EFFECTIVENESS RETENTION RATIO AND MULTISTATE SYSTEMS

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Abstract

This paper analyzes approaches to dependability assessment of multistate systems in which partial failures can occur. It is shown that for many multistate systems it is advisable to use the effectiveness retention ratio as a dependability measure. The paper explains the meaning and advantages of this measure, and presents methods for its calculation for two classes of systems covering typical situations. They are additive systems in which the output effect is obtained by summing the output effects of the subsystems, and multimode systems that can perform some function or task in different modes depending on their state. Besides that, the presence and use of the effectiveness retention ratio in international and regional Euro-Asian standards are considered.

Keywords: dependability, multistate systems, partial failures, effectiveness retention ratio, international standards, additive and multimode systems.

I. Introduction

The traditional assumption in dependability theory is that there are two possible states of an item: up and down (definitions of these and other basic terms necessary for a proper understanding of this paper are given in Section II.). However, many complex systems can have intermediate states that they go to as a result of partial failures. These states are characterized by a loss of the ability to perform some, but not all, required functions, or by reduced performance. This led to the need to consider multistate systems. In recent years, a number of books have been published specifically dedicated to this topic: [1–4]. Besides that, a number of well-known handbooks [5–7] and monographs [8–10] have sections on multistate systems. They described different approaches and measures for such systems. Interestingly, in [6, 9], two approaches are described independently in different sections written by different authors. Thus, systematization is required.

This paper identifies and discusses two main approaches to assessing the dependability of multistate systems. The mathematical models used in each of the approaches are described, the corresponding dependability measures are given, the approaches are compared, i.e. their advantages and disadvantages are indicated. The first approach is based on the evaluation of system effectiveness. I. A. Ushakov, the founder and first editor-in-chief of the journal “Reliability: Theory & Applications”, in the first paper of its first issue pointed out effectiveness (“performability”) among “main directions of modern reliability theory” [11]. The principal dependability measure that arises within this approach is the effectiveness retention ratio (ERR) [12, 13]. The paper gives its definition, explains the meaning and advantages. All these issues constitute the content of Section III.

Standardization plays an important role in any field of engineering. Dependability is no exception. Therefore, Section IV analyzes the presence and use of the ERR in standards. International and regional Euro-Asian standards are considered.

A number of methods can be used to calculate the ERR (see e.g. [5–7, 9, 10, 12, 13], some other works will be given below). Section V presents methods for its calculation for two classes of systems covering typical situations. They are additive systems in which the output effect is obtained by summing the output effects of the subsystems, and multimode systems that can perform some function or task in different modes depending on their state. In particular, for multimode systems, a technique is proposed that allows calculating the ERR in a fairly general situation and going beyond the two previously known special cases.

II. Some Terminology Remarks

Standardization plays an important role in any field of engineering. The leading international organization for the standardization of dependability is the International Electrotechnical Commission (IEC), or rather, its special technical committee No. 56 (TC56). In accordance with an agreement with the International Organization for Standardization (ISO), the TC56 develops dependability standards not only for the electrotechnical field, but address generic dependability issues across all disciplines, thus making it what is referred to as a horizontal committee [14].

An important area of standardization is terminology. It is necessary to ensure an unambiguous interpretation of terms and mutual understanding. This section is devoted to basic standardized dependability terms, and other aspects of standardization within the topic of this paper will be discussed later.

The standard [15] gives the general terminology used in the field of dependability. It is one of the parts (namely 192) of the International Electrotechnical Vocabulary (IEV), which is presented on the portal Electoropedia (also known as the "IEV Online"): https://electropedia.org/. The terms in [15] are generic and are applicable to all fields of dependability methodology. Unfortunately, some researchers and engineers do not know and do not use this standard. Some examples of incorrect and sometimes misleading use of terms related to dependability in modern information and communication technologies were given in [16]. Therefore, the definitions of the basic terms necessary for a proper understanding of this paper are given below.

Dependability of an item is its ability to perform as and when required. The same definition with the reference to [15] is repeated in the well-known standard [17]. There are two notes to this term in [15]. The first one states that dependability includes availability, reliability, recoverability, maintainability, and maintenance support performance (and, in some cases, other characteristics). The second note states that dependability is used as a collective term for the time-related quality characteristics of an item. In other words, dependability is an umbrella term for the above characteristics [14].

