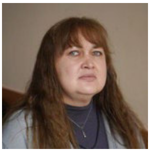
https://doi.org/10.31713/m1322

DEVELOPMENT OF A MODEL OF FAILURE RELATIONSHIPS FOR COMPLEX TECHNICAL FACILITY FOR RESOURCE-SAVING TECHNOLOGIES FOR MINING AND PROCESSING OF MINERALS



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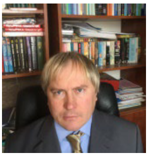

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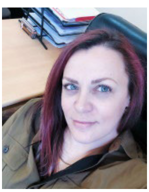

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Annotation

Complex technical objects in modern society are extremely important. Such objects belong to the class of recoverable objects of long-term multiple used. They tend to be expensive and require significant maintenance costs. To ensure the required level of reliability during their operation, maintenance is usually carried out, the essence of which is the timely preventive replacement of elements that are in a pre-failure state, which is very important for military equipment.

The problem is that when developing such objects of military equipment, all issues related to maintainability and maintenance should be addressed already at the early stages of designing an 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 "embed" the maintenance technology into the object, then it will not be possible to realize in the future a possible gain in the reliability of the object due to the maintenance. Since all these issues must be resolved at the stage of creating an 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 the object due to maintenance, to estimate the cost costs required for this. In this paper, we develop a methodology for optimizing the parameters of the strategy for regulated maintenance of military equipment.

Keywords: maintenance, object of military equipment, regulated maintenance of military equipment, costs for the cost military equipment

Model of failure-free operation of a non-recoverable object.

The model being developed is intended to obtain probability functions of failure-free operation $P(t)$ (or time-to-failure $F(t)$=1-$P(t)$ distribution functions) for the object as a whole and all its structural elements based on the available information on the failure-free performance of component elements. The functions $P(t)$ and $F(t)$ indicators of the reliability of non-recoverable objects, therefore we will call the model the model of failure-free operation (MF) of a non-recoverable object.

The structural structure of a complex technical object is almost always hierarchical. Elements belonging to different design levels can be called, for example, units (cabinets), devices (blocks), nodes (boards), etc. In this case, an object can consist of units, units - of devices, devices - of nodes, etc.

Let us denote E_{ijk}^{u} k-th element of u-th structural level, which is part of j-th element of (u-1) level. The index ij-k in this case indicates a chain of numbers elements of higher levels (including this one) in the sequence of their occurrence in elements of previous (higher) levels. Numbering of levels starts from the top, starting from the object level (u=0). The numbering of u-th level elements included in (u-1)-th level element is independent within this element. Thus, the number of numbers in the lower index is always equal to the value of the upper index u-the number of design level.

The object as a whole is treated as a level zero element E^0. It is always unique and is not included in any other elements. In figure 1 shows a fragment of the hierarchical structural structure of the object.

Each structural element of some u-th level E^{u}_{ijk} can include structural elements of next (u+1)-th level E^{u+1}_{ijkr} . In fig. 1, elements of the lower level are indicated by circles, all other elements are indicated by rectangles.

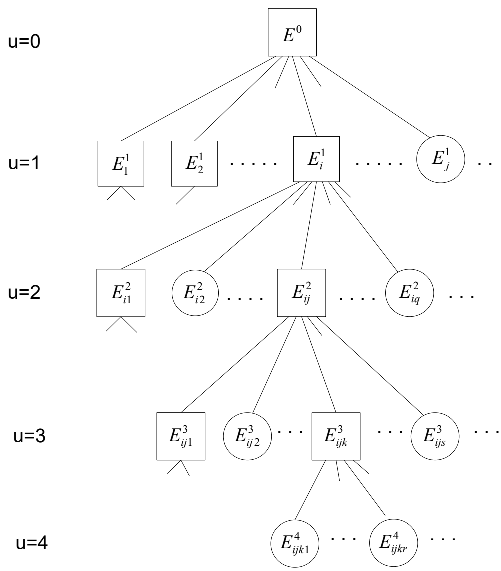

Fig. 1. Fragment of the hierarchical structural structure of the object

We will use the term structural element in the case when it is necessary to pay attention to the place occupied in the structural structure of an object. Structural elements of the lower level, following the terminology adopted in [1], we will agree to call zero-rank products (ZRP). An ZRP can be either a very complex device or consist of a single simplest element (for example, a resistor, microcircuit, transformer, bearing, etc.). ZRP is an inseparable element and is always considered as one whole.

