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D.Sc. **Lienkov S.V.** (MIKNU)
Ph.D. **Tolok I.V.** (MIKNU)
Ph.D. **Banzak G.V.** (OSATRQ)
Ph.D. **Koltsov R.Yu.** (MIKNU)
Ph.D. **Lienkov E.S.** (MIKNU)
Dobrovolskaya S.V. (OSATRQ)

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JUSTIFICATION OPTIMAL PARAMETERS OF REGULATED MAINTENANCE STRATEGY

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 component parts that have different levels of reliability, different patterns of their wear and tear processes. This feature requires a more subtle approach to the organization and planning maintenance in the course of their operation.

The problem is that in the development of such facilities, all issues related to maintainability and maintenance should be addressed already at the early stages of facility design. If you do not provide in advance the necessary hardware and software for the built-in monitoring of the technical condition (TC) of the facility, do not develop and "build" the maintenance technology into facility, then it will not be possible to realize in the future a possible gain in the reliability of the facility due to maintenance. Since all these issues must be resolved at the stage of object creation (when 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 facility due to maintenance, estimate the cost costs required for this. Then, based on such calculations, make a decision on the need for maintenance given type of objects and, if such a decision is made, develop the structure of the maintenance system, choose the most acceptable maintenance strategy, and determine its optimal parameters.

The paper shows that the model for the regulated maintenance strategy is an improved version of the already known models and is introduced into the complex model for the purpose of comparative assessment of various maintenance strategies. In addition, it should be borne in mind that in practice, some cases, a regulated maintenance strategy may be preferable to MCC strategies.

Keywords: complex technical objects, maintenance strategies, technical condition, component parts

Introduction. Complex technical objects in modern society are extremely important. We are talking primarily about various radio-electronic complexes for military and special purposes, radar stations, automated control systems (air traffic, energy facilities, etc.). The state's defense capacity, economic security, and the lives of hundreds and thousands of people depend on the level of reliability such facilities.

Such objects belong to the class of recoverable objects of long-term repeated use. They tend to be costly and costly to operate. To ensure the required level of reliability during their operation, maintenance is usually carried out, the essence of which is timely preventive replacement of elements in a pre-failure state.

Analysis of previous studies and problem statement. Certain "surge" in the number of theoretical works on the maintenance of complex systems falls on 70s of the last century, which can be explained by the mass production of complex radio-electronic equipment for military and special purposes at that time [for example 1-5]. Currently, there is a decline in the number of scientific publications devoted to the maintenance of complex technical objects. One of the reasons for this, in our opinion, is sharp increase in the level of integration and reliability of components. Thanks to this, the developers of complex equipment were able to solve the issues of ensuring the required level of reliability without significant maintenance costs (or even without maintenance at all). However, the same reason (high integration and reliability of component parts) opened up the possibility of implementing more and more complex technology with new functions, which was impossible with the old element base. This again leads objectively to the problems of ensuring reliability and, therefore, the question of need for maintenance and the choice of optimal strategy for its implementation again becomes relevant.

Formulation of the problem. Unfortunately, the currently known mathematical models and methods for calculating the optimal parameters of maintenance processes are not very suitable for application to real modern technical objects. The main disadvantage of these models is that they either do not take into account the complex structure of an object at all, or it is possible to take into account only some of the simplest structures [6-8]. In [9], a comparative analysis of the problems arising in solving the problems of maintenance "by resource" and "by state" is made. In [10] provides an overview of the latest work in the field of maintenance and repair of complex systems. The authors of this article made a theoretical generalization of the known mathematical models of maintenance processes. In the works [11-13] foreign developments in this subject area are given. However, these models do not allow building on their basis suitable for practical use techniques. The closest on the subject of the article are given in the works [10,14,15].

Main part. The essence of regulated maintenance strategy is that maintenance is carried out at pre-planned times with a given fixed amount of work. At the same time, the timing and scope of maintenance work does not depend on the actual technical condition of the facility. The parameters of the regulated maintenance strategy are:

$N_{\text{то}}$ - number of types maintenance;

$T_{\text{то}\,j}$ and $E_{\text{то}\,j}$ - are the frequency and volume of maintenance j-th type ($j=\overline{1,N_{\text{то}}}$). The scope of maintenance is set $E_{\text{то}\,j}$ here by a set of elements that are subject to maintenance during maintenance of *j*-th type.

Test objects of different structure and reliability were used to check and study the developed models and techniques. The characteristics of test objects are selected in such a way as to cover all typical cases of possible real objects encountered in practice. With the help of test objects, the following sections demonstrate the features of application developed models and their capabilities. This section contains the main characteristics of test objects, as well as the simulation results obtained for them using the MB software.

The Test-1 object is an example of the simplest object with a consistent reliability structure and a structural structure with 6 nesting levels. Consists of 20 elements-INR, which are part of other structural elements of senior levels. INR elements are indicated by circles. All INRs have same reliability characteristics: $T_{\text{ср}}$ = 20,000 h; $\nu = 1$. Elements included in the set are marked with shading.

The Test-2 object is an example of a low reliability object that uses redundancy to improve reliability. The three least reliable elements have a reserve: 11 (n = 3), 12 (n = 3) and 131 (n = 2). All other elements are sequential (in terms of reliability) of all the elements included in them. The total number of INR is 900. The elements included in the set of recoverable elements are also marked with shading.

The Test-3 and Test-4 objects are examples of objects that have a single-level design structure. The number of all elements is 50. The elements of objects differ significantly in their level of reliability. Object Test-3 is an example of an object with a high level of reliability, object Test-4 is an example of an object with low reliability. Since the structural structure is one-level, all elements are INR, and all of them are recoverable.

