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Dear colleagues,

The development of the theory and practice of dependability involves the creation of new systems, technologies, processes. In the course of implementation of advanced systems and processes, they are digitized in order to improve their end-user performance. That ensures the efficient and prompt user service. Now, dependability is considered as the ability of a system to deliver a service that can be reasonably trusted. Here, system failure is the transition of correct service into incorrect, whereas system function is not performed, while a fault is a system state that may eventually cause a failure. Obviously, no one can fully guarantee unfailing service by a system, as there is always a risk of disruption of correct service. The management of system dependability risk is a whole new subject matter of its own that includes the principles and methods of risk evaluation, methods of collection and processing of data for risk management, risk level estimation, integral risk estimation and decision techniques based on the results of risk processing. Given the above, the areas of focus of the Dependability Journal should include a new one: Risk management. Theory and practice.

The theoretic and practical aspects of dependability and reliability subject to risk assessment attract the attention of many researchers both in Europe, US and Russia and, since recently, in Southeast Asia, China, India. Many useful findings and practical information have been collected. The inclusion of these findings in the activities performed by the Dependability contributors will improve the scientific and application value of the published papers and increase the citation of the Journal in international databases.

The Editorial Board of Dependability hopes to receive papers that summarize original findings and/or practical research by authors, as well as analysis of the latest achievements in the area of system dependability. The Journal welcomes reviews of research and engineering conferences and workshops dedicated to its subject matter.

To the Dependability contributors, we wish great creative achievements, good health and well-being.

Original article
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Ensuring the dependability of technical facilities through triplication and quadrupling

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Sergey F. Tyurin

Abstract. *Redundancy, e.g. structural redundancy, is one of the primary methods of improving the dependability, ensures failsafety and fault tolerance of components, devices and systems. According to the International Patent Classification (IPC), the class of systems and methods G06F11/18 is defined as «using passive fault-masking of the redundant circuits, e.g. by quadrupling or by majority decision circuits». Obviously, «fault-masking» masks not only faults, but failures as well. The majority decision circuits (MDC) in the minimal configuration implements a «2-out-of-3» choice. According to the above definition, such redundancy should not require a special decision circuit. However, that is not always the case. In cases when the resulting signal out of a quadruple logic is delivered to, for instance, an executive device, a «3-out-of-4» selection circuit is required anyway. Another dependability-improving solution is defined by class G06F 11/20, «using active fault-masking, e.g. by switching out faulty elements or by switching in spare elements». The word «active» is missing here, thus we have active and passive fault tolerance. The paper examines passive fault tolerance that uses triplication and quadrupling and compares the respective probabilities of no-failure.The Weibull distribution is used that most adequately describes dependability in terms of radiation durability under the effects of heavy ions. It shows that in a number of cases quadrupling has a lower redundancy than triplication. A formula is proposed that describes the conditions of preferability of quadrupling at transistor level.*

Keywords: *dependability, redundancy, triplication, quadrupling, failures, faults, failure rate.*

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Introduction

Redundancy, according to the new GOST [1] is "the method of guaranteeing the dependability of an item through the use of additional means and/or capabilities redundant as regards those minimally required for the performance of the desired function". Redundancy is especially important for systems whose operation is affected by radiation, e.g. spacecraft control systems. In this area the principle of radiation hardened by design (RHBD) is employed that involves, for example, triplication (triple modular redundancy, TMR) [2, 3]. Majority redundancy, whereas a failure or a fault are masked with no significant time expenditure, is indicated in the GOST [1]. However, the associated terms "passive" fault tolerance is not specified. Active, adaptive fault tolerance [4, 5] has a lower redundancy as compared to passive fault tolerance, but it requires procedures for supervision, diagnostics, reconfiguration that take significant time. In critical systems with relatively short time of operation, including those affected by radiation, majority redundancy of 300 percent or more is frequently used. At the same time, so-called quadrupling is also applicable. As it turns out, in some cases 300-percent redundancy can be more costly than 400-percent redundancy, if we take into consideration the required additional equipment that sometimes is not required in case of quadrupling. Let us examine the special features of such redundancy solutions.

Problem definition

Triplication involves "2-out-of-3" voting, i.e., in the binary case, the majority of entities. More generally, majority voting means the choice

$$(r+1)\text{–}out\text{–}of\text{–}(2r+1), \quad (1)$$

where r is the number of masked (countered) failures.

The probability of no-failure $P(t)$ for Weibull's exponential model [6] is as follows:

$$P_{(r+1)from(2r+1)}(t)=\sum_{i=0}^{r} C_{2r+1}^{i+1}\left\{e^{-\left[(2r+1)-i\right]\cdot\lambda\cdot t^{\alpha}}\cdot\left(1-e^{-\lambda\cdot t^{\alpha}}\right)^{i}\right\}, \quad (2)$$

where λ is the failure rate of one channel (the dimensionality is 1/h); α is the Weibull distribution coefficient, $1<\alpha<2$; t is the time of operation in hours; r is the number of countered failures (faults).

Thus, the redundancy for r failures (faults) by means of majority voted redundancy is described by formula

$$2r+1. \quad (3)$$

I.e. failures (faults) are countered in r channels out of possible $2r + 1$.

In case of quadrupling, one failure (fault