We will formally represent the constructive structure of an object as a hierarchical list structure. Each structural element $E^{u}_{ij\ldots r}$ is treated as a list

$$E^{u}_{ij\ldots r} = \{E^{u+1}_{ij\ldots r0}, E^{u+1}_{ij\ldots r1}, \ldots, E^{u+1}_{ij\ldots rs}, \ldots\};\ s = \overline{0,\left|E^{u}_{ij\ldots r}\right|};\ u = \overline{0,U}, \quad (1)$$

where $E^{u+1}_{ij\ldots rs}$ - is (u+1)-level element included in the element $E^{u}_{ij\ldots r}$;
U - maximum level (nesting) of structural elements for a given RET object.

The object as a whole is represented by a list of 1-st level elements

$$E^{0} = \{E^{1}_{0}, E^{1}_{1}, \ldots, E^{1}_{i}, \ldots\};\ i = \overline{0,\left|E^{0}\right|}. \quad (2)$$

ZRP elements are represented as empty lists.

The set of all nested lists of the form (1) represents a mathematical model of the constructive structure of an object.

The reliability structure of an object can be an arbitrary series-parallel structure. This means that each structural element $E^{u}_{ij\ldots k}$ can be either an ZRP-element, or represent a series connection of its constituent elements, or be a redundant group of elements - a group of elements connected in parallel in the sense of reliability. Elements of a reserved group can only be elements of the same type. Reservations in groups can be loaded (permanent) or unloaded (replacement).

If an element $E^{u}_{ij\ldots k}$ consists of series-connected elements of (u+1) level, then the probability of failure-free operation of this element is defined as the product

$$P(t / E^{u}_{ij\ldots k}) = \prod_{\forall E^{u+1}_{ij\ldots kr} \in E^{u}_{ij\ldots k}} P(t / E^{u+1}_{ij\ldots kr}), \quad (3)$$

where r - is the number of (u+1)-level element $E^{u+1}_{ij\ldots kr}$ included in u-th level element $E^{u}_{ij\ldots k}$;

$P(t/E^{u+1}_{ij...kr})$ - probability of failure-free operation elements $E^{u+1}_{ij...kr}$.

If an element $E^{u}_{ij...k}$ is a redundant group consisting of *n* identical elements $E^{u+1}_{ij...k0}$ connected in parallel, then in the case of a constant reserve the probability of failure-free operation for it is equal to [2]

$$P(t/E^{u}_{ij...k}) = 1 - [1 - P(t/E^{u+1}_{ij...k0})]^{n}. \qquad (4)$$

The model does not take into account the possibility of multiple failures, since within the framework of the tasks for which this model is developed, the probability of multiple failures can be neglected.

From what has been considered, it is clear that the initial information for the model should be the probability functions of failure-free operation of ZRP *P*(*t/e*) (e_m - designation of an arbitrary ZRP). For all structural elements of higher levels, including the object as a whole, functions $P(t/E^{u}_{ij...r})$ must be calculated.

In practice, functions $P(t/e_m)$ are rarely known exactly. At best, the first two moments are known and there are certain assumptions about the class of distribution laws to which the function $P(t/e_m)$ may belong. As a rule, only the estimate of the first moment (the mathematical expectation of time to failure) is known. In the worst case, neither the distribution function nor its moments are known. Therefore, in practice, one has to make an assumption about the form of the distribution law, taking into account the type of a given element and the available information about the physical laws of failure for elements of this type. The average time to failure of elements must be estimated based on information about analogue-elements.

The model being developed is intended to solve problems of assessing the reliability of aging objects, so we need to use the laws of time-to-failure distribution that take into account degradation processes in materials of different types of elements. Failures generated by various degradation processes are usually called gradual [5, 6]. It has now become generally accepted that gradual failures occur due to the fact that the value of some defining parameter reaches the maximum permissible value. Failure models based on the concept of a defining parameter are usually called probabilistic-physical (*WF*-models) [6,8].

The most universal model of gradual failures is the diffusion nonmonotonic distribution (*DN*-distribution) [6].

For *DN*-distribution, the probability density has the following form

$$f(t)=f(t;\mu,\nu)=\frac{\sqrt{\mu}}{\nu t\sqrt{2\pi t}}\exp\left(-\frac{(t-\mu)^2}{2\nu^2\mu t}\right), \tag{5}$$

where μ - is the scale parameter (mean time to failure);

ν- coefficient of variation.