For each of the test objects, a separate database has been created, into which the necessary information about the object is entered. For all IDRs, the coefficient of variation is set equal, equal to 1.

Table 1 shows the main characteristics of the test objects.

The values of reliability indicators given in the table (mean time to failure and coefficient of variation) are generated automatically when starting the database program and are displayed on the PC screen. For the Test-2 object, the resulting coefficient of variation is not equal to 1 due to the presence of redundant groups elements in the object.

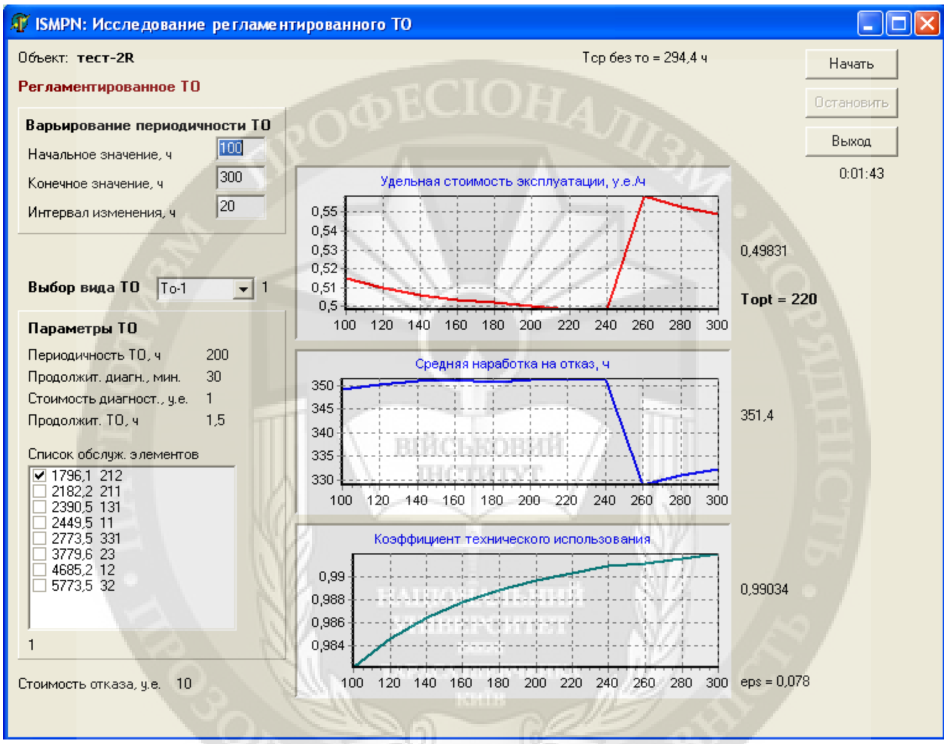
Table 1

Test object characteristics

Object	Number of INR	Number of recoverable elements	Mean time to failure, h	Coefficient of variation
Test-1	20	15	4472,1	1,0
Test-2	900	16	745,8	0,726
Test-3	50	50	29930,7	1,0
Test-4	50	50	1783,2	1,0

Test-2 object.

The Test-2 object includes 8 recoverable elements. All of them are potentially serviceable (Table 2).



Объект: тест-2R

Тср без то = 294,4 ч

0:01:43

Регламентированное ТО

Варьирование периодичности ТО

Начальное значение, ч 100

Конечное значение, ч 300

Интервал изменения, ч 20

Выбор вида ТО То-1 1

Параметры ТО

Периодичность ТО, ч 200

Продолжит. диагн., мин. 30

Стоимость диагност., у.е. 1

Продолжит. ТО, ч 1,5

Список обслуж. элементов

☑ 1796,1 212
☐ 2182,2 211
☐ 2390,5 131
☐ 2449,5 11
☐ 2773,5 331
☐ 3779,6 23
☐ 4685,2 12
☐ 5773,5 32

1

Стоимость отказа, у.е. 10

0,49831

Topt = 220

351,4

0,99034

eps = 0,078

Figure 1 – Results of calculations at the 1st step (object Test-2)

As a result of calculations at the 1st step, we obtain a conditionally optimal solution (see fig.1):

$$\mathbf{STO}_R^{(1)} = \left\langle E_{\text{то}1}^{(1)}, T_{\text{то}1}^{(1)} \right\rangle = \left\langle \{212\}, 220\,\text{h} \right\rangle.$$

In this case, the following values of indicators are obtained:

$$c_{\text{уд}}^{(1)} = 0{,}49831 \text{ c.u./h}; \quad T_0^{(1)} = 351 \text{ h.}; \quad \text{and} \quad K_{\text{ти}}^{(1)} = 0{,}99034.$$

Next, we will carry out all the subsequent steps - we will perform calculations with the sequential inclusion of all serviced elements in the set $E_{\text{то}1}^{(k)}$. The results are shown in table 1.

With an increase in the number of serviced elements, we see a tendency for a monotonic increase in the indicator $T_0^{(k)}$ (decrease in indicator $c_{\text{уд}}^{(k)}$), therefore there is no need to introduce the 2nd type of maintenance.

