Розроблено методику та алгоритми формування оптимальних множин елементів, які беруть участь в процесі моделювання відмов-відновлень складних технічних об'єктів. Вибір множин елементів, що відмовляють і відновлюються, базується на ієрархічній конструктивній структурі складного технічного об'єкта, а також показниках безвідмовності, ремонтопридатності і вартості його елементів, блоків та вузлів. Сформовані оптимальні множини елементів використовуються для розрахунку прогнозних показників надійності і вартості експлуатації самого об'єкта. На прикладі показано, як від вибору множин елементів, що відмовляють і відновлюються, змінюються прогнозні оцінки надійності і вартості експлуатації складного технічного об'єкта

Ключові слова: складний технічний об'єкт, ієрархічна конструктивна структура, середнє напрацювання на відмову, питома вартість експлуатації, імітаційне статистичне моделювання

Разработаны методика и алгоритмы формирования оптимальных множеств элементов, которые принимают участие в процессе моделирования отказов-восстановлений сложных технических объектов. Выбор множеств отказывающих и восстанавливаемых элементов базируется на иерархической конструктивной структуре сложного технического объекта, а также показателях безотказности, ремонтопригодности и стоимости его элементов, блоков и узлов. Сформированные оптимальные множества элементов используются для расчета прогнозных характеристик надежности и стоимости эксплуатации самого объекта. На примере показано, как от выбора множеств отказывающих и восстанавливаемых элементов изменяются прогнозные оценки надежности и стоимости эксплуатации сложного технического объекта

Ключевые слова: сложный технический объект, иерархическая конструктивная структура, средняя наработка на отказ, удельная стоимость эксплуатации, имитационное статистическое моделирование

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FEATURES OF MODELING FAILURES OF RECOVERABLE COMPLEX TECHNICAL OBJECTS WITH A HIERARCHICAL CONSTRUCTIVE STRUCTURE

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1. Introduction

Vital functions of states, industrial enterprises of the whole society, is provided by the functioning of complex technical objects. Such facilities include power plants, production lines, communication and navigation systems, vehicles, computer systems, etc. From the whole variety of such objects, a group can be separated that includes complex recoverable technical objects that have a hierarchical constructive structure and are intended for a long-term operation. Typical examples of such objects are objects of electrical and radio-electronic equipment, for example, radar stations, elements of automated control systems, etc., which from the reliability point of view, are recoverable objects. Such objects are characterized by a high price, both in development and in operation. To provide the required (preset) level of reliability during operation, their technical maintenance is carried out. The need for maintenance is based on well-timed replacement of elements, which are in a pre-failure state, which leads to improved reliability. The repair is performed with the purpose of recovering the serviceable or operational state of the object or its part [1]. The considered objects are characterized by certain features that affect and complicate the task of constructing mathematical models for estimating and predicting the reliability index (RI) as well as operation cost (OC) of these objects on all stages of their lifecycle. In addition, these objects are constantly subjected to modernization during the various lifecycle periods of development and operation, therefore they require constant refinements of predicting the RI and OC. Such objects are quite complicated, primarily in the sense of a large number (tens and hundreds of thousands) and the variety of types of component elements. Therefore, the method of simulation statistical modeling is mostly used to estimate and predict object's RI and OC considering their constructive structure [2].

2. Literature review and problem statement

The question of how the constructive structure of a technical object affects its RI and OC is not well researched. It is highly important for a developer of a complex technical object to have tools (methods) to quantify this effect and use it when making certain constructive decisions on predicting of RI and OC. A large number of studies are devoted to calculating and predicting the reliability, as well as creating models (including simulation ones). The paper [3] offers a method of inheritance and development of modern methods of reliability estimation based on numerical modeling, based on dynamic Bayesian networks and numerical modeling. Thus, it overcomes the limitations of the analytical method and the multilevel synthesis method, and also provides an effective tool for assessing the reliability of complex dynamic systems. The paper [4] offers a method of calculating the structural reliability, based on graphs. The paper [5] presents a MEMS method of modeling the structural reliability and FORM method is described for obtaining the RI and its sensitivity to the random input values and their parameters that can not only be used to estimate object's reliability but also to help to define key factors for additional structural improvements. The paper [6] offers a method of assessing the reliability of a bistable compliant mechanism taking into account the degradation and uncertainty of the parameters. The paper [7] offers an extended covariation Weibull-Corrosion model for assessment of the reliability of a system, encountering operating voltages. In [8], a model of dynamic reliability with a cyclic period of multiple missions for non-recoverable discrete systems was developed. In [9], algorithms are developed to evaluate the reliability of a system in the form of Bayesian networks with the exponentially increasing amount of data that has to be saved as the number of system components increases. The paper [10] offers a combinational method for analyzing the reliability of a multivariate system. The method is based on a combination of BDD and MMDD models. It is proposed in [11, 12] to use the Bayesian semiparametric approach to obtain reliability indicators for multi-level hierarchical systems, both with parallel and series connection of components. The reliability of multi-level hierarchical systems is also discussed in [13], which is devoted to the problem of determining the reliability requirement for structural elements of the system in order to ensure a given level of reliability of the entire system with the minimum total cost of the product.

In these works, the methodology for determining the reliability indices of a system for a given set of failing elements and their characteristics is described in detail. However, the task of investigating the reduction of the set of failing elements (enlargement of elements), taking into account the hierarchical constructive structure, and its impact on changes in the reliability and value of the object as a whole, was not considered. Also, the problem of determining the optimal set of recoverable elements was not solved.

