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FAILURE MODEL OF NON-RESTORABLE COMPLEX TECHNICAL OBJECT OF MILITARY EQUIPMENT

Maintenance (MT) is a necessary component the process of operating a complex technical object of military equipment, intended for long-term operation in wartime and harsh operating conditions. The volume, content and timing of maintenance must be completely determined by the reliability properties of the object, conditions and modes of its use. Effective implementation of any maintenance operation is possible only if the design of the object provides special means for this purpose (for measuring the defining parameters) and ensures the accessibility and convenience of performing the operation.

Complex technical objects in modern society are extremely important. Such objects belong to the class of restored objects long-term repeated use. They are usually expensive and require significant operating costs. To ensure the required level of failure-free operation 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.

A characteristic feature of complex technical objects for special purposes (military equipment) is the presence in their composition of a large number (tens, hundreds of thousands) 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 organizing and planning maintenance during operation (of military equipment).

The above statements fully justify the conclusion about need to determine the main characteristics of the maintenance system in early stages of its design, when it is still possible to make changes to design of the object.

In this work, a model of failure-free operation non-repairable complex technical object of military equipment is developed.

The work also confirms the general idea that data obtained fully confirm the assumption that a maintenance strategy that is not restored is more preferable in the case of unreliable (inaccurate) information about the reliability indicators of elements of a military equipment object.

Key words: maintenance, military equipment object, non-repairable military equipment object, complex technical objects for special purposes equipment, costs for the cost military equipment

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

Complex technical objects are understood as objects consisting of a large number different types of elements (tens, hundreds of thousands), each of which can represent a fairly complex technical device. Elements can be radio-electronic, mechanical, electromechanical, hydraulic, etc. The diversity of elements leads to the fact that different elements are characterized by fundamentally different physical processes (and, therefore, 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 - of devices (blocks), etc.

Analysis of previous studies. A “surge” in the number of theoretical works on the maintenance of complex systems occurred in the 70-s of the last century, which can be explained by the mass production at that time of complex electronic equipment for military and special purposes [1-6]. Currently, there is a decline in the number of scientific publications devoted to the maintenance of complex technical objects. One of the reasons for this, in our opinion, is the sharp increase in the level of integration and reliability of component products. Thanks to this, developers of complex equipment were able to solve issues of ensuring the required level of reliability without significant maintenance costs (or without maintenance at all). However, the same reason (high integration and reliability of component elements) 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, question of the need for maintenance and the choice of optimal strategy for its implementation again becomes relevant.

Formation of the problem. Unfortunately, the currently known mathematical models and methods for calculating the optimal parameters of maintenance processes are not very suitable for application to real technical objects. The main disadvantage of these models is that they either do not take into account the complex structure of the object at all, or it is possible to take into account only some of the simplest structures [7,8]. In [9], a comparative analysis of the problems arising when solving maintenance problems “by resource” and “by state” was carried out. An overview of the latest work at that time in the field of maintenance and repair of complex systems is provided. In [10], a theoretical generalization of known mathematical models of maintenance processes was made. However, these models do not allow us to build on their basis methods suitable for practical use.

In our opinion, the situation is even worse with mathematical models of “state-by-state” maintenance processes. Only a small number of scientific works are devoted to this area of research [11, 12].

Results. The model being developed is intended to obtain probability functions of failure-free operation $P(t)$ (or time-to-failure distribution functions $F(t) = 1 - P(t)$) for the object as a whole and all its structural elements based on the available information on the failure-free performance of component elements. The functions $P(t)$ and $F(t)$ are 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^u_{ijk} *k*-th element of *u*-th structural level, which is part of *j*-th element of (*u*-1) -th level. The index *ijk* 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 the *u*-th level elements included in the (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* - number of the 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. 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 the next (u+1)-th level. In figure 1, elements of the lower level are indicated by circles, all other elements are indicated by rectangles.

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 [3,8], 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.

