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# DEVELOPMENT OF A RELIABILITY MODEL FOR A COMPLEX TECHNICAL OBJECT

***Complex technical objects today are of exceptional importance in modern society. First of all, we are talking about various military and special-purpose radio-electronic systems, radar stations, automated control systems (air traffic, energy facilities, etc.). The level of reliability such objects determines the defense capability of the state, economic security, and the lives of hundreds and thousands of people.***

***Such objects belong to the class of long-term, reusable, and refurbished objects. They are usually expensive and require significant costs for their operation. To ensure the required level of reliability during their operation, maintenance (MC) is usually carried out, the essence of which is the timely preventive replacement of elements that are in a pre-failure state.***

***A characteristic feature of complex technical objects for special purposes is the presence in their composition of a large number (tens, hundreds of thousands) of different types of components that have different levels of reliability, different patterns of their wear and aging processes. This feature requires a more subtle approach to the organization and planning of MC during their operation. The DN-distribution is used as a failure model for all elements and the object as a whole. The DN-distribution is considered to be an adequate model of gradual failures both for electronic products and for various mechanical units and elements. An important advantage of DN-distribution is that its appearance is preserved when transforming 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.***

***The failure-free operation model (FM) allows obtaining estimates of the failure-free operation indicators (FMI) of individual structural elements and the object as a whole based on the FMI information of the elements lower structural level. FM represents hierarchical structural structure of the object. Structural elements of a certain u-th structural level are a sequential (in terms of reliability) connection of the elements of (u+1)-th level included in it. Individual structural elements can represent a redundant group (parallel connection) of similar elements.***

***Keywords: complex technical objects, automated control systems, objects that are restored***

**Introduction.** Complex technical objects of military equipment are of exceptional importance in modern society. This primarily concerns various military and special-purpose radio-electronic systems, radar stations, automated control systems (air traffic, energy facilities, etc.). The level of reliability of such objects determines the defense capability of the state, economic security, and the lives of hundreds and thousands of people. Complex technical objects are understood to be objects consisting of a large number of different types of elements (tens, hundreds of thousands), each of which can be a fairly complex technical device. Elements can be electronic, mechanical, electromechanical, hydraulic, etc. The heterogeneity of elements leads to the fact that different elements are characterized by fundamentally different physical processes (and, consequently, rates) of degradation, leading to their failures. Objects can have an arbitrary reliability structure (usually series-parallel). The structural structure of such objects is usually hierarchical, that is, the object consists of subsystems, subsystems consist of units (cabinets), units consist of devices (blocks), etc.

**Analysis of previous studies.** The “surge” in the number of theoretical works on the issues of maintenance complex systems occurred in the 70-s of the last century, which can be explained by the mass production of complex military and special-purpose electronic equipment at that time [1-6]. Currently, there is a decline in the number of scientific publications devoted to the issues maintenance of complex technical objects. One of the reasons for this, in our opinion, is a sharp increase in the level of integration and reliability of component parts. Due to this, developers of complex equipment were able to solve the issues of ensuring required level of failure-free operation without significant costs for maintenance (or without maintenance at all). However, the same reason (high integration and reliability of component parts) opened up the possibility of implementing increasingly complex equipment with new functions, which was impossible with the old element base. This again objectively leads to problems of ensuring reliability and, therefore, the question of need for maintenance and the choice of optimal strategy for its implementation again becomes relevant.

**Main part**

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

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

Let us designate $E^u_{ijk}$ *k*-th element of *u*-th structural level, which is part of *j*-th element (*u*-1)-th level. In this case, index *ijk* indicates chain of numbers of elements higher levels (including this one) in the sequence of their inclusion in the elements of the previous (higher) levels. The numbering of levels starts from the top, starting with the object level (*u*=0). The numbering of the *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 value of the upper index *u* – number of design level.

The object as a whole is considered as a zero-level element $E^0$. It is always unique and is not included in any other elements. Fig. 1 shows a fragment of the hierarchical design structure of the object.

Each design element of a certain *u*-th level $E^u_{ijk}$ can include design elements of the next (*u*+1)-th level. In fig. 1, the lower-level elements are designated by circles, all other elements – by rectangles.

The term design element will be used when it is necessary to pay attention to the place occupied in the design structure of the object. Following the terminology adopted in [3, 8], we will agree to call the design elements of the lower level zero-rank products (ZRP). ZRP can be either a very complex device or consist of a single simple element (for example, a resistor, microcircuit, transformer, bearing, etc.). ZRP is a non-separable element and is always considered as a single whole.