Thus, it is of considerable interest to develop a methodology and algorithms for the formation of optimal sets of failing and recoverable elements that participate in the process of modeling reliability indicators and operating costs of a complex technical facility.

3. The aim and objectives of the study

The aim of the work is to develop a methodology for determining the optimal sets of failing and recoverable elements in recoverable complex technical objects of various purposes.

To achieve this aim, the following objectives were set:

– to develop an algorithm for the preliminary formation of the set of failing elements E_0 and the set of correspondences W between the failing and recoverable elements;

– to develop an algorithm for eliminating the possible redundancy of the set E_0;

– to develop an algorithm for the final formation of the set W.

4. Research methods of determining the optimal set of failing elements in the development of a statistical simulation model of a complex technical object and verifying its adequacy

The following methods were used to solve the tasks of the study:

– probabilistic modeling and elements of graph theory (to determine RI and OC based on the constructive structure of an object);

– statistical simulation modeling (to obtain predictive estimates of RI and OC of an object);

– methods of mathematical statistics (to check the accuracy of the model).

5. Results of research on the development of a methodology and algorithms for the formation of optimal sets of failing E_0 и recoverable E_R elements

5. 1. Object constructive structure and the structure of its reliability

The following indicators are considered as parameters of reliability and operating costs:

T_0 – mean time between failures (RI);

T_R – mean time to recovery (maintainability index);

c_e – unit operating cost (OC index).

Operation cost is understood in a narrow sense – only the cost of replaced elements, repair work and used consumables is taken into an account.

In [1], the simulation statistical model (SSM) is developed, which helps to get predictive estimates for RI and OC. The initial data for the SSM are the parameters of an object, which can be generalized as an expression (1):

$$P_{gen} = \{G, \mathrm{Re}, M, C\}, \quad (1)$$

where P_{gen} is a generalized parameter that represents object characteristics; G is a graph that describes a constructive structure of an object; Re, M and C are generalized parameters that characterize the properties of reliability, maintainability (repairability) and the cost of the object. A more detailed content of these parameters will be considered below.

The constructive structure of an object is described by a graph (tree) G: $\mathrm{G} = \langle E, R\rangle$, where E is the set of graph vertices representing the individual object elements; R is the set of edges connecting these vertices. The set R defines the nesting relation of constructive elements. An arbitrary constructive element will be denoted by e_i^u, where u is an index of the constructive level of the element (nesting level), i is the index of the element ($e_i^u \in E$). The constructive level number is counted from the root vertex e^0 of the graph, which represents the object as a whole. The relation R is the set of pairs $\langle e_i^u, e_j^{u-1}\rangle$, in which the element e_j^{u-1} is nested into the element e_i^u ($\langle e_i^u, e_j^{u-1}\rangle \in R$). Every pair $\langle e_i^u, e_j^{u-1}\rangle$ represents the corresponding edge on the graph G, shown in Fig. 1.

The elements that contain other elements will be called composite elements. If the elements composition is not detailed (no other constructive elements are defined in its composition), then such element will be called simple. Simple element can be in fact an arbitrary complex technical product, but in the particular case, we are not interested in its internal construction. In Fig. 1, composite elements are shown as rectangles, and the simple elements as circles. At the bottom level of a constructive structure, all the simple elements are located.

We will denote the set of all simple elements by E_{se}, the set of all elements of the (u+1)-th level that are a part of the element e_i^u, will be denoted by $E(e_i^u)$.

The depth of detail in the construction of the graph G should be such that all potentially removable and replaceable in the process of operation elements are presented in this graph. At the lowest level, the smallest elements should be presented, disassembly of which in the operating conditions is impossible or impractical.

The structural diagram of the object's reliability is series-parallel. All elements of the set $E(e_i^u)$ are considered connected in series in a sense of reliability. Every presented element in the graph G can represent a group of series or parallel connected identical elements. Parallel element connection is, in fact, the structural redundancy. The redundancy in the groups can be loaded (permanent) or unloaded (replacing).

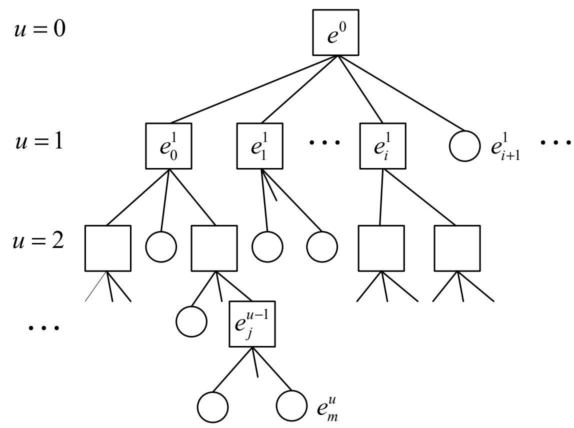

Fig. 1. The constructive structure tree of an object

5. 2. Concepts of sets of failing and recoverable elements

It is impossible to model the failure of all simple elements, because their number is too large. On the other hand, this is impractical, since for every composite element with known constructive structure, it is always possible to calculate the reliability indices that are necessary for modeling, and then use them as initial data for SSM.