The density function (5) corresponds to the integral function of *DN*-distribution

$$F(t)=DN(t;\mu,\nu)=\Phi\left(\frac{t-\mu}{\nu\sqrt{\mu t}}\right)+\exp\left(\frac{2}{\nu^2}\right)\Phi\left(-\frac{t+\mu}{\nu\sqrt{\mu t}}\right)=$$

$$=\Phi\left(\frac{at-1}{\nu\sqrt{at}}\right)+\exp\left(\frac{2}{\nu^2}\right)\Phi\left(-\frac{at+1}{\nu\sqrt{at}}\right) \tag{6}$$

where $\Phi(z)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{z}\exp\left(-\frac{x^2}{2}\right)dx$ - is the normalized normal distribution;

a - average rate of the degradation process (average rate of change of the defining parameter), equal *t a*=1/μ.

DN-distribution has one important property, which is that the coefficient of variation of the distribution of time to failure coincides with the coefficient of variation of the distribution of the random variable of the determining parameter. This property, combined with the fact that the mean time to failure is equal to the reciprocal of the mean degradation rate of the governing parameter, opens up great opportunities for the use of *DN*-distribution in maintenance modeling problems.

The universality of *DN*-distribution lies in the fact that its coefficient of variation (shape parameter) practically coincides with the shape parameters of *DN*-distribution and is approximately equal to the inverse value of the shape parameter of Weibull distribution and alpha distribution [6]. This makes it possible to use *DN*-distribution as a model of failures of elements of various types that have different physical mechanisms of degradation processes. To ensure the adequacy of the failure model, it is enough to correctly set the value of the coefficient of variation. Recommendations for choosing the coefficient of variation are given in [8]. In table 1 shows some data taken from [8] on the characteristic values of the coefficient of variation.

Table 1

Generalized estimates of the coefficients variation various physical processes

Type of degradation process	Coefficient of variations destruction process	Name of elements undergoing destruction
Fatigue (high-cycle)	0,40–1,00	Housing parts, rolling bearings, shafts, axles, springs, connecting rods, bolts, etc.
Wear (mechanical-chemical)	0,20–0,50	Sliding bearings, shafts, axles, guides, bushings, etc.
Aging	0,40–1,00	Elements and parts made of metals, polymers, rubber products, seals, semiconductors, etc.
Electrical (electrolysis, charge migration, electrodiffusion)	0,70–1,50	Semiconductor devices, integrated circuits, capacitors and other electronic products.

The choice of a numerical value of the coefficient of variation from the specified range in each specific case can be carried out taking into account the following general considerations: the greater the average ratio of load to endurance limit (strength), the lower the coefficient of variation, and vice versa, that is, the lower the loading coefficient, the higher coefficient of variation.

Taking into account everything considered as a failure model for all structural elements and the object as a whole, we choose *WF*-model of *DN*- distribution. The initial information for MB in this case is the set of pairs of parameters $\langle \mu_{i,} \nu_i \rangle$ of all elements-ZRP. Based on this information, the corresponding parameters for all other structural elements of higher levels must be calculated.

In [8] it is proved that if a system consists of elements whose failures are subject to *DN*-distribution, then the failures of the system are also subject to the DN distribution. The parameters of *DN*-distribution of system time to failure (scale parameter μ and shape parameter ν), depending on the method of reliable connection of elements in the system, are calculated using the following formulas.

Calculation formulas for determining the scale μ parameter and shape parameter for structural elements of higher levels (not ZRP):

Series connection of different types of elements

$$\mu = 1 \Big/ \sqrt{\sum_{i=1}^{N} \frac{n_i}{\mu_i^2}} \; ; \tag{7}$$

$$\nu = \sqrt{\sum_{i=1}^{N} \frac{n_i \nu_i^2}{\mu_i^2}} \Big/ \sqrt{\sum_{i=1}^{N} \frac{n_i}{\mu_i^2}} \; , \tag{8}$$

where n_i - is the number of elements i-th type;

μ_i - scale parameter *DN*-distribution of time to failure of elements i-th type (average time to failure of elements i-th type);

ν_i - parameter of form *DN*-distribution of time to failure elements i-th type (variation coefficient);

N - is the number of element types in system.

Series connection of identical elements

$$\mu = \mu_0 / \sqrt{n} \; ; \tag{9}$$

$$\nu = \nu_0 \, , \tag{10}$$

where μ_0 - is the scale parameter of *DN*-distribution of elements included in the system (average time to failure of one element);

n - is the number of identical elements in the system.