If for the Test-2 object set the required $T_0^{\text{тр}}$ = 600 h, then the optimal parameters of regulated maintenance are:

$$\mathbf{STO}_R^{*} = \left\langle \{212, 211, 131, 11, 331\};\ 240\,\text{h} \right\rangle. \tag{1}$$

In this case, the following values of indicators are provided:

$$T_0(\mathbf{STO}_R^*) = 676 \text{ h};$$

$$c_{\text{уд}}(\mathbf{STO}_R^*) = 0{,}12009 \text{ c.u./h};$$

$$K_{\text{ти}}(\mathbf{STO}_R^*) = 0{,}97564. \ \ (\boldsymbol{\varepsilon} = 0{,}116).$$

Table 2

Calculation results of the conditionally optimal parameters of regulated maintenance for Test-2 object (1 type of maintenance)

Step number k	Service type number j	Conditionally optimal parameters $\left\langle E_{\text{то }j}^{(k)}, T_{\text{то }j}^{(k)} \right\rangle$		The values of the indicators obtained with conditionally optimal parameters $\mathbf{STO}_R^{(k)}$			
		$E_{\text{то }j}^{(k)}$	$T_{\text{то }j}^{(k)}$, h	$T_0^{(k)}$, h	$c_{\text{уд}}^{(k)}$, c.u./h	$K_{\text{ти}}^{(k)}$	ε
1	1	{212}	220	351	0,49831	0,99034	0,078
2	1	{212, 211}	240	417	0,40265	0,98720	0,082
3	1	{212, 211, 131}	240	476	0,30026	0,98334	0,090
4	1	{212, 211, 131, 11}	240	546	0,16558	0,97945	0,105
5	1	{212, 211, 131, 11, 331}	240	676	0,12009	0,97564	0,116
6	1	{212, 211, 131, 11, 331, 23}	240	826	0,10196	0,97174	0,127
7	1	{212,211,131, 11, 331, 23,12}	240	874	0,07759	0,96765	0,131
8	1	{212,211,131,11,331,23,12,32}	240	1036	0,07408	0,96367	0,149

Test-3 object.

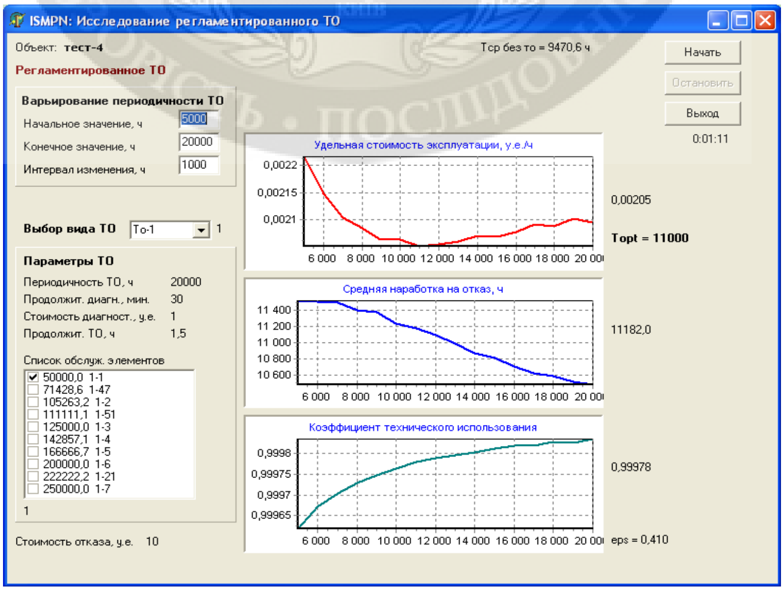
The Test-3 object is an example of a highly reliable object. The facility includes 50 recoverable items, of which 10 are potentially serviceable.

As a result of calculations at the 1st step, we obtain a conditionally optimal solution (fig. 2):

$$\mathbf{STO}_R^{(1)} = \left\{ \left\langle E_{\text{то}1}^{(1)}, T_{\text{то}1}^{(1)} \right\rangle \right\} = \left\{ \left\langle \{1\}, 11000\,\text{h} \right\rangle \right\}.$$

With these parameters, the following values of indicators are obtained:

$$c_{\text{уд}}^{(1)} = 0{,}00205 \text{ c.u./h}; \quad T_0^{(1)} = 11182 \text{ h.}; \quad \text{and} \quad K_{\text{ти}}^{(1)} = 0{,}99978.$$



Объект: **тест-4**

Тср без то = 9470,6 ч

Регламентированное ТО

Варьирование периодичности ТО

Начальное значение, ч 5000

Конечное значение, ч 20000

Интервал изменения, ч 1000

0:01:11

0,00205

Topt = 11000

11182,0

0,99978

eps = 0,410

Выбор вида ТО То-1 1

Параметры ТО

Периодичность ТО, ч 20000

Продолжит. диагн., мин. 30

Стоимость диагност., у.е. 1

Продолжит. ТО, ч 1,5

Список обслуж. элементов

☑ 50000,0 1-1
☐ 71428,6 1-47
☐ 105263,2 1-2
☐ 111111,1 1-51
☐ 125000,0 1-3
☐ 142857,1 1-4
☐ 166666,7 1-5
☐ 200000,0 1-6
☐ 222222,2 1-21
☐ 250000,0 1-7

1

Стоимость отказа, у.е. 10

Figure 2 – Results of calculations at the 1st step (object Test-3)

Next, we will make calculations in accordance with the developed methodology. We will make calculations on the assumption that there is 1 type of maintenance, and all elements $E_{\text{то}1}^{(k)}$ from are sequentially included in the set of serviced elements $E_{\text{то}}$. The results are shown in table. 3.

Analysis of the results obtained shows that the indicators $T_0^{(k)}$ and $c_{\text{уд}}^{(k)}$ monotonically improve as the volume of maintenance increases. However, in the last steps (starting from 6th step), the improvement becomes insignificant. This suggests that it is possible to improve solution by introducing 2nd type of maintenance. To test this assumption, we will continue the calculations.

First, according to the results obtained, it is necessary to select and record in the database the optimal parameters of 1st type maintenance.