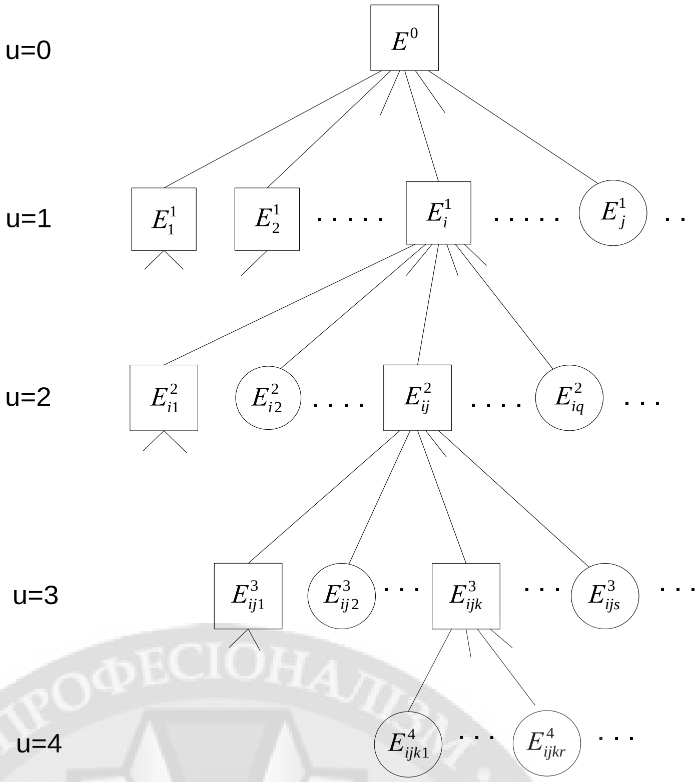

Figure 1 – Fragment of the hierarchical structural structure of the object

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

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

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:

$$E^0 = \{E^1_0, E^1_1, \ldots, E^1_i, \ldots\};\ \ i=\overline{0,|E^0|}. \qquad (2)$$

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.

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:

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

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

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

If an element $E^u_{ij\ldots k}$ is a redundant group consisting of n identical elements $E^{u+1}_{ij\ldots k0}$ connected in parallel, then in the case of a constant reserve the probability of failure-free operation for it is equal to [2,4]:

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

The model does not take into account the possibility of multiple failures, since within the framework of tasks for which this model is developed, 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 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 $P(t/E^{u}_{ij\dots r})$ must be calculated.

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 [5,13]. 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:

$$\begin{aligned} F(t) = DN(t;\mu,\nu) &= \Phi\left(\frac{t-\mu}{\nu\sqrt{\mu t}}\right) + \exp\left(\frac{2}{\nu^2}\right)\Phi\left(-\frac{t+\mu}{\nu\sqrt{\mu t}}\right) = \\ &= \Phi\left(\frac{at-1}{\nu\sqrt{at}}\right) + \exp\left(\frac{2}{\nu^2}\right)\Phi\left(-\frac{at+1}{\nu\sqrt{at}}\right), \end{aligned} \tag{6}$$

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

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

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]. Table 1 shows some data taken from [8] on the characteristic values of the coefficient of variation.

Table 1

Generalized estimates of the coefficients of variation of various physical processes

Type of degradation process	Coefficient of variation 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 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 coefficient of variation, and vice versa, that is, the lower 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 the MB in this case is the set of pairs of parameters 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 failures of the system are also subject to 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 parameter μ and shape parameter ν 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 of *i*-th type (average time to failure of elements of *i*-th type);

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

N - 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 μ_0 - is the scale parameter of *DN*-distribution 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, expression for the probability of failure objects (or element) $F(t)$ (6) and the calculation expressions (7-14) together represent a mathematical model of the failure-free operation a non-repairable object.

The prototype of the considered MB can be considered the model described in [10]. The main difference between the MB and the prototype is the 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 database. For the software implementation of the 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 [13]. 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 the database: tbE1 – for 1st level elements included in the object, tbE2 – 2-nd level elements included in 1-st level elements, etc. One table entry contains information about one *u*-level structural element.
- tables tbKEu – contain information about the elements that are ZRP and related to the design level u: tbKE1 – ZRP included directly in 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 tables is equal to the number of tbEu 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);
- table tbGTipKE – contains information about groups of ZRP types. Type groups were introduced for convenience of working with the database;
- table tbSprav – a 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 the 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 the 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 of ZRP types

Table 5

Structure of the tripLE table (reliability indicators of ZRP)