We will formally represent the design structure of the object as a hierarchical list structure. Each design element $E^u_{ij\ldots r}$ is considered as a list

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

where $E^{u+1}_{ij\ldots rs}$ – is the element of (*u*+1)-th level, which is part of element $E^u_{ij\ldots r}$;

$U$ – is the 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:

$$E^0 = \{E_0^1, E_1^1, ..., E_i^1, ...\}; \; i = \overline{0, |E^0|}. \tag{2}$$

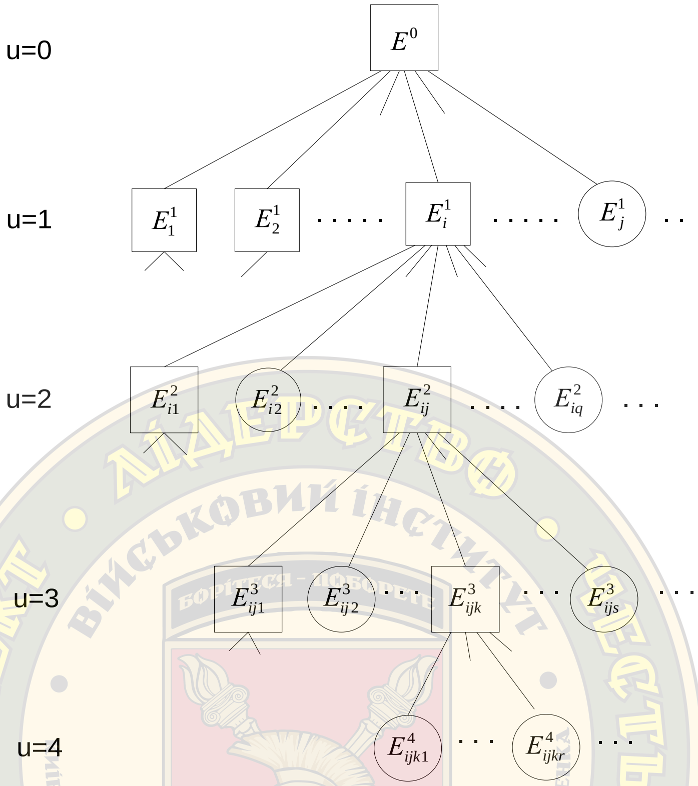


Figure 1 – Fragment of the hierarchical structural structure of the object

ZRP elements are represented by empty lists.

The set of all nested lists of the form (1) is a mathematical model of the structural structure of the object.

The reliability structure of the object can be an arbitrary series-parallel structure. This means that each structural element $E_{ij...k}^u$ can be either an ZRP element, or a series connection of its constituent elements, or a redundant group of elements – a group of elements connected in terms of reliability in parallel. Only elements of the same type can be elements of a redundant group. Redundancy in groups can be loaded (permanent) or unloaded (substitute).

If an element $E_{ij...k}^u$ consists of series-connected elements of ($u$+1)-th level, then the probability of failure-free operation of this element is determined as the product:

$$P(t / E_{ij...k}^u) = \prod_{\forall E_{ij...kr}^{u+1} \in E_{ij...k}^u} P(t / E_{ij...kr}^{u+1}), \tag{3}$$

where $r$ - number of element of the ($u$+1)-th level $E_{ij...kr}^{u+1}$, which is part of the element of $u$-th leve $E_{ij...k}^u$;

$P(t / E_{ij...kr}^{u+1})$ - probability failure-free operation of an element $E_{ij...kr}^{u+1}$.

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

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

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

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

In practice, functions $P(t/e_m)$ are rarely known exactly. In the best case, the first two moments are known and there are certain assumptions about the class of distribution laws to which the function $P(t/e_m)$ possibly belongs. As a rule, only the estimate of the first moment (the mathematical expectation of the time to failure) is known. In the worst case, neither the distribution function nor its moments are known. Therefore, in practice, it is necessary to make an assumption about the type of 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 estimate of the average time to failure of elements has to be specified based on information about analogous elements. The developed model is intended to solve the problems of assessing the reliability of aging objects, so we need to use the laws of distribution of the time to failure, taking into account the degradation processes in the materials of different types of elements. Failures caused by various degradation processes are usually called gradual [3-5]. At present, it has become generally accepted that gradual failures occur due to the fact that the value of some determining parameter reaches the maximum permissible value. Failure models based on the concept of the determining parameter are usually called probabilistic-physical (*VF*-models) [6-8].

The most universal model of gradual failures is the diffusion non-monotonic distribution (*DN*-distribution) [9].

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 $\mu$ - is the scale parameter (mean time to failure);

is $\nu$ - variation coefficient.

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

$a$ - the average rate of degradation process (average rate of change determining parameter), equal to $a = 1/\mu$.