Table 3

Calculation results of conditionally optimal parameters regulated maintenance for Test-3 object (1 type of maintenance)

Step number k	Service type number j	Conditionally optimal parameters $\langle E_{\text{то}\,j}^{(k)}, T_{\text{то}\,j}^{(k)} \rangle$		The values of indicators obtained with conditionally optimal parameters $\mathbf{STO}_R^{(k)}$			
		$E_{\text{то}\,j}^{(k)}$	$T_{\text{то}\,j}^{(k)}$, h	$T_0^{(k)}$, h	$c_{\text{уд}}^{(k)}$, c.u./h	$K_{\text{ти}}^{(k)}$	ε
1	1	{1}	11000	11182	0,00205	0,99978	0,410
2	1	{1, 2}	11000	12962	0,00188	0,99971	0,457
3	1	{1, 2, 3}	15000	13775	0,00178	0,99970	0,401
4	1	{1, 2, 3, 4}	16000	15009	0,00169	0,99967	0,493
5	1	{1, 2, 3, 4, 5}	16000	16802	0,00160	0,99962	0,539
6	1	{1, 2, 3, 4, 5, 6}	16000	18497	0,00154	0,99957	0,577
7	1	{1, 2, 3, 4, 5, 6, 7}	16000	20446	0,00149	0,99952	0,613
8	1	{1, 2, 3, 4, 5, 6, 7, 8}	18000	20976	0,00147	0,99951	0,616
9	1	{1, 2, 3, 4, 5, 6, 7, 8, 9}	20000	21338	0,00145	0,99951	0,633
10	1	{1, 2, 3, 4, 5, 6, 7, 8, 9, 10}	20000	22715	0,00143	0,99947	0,669

If you set the required mean time between failures $T_0^{\text{тр}}$ = 15000 h, then the following can be taken as the optimal parameters of 1st type of maintenance:

$$\mathbf{STO}_R^{*} = \left\{ \left\langle E_{\text{то}1}^{(5)};\ T_{\text{то}1}^{(5)} \right\rangle \right\} = \left\{ \left\langle \{1,\ 2,\ 3,\ 4,\ 5\};\ 16000\,\text{h} \right\rangle \right\}. \qquad (2)$$

In this case, the following values of indicators will be provided:

$$T_0(\mathbf{STO}_R^{*}) = 16802 \text{ h};$$

$$c_{\text{уд}}(\mathbf{STO}_R^{*}) = 0{,}00160 \text{ c.u./h};$$

$$K_{\text{ти}}(\mathbf{STO}_R^{*}) = 0{,}99962. \quad (\varepsilon = 0{,}539)$$

Parameters (2) will be entered into the database as parameters of the 1st type of maintenance. After that, we will enter the 2nd type of maintenance into the database and introduce one element for it into the set of serviced elements - the next element from $E_{\text{то}}$. This will be item 6 ($E_{\text{то}2}^{(6)}$ ={6}). After that we will continue the calculations. According to the methodology, next step will be the 6th step.

As a result of calculations at step 6, we obtain the following conditionally optimal solution (Fig. 3):

$$\mathbf{STO}_R^{(6)} = \left\{ \left\langle E_{\text{то}1}^{*}, T_{\text{то}1}^{*} \right\rangle, \left\langle E_{\text{то}2}^{(6)}, T_{\text{то}2}^{(6)} \right\rangle \right\} = \left\{ \left\langle \{1,2,3,4,5\}, 16000\,\text{h} \right\rangle, \left\langle \{6\}, 36000\,\text{h} \right\rangle \right\}.$$

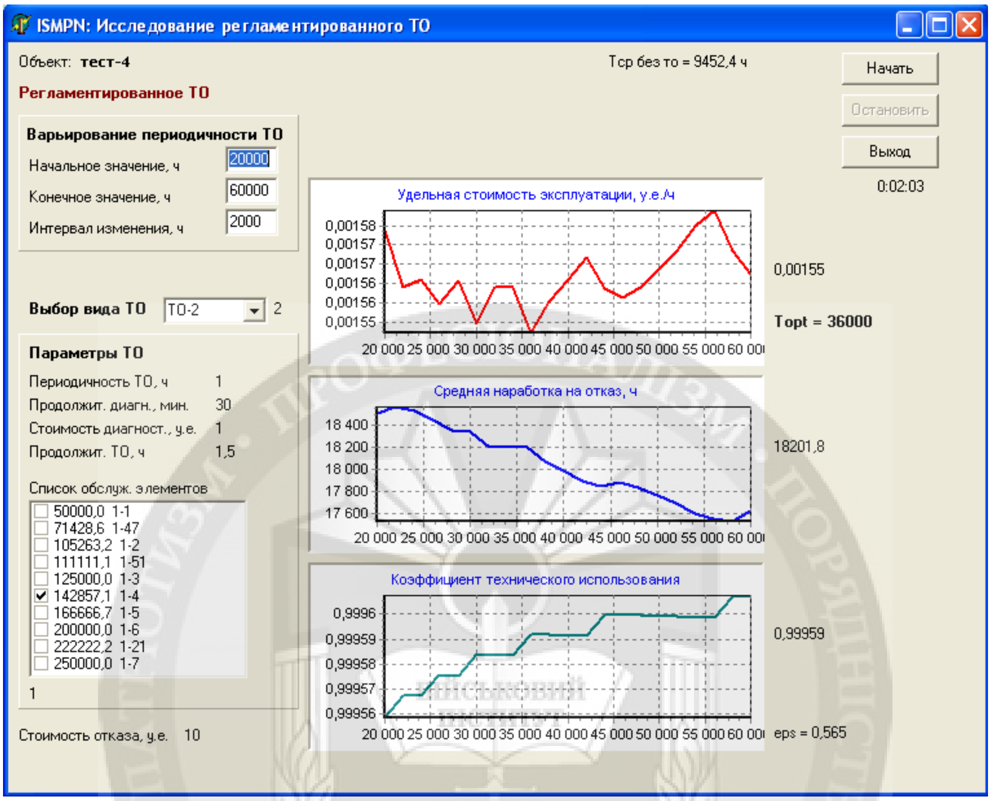
In this case, following values of indicators are obtained:

$$c_{\text{уд}}^{(6)} = 0{,}00155 \text{ c.u./h}; \quad T_0^{(6)} = 18201 \text{ h.}; \quad \text{and } K_{\text{ти}}^{(6)} = 0{,}99959.$$