By the way, this definition was created as a result of long and active discussions, and some experts still disagree with it. The issue of developing such a definition was discussed in detail in [18].

The main states of an item are up state and down state. Up (or available) state is the state of being able to perform as required. Down (or unavailable) state is the state of being unable to perform as required, due to internal reason.

Reliability of an item is its ability to perform as required, without failure, for a given time interval, under given conditions. Availability of an item is its ability to be in a state to perform as required. Reliability and availability may be quantified using appropriate measures. Some of them have the same words in their names:

- reliability is the probability of performing as required for the time interval (t_1, t_2), under given conditions;
- instantaneous (point) availability is the probability that an item is in a state to perform as required at a given instant;
- steady state (asymptotic) availability is the limit, if it exists, of the instantaneous availability when the time tends to infinity.

In other words, reliability is the probability of being in up state during the given time interval, and availability is the probability of being in up state at an instant of time (usually, very far from the original moment).

III. Two Approaches to Dependability Assessment of Multistate Systems

The traditional assumption in dependability theory is that there are two possible states of an item: up and down. Under this assumption, consider a system consisting of n elements. Then the states of the elements and the whole system can be expressed as binary variables. The following symbols are usually used for them. The indicator of the state of the ith element is denoted by x_i: $x_i = 1$, if the ith element is in up state, and $x_i = 0$, if the ith element is in down state. To describe the state of the system, the n-dimensional binary vector $\mathbf{x} = (x_1,...,x_n)$ is introduced. If we denote the two-element set {0, 1} by B, then the set of all states of the system S is B^n.

For the system, the structural function $\varphi : B^n \to B$ is defined [19]: $\varphi(\mathbf{x}) = 1$, if the state $\mathbf{x}$ is up state for the system, and $\varphi(\mathbf{x}) = 0$, if the state $\mathbf{x}$ is down state for the system. Usually, monotone systems (or coherent structures) are considered, which imposes certain restrictions on the function $\varphi(\mathbf{x})$ [19]. Namely, structural functions are 0-preserving, 1-preserving, and monotonic (in the terminology of Boolean functions).

The set of all states of the system S is divided into two disjoint subsets: the subset of up states $S_1 = \{\mathbf{x} \mid \varphi(\mathbf{x}) = 1\}$ and the subset of down states $S_0 = \{\mathbf{x} \mid \varphi(\mathbf{x}) = 0\}$. The main dependability measure in this case is the probability that the system is in up state, which is equal to the mathematical expectation of the structural function:

$$P = \mathbf{P}\{\varphi(\mathbf{x}) = 1\} = \mathbf{E}[\varphi(\mathbf{x})]. \quad (1)$$

However, many complex systems can have intermediate states that they go to as a result of partial failures. These states are characterized by a loss of the ability to perform some, but not all, required functions, or by reduced performance. This led to the need to consider multistate systems. There are two main approaches to assessing the dependability of such systems, which are discussed below.

The first of them originated in the late 1950s [20] and was developed in the 1960s. Its idea was well expressed in the classic monograph [21] (its original Russian edition was published in 1965). According to it, for complex systems "the reliability of the system should be understood to mean the stability of the efficiency with consideration of the reliability of the parts composing the system". However, this idea was not further developed in this book.

I. A. Ushakov made a significant contribution to the development and promotion of this approach. He considered system effectiveness, determined by taking into account the reliability of system's elements. This was the subject of his works [22, 23] and many subsequent ones, the corresponding sections were included in popular handbooks [5–7] and monographs [9, 10] (two handbooks by B. A. Kozlov and I. A. Ushakov have been translated into German, Bulgarian, and Czech; there was also a German version of [9]).

In practice, it is much more convenient to deal with dimensionless relative values. This leads to a dependability measure called the effectiveness retention ratio (ERR). It is defined as the ratio of the value of the effectiveness index of an item's intended use over a certain period of operation to the nominal value of this index, calculated on the assumption that the item did not affected by failures during the specified period. The ERR has a simple and clear meaning. For example, if $ERR = 0.95$, it means that due to failures, the effectiveness is reduced by an average of 5%.