Loaded (permanent) reservation

$$\mu = \mu_0 \sqrt{n} \; ; \tag{11}$$

$$\nu = \nu_0 / \sqrt{n} \; . \tag{12}$$

Unloaded (replacement) reservation

$$\mu = \mu_0 n \; ; \tag{13}$$

$$\nu = \nu_0 / \sqrt{n} \; . \tag{14}$$

The formal descriptions of the structural and reliability structures of an object introduced above, the expression for probability of failure of an object (or element) $F(t)$ (6) and the calculation expressions (7)-(14) together represent a mathematical model of the failure-free operation of a non-repairable object.

The prototype of the considered MB can be considered the model described in [6]. The main difference between MB and the prototype is use of the important property of *DN*-distribution to preserve the type of distribution when transforming the reliability structure of structural elements (when moving from a sequential structure to a parallel one, and vice versa).

Model of failure-free operation of a restored object.

In previous section, MB was developed for the case when an object is considered unrecoverable. In the developed model

a - hierarchical structural structure of the object is represented;

b - reliability structure is determined by specifying the redundant group attribute for each structural element;

c - automatic (software) calculation of the parameters *DN*-distribution of time to failure is carried out for each elements of object.

Thus, MB contains all the necessary information for modeling failures of any of the structural elements of the object.

However, this is not enough for IMS, in which maintenance processes must be modeled. For IMS, it is necessary to indicate specific elements whose failures and recovery should be modeled.

Let us introduce the concept of a set recoverable elements $E_в$ as follows. The set $E_в$ must include structural elements that will be replaced in case of failure of the object. The set $E_в$ includes the most repairable elements, that is, elements whose replacement time is minimal, these are the so-called standard replacement elements (SRE). The set $E_в$ must satisfy the requirements of completeness and non-redundancy.

The completeness requirement is that the set must include all elements whose failures can lead to the failure of the object. Formally, the requirement of completeness is ensured by the following condition: there should not be a single path between the root of the tree (object) and the hanging node (INR element) that does not contain an element belonging to set $E_в$ (such an element must be unique).

The nonredundancy requirement is that set $E_в$ must not contain more than one element that belongs to the path between the root of tree and any hanging node.

With this definition of set $E_в$ and with the previously accepted assumption about the sequential reliable connection of structural elements, the probability of failure-free operation of the object is equal to

$$P(t)=\prod_{i\in E_{\text{в}}}[1-F_i(t)], \qquad (15)$$

where $F_i(t)$- is the probability of failure i-th element from set $.E_в$

The probability $P(t)$ does not depend on the choice of set $.E_в$

In the same way, value of $E_в$ average time to failure does not depend on

$$T_{\text{ср}}=\int_0^{\infty}P(t)dt\,. \qquad (16)$$

If an object is considered as recoverable, then the failure flow parameter $\omega(t)$ and average time between failures should be used as indicators of failure T_0 [7].

When connecting elements in series, the failure flow parameter is defined as the sum

$$\omega(t)=\sum_{i\in E_{\text{в}}}\omega_i(t)\,, \qquad (17)$$

where $\omega_i(t)$ - is failure flow parameter of i-th element from the set $E_в$.

The failure flow parameter of i-th element $\omega_i(t)$ is found as a solution to the integral equation of the following form [7]:

$$\omega_i(t)=f_i(t)+\int_0^t f_i(t-x)\omega_i(x)\,dx\,. \qquad (18)$$

where $f_i(t)$ - is the probability density of failure of i-th element ($i\in E_в$).

The failure flow parameter always has a steady-state value

$$\omega^{\infty}=\lim_{t\to\infty}\omega(t)\,.$$

In this case, the average time between failures of the object is equal to $T_0=1/\omega^{\infty}$.

For real technical objects, within the operating period of interest to the user T_0, the steady-state value of the failure flow parameter may not occur. In this case, the average time to failure of an object is determined by the formula:

$$T_0=T_0(T_э)=1\Big/\frac{1}{T_э}\int_0^{T_э}\omega(t)dt\,. \qquad (19)$$

The value T_0 (in contrast to T_{cp}) significantly depends on the choice of set $E_в$. The higher the average level of elements included in $E_в$, greater the value. This is easily explained, since when larger structural elements are replaced, a larger number of serviceable elements are simultaneously updated. Consequently, the higher the structural level of the restored elements (lower the level number u), the greater proportion of elements that are updated after ongoing repairs, which leads to an increase in the indicator T_0.

Model database.