The calculation results in all subsequent steps are shown in table 3. According to the results obtained, it is clear that due to the introduction of the 2nd type of maintenance, it is not possible to improve the indicators $T_0^{(k)}$ and $c_{\text{уд}}^{(k)}$. So, at the 6th step, $T_0^{(6)}$ and $c_{\text{уд}}^{(6)}$ indicators worsen ($T_0^{(6)} = 18201$ hours instead of 18497 hours, $c_{\text{уд}}^{(6)} = 0.00155$ instead of 0.00154).

With this in mind, we finally accept as the optimal solution for Test-3 object:

$$\mathbf{STO}_R^* = \left\{\left\langle E_{\text{то}1}^*;\, T_{\text{то}1}^* \right\rangle\right\} = \left\{\left\langle \{1,\, 2,\, 3,\, 4,\, 5\};\ 16000\,\text{h} \right\rangle\right\}.$$


ISMPN: Исследование регламентированного ТО

Объект: **тест-4**

Тср без то = 9452,4 ч

Регламентированное ТО

Варьирование периодичности ТО
Начальное значение, ч 20000
Конечное значение, ч 60000
Интервал изменения, ч 2000

Выбор вида ТО ТО-2 2

Параметры ТО
Периодичность ТО, ч 1
Продолжит. диагн., мин. 30
Стоимость диагност., у.е. 1
Продолжит. ТО, ч 1,5

Список обслуж. элементов
☐ 50000,0 1-1
☐ 71428,6 1-47
☐ 105263,2 1-2
☐ 111111,1 1-51
☐ 125000,0 1-3
☑ 142857,1 1-4
☐ 166666,7 1-5
☐ 200000,0 1-6
☐ 222222,2 1-21
☐ 250000,0 1-7
1

Стоимость отказа, у.е. 10

0:02:03

0,00155

Topt = 36000

18201,8

0,99959

eps = 0,565

Figure 3 – Results of calculations at the 6th step (object Test-3)

Table 4

Calculation results of conditionally optimal parameters of regulated maintenance for the Test-3 object (2 types of maintenance)

Step number k	Service type number j	Conditionally optimal parameters $\left\langle E_{\text{то}\,j}^{(k)}, T_{\text{то}\,j}^{(k)} \right\rangle$		The values of indicators obtained with conditionally optimal parameters $\mathbf{STO}_R^{(k)}$			
		$E_{\text{то}\,j}^{(k)}$	$T_{\text{то}\,j}^{(k)}$, h	$T_0^{(k)}$, h	$c_{\text{уд}}^{(k)}$, c.u./h	$K_{\text{ти}}^{(k)}$	ε
6	2	{ 6}	36000	18201	0,00155	0,99959	0,565
7	2	{ 6, 7}	36000	19617	0,00149	0,99957	0,599
8	2	{ 6, 7, 8}	38000	20698	0,00144	0,99955	0,627
9	2	{ 6, 7, 8, 9}	36000	22466	0,00140	0,99953	0,647
10	2	{ 6, 7, 8, 9, 10}	36000	23992	0,00136	0,99951	0,688

Test-4 object.

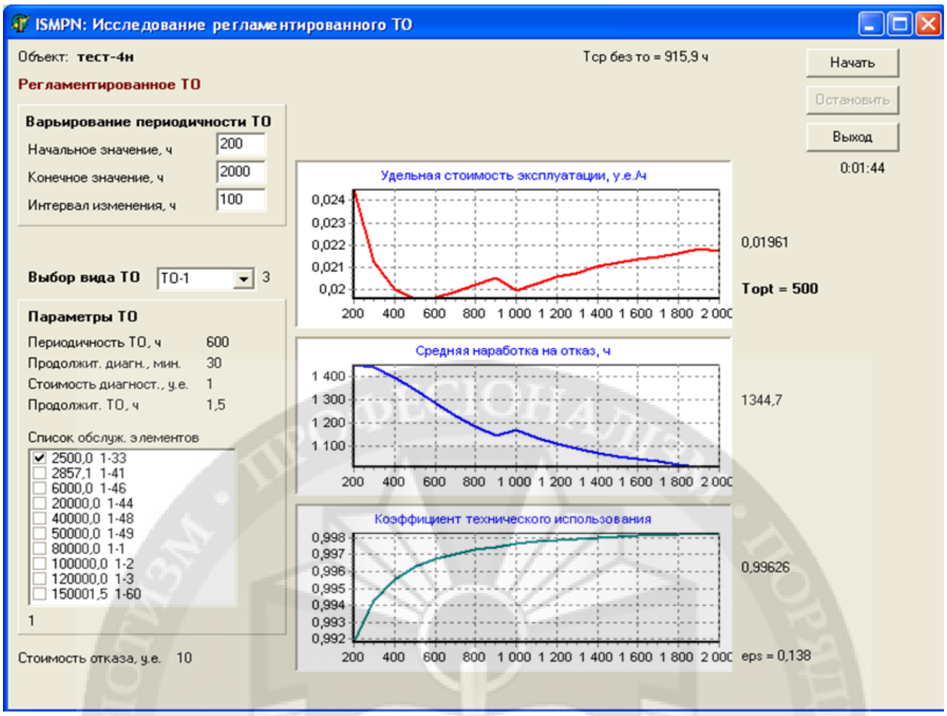
The Test-4 object includes 50 recoverable elements, of which 10 are potentially serviceable (Table 8).

