Проблема полягає в тому, що при розробці таких об'єктів усі питання, пов'язані з ремонтопридатністю та технічним обслуговуванням, повинні вирішуватися вже на ранніх етапах проектування об'єкта. Якщо не передбачити заздалегідь необхідні апаратні та програмні засоби вбудованого контролю технічного стану (ТЗ) об'єкта, не розробити і не вбудувати в об'єкт технологію проведення ТО, то реалізувати в майбутньому можливий виграш у безвідмовності об'єкта за рахунок проведення ТО не вдасться. Оскільки всі ці питання повинні вирішуватися на етапі створення об'єкта (коли об'єкта ще немає), необхідні математичні моделі процесу ТО, за допомогою яких можна було б прорахувати можливий виграш у рівні безвідмовності об'єкта за рахунок проведення ТО, оцінити необхідні вартісні витрати. Потім на підставі таких розрахунків прийняти рішення про необхідність проведення ТО для цього типу об'єктів і, якщо таке рішення прийнято, розробити структуру системи ТО, вибрати найбільш прийнятну стратегію ТО, визначити її оптимальні параметри.

У статті розглядаються різноманітні методики оптимізації процесів технічного обслуговування.

Ключові слова: елементи, що комплектуються, вбудований контроль технічного стану, рівень надійності