For software implementation of MB and ensuring its application for real technical objects, a database (DB) is required in which information about the object (composition, structural and reliability structure, failure-free performance indicators of ZRP, etc.) could be stored. As is known, information in the database is presented in the form of tables [4]. The following tables were created in the developed database for MB:

- tbEu tables - contain information about the structural elements of an object at level u. The number of tables tbEu is equal to the maximum number of levels of structural elements that can be represented in database: tbE1 - for 1-st level elements included in object, tbKE2 - 2-nd level elements included in 1-st level elements, etc.d. One table entry contains information about one u-level structural element.

- tables tbKEu - contain information about elements that are ZRP and related to the design level u : tbKE1 - ZRP included directly in the object; tbKE2 - ZRP included directly in the structural elements of the 1st level; tbKE3 - ZRP included directly in the structural elements of the 2nd level, etc. One record contains information about one element - u-level ZRP. The number of tbKEu u tables is equal to the number of tbKEu tables plus one;

- table tbTipKE – contains information about the types of component elements - ZRP and their reliability indicators (information is taken from reference books and product passports);

- tbGTipKE – contains information about groups of ZRP types. Type groups were introduced for convenience of working with the database;

- tbSprav – table containing a list of reference books from which information about the reliability indicators of ZRP was taken.

In table 2-6 shows the structure of these tables. Only information that is directly used by MB is indicated.

Table 2

Structure of tbEu tables (parameters of structural elements)

Field name	Data type	Key attribute	Field purpose
i1	INTEGER	*	Structural element code
I2	INTEGER		Code of the “higher” level structural element that includes this element
NAME	VARCHAR		Element name
PZ	CHAR(1)		Restoration attribute (0 – attribute is not defined; 1 – element is restored (replaced) in case of failures; 2 – element is replaced and serviced during maintenance
TG	CHAR(1)		Type of connection in the group (0 – separate element; 1 – serial connection; 2 – loaded reserve; 3 – unloaded reserve)
N	INTEGER		Number of elements in the group.
. . . .	. . . .		. . . .

Table 3

Structure of tbKEu tables (parameters of elements - ZRP)

Field name	Data type	Key attribute	Field purpose
Kod	INTEGER	*	Element code – ZRP
I2	INTEGER		Code of the “senior” level structural element that includes this element
NAME	VARCHAR		Item name
KOD_GTIP	INTEGER		ZRP type group code
KOD_TIP	INTEGER		ZRP type code
N	INTEGER		The purpose of the fields is the same as tblEu table fields of the same name
PZ	CHAR(1)		
TG	CHAR(1)		
. . . .	. . . .		

Table 4

Structure of tbGTipKE table (ZRP type groups)

Field name	Data type	Key attribute	Field purpose
Kod_GTipKE	INTEGER	*	ZRP type group code
name	VARCHAR		Name of the group ZRP types

Table 5

Structure of tbTipKE table (ZRP reliability indicators)

Field name	Data type	Key attribute	Field purpose
Kod_TipKE	INTEGER	*	ZRP type code
Kod_GTipKE	INTEGER		ZRP type group code
name	VARCHAR		Element type name
Mu	FLOAT		Average time to failure, h
Nu	FLOAT		The coefficient of variation
z	INTEGER		Distribution law code
Kod_Sprav	INTEGER		Directory code - source of information

Table 6

Structure of tbSprav table (list of reference books)

Field name	Data type	Key attribute	Field purpose
Kod_Sprav	INTEGER	*	Directory code
name	VARCHAR		Name

Relationships of "master-slave" type have been created between the database tables (they are also called "one-to-many" relationships). In fig. 2. shows a diagram of connections "master-slave" type between the tables tbEu and tbKEu.

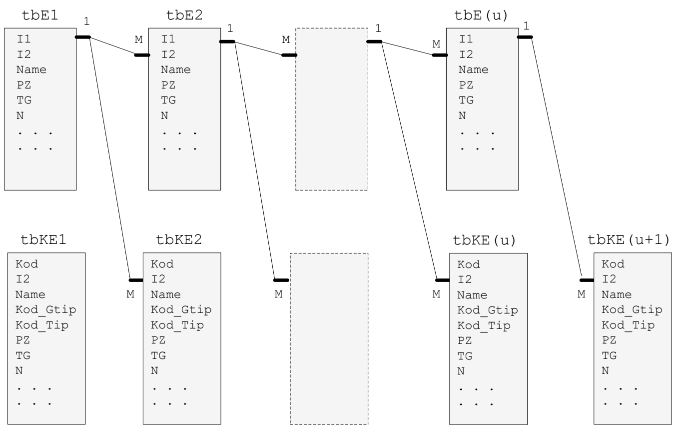

Fig. 2. Master-slave relationships between tables tbEu and tbKEu

A 1:M relationship means that one record in the main table corresponds to 0 or more records in the slave table. For example, tables tbE2 and tbKE2 are subordinate to table tbE1. The link key in subtables tbEu and tbKEu is the key field I2.