As a result of calculations at the 1st step, we find that the optimal frequency of maintenance of the 1st type, provided that the set of serviced elements $E_{\text{то}1}^{(1)} = \{1\}$, is equal to $T_{\text{то}1}^{(1)} = 500$ hours.

In this case, the following values of indicators are obtained (see fig. 4):

$$c_{\text{уд}}^{(1)} = 0{,}01961 \text{ c.u./h}; \quad T_0^{(1)} = 1345 \text{ h.}; \quad \text{and} \quad K_{\text{ти}}^{(1)} = 0{,}99626.$$

Table 4 shows results obtained after completing the first 6 steps. The results presented in the table show that, starting from step 4, the unit cost of operation $c_{\text{уд}}^{(k)}$ begins to increase. This is a sign of the need to enter 2nd type of maintenance.



Объект: **тест-4н**

Регламентированное ТО

Тср без то = 915,9 ч

0:01:44

Варьирование периодичности ТО

Начальное значение, ч 200

Конечное значение, ч 2000

Интервал изменения, ч 100

Выбор вида ТО ТО-1 3

Параметры ТО

Периодичность ТО, ч	600
Продолжит. диагн., мин.	30
Стоимость диагност., у.е.	1
Продолжит. ТО, ч	1,5

Список обслуж. элементов

☑ 2500,0 1-33
☐ 2857,1 1-41
☐ 6000,0 1-46
☐ 20000,0 1-44
☐ 40000,0 1-48
☐ 50000,0 1-49
☐ 80000,0 1-1
☐ 100000,0 1-2
☐ 120000,0 1-3
☐ 150001,5 1-60

1

Стоимость отказа, у.е. 10

0,01961

Topt = 500

1344,7

0,99626

eps = 0,138

Figure 4 – Results of calculations at 1st step (Test-4)

As optimal parameters of maintenance 1st type, we take the parameters obtained in 3rd step (see table 4):

$$\mathbf{STO}_R^{(3)} = \left\langle \left\langle \{1,2,3\}, 600\,\text{h} \right\rangle \right\rangle. \tag{3}$$

Table 5

The results of calculating optimal parameters for one (1st) type of TO (object Test-4)

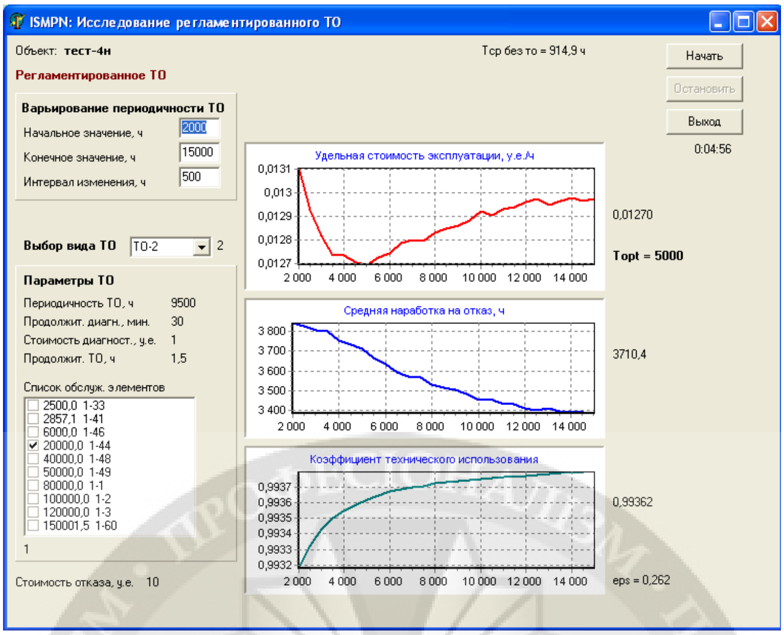
Step number k	Service type number j	Conditionally optimal parameters $\left\langle E_{\text{то } j}^{(k)}, T_{\text{то } j}^{(k)} \right\rangle$		The values of indicators obtained with conditionally optimal parameters $\mathbf{STO}_R^{(k)}$			
		$E_{\text{то } j}^{(k)}$	$T_{\text{то } j}^{(k)}$, h	$T_0^{(k)}$, h	$c_{\text{уд}}^{(k)}$, c.u./h	$K_{\text{ти}}^{(k)}$	ε
1	1	{1}	500	1345	0,01961	0,99626	0,138
2	1	{1,2}	500	2416	0,01468	0,99459	0,195
3	1	{1,2,3}	600	3230	0,01314	0,99388	0,238
4	1	{1,2,3,4}	600	3836	**0,01378**	0,99227	0,260
5	1	{1,2,3,4,5}	1000	2501	**0,01437**	0,99413	0,217
6	1	{1,2,3,4,6}	1000	2637	**0,01499**	0,99315	0,218

With these parameters, indicators are provided:

$$c_{\text{уд}}^{(3)} = 0{,}01314 \text{ c.u./h}; \quad T_0^{(3)} = 3230 \text{ h.}; \quad \text{and} \quad K_{\text{ти}}^{(3)} = 0{,}99388.$$

We enter the parameters of 1st type of maintenance into database and continue the search in order to determine the optimal parameters for 2nd type of maintenance.