Therefore, when using the SSM, the task of determining the initial set of constructive elements, for which failure simulation is to be performed, is solved.

We introduce the notion of a set of failing elements (we denote it by E_0), by which we mean such a subset of constructive elements, the failures of which have to be modeled (simulated) in the SSM when estimating the RI and OC of an object ($E_0 \subset E$, $|E_0| << |E|$). The composition of the set E_0 is defined by the user and can be adjusted by him. To provide the accuracy of calculations, E_0 has to satisfy the requirements of completeness and non-redundancy.

The requirement of completeness is that E_0 has to include all elements that can lead to the object failure. If the constructive structure of an object is presented by a tree G, the requirement for completeness can formally be ensured by the following condition: there should not exist any path between the root of the tree (object) and a pendant vertex (simple element) that does not contain an element belonging to the set E_0.

The requirement of non-redundancy is that any path between the root of the tree G and any pendant vertex of it should not contain more than one element of E_0.

Obviously, the set of all simple elements E_{se} is always complete and non-redundant. E_{se} may contain a large number of elements and it is impractical to model every failure. For reasons of machine-time saving, it is desirable for E_0 to contain a small number of elements. On the other hand, for reasons of providing the model adequacy, it is necessary for E_0 to contain constructive elements that are most likely going to be replaced during the object operation.

Fig. 2 shows one of the possible options for specifying the set E_0.

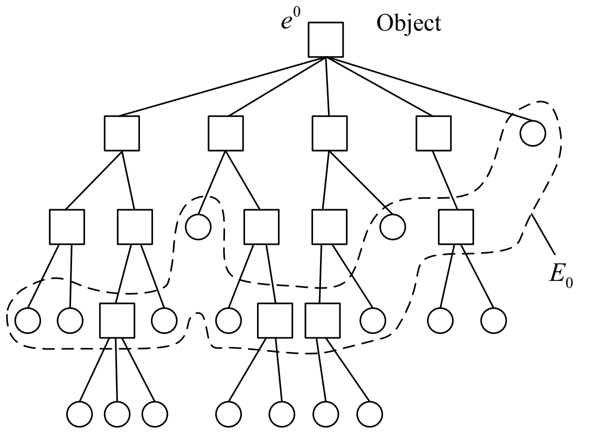

Fig. 2. One of the possible options of choosing the set E_0

In case of object failures, its operability is restored by replacing the failed element. However, the actual failed constructive element is not necessarily replaced. The element of a higher constructive level that requires less amount of replacement time may be replaced.

Recoverable elements are such elements that are replaced during the object operation in case of failures. The set of recoverable elements will be denoted by E_R, each failed element $e_i \in E_0$ will be associated with a unique recoverable element $e_j \in E_R$.

The sets E_0 and E_R are model concepts and their correct selection is very important for the adequate modeling of failure-recovery processes in the SSM. Below we consider algorithms and methodology for determining the sets E_0 and E_R.

We will denote by W a relation by which we will establish a correspondence between the failing and recoverable elements. The relation W is a set of pairs $\langle e_i^u, e_j^r \rangle$, where $e_i^u \in E_0$ is a failing element, and $e_j^r \in E_R$ is an element that is going to be replaced in case of failure of the element e_i^u. The relation W defines a functional mapping of the following form: $W: E_0 \rightarrow E_\mathrm{R}$ [14]. The relation W assigns a single recoverable $e_j^r \in E_R$. element to each element $e_i^u \in E_0$ Considering this fact, $e_j^r = W(e_i^u)$. is the recoverable element that corresponds to the failing element e_i^u.

5. 3. Algorithms and methodology of forming the sets E_0 and E_R

To form the optimal sets E_0 and E_R, the following procedure is proposed, including three steps:

– preliminary formation of the sets E_0 and W;

– elimination of possible redundancy of the set E_0;

– the final formation of the set (relation) W.

Each of the proposed stages is an algorithm. Let us consider these algorithms.

Algorithm No. 1 is the algorithm for the preliminary formation of the sets E_0 and W. Its flow chart is shown in Fig. 3. Statement 1 carries out preparatory activities. Statements 2, 7, 8 form a cycle, in which all elements of E_{se} are enumerated. For each simple element $e_m \in E_{se}$, a path $P(e_m)$ is formed that connects a pendant vertex e_m with the root vertex e^0 (statement 3). Among the elements $e_i \in P(e_m)$, an element is defined for replacing of which the least time $\tau_{sub}(e_i)$ is needed (statement 4). The found element e_i is added to the set E_0 and at the same time a pair $\langle e_m, e_j \rangle$ is formed, which is added to the set W (statements 5, 6). Statement 9 removes duplicate elements from the set.

The set E_0, created by an algorithm No. 1 can be redundant, the redundancy lies in the fact that E_0 can contain elements that belong to the same path $P(e_m)$. Elimination of the redundancy of the set E_0 is performed on the second stage of the considered technique and is implemented by algorithm No. 2, the structural diagram of which is shown in Fig. 4.