The effectiveness index is usually defined as the expectation of the output effect of the system. Particular form of the output effect depends on the nature of the considered system. For example, it can be the quantity of released products for production systems, the amount of information transmitted, collected or processed for information and communication systems, and so on. For systems that perform individual tasks or jobs, the probability of successful completion of the task can be used as an index of effectiveness. Note that this index can also be represented as a mathematical expectation of the output effect. To do this, the output effect is assumed to be 1 if the task is completed and 0 otherwise. In this case, the ERR has a direct probabilistic meaning. It is equal to the probability that the task completion is not disrupted by failures [12].

Although I. A. Ushakov pointed out the expediency of relative effectiveness (for example, in [24]), the term ERR was not used in his works. The first book to discuss the ERR in detail was [12]. In English it was described in [13].

To construct a mathematical model when determining the ERR, the effectiveness function $\varphi(\mathbf{x})$ can be introduced. It generalizes the classical structural function, and can take not only the values 0 and 1, but also any value from the unit interval $I = [0, 1]$, so in this case $\varphi : B^n \to I$. The value $\varphi(\mathbf{x})$ is the relative output effect of the system in the state $\mathbf{x}$. Its maximum value, which is reached when all elements are in up state, is taken as one. Effectiveness functions, as well as structural functions, are 0-preserving, 1-preserving, and monotonic. Of course, the image of such a function is always a finite set, the number of its elements cannot be greater than 2^n. However, it is often unknown in advance and is determined during the dependability assessment.

This can be interpreted as the fuzzification of the failure criterion [25]. In other words, we can also consider the subsets of up and down states for the system, but they are complementary fuzzy ones with membership functions $\varphi(\text{x})$ and $\overline{\varphi(\mathbf{x})} = 1 - \varphi(\mathbf{x})$ for the subsets of up and down states respectively.

The ERR can be expressed as the mathematical expectation of $\varphi(\mathbf{x})$, which is similar to the right member of the equality (1):

$$ERR = \mathbf{E}[\varphi(\mathbf{x})] = \sum_{\mathbf{x}\in S} \varphi(\mathbf{x})p(\mathbf{x}), \tag{2}$$

where $p(\mathbf{x})$ is the probability that the system is in state $\mathbf{x}$.

The ERR can also be used for traditional two-state items, in which cases it is usually reduced to measures such as availability and reliability [12, 13]. This can make it easier to choose the right dependability measures.

Unfortunately, this approach and the ERR are little known outside of Russia, despite the above-mentioned publications in English and other languages and the fact that works on this topic by I. A. Ushakov, E. V. Dzirkal and V. A. Netes were mentioned in the survey [26] (these researchers based their works on extensive practical experience in assessing the dependability of complex information, control, and communication systems).

If necessary, besides the ERR, the probability $\mathbf{P}\{\varphi(\mathbf{x}) \geq u\}$ $(0 < u \leq 1)$ can be used as dependability measure. However, it is often difficult to reasonably choose the level u. Besides that, choosing a single value of u actually leads to the traditional scheme: then $\{\mathbf{x} \mid \varphi(\mathbf{x}) \geq u\}$ is the set of up states, and $\{\mathbf{x} \mid \varphi(\mathbf{x}) < u\}$ is the set of down states. This means that some partial failures are considered as complete ones, while others are not considered at all. In some situations, this may be justified, but in most cases it can lead to a misconception about the system dependability. If we calculate such probabilities for several values $u_1, ..., u_k \in (0, 1]$, then the dependability assessment becomes more complicated, and its results are less clear and inconvenient for analysis.

The second approach emerged in the late 1970s (see [27–29], just name a few). It is used and described in a number of publications by authors from many countries (e.g. [6, 8, 9]). It is assumed that each element and the entire system can be in a finite set of states. Let $D_i = \{0, 1, ..., m_i\}$ be the set of states for the ith element and $D = \{0, 1, ..., m\}$ be the set of states for the system. In a frequently used special case, $m_i = m$, so $D_i = D\ \forall i$. The elements of the sets D_i and D are arranged in ascending order of the performance level. In this case, a generalized structural function can be introduced: $\varphi : D_1 \times ... \times D_n \to D$. Such functions are also monotonic, 0-preserving, and satisfy the condition $\varphi(m_1, ..., m_n) = m$.