Taking into account the already completed 3 steps, we will continue the search starting from 4th step. In fig. 5 shows the screen view after calculations for 2nd type of maintenance in step 4.



ISMPN: Исследование регламентированного ТО

Объект: **тест-4н**

Регламентированное ТО

Варьирование периодичности ТО

Начальное значение, ч 2000

Конечное значение, ч 15000

Интервал изменения, ч 500

Выбор вида ТО ТО-2 2

Параметры ТО

Периодичность ТО, ч 9500

Продолжит. диагн., мин. 30

Стоимость диагност., у.е. 1

Продолжит. ТО, ч 1,5

Список обслуж. элементов

- ☐ 2500,0 1-33
- ☐ 2857,1 1-41
- ☐ 6000,0 1-46
- ☑ 20000,0 1-44
- ☐ 40000,0 1-48
- ☐ 50000,0 1-49
- ☐ 80000,0 1-1
- ☐ 100000,0 1-2
- ☐ 120000,0 1-3
- ☐ 150001,5 1-60

1

Стоимость отказа, у.е. 10

Тср без то = 914,9 ч

0:04:56

0,01270

Topt = 5000

3710,4

0,99362

eps = 0,262

Figure 5 – Results of calculations at the 4th step (object Test-4)

Table 6

The results of calculating optimal parameters for 2nd type of maintenance (object Test-4)

Step number k	Service type number j	Conditionally optimal parameters $\left\langle E_{\text{то}\,j}^{(k)}, T_{\text{то}\,j}^{(k)} \right\rangle$		The values of indicators obtained with conditionally optimal parameters $\mathbf{STO}_R^{(k)}$			
		$E_{\text{то}\,j}^{(k)}$	$T_{\text{то}\,j}^{(k)}$, h	$T_0^{(k)}$, h	$c_{\text{уд}}^{(k)}$, c.u./h	$K_{\text{ти}}^{(k)}$	ε
4	2	{4}	5000	3710	0,01270	0,99362	0,262
5	2	{4,5}	5500	4030	0,01239	0,99349	0,273
6	2	{4,5,6}	6000	4287	0,01218	0,99339	0,285
7	2	{4,5,6,7}	7000	4514	**0,01210**	0,99334	0,291
8	2	{4,5,6,7,8}	8000	4592	**0,01205**	0,99321	0,297
9	2	{4,5,6,7,8,9}	8500	4593	**0,01203**	0,99322	0,304
10	2	{4,5,6,7,8,9,10}	10500	4508	**0,01204**	0,99327	0,298

Table 6 shows all the results obtained in the search for optimal parameters for the 2nd type of maintenance.

According to the data obtained, it can be seen that the inclusion of the last elements in the number of serviced during maintenance -2 leads to an insignificant improvement in indicators (this improvement is practically within the statistical error).

Therefore, the user has the right to decide not to service these elements at all during operation.

If, for example, during maintenance -2, only 3 elements are serviced ($E_{\text{то}\,2}^{(6)}$ ={4,5,6}), then the optimal parameters of maintenance for two types of maintenance are:

$$\mathbf{STO}_R^{(6)} = \left\langle \langle\{1,2,3\},600\,\text{h}\rangle, \langle\{4,5,6\},6000\,\text{h}\rangle \right\rangle. \tag{4}$$

At same time, indicators are provided:

$$c_{\text{уд}}^{(6)} = 0{,}01218 \text{ c.u./h}; \quad T_0^{(6)} = 4287 \text{ h.}; \quad \text{and } K_{\text{ти}}^{(3)} = 0{,}99339.$$

According to results obtained, it is clear that due to the introduction of 2nd type of maintenance, it was possible to significantly improve the indicators $T_0^{(k)}$ and $c_{\text{уд}}^{(k)}$.

Earlier, for the Test-4 object, we set $T_0^{\text{тр}}$ = 5000 hours as the required reliability level. In this case, we see that this requirement is not met with a regulated maintenance strategy. Therefore, we will continue the calculations in order to check the possibility of further improvement of indicators due to the introduction of the third type of maintenance.

Before continuing the search, you need to enter the obtained optimal parameters for 1st and 2nd types of maintenance into the database. After that, we will continue the calculations, starting from 7th step. The results obtained in this case are presented in table. 7.

Table 7

The results of calculating the optimal parameters for the 3rd type of maintenance (object Test-4)

Step number k	Service type number j	Conditionally optimal parameters $\left\langle E_{\text{то}\,j}^{(k)}, T_{\text{то}\,j}^{(k)} \right\rangle$		The values of indicators obtained with conditionally optimal parameters $\mathbf{STO}_R^{(k)}$			
		$E_{\text{то}\,j}^{(k)}$	$T_{\text{то}\,j}^{(k)}$, h	$T_0^{(k)}$, h	$c_{\text{уд}}^{(k)}$, c.u./h	$K_{\text{ти}}^{(k)}$	ε
7	3	{7}	18500	4490	0,01207	0,99332	0,291
8	3	{7,8}	16000	4668	0,01196	0,99326	0,304
9	3	{7,8,9}	18000	4816	0,01186	0,99323	0,305
10	3	{7,8,9,10}	22000	4879	0,01180	0,99323	0,311

As a result of calculations for 3 types of maintenance, we received the following solution:

$$\mathbf{STO}_R^{(10)} = \left\{ \left\langle \{1,2,3\}, 600\text{h} \right\rangle, \left\langle \{4,5,6\}, 6000\text{h} \right\rangle, \left\langle \{7,8,9,10\}, 22000\text{h} \right\rangle \right\}. \quad (5)$$

At the same time, indicators are provided:

$$c_{\text{уд}}^{(10)} = 0{,}01180 \text{ c.u./h}; \quad T_0^{(6)} = 4879 \text{ h.}; \quad \text{and } K_{\text{ти}}^{(3)} = 0{,}99323.$$

So, we see that the introduction of the 3rd type of maintenance leads to a further improvement in performance in comparison with case of 2 types of maintenance. However, the requirement $T_0^{\text{тр}}$ = 5000 h is not met in this case. Since solution (5) has already used all serviced elements from the set, it can be concluded that with a regulated maintenance strategy, the requirement $T_0^{\text{тр}}$ = 5000 h for Test-4 object is unattainable.