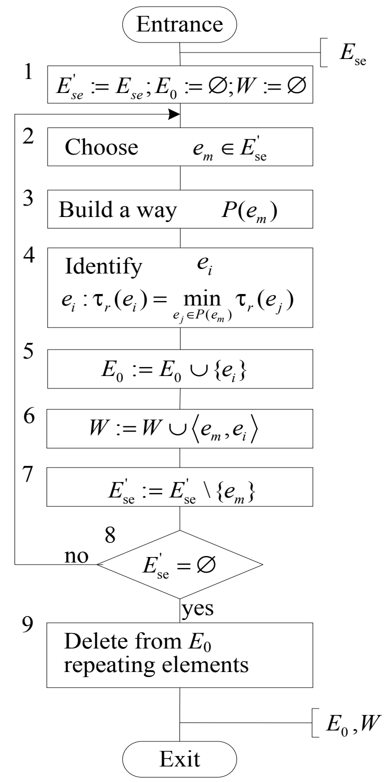

Fig. 3. The algorithm for the preliminary formation of the sets E_0 and W

Statement 1 forms an auxiliary set $E_0^{'}$, that is used to enumerate the elements of the initial set E_0 (obtained as a result of the algorithm No. 1 execution), and the auxiliary sign p, the purpose of which will be explained below.

Statement 2 arbitrarily selects an element e_i from the set $E_0^{'}$ (and immediately removes it from the set $E_0^{'}$). If the element e_i was the only one in the set, the algorithm execution ends here. Statement 4 selects the second element $E_0^{'}$ from the set e_j. Statement 5 checks, if the element e_i is nested relative to the element e_j. If the answer is "yes", then the statements 5 and 6 are executed. Statement 6 forms the set $E1$ of elements that are directly included in the composition of e_j. Statement 7 builds the path $P(e_i)$ that connects the element e_i with the root e^0 of the tree and then finds the vertex (element) e_k, that lies at the intersection of the path $P(e_i)$ and the set $E1$. Such intersection always exists because the element e_i is nested relative to the element e_j.

After that, statement 11 is executed that removes the element e_k from the set $E1$. Statement 12 adds all elements that have been left in the set $E1$ to the set E_0. Statement 13 forms a value of p=1, by doing so it fixes the fact that the set E_0 contained redundant elements.

If the element e_i is not nested relative to the element e_j, statement 8 is executed, that checks, if e_j is nested relative to e_i. If "yes", then statements 9 and 10 are executed, whose actions are similar to those of statements 6 and 7 (e_i and e_j

swapping places). After that, statements 12 and 13 are executed, the purpose of which was considered before.

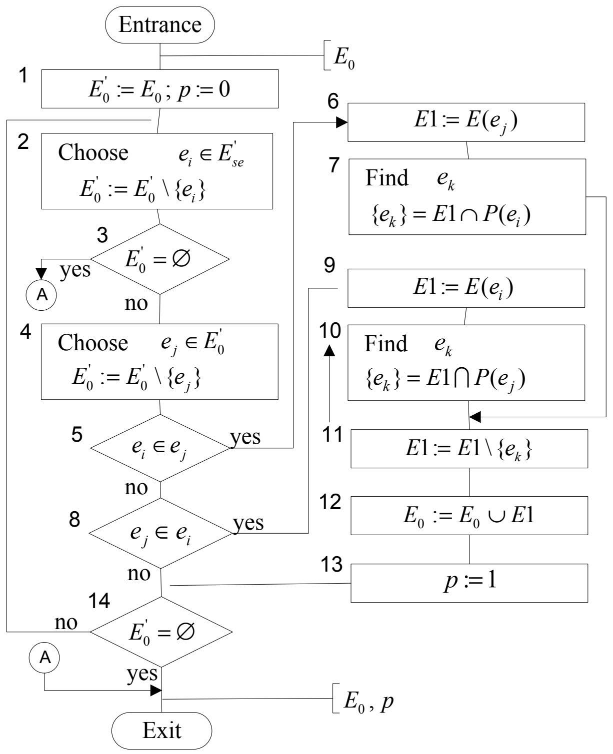

Fig. 4. The algorithm of elimination of redundancy of the set E_0

Statement 14 checks the completion condition of viewing all elements that are contained in the initial set E_0. The resulting information of the algorithm is the set E_0 and the characteristic p. If p=1, this means that the initial set E_0 was redundant and, consequently, actions were taken to eliminate it (statements 6, 7, 11, 12 or statements 9–12). As this adds new elements to the set E_0, redundancy retesting of the set is necessary (re-execution of algorithm No. 2). If p=0, this means that E_0 is complete and non-redundant.

In step 3, the previously created set (relation) W is transformed, based on the set E_0 obtained in step 2. This transformation is implemented by algorithm No. 3, the structural diagram of which is shown in Fig. 5.

Statements 2, 8 and 9 form a cycle in which all simple elements $e_m \in E_{se}$ are enumerated and the path e_m is built for each element $P(e_m)$. In this path, there is an element e_k, that belongs to E_0 at the same time (such an element always exists and it is unique). In the set W, which had been formed earlier right after the algorithm No. 1 execution, there is the pair $\langle e_m, e_j \rangle$, where e_j is an element that must be replaced in case of failure of the element e_m (statement 5). In the found pair $\langle e_m, e_j \rangle$, the element e_m is replaced by the element e_k (statement 6), after these steps the changed pair is stored in the set W (statement 7).

Together, the three considered above algorithms implement the method of forming the optimal sets E_0 and E_R, in that case the set E_R exists implicitly through the set (relation) W. In Fig. 6 the scheme that determines the sequence of execution of the algorithms that implement this technique is depicted.