Relationships between tables are created to ensure data integrity as well as ease of data management. The linked records in table tbE2 contain data about the 2nd level structural elements that are part of the 1st level structural element, the data for which is contained in the linked record in table tbE1. In the same way, the related records of table tbKE2 contain data on ZRP, which are elements of 2-nd level and are parts same structural element of 1-st level.

Thanks to the presence of relationships in subordinate tables, it is easy to find only those records that are related to the current, currently selected record in the main table.

Connections were also created between the tables tbGTipKE and tbTipKE and between tbSprav and tbTipKE (fig. 3).

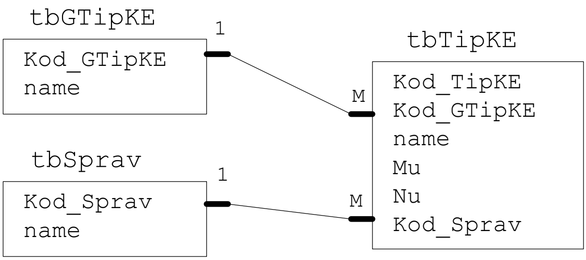

Fig. 3. Diagram of relationships between tables tbGTipKE, tbSprav and tbTipKE

One record in tbGTipKE table (one group of types) can correspond to 0 or more records in tbGTipKE table (0 or more ZRP types). In the same way, one record in tbKEu table (one directory) can correspond to 0 or more records in the tbTipKE table (data of the same ZRP type is always taken from one directory).

There are also M:1 type connections between tbKEu tables and tbTipKE table (not shown in the figures). The communication keys here are Kod_Tip and Kod_TipKE fields. Using this connection, each ZRP presented in tbKEu table is associated with a single entry in tbTipKE table, containing information about the reliability parameters of an element of this type.

Thus, the constructive structure of an object in the database is represented by placing data on elements of various levels in various tables and creating appropriate connections between the tables. Information about the reliability structure of structural elements is presented using the TG field (group type), which is available in tbEu and tbKEu tables.

A brief description of MB database, as well as information on possible ways to improve it, is given [5].

Reliability model user interface.

The MB is implemented in such a way that when the software is launched, all data structures used in the model are immediately (automatically) created in the PC OS and become available to other models. At the same time, indicators of the reliability of the object and all its elements are immediately formed.

In the “Database” mode, it is possible to create a database and correct previously entered information. The PC screen view in this mode is shown in fig. 5.

The left side of the screen displays the object's structural structure tree. In this tree, you can collapse or expand the internal structure of any of the elements. When you select (by clicking) any of the elements in this tree, the tables located on the right display information about elements that make up selected element. The top table displays data about the constituent structural elements that make up the selected element. The lower table displays data on ZRP that is directly included in the selected element. You can edit the data in these tables.

At the bottom left (under the tree) a panel with data is displayed:

- average time to failure of the selected element (*h*);
- cost of element (c.u);
- number of structural elements included in the selected element;
- total number of ZRP -elements in the selected element.

At the bottom of the screen (under the tables) a histogram of the density *DN*-distribution of the selected element is displayed.