Conclusions. The mode of modeling regulated maintenance was introduced in order to ensure the completeness of analysis possible maintenance strategies of designed facility and predicting the possible gain in reliability and cost of operating the facility through use of strategies for maintenance.

REFERENCES:

1. Barzilovich E.Yu. Maintenance models for complex systems. M .: Higher school, 1982. 231 p.
2. Technology of system modeling / E.F. Avramchuk, A.A. Vavilov, S.V. Emelyanov and others - M.: Mechanical engineering; Berlin: Technician, 1988. 520 p.
3. Operation of radio engineering complexes. Edited by A.I. Alexandrova. M., Sov. Radio, 1976.280 p.
4. Reliability and efficiency in technology. Directory. T.2. Mathematical methods in the theory of reliability and efficiency / Ed. B.V. Gnedenko. M.: Mashinostroenie, 1988. 280 p.
5. Computational methods of research and design of complex systems. Mikhalevich V.S., Volkovich V.L. - M.: Nauka, 1982.286 p.
6. Volokh OP Methodology for the determination of the rational values of the periodicity of the technical maintenance of the machines of the engineering plant during the hour of exploitation // Collection of Science Practices of the Institute of Science and Technology of Ukraine .. T. Shevchenko. Vip. 2.K .: MIKNU, 2005. P. 29-32.

7. Brown V.O., Boryak K.F., Lantvoit O.B., Tsytsarev V.N. Modeling of maintenance processes of complex recoverable objects of radio-electronic equipment // Bulletin of the Engineering Academy of Ukraine. K., 2008. №1. P. 47 - 52.

8. Boryak K.F. Pre-service to the process of technical servicing of foldable radioelectronic equipment for additional and statistical statistical model // Bulletin of the Engineering Academy of Ukraine. K., 2008. No. 2. P. 85 - 91.

9. Banzak G.V. Database on the reliability of complex objects of radio-electronic equipment / G.V. Banzak, K.F. Boryak, V.N. Tsytsarev // Book of Science Practitioners of Military Institute of Kyiv National University for the Name of Taras Shevchenko. 2010. No. 27. P.89 - 97.

10. Forecasting to reliability complex object radio-electronic texnology and optimization parameter their technical usage with use the simulation statistical models: [monography] in English / Sergey Lienkov, Konstantin Borjak, Gennadii Banzak, Vadim Braun, ets.; under edition S.V. Lenkov. Odessa: Publishing house “VMV”, 2014. 252 p.

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

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

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

14. Boryak K.F. Reliability model of a complex restored object of radio-electronic equipment // Book of Science Practitioners of Military Institute of Kyiv National University for the Name of Taras Shevchenko. K.: 2009. № 21. P.33-41.

15. Lienkov S.V., Tolok I.V., Lienkov Ye.S. Prognostication of composition and resource of groupment of objects of technigue // Book of Science Practitioners of Military Institute of Kyiv National University for the Name of Taras Shevchenko. K.: MIKNU, 2019. №63. P. 54 - 65.

д.т.н., проф. Лєнков С.В., к.пед.н., доц. Толок І.В., к.т.н. Кольцов Р.Ю.,
к.т.н. Банзак Г.В., к.т.н.Лєнков Є.С., Добровольська С.В.

ОБГРУНТУВАННЯ ОПТИМАЛЬНИХ ПАРАМЕТРІВ СТРАТЕГІЇ ТЕХНІЧНОГО ОБСЛУГОВУВАННЯ, ЩО РЕГЛАМЕНТУЄТЬСЯ

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

Проблема полягає в тому, що при розробці таких об'єктів всі питання, пов'язані з ремонтопридатністю і технічним обслуговуванням повинні вирішуватися вже на ранніх етапах проектування об'єкта. Якщо не передбачити заздалегідь необхідні апаратні і програмні засоби вбудованого контролю технічного стану (ТС) об'єкта, що не розробити і не "вбудувати" в об'єкт технологію проведення ТО, то реалізувати в майбутньому можливий виграш в 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 в рівні безвідмовності об'єкта за рахунок проведення ТО, оцінити необхідні для цього вартісні витрати. Потім на підставі таких розрахунків прийняти рішення про необхідність проведення ТО для даного типу об'єктів і, якщо таке рішення прийнято, розробити структуру системи ТО, вибрати найбільш прийнятну стратегію ТО, визначити її оптимальні параметри.

У роботі показано, що модель для стратегії регламентованого ТО є вдосконаленим варіантом вже відомих моделей і введена в комплексну модель з метою порівняльної оцінки різних стратегій ТО. Крім того слід враховувати, що на практиці в деяких випадках стратегія регламентованого ТО може виявитися більш кращою у порівнянні зі стратегіями ТОС.

Ключові слова: складні технічні об'єкти, стратегії технічного обслуговування, технічний стан, комплектуючих елементів.