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

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

Table 1

Generalized estimates of coefficients variation of various physical processes

| Type of degradation process | Coefficient of variation of the destruction process | Name of elements subject to destruction |
|---|---|---|
| Fatigue (multi-cycle) | 0,40 – 1,00 | Housing parts, rolling bearings, shafts, axles, springs, connecting rods, bolts, etc. |
| Wear (mechanical-chemical) | 0,20 – 0,50 | Housing parts, rolling bearings, shafts, axles, springs, connecting rods, bolts, etc. |
| Aging | 0,40 – 1,00 | Plain bearings, shafts, axles, guides, bushings, etc. |
| Electrical (electrolysis, charge migration, electrodiffusion) | 0,70 – 1,50 | Semiconductor devices, integrated circuits, capacitors and other electronic products. |

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

Taking into account all of the above, we select *VF*-model of *DN*-distribution as a failure model for all structural elements and the object as a whole. The initial information for MC in this case is a set of pairs of parameters of all ZRP elements. Based on this information, the corresponding parameters $\langle \mu_i, \nu_i \rangle$ for all other structural elements of higher levels should be calculated.

In [10], it is proved that if a system consists of elements whose failures are subject to *DN*-distribution, then failures of the system are also subject to *DN*-distribution. The parameters of the *DN*-distribution of the operating time to failure of the system (the scale parameter and the shape parameter) depending on the method of reliable connection of the elements in the system are calculated using the following formulas. Calculation formulas for determining the scale parameter and shape parameter for structural elements of higher levels (not ZRP):

Sequential 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 of the i-th type;

$\mu_i$ - is the scale parameter of *DN*-distribution of the time to failure of elements of the i-th type (average time to failure of elements of *i*-th type);

$\nu_i$ - is the shape parameter of *DN*-distribution of the time to failure of elements of *i*-th type (variation coefficient);

*N* - is the number of element types in the system.

Series connection of identical elements:

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

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

where $\mu_0$ - is the scale parameter of *DN*-distribution of elements included in the system (mean time to failure of one element);

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

Loaded (constant) redundancy:

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

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

Unloaded (replacement) redundancy:

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

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

The formal descriptions of the constructive and reliability structures of the object introduced above, the expression for the probability of failure of the 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-recoverable object.

The prototype of the considered MC can be considered the model described in [12]. The main difference between the MC and the prototype is the use of an important property of *DN*-distribution to preserve the type of distribution when transforming the reliability structure of the structural elements (when switching from a sequential structure to a parallel one, and vice versa).

**Model of failure-free operation of a recoverable object.** In the above, a MC was developed for the case when the object is considered non-recoverable. In the developed model

(a) hierarchical structural structure of the object is presented;

(b) reliability structure is determined by specifying a redundant group attribute for each structural element;

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

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

However, this is not enough for the simulation statistical model (ISM), in which the maintenance processes must be modeled. For the ISM, it is necessary to specify specific elements whose failures-recoveries must be modeled.

Let us introduce the concept of a set of recoverable elements $E_{\text{в}}$ as follows (fig. 2). The set $E_{\text{в}}$ must include structural elements that will be replaced in the event of object failures. The set $E_{\text{в}}$ includes the most repairable elements, that is, elements whose replacement time is minimal, these are the so-called typical replacement elements (TRE). The set $E_{\text{в}}$ must satisfy the requirements of completeness and non-redundancy.

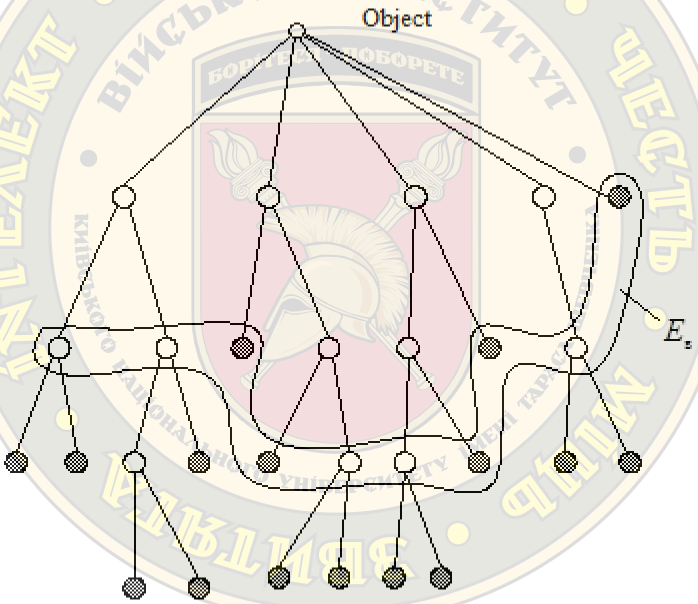


Figure 2 – Towards an explanation of set $E_{\text{в}}$

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

The non-redundancy requirement is that the set $E_{\text{в}}$ must not contain more than one element belonging to the path between the root of the tree and any hanging node.