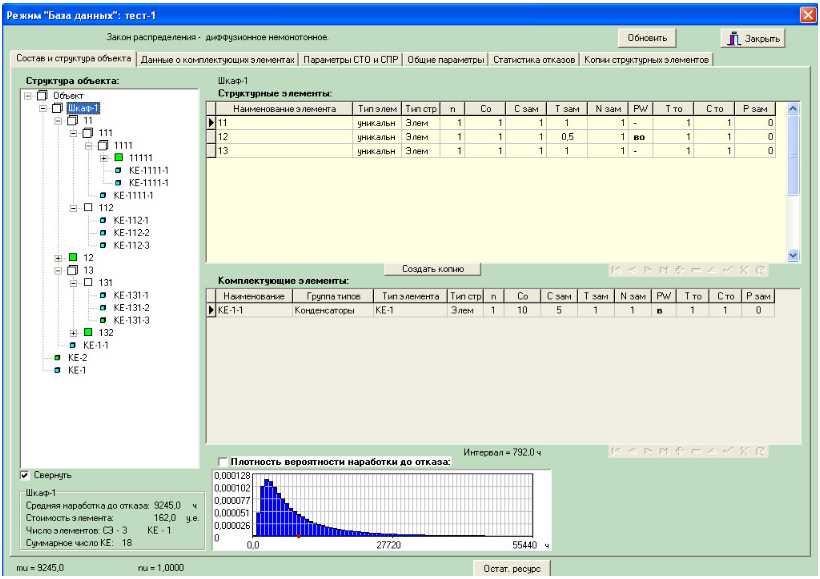

Fig. 4. PC screen view in "Database" mode

Examples of using the model for test objects.

To verify and study the developed models and methods, test objects with different structures and reliability were used. The characteristics of test objects are selected in such a way as to cover all typical cases of possible real objects encountered in practice. Using test objects, the following sections demonstrate the application features of the developed models and their capabilities. This section provides the main characteristics of the test objects, as well as the simulation results obtained for them using MB software.

The Test-1 object is an example of the simplest object that has a consistent reliability structure and a design structure with 6 nesting levels (fig. 5). It consists of 20 elements- ZRP, which are part of other structural elements of higher levels. ZRP elements are indicated by circles. All ZRP have the same reliability characteristics: T_{cp}=20,000 h; ν=1. Elements included in the set $E_в$ are marked with shading.

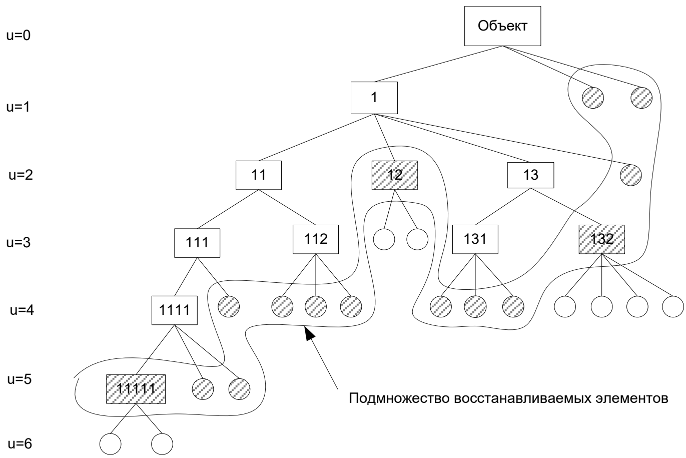

Fig. 5. Constructive structure of the Test-1 object

Object Test-2 is an example of a low-reliability object that uses redundancy to improve reliability. The structural structure of the object is shown in fig. 5. The three least reliable elements have reserve: 11 (n=3), 12 (n=3) and 131 (n=2). All other elements represent a sequence (in terms of reliability) of all the elements included in them. The total number of ZRP is 900. Elements included in the set of restored elements $E_в$ are also marked with shading.

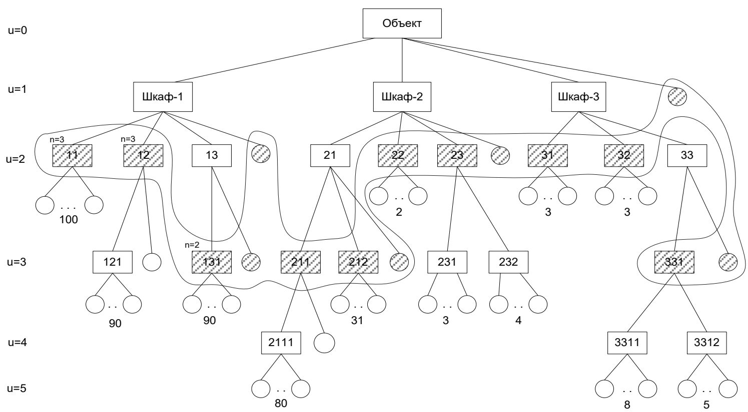

Fig. 6. Constructive structure of the Test-2 object

Objects Test-3 and Test-4 are examples of objects that have a single-level structural structure (fig. 7). 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 single-level, all elements are ZRP, and all of them are restored.