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

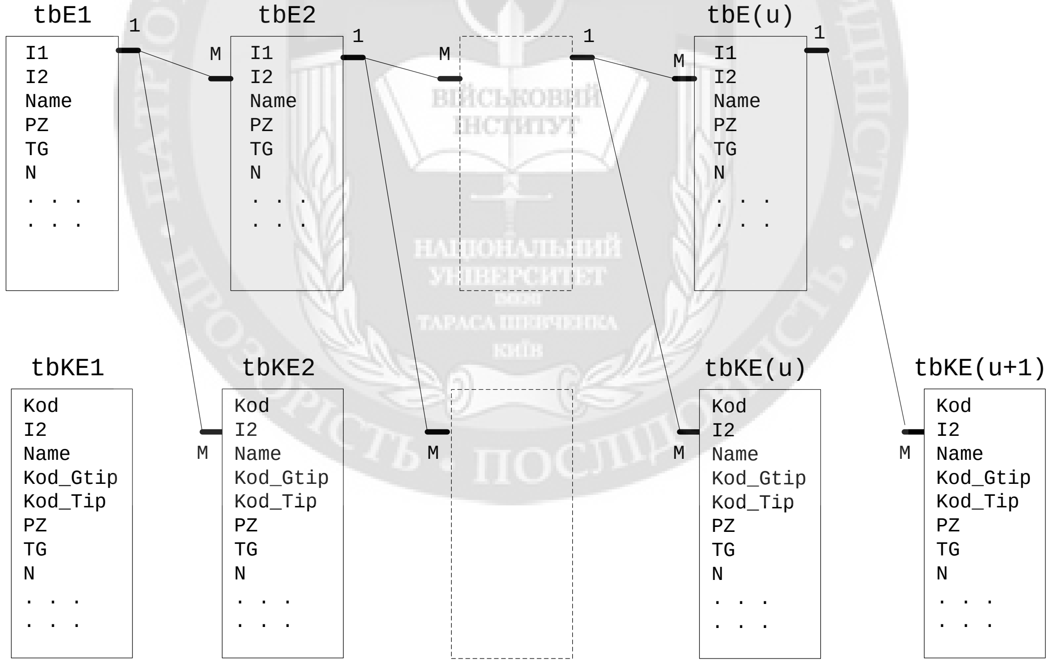

Figure 2 – Master-slave relationships between tables tbEu and tbKEu

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 the 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 2-nd 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 INR, which are elements of 2-nd level and are part of the 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).

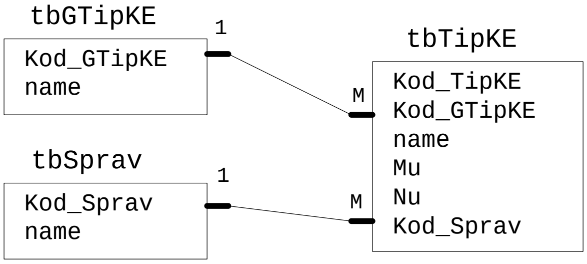

Figure 3 – Diagram of connections between tables tbGTipKE, tbSprav and tbTipKE

One record in the tbGTipKE table (one group of types) can correspond to 0 or more records in the tbTipKE table (0 or more ZRP types). In the same way, one record in the tbSprav 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 the tbKEu tables and the tbTipKE table (not shown in the figures). The communication keys here are the Kod_Tip and Kod_TipKE fields. Using this connection, each ZRP presented in the tbKEu table is associated with a single entry in the tbTipKE table, containing information about the reliability parameters of an element of this type.

Conclusions. 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 the tbEu and tbKEu tables.

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МОДЕЛЬ БЕЗВІДМОВНОСТІ СКЛАДНОГО ТЕХНІЧНОГО ОБ'ЄКТУ, ЩО НЕВІДНОВЛЮВАЄТЬСЯ, ВІЙСЬКОВОЇ ТЕХНІКИ

Технічне обслуговування (ТО) є необхідною складовою процесу експлуатації складного технічного об'єкта військової техніки, призначеного для тривалої експлуатації в умовах воєнного часу та важких умов експлуатації. Обсяг, зміст та терміни проведення ТО повинні повністю визначатися надійними властивостями об'єкта, умовами та режимами його застосування. Ефективне виконання будь-якої операції ТО можливе лише в тому випадку, якщо в конструкції об'єкта передбачені спеціально призначені для цього засоби (для вимірювання визначальних параметрів) та забезпечені доступність та зручність виконання операції.

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

Характерною особливістю складних технічних об'єктів спеціального призначення (військової техніки) 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 потребує більш тонкого підходу до організації та планування ТО у процесі експлуатації (військової техніки).

Наведені твердження цілком обґрунтовують висновок необхідність визначення основних характеристик системи ТО на ранніх стадіях його проектування, коли ще є можливість внесення змін у конструкцію об'єкта.

У цій роботі розробляється модель складного технічного об'єкта військової техніки, що не відновлюється.

Також у роботі підтверджується загальне міркування у тому, що отримані дані повністю підтверджують висунуте припущення у тому, що стратегія ТО, яке відновлюється, є кращою у разі недостовірної (неточної) інформації про показники надійності елементів об'єкта військової техніки.

Ключові слова: технічне обслуговування, об'єкт військової техніки, об'єкт військової техніки, що не відновлюється, складні технічні об'єкти спеціального призначення