The main dependability measures are the probabilities of keeping a given performance level; they are similar to the middle member of the equality (1):

$$P(\nu) = \mathbf{P}\{\varphi(\mathbf{x}) \geq \nu\} \quad (x_i \in D_i,\ \nu \in D). \tag{3}$$

The drawbacks of such measures for multistate systems were discussed above.

Comparing these two approaches to each other, the first immediately noticeable thing is the wider possibilities for describing the states of elements in the second approach. However, in the first approach, some parts composing the system can, if necessary, be considered as subsystems with more than two states. This can lead to the decomposition of systems, considered in particular in [6, 7, 9, 13]. However, this interesting issue is beyond the scope of this paper.

On the other hand, a less obvious but important circumstance is that the values of the cstructural function and the effectiveness function are expressed using different scales of measure (levels of measurement). These are the ordinal scale for the structural function and the absolute scale (the ratio scale having fixed natural 0 and 1) for the effectiveness function. The former is non-metric (qualitative), and the latter is metric (quantitative). Therefore, the values of the structural function can only be compared (equal, greater, or less), and arithmetic operations can be performed with the values of the effectiveness function. This explains and justifies the use of measures (2) and (3). Some works (e.g. [9]) have also introduced the mathematical expectation of the performance level similar to (2), but this does not make sense for ordinal variables.

III. Standardization

The standardization of ERR was specifically reviewed in [31]. However, it mainly discussed Russian and interstate standards. This section is mainly devoted to IEC standards. But first, a brief summary on the ERR in the interstate standards is given. These are regional standards adopted by the Euro-Asian Council for Standardization, Metrology and Certification (EASC) of the Commonwealth of Independent States. The terminology standard [32] gives the definition of the ERR. By the way, it first appeared in the Soviet terminology standard on dependability in 1983. The scope of application and recommendations for using the ERR are given in [33]. Besides that, this standard explains that the effectiveness of an item's intended use is understood as its property to create some useful result (output effect) during the operation under certain conditions.

The ERR is not included in the international terminology standard on dependability [15]. However, the previous version of such a standard [34] contained terms "effectiveness (performance)" and "capacity". They had the following definitions. Effectiveness (performance) is the ability of an item to meet a service demand of given quantitative characteristics. The note to this definition states that this ability depends on the combined aspects of the capability and the availability performance of the item. Capability is the ability of an item to meet a service demand of given quantitative characteristics under given internal conditions. The note explains that internal conditions refer for example to any combination of faulty and non faulty sub-items. These concepts made it possible to go to the ERR, but this step was not taken, on the contrary, they were excluded during the development of [15].

As noted above, the ERR is primarily required for systems that might be affected by partial failures. This term is defined in [15] as a failure characterized by the loss of some, but not all, required functions. The note to this definition states that a partial failure may lead to a degraded state. The latter is defined as a state of reduced ability to perform as required, but with acceptable reduced performance.

Thus, the definition of partial failure in [15] is only suitable for multifunctional items. However, this concept also makes sense for single-function items, which may be in a degraded state with reduced performance. Therefore, it is advisable to expand this definition by stating it as follows: a failure characterized by the loss of the ability to perform some, but not all, required functions or by reduced performance (output effect).

There are two IEC standards in which the ERR is actually implicitly present. The first of them is [35]. Its subsection on availability contains paragraph 6.1.2.4, which deals with multistate systems with reference to [2]. It gives a simple example of such a system consisting of two elements. In fact, the measure introduced there is the ERR [31].

Another IEC standard that implies the ERR is [36]. It is devoted to communication network dependability. There are two network service scenarios of interest to network dependability. The first of them has the objective to determine the network dependability characteristics of end-to-end (E2E) network services from the perspective of network end-users. It is associated with the specific service paths selected for the E2E connections. The objective of the second scenario is to determine the network dependability characteristics of the entire network from the network operator or the network service provider perspective. Accordingly, two dependability measures are recommended: the E2E network availability and the full-end network availability.

The E2E network availability is the availability of an E2E network connection between a pair of nodes in question, including all available service paths. However, the full-end network availability is not really availability, that is, the probability that some item is in up state. It is the weighted sum of E2E availabilities for different pairs of nodes and actually turns out to be the ERR [37]. In this case, the output effect is defined as the number of connected pairs of users. In general, the feasibility of using the ERR for communication networks and some methods of its calculation were given in [37].

Notable that both of these examples in [35, 36] fit into the same fairly general scheme, which is discussed below.