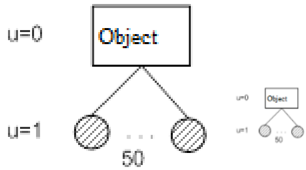

Fig. 7. Constructive structure of objects Test-3 and Test-4

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

In table 7 presents the main characteristics of the test Characteristics of test objects

Object	Number of INR	Number of restored elements	Average time to failure, h	Variation coefficient
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

The values of reliability indicators given in the table (mean time to failure and coefficient of variation) are generated automatically when DB program is launched and are displayed on PC screen (fig. 4). For Test-2 object, the resulting coefficient of variation is not equal to 1 due to the presence of reserved groups elements in the object.

The most important characteristic of an object that affects the operational reliability and cost of object is the distribution of object's failure-free performance indicators among its elements. In fig. 8

shows histograms of the distribution of the average time to failure of elements test objects. The grouping intervals are shown horizontally, and the number of elements in the intervals are shown vertically.

The histograms shown in the figures were generated using model software in “Database” mode.

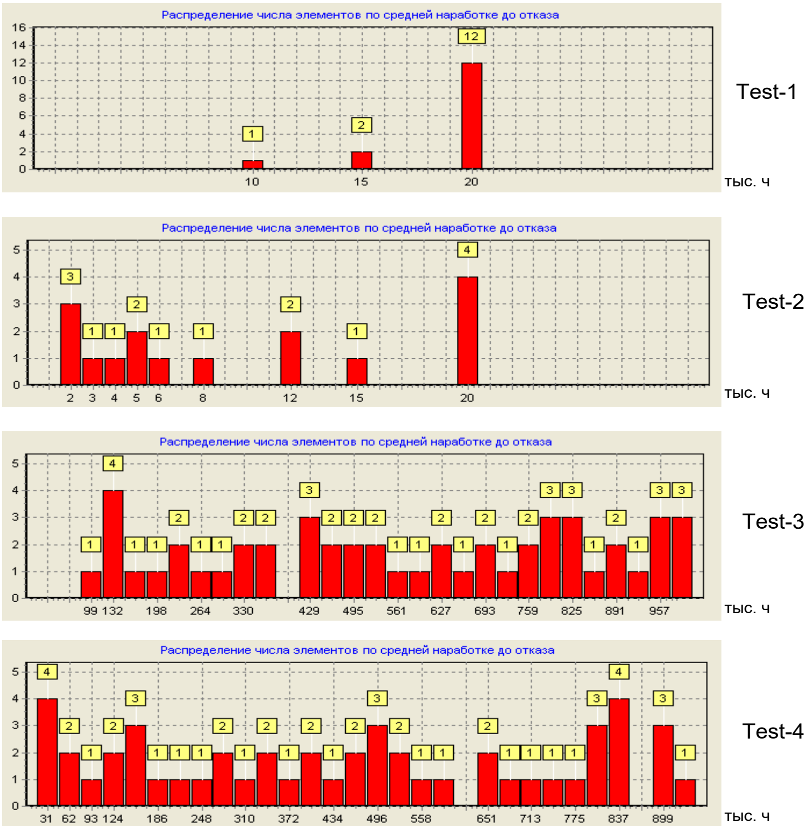

Fig. 8. Histograms of distribution of average time to failure of restored elements of test objects

Conclusions

1. The reliability model (RM) allows you to obtain estimates of the reliability indicators (RI) of individual structural elements and the object as a whole based on information about RI of elements of

the lower structural level. The RM represents the hierarchical structural structure of the object. Structural elements of some u-th structural level are a sequential (in the sense of reliability) connection of its constituent elements of (u+1)-th level. Individual structural elements can be a redundant group (parallel connection) of similar elements. Thus, with the help of RM, the representation of a hierarchical structural structure is combined with an arbitrary serial-parallel reliability structure of an object, which is an acceptable representation for most technical objects encountered in practice.

2. The *DN*-distribution is used as a failure model for all elements and the object as a whole. The *DN*-distribution is considered an adequate gradual failure model for both electronic products and various mechanical components and elements. An important advantage of *DN*-distribution is that its appearance is preserved during transformations of the reliability structure of the system. It is this feature of *DN*-distribution that made it possible to apply it to a system with a hierarchical structure.

3. The software implementation of the MB was developed in Delphi programming system. The hierarchical constructive structure of an object is represented programmatically using list data structures (TList are used). The elements of the lists are objects (instances of Delphi classes) representing individual structural elements of a technical object. Such objects encapsulate all the necessary data related to individual structural elements, including the parameters of *DN*-distributions of mean time to failure.

Information about the composition, structure and reliability indicators of the object elements is stored in the model database, built using tables in the InterBase DBMS format.

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