With such a definition of the set $E_{\text{в}}$ and with the previously adopted assumption of a sequential reliable connection of structural elements, the probability of failure-free operation of the object is equal to

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

where $F_i(t)$ - is the probability of failure the *i*-th element from the set $E_{\text{в}}$.

The probability $P(t)$ does not depend on the choice of the set $E_{\text{в}}$.
Similarly, the value of the mean time to failure does not depend on and $E_{\text{в}}$

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

If the object is considered as recoverable, then the failure rate parameter $\omega(t)$ and the mean time between failures should be used as reliability indicators $T_0$ [14].

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

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

where $\omega_i(t)$ - failure flow parameter of *i*-th element from the set $E_{\text{в}}$.

The failure flow parameter of *i*-th element $\omega_i(t)$ is found as a solution to an integral equation of the following type [13, 14]:

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

where $f_i(t)$ - probability density of failure of *i*-th element ($i\in E_{\text{в}}$).

The failure flow parameter always has a steady-state value

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

In this case, the mean time between failures of object is equal to

$$T_0=1/\omega^{\infty}.$$

For real technical objects within the operating period $T_{\text{э}}$ of interest to the user, steady-state value of failure flow parameter may not occur. In this case, the mean time to failure of the object is determined by the formula:

$$T_0=T_0(T_{\text{э}})=\frac{1}{\frac{1}{T_{\text{э}}}\int_0^{T_{\text{э}}}\omega(t)dt}. \tag{19}$$

The value $T_0$ (in contrast to $T_{\text{ср}}$) depends significantly on the choice of set $E_{\text{в}}$. The higher average level of elements included in $E_{\text{в}}$, the greater value of $T_0$. This is easily explained, since when replacing larger structural elements, a greater number of serviceable elements are simultaneously updated. Consequently, the higher structural level of restored elements (smaller the level number *u*), the greater the proportion of elements is updated after current repairs, which leads to an increase in the indicator $T_0$.

**Conclusions.** The failure-free operation model (FM) allows obtaining estimates of the failure-free operation indicators (FMI) of individual structural elements and the object as a whole based on the FMI information of the elements of the lower structural level. The FR represents the hierarchical structural structure of the object. Structural elements of a certain *u*-th structural level are a sequential (in terms of reliability) connection of the elements of (*u*+1)-th level included in it. Individual structural elements can represent a redundant group (parallel connection) of similar elements. Thus, with the help of FM, the representation of a hierarchical constructive 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.

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 model of gradual failures both for electronic products and for various mechanical units and elements. An important advantage of *DN*-distribution is also that its appearance is preserved when transforming 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.

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## РОЗРОБКА МОДЕЛІ БЕЗВІДМОВНОСТІ СКЛАДНОГО ТЕХНІЧНОГО ОБ'ЄКТУ

***Складні технічні об'єкти сьогодні у суспільстві мають виключно важливе значення. Йдеться насамперед про різні радіоелектронні комплекси військового та спеціального призначення, радіолокаційні станції, автоматизовані системи управління (повітряним рухом, об'єктами енергетики тощо). Від рівня безвідмовності таких об'єктів залежить обороноздатність держави, економічна безпека, життя сотень та тисяч людей.***

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

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

***Як модель відмов для всіх елементів та об'єкта загалом використовується DN-розподіл. DN-розподіл вважається адекватною моделлю поступових відмов як виробів електронної техніки, так різних механічних вузлів і елементів. Важливим достоїнством DN-розподілу також є те, що його вид зберігається при перетвореннях надійності системи. Саме ця особливість DN-розподілу дозволила застосувати його до системи, що має ієрархічну структуру.***

***Модель безвідмовності (МБ) дозволяє отримувати оцінки показників безвідмовності (ПБ) окремих конструктивних елементів та об'єкта загалом за інформацією про ПБ елементів нижнього конструктивного рівня. У МБ представляється ієрархічна конструктивна структура об'єкта. Конструктивні елементи деякого u-го конструктивного рівня є послідовним (у сенсі надійності) з'єднанням елементів, що входять до нього (u+1)-го рівня. Окремі конструктивні елементи можуть бути резервованою групою (паралельне з'єднання) однотипних елементів.***

***Ключові слова: складні технічні об'єкти, автоматизовані системи управління, об'єкти, що відновлюються***