IV. Calculation of the ERR

I. General Consideration

According to the above definition,

$$ERR = E/E_0,$$

where E is the index of effectiveness and E_0 is the nominal value of this index calculated under the condition that failures do not occur. However, this formula is usually not suitable for calculating in practice. On the contrary, if necessary, E can be calculated as the product of E_0 and the ERR. Formula (2) is suitable for calculations only with a small number of elements. Various techniques that can be used to calculate the ERR are given in the above-mentioned publications [5–7, 9, 10, 12, 13, 22–25].

Here we present methods for calculating the ERR for two classes of systems, for which it is expressed in terms of dependability measures of subsystems. They cover typical situations and have not been published in English. In both cases, it is assumed that the system has a certain number of subsystems. Generally speaking, they can intersect, i.e. have common elements. Each subsystem is considered binary, i.e. it can be either in up state or in down state. Denote P_j the probability that the j-th subsystem is in up state. Depending on the situation, it can be its availability or reliability.

II. Additive Systems

The first class consists of so-called additive systems. For such systems, the output effect is obtained by summing the output effects of the subsystems. In particular, the systems mentioned above, which are considered in the standards [35, 36], belong to this class. It also includes multifunctional systems, in which it is possible to allocate subsystems responsible for performing functions, and the output effects for all functions are added up.

Let the system have k subsystems and each non-failed subsystem contributes to the overall output effect. Then

$$E = \sum_{j=1}^{k} E_j , \qquad E_0 = \sum_{j=1}^{k} E_{j0} ,$$

where E_j and E_{j0} are the effectiveness and the nominal effectiveness of the j-th subsystem. Also, for binary subsystems $E_j = P_j E_{j0}$.

From these equalities, the formula for calculating the ERR follows:

$$ERR = E \Big/ E_0 = \sum_{j=1}^{k} E_j \Big/ E_0 = \sum_{j=1}^{k} P_j E_{j0} \Big/ E_0 = \sum_{j=1}^{k} (E_{j0}/E_0) P_j = \sum_{j=1}^{k} w_j P_j,$$

where $w_j = E_{j0} / E_0$ is the “weight” of the j-th subsystem.

III. Multimodal Systems

The second class is multimodal systems. They have been known for a long time (see, for example, [38, 20, 23, 5–7]). In some publications (in particular, in [5–7]), they were called multifunctional, which does not fully correspond to the principle of their functioning. Indeed, such a system performs one function or task, but can do it in different modes, depending on its state. For each state, the mode that is possible for it, which gives the maximum output effect, is applied. Each mode corresponds to a specific subsystem that must be in up state in order for the system to operate in this mode.

An example is a communication network in which several paths with different performance parameters (bandwidth, delay, packet loss ratio, etc.) can be used to transmit information. The paths can be characterized by the probability of successful delivery (in time, without errors), and the best of the available paths is chosen.

Let there are m modes, the corresponding subsystems are $G_1, \dots, G_m$, and the corresponding values of the relative output effect are $v_1, \dots, v_m$. They are assumed to be numbered in decreasing order: $v_1 \geq v_1 \geq \cdots \geq v_m > 0$. If we denote by H_l the probability of performing the function in the lth mode, then

$$ERR = \sum_{l=1}^{m} v_l H_l.$$

Thus, the calculation of the ERR is reduced to the calculation of the probabilities H_l. It is clear that $H_1 = P_1$. For $l > 1$, H_l is the probability that the subsystem G_l is in up state, and all subsystems with smaller numbers have failed.

Formulas for calculating the probabilities H_l for $l > 1$ were known for two special cases [5–7, 23].

1. Each element can be included in only one subsystem, i.e. the subsystems are pairwise disjoint. Then

$$H_l = P_l \prod_{j=1}^{l-1} (1 - P_j).$$

2. Each subsequent subsystem is contained in the previous one, that is $G_1 \supset G_2 \supset \cdots \supset G_m$. This means that the 1st (the best) mode require all elements, the 2nd mode require fewer elements, and so on. Then

$$H_l = P_l - P_{l-1}.$$

Let all subsystems are series ones. Then

$$P_l = \prod_{i \in G_l} p_i,$$

where $p_i = \mathbf{P}\{x_i = 1\}$ is the probability that the ith element is in up state. In this case, a general technique can be proposed for calculating the probabilities H_l. It is based on their representation in the following form:

$$H_l = \mathbf{P}\left[\left(1 - \prod_{i \in G_1} x_i\right) \cdots \left(1 - \prod_{i \in G_{l-1}} x_i\right) \prod_{i \in G_l} x_i = 1\right] = \mathbf{E}\left[\left(1 - \prod_{i \in G_1} x_i\right) \cdots \left(1 - \prod_{i \in G_{l-1}} x_i\right) \prod_{i \in G_l} x_i\right].$$