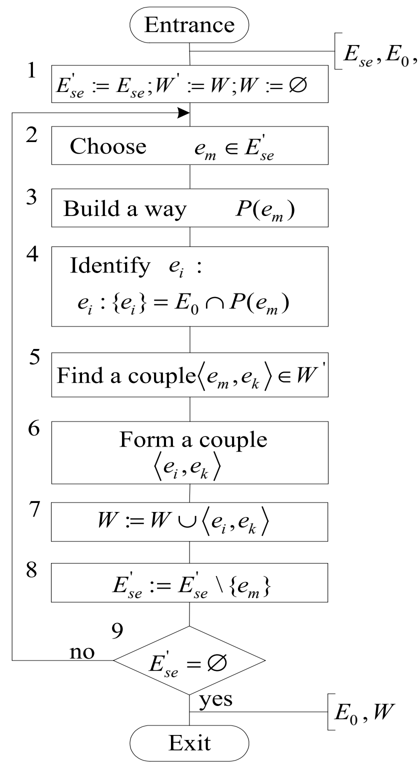

Fig. 5. The algorithm for forming the set (relation) W

According to this scheme, algorithm No. 2 can be executed repeatedly, until the redundancy of the initial set E_0 is eliminated (theoretically, a situation is possible when algorithm No. 2 is executed once, if the initial set E_0 was straight off non-redundant).

The obtained sets E_0 and E_R are optimal in the sense that using them during the failure-recovery process modeling corresponds to the real properties of object maintainability in the greatest extent. The use of the obtained sets E_0 and E_R in the SSM ensures the best approximation of the simulated process to the actual process performed by the maintenance personnel.

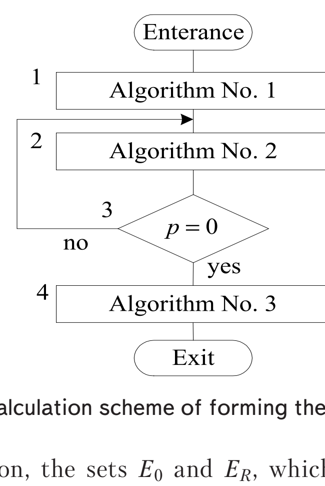

Fig. 6. The calculation scheme of forming the sets E_0 and W

In addition, the sets E_0 and E_R, which are obtained by this method are optimal from the viewpoint of minimizing the expenditure of computer time for modeling, since E_0 contains the smallest number of elements and it is complete.

Based on the developed algorithms, simulation-statistical models have been created and implemented by the program ISMPN, a brief description of which is available in [1].

6. Discussion of results: implementation of algorithms in ISMPN

Let us consider a simple example illustrating the dependence of optimal sets E_0, E_R and the predictive estimates of RI and OC on the maintainability (MA) properties of an object. For this, we will use a test object, whose constructive structure (graph G) is shown in Fig. 7.

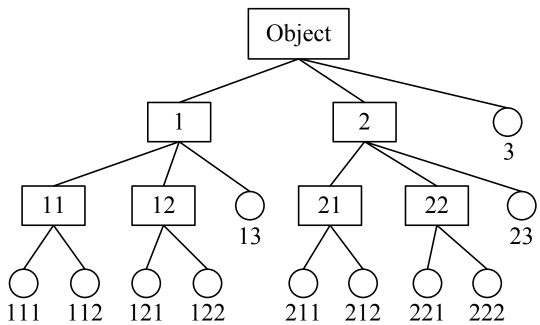

Fig. 7. Constructive structure of the test object

The calculations will be made using the program ISMPN, in the database of which you need to enter all information about the parameters of the object (1). Such object parameters are:

– $G=\langle E,R\rangle$ – graph, which determines the composition and the constructive structure of the object, where E is the set of all constructive elements of the object; R is the set of edges of the graph that determine the nesting of elements. This information was entered interactively, as shown in Fig. 8;

– $\mathrm{Re}=\left\{\left\langle T_{mean\,i}, v_i, ps_i\right\rangle, i=\overline{1,N}\right\}$ – reliability parameters, where $T_{mean\,i}$ is mean time between failures of the i-th element; v_i is the coefficient of variation of mean time between failures; ps_i is the type of structure of the i-th element (0 – single element, 1 – group of consecutively connected elements, ...). In the program ISMPN, DN-distribution is used as a model for element failures, which is considered the most adequate description of patterns of degradation processes in materials of elements of radio-electronic engineering [15];

– $\mathrm{M}=\left\{\tau_{ctc}, \tau_{st}, \left\{\tau_{sub\,i}; i=\overline{1,N}\right\}\right\}$ – maintainability parameters, where τ_{ctc} is the duration of control of technical condition of the facility; τ_{st} is the duration of troubleshooting; τ_{subi} is the replacement time of the i-th element;

– $\mathrm{C}=\left\{C_{ctc}, C_{st}, \left\{C_{sub\,i}; i=\overline{1,N}\right\}\right\}$ – cost parameters, where C_{ctc}, C_{st} and $C_{sub\,i}$ are the operating costs for monitoring the technical condition, troubleshooting and replacing the i-th element, respectively.

In addition to the object parameters, the simulation parameters $P_{\mathrm{mod}}=\left\{T_{\mathrm{E}}, N_I^{\max}\right\}$, should also be specified, where T_E is the duration of operation of the object; $N_I^{\max}$ is the number of the simulation iterations (a parameter that influences the accuracy of the received estimates of RI and OC).