The expression in the brackets in the right member of this formula should be transformed so that there are no repeated variables x_i in it, i.e. that they are all different. This can be done by using the following equalities:

$$(1 - xy)\cdot x = (1 - y)\cdot x, \quad (1 - xy)\cdot(1 - x) = (1 - x), \quad (1 - xy)\cdot(1 - xz) = 1 - x\cdot(y + z - yz).$$

They are valid for any variables $x, y, z \in B$ since they are idempotent. After that, the final result is obtained by substituting p_i instead of x_i in the resulting expression. This follows from the properties of the mathematical expectation and the equality $p_i = \mathbf{E}[x_i]$.

This technique is similar to the one used in [39] to calculate the interval reliability of communication networks.

V. Conclusion

This paper analyzes approaches to dependability assessment of multistate systems in which partial failures can occur. Along the way, the incompleteness of the definition of partial failure in the basic terminology standard on dependability IEC 60050-192:2015 is revealed and its extended formulation is proposed.

It is shown that for many multistate systems it is advisable to use the effectiveness retention ratio as a dependability measure. It is defined as the ratio of the value of the effectiveness index of an item's intended use over a certain period of operation to the nominal value of this index, calculated on the assumption that the item did not affected by failures during the specified period. The effectiveness index is usually defined as the expectation of the output effect of the system. This approach can be interpreted as the fuzzification of the failure criterion. Unfortunately, this measure is not very well known (especially outside of Russia), and it is used less often than it deserves. Its usage is recommended in reginal interstate (Euro-Asian) standards adopted by EASC (GOST 27.002–2015 and GOST 27.003–2016). It is also implicitly present in two international standards IEC 61703:2016 and IEC 62673:2013, which do not quite correctly attribute it to availability measures.

The paper explains the meaning and advantages of the effectiveness retention ratio, and presents methods for its calculation for two classes of systems covering typical situations. They are additive systems in which the output effect is obtained by summing the output effects of the subsystems, and multimode systems that can perform some function or task in different modes depending on their state. Additive systems include, in particular, the systems considered in the above-mentioned IEC standards. For multimode systems, a technique is proposed that allows calculating the ERR in a fairly general situation and going beyond the two previously known special cases.

The author hopes that this paper will contribute to the dissemination of information about the effectiveness retention ratio and its wider application.

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References

[1] Lisnianski, A., Levitin, G. Multi-state System Reliability: Assessment, Optimization and Applications, World Scientific, Singapore, 2003.

[2] Lisnianski, A., Frenkel, I., Ding, Y. Multi-state System Reliability Analysis and Optimization for Engineers and Industrial Managers, Springer-Verlag, London, 2010.

[3] Natvig, B. Multistate Systems Reliability Theory with Applications, John Wiley & Sons, Chichester, 2011.

[4] Recent Advances in Multi-state Systems Reliability, eds. Lisnianski, A., Frenkel, I., Karagrigoriou, A., Springer, 2018.

[5] Kozlov, B., Ushakov, I. Reliability Handbook, Holt, Rinehart and Winston, New York, 1970.

[6] Reliability of Technical Systems: Handbook, ed. Ushakov, I. A. Radio i Sviaz, Moscow, 1985 (in Russian).

[7] Handbook of Reliability Engineering, ed. Ushakov, I. A. John Wiley & Sons, New York, 1994.

[8] Beichelt, F., Franken. P. Zuverlässigkeit und Instandhaltung. Mathematische Methoden, VEB Verlag Technik, Berlin, 1983.

[9] Reinschke, K., Ushakov, I. A. Application of Graph Theory in Reliability Analysis, Radio i Svyaz, Moscow, 1988 (in Russian).

[10] Gnedenko, B. V., Ushakov, I. A. Probabilistic Reliability Engineering, John Wiley & Sons,

New York, 1995.

[11] Ushakov, I. (2006). Reliability: past, present, future. *Reliability: Theory & Applications*, 1: 10–16.

[12] Dzirkal, E. V. Setting and Testing Requirements to the Reliability of Complex Items, Radio i Svyaz, Moscow, 1981 (in Russian).

[13] Netes, V. A. (2012). Effectiveness retention ratio: a dependability measure for complex systems. *Dependability*, 4:24–33.

[14] Van Hardeveld, T. International Perspectives on Reliability, https://reliabilityweb.com/articles/entry/international_perspectives_on_reliability.

[15] IEC 60050-192:2015. International Electrotechnical Vocabulary – Part 192: Dependability.

[16] Netes, V. (2020). Modern network technologies and dependability. In: Proceedings of the 3rd International Science and Technology Conference "Modern Network Technologies" (MoNeTec-2020).

[17] ISO 9000:2015. Quality Management Systems. Fundamentals and Vocabulary.

[18] Netes, V. A., Tarasyev, Yu. I., Shper, V. L. (2014). How we should define what "dependability" is, *Dependability*, 4:15-26.

[19] Barlow, R. E., Proschan, F. Mathematical Theory of Reliability, John Wiley & Sons, New York, 1965.

[20] Fridell, H. G., Jack, H. G. (1959). System operational effectiveness (reliability, performance, maintainability). In: Proceedings of the 5th National Symposium on Reliability and Quality Control in Electronics.

[21] Gnedenko, B. V., Belyayev, Yu. K., Solovyev, A. D. Mathematical Methods in Reliability Theory, Academic Press, New York and London, 1969.

[22] Ushakov, I. A. (1960). An estimate of effectiveness of complex systems. In: Reliability of Radioelectronic Equipment, Sovietskoye Radio, Moscow (in Russian).

[23] Ushakov, I. A. (1966). Performance effectiveness of complex systems. In: On Reliability of Complex Technical Systems, Sovietskoye Radio, Moscow (in Russian).

[24] Ushakov, I. A. Theory of System Reliability, Drofa, Moscow, 2009 (in Russian).

[25] Netes, V. A. (1976). Method of estimating complex systems dependability and its application to tree-like information networks. *Transactions of ZNIIS*, 2:17–23 (in Russian).

[26] Rukhin, A. L., Hsieh, H. K. (1987). Survey of Soviet works in reliability. *Statistical Science*, 2(4):484–503.

[27] Barlow, R. E., Wu, A. S. (1978). Coherent systems with multi-state components, *Mathematics of Operations Research*, 3:275–281.

[28] El-Neweihi, E., Proschan, F., Sethuraman, J. (1978). Multistate coherent systems, *Journal of Applied Probability*, 15:675–688.

[29] Ross, S. M. (1979). Multivalued state component systems, *Annals of Probability*, 7:379–383.

[30] Reinschke, K. Zuverlässigkeit von Systemen. Bd. I. Systeme mit Endlich Vielen Zuständen, VEB Verlag Technik, Berlin, 1979.

[31] Netes, V. A. (2021). Effectiveness retention ratio and its standardization, *Dependability*, 2:3–8.

[32] GOST 27.002–2015. Dependability in Technics. Terms and Definitions (in Russian).

[33] GOST 27.003–2016. Industrial Product Dependability. Contents and General Rules for Specifying Dependability Requirements (in Russian).

[34] IEC 50(191):1990. International Electrotechnical Vocabulary – Chapter 191: Dependability and Quality of Service.

[35] IEC 61703:2016. Mathematical Expressions for Reliability, Availability, Maintainability and Maintenance Support Terms.

[36] IEC 62673:2013. Methodology for Communication Network Dependability Assessment

and Assurance.

[37] Netes, V. (2020). Dependability measures for access networks and their evaluation. In: Proceedings of the 26th Conference of Open Innovation Association FRUCT.

[38] Zagor, H. I., Curtin, K., Greenberg H. (1958). Reliability of multi-moded systems. *Electronic Industries,* 4:101–104,164–165.

[39] Netes, V. (2021). The interval reliability, its usage and calculation for information and communication systems and networks. In: Proceedings of the 29th Conference of Open Innovation Association FRUCT.