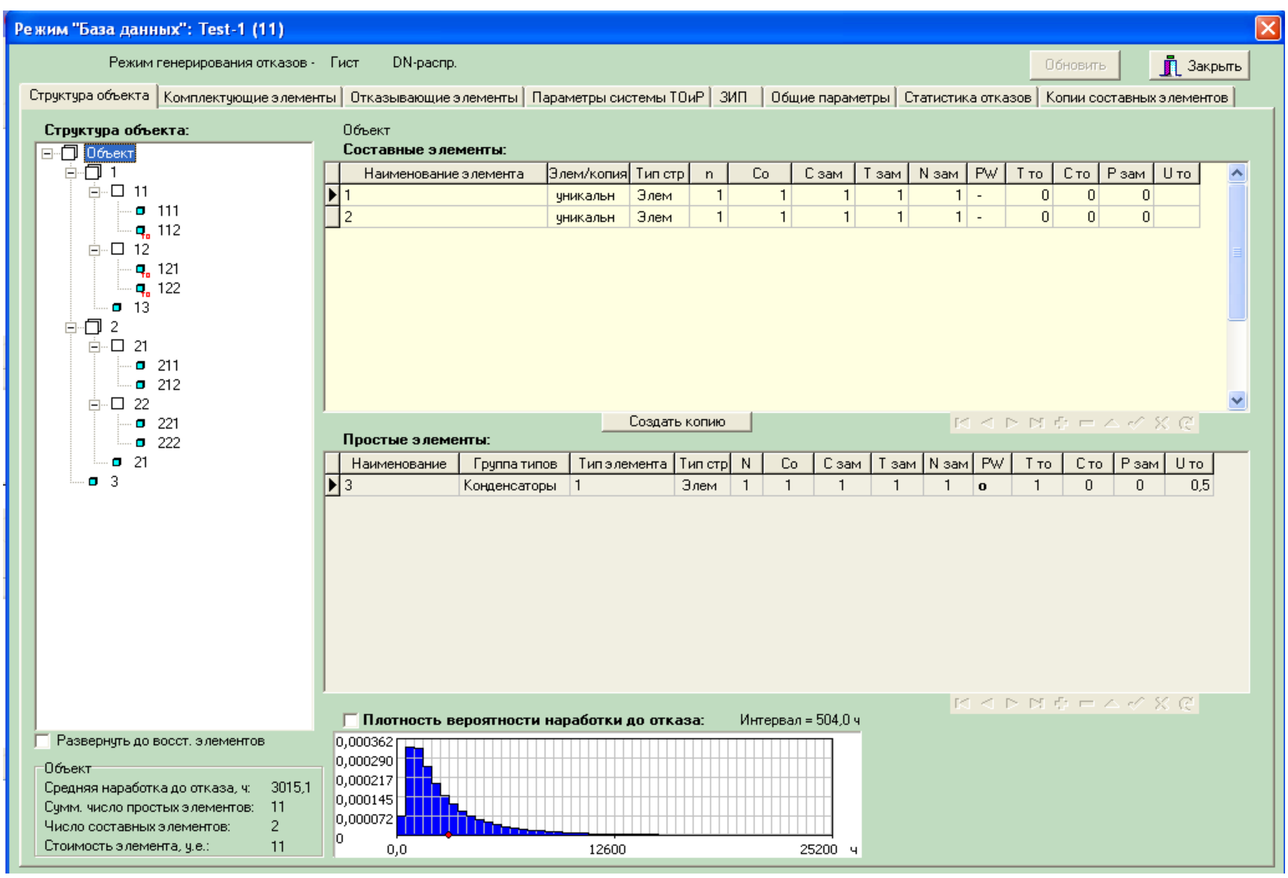

Fig. 8. The screen of the PC program ISMPN while entering the source data

Let us create a database (DB) for the test object and enter the following initial data in it:

– $T_{mean\,i}$=10000 h, v_i=1.0, ps_i=0;

– τ_{ctc}=0 h, τ_{st}=0 h, τ_{subi}=1 h (these data correspond to an ideal control system, in which the state of the object and the failed element are determined instantly);

– C_{ctc}=1 c.u., C_{st}=0 c.u., C_{subi}=1 c.u.

Let us set the following simulation parameters: T_e=10 years, $N_I^{\max}=500$.

As a result of modeling with the help of ISMPN, the predictive estimates RI and OC of the object, which are dependent on the given parameters, are obtained:

$$\tilde{T}_0=\tilde{T}_0(\mathrm{G,Re,M});\ \tilde{T}_\mathrm{R}=\tilde{T}_\mathrm{R}(\mathrm{G,Re,M});\ \tilde{c}_e=\tilde{c}_e(G,\mathrm{Re},M,C).$$

In addition to the specified point estimates, as a result of simulation at the given operation interval [0, T_e], an estimate of the function of the failure flow parameter $\tilde{\omega}(t_k)$ is formed. The PC screen after completion of the simulation with the obtained results (bottom left) and the graph of the function $\tilde{\omega}(t_k)$ (in the center) is shown in Fig. 9.

With the given initial data for the test object, the computed (in accordance with the method discussed above) set E_0 coincides with the set of all simple elements E_{se}, the set E_R coincides with E_0. As a result of simulation, for these initial data, we obtain the following predictive estimates for the PI and OC of the test object:

– mean time between failures $\tilde{T}_0=909.1$ h;

– mean time to recovery $\tilde{T}_R=1$ h;

– unit operating cost $\tilde{c}_e=0.003330$ c.u./h.

Next, we will carry out a small study to determine the effect of object maintainability on the optimal choice of the sets E_0 and E_R on the predictive estimates of RI and OC of the object. We will change the property of maintainability of the object (by changing τ_{subi} for a part of the elements), to determine, taking into account these changes, the optimal sets E_0 and E_R, and by modeling to determine the predictive estimates of RI and OC for the new sets E_0 and E_R.

Let us consider three options for setting the initial data about the maintainability of the object, with each subsequent variant corresponding to improved properties of maintainability. The constructive structures of the object are shown in Fig. 10.

Option No. 1. For the element '11', we set the average replacement time τ_{sub11}=0.5 h, for the remaining elements, the values τ_{subi} remain the same. With this change, the calculated set E_0 should be as shown in Fig. 10, *a* (the elements belonging to E_0 are shaded). Element '11' is both failing and recoverable. Let us enter the appropriate changes in the database (we set the sign of the failing element for the element '11'), restart the ISMPN program in the simulation mode and get the predictive estimations of the object RI and OC. The results are shown in Table 1 (option 1).

Option No. 2. Let us continue the changes improving the property of the object MA – set the value of τ_{sub1}=0.8 h. for the element '1'. Then we enter these changes into the ISMPN database, perform calculations and verify that the calculated sets E_0 and E_R exactly correspond to those, which are shown in Fig. 10, *b*. Element '11' still remains simultaneously both failing and recoverable.

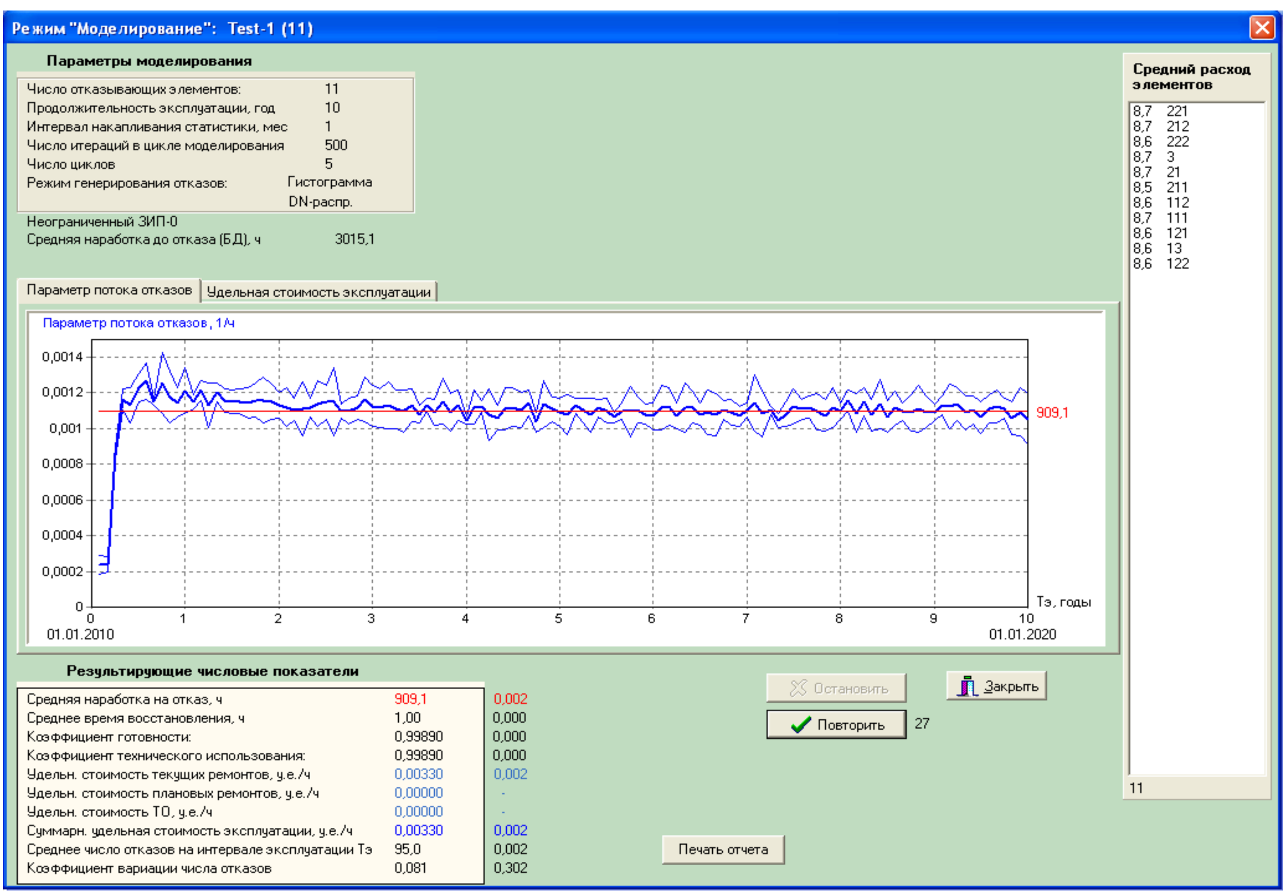

Fig. 9. The PC screen after the simulation process is completed

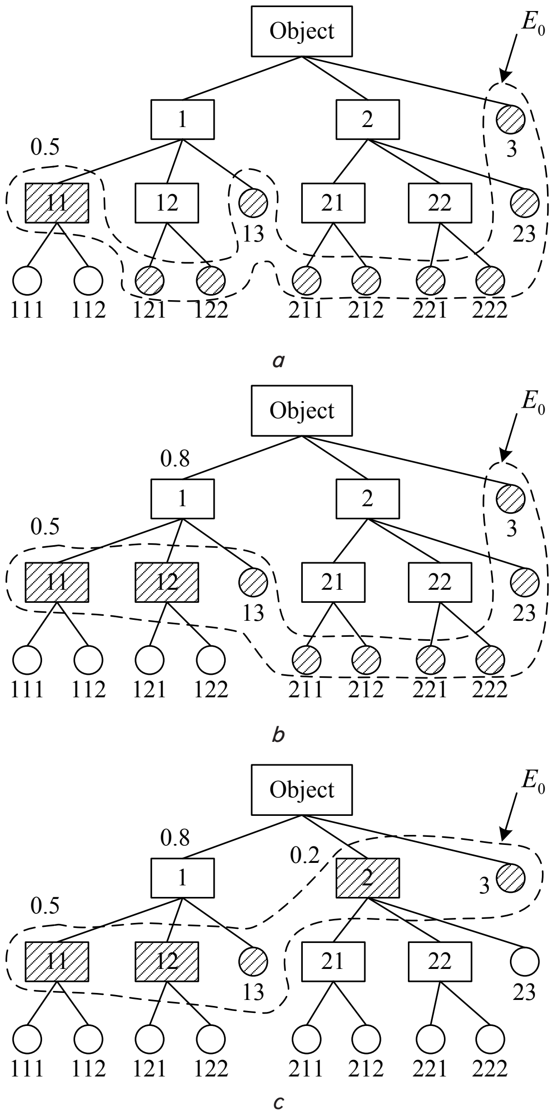

Fig. 10. Examples of obtaining a different calculated (optimal) set E_0, with various options of setting the values of time of elements replacement:
a – Option No. 1; *b* – Option No. 2; *c* – Option No. 3

For the elements '12' and '13', the element to be restored is the element '1'. The other simple elements: '211', '212', ..., are both failing and recoverable. Run the ISMPN program in the simulation mode and get new estimates of RI and OC. The results are presented in Table 1 (option 2).

Option No. 3. In addition to the previously made changes, we also set the value of τ_{sub2}=0.2 h (and enter the corresponding changes in the database) for the element '2' (for example). In view of this change, the calculated set of failing elements E_0 should be as shown in Fig. 10, *c*. Element '2' in this case becomes both a failing and recoverable one. We will make the appropriate changes to the database, re-run the ISMPN program in the simulation mode to get the new results presented in Table 1 (option 3).

7. Conclusions

To predict the reliability and operating costs of a complex technical object at the stage of its design or modernization, we propose the approach based on the reduction (enlargement) of the set of failing elements E_0, which are taken into account in the calculation of reliability indicators. To this end, a methodology for determining the optimal sets of failing and recoverable elements of a complex technical object was developed. The methodology is based on the hierarchical constructive structure of the object, takes into account the redundancy of failing elements, as well as the maintainability of the product elements and their cost, which distinguishes this methodology from the known ones.

Structurally, the methodology is implemented as a set of three algorithms:

– the algorithm for the preliminary formation of the set of failing elements E_0 and the set of correspondences between the failing and recoverable elements *W*;

– the algorithm for eliminating the possible redundancy of the set E_0;

– the algorithm for the final formation of the set *W*, whereas the set of all recoverable elements E_R being formed implicitly through the set (relation) *W*.

In order to confirm the reliability of the developed methods and algorithms, computer simulation was performed using the software product ISMPN. The obtained results confirm the influence of the object maintainability parameters on the calculated (optimal) sets E_0 and E_R, and on the predictive estimates RI and OC of the object: with the improvement of the maintainability property, the predicted values of the indicators T_0 and T_R are correspondingly improved. Improvement of the indicator c_e is not mandatory; provided different input data, there may not be such an improvement.

It is practically confirmed that each variant of the values of the object maintainability parameters corresponds to "their" optimal sets E_0 and E_R at which adequate predictive estimates of the object RI and OC are provided.

Table 1

The results of calculations of the sets E_0, E_R and the predictive estimates of RI and OC of the test object

Number of option	Object maintainability parameter changes	The set E_0 (the number of elements)	RI and OC of the test object		
			$\tilde{T}_0$, h	$\tilde{T}_R$, h	$\tilde{c}_e$, c.u./h
0	$\tau_{subi}=1$ h $(\forall i)$	$\lvert E_0\rvert=11$	909.1	1.0	0.00330
1	$\tau_{sub11}=0.5$ h	$\lvert E_0\rvert=10$	960.1	0.93	0.00320
2	$\tau_{sub11}=0.5$ h, $\tau_{sub1}=0.8$ h	$\lvert E_0\rvert=9$	1062.3	0.89	0.00373
3	$\tau_{sub11}=0.5$ h, $\tau_{sub1}=0.8$ h, $\tau_{sub2}=0.2$ h	$\lvert E_0\rvert=5$	1504.7	0.57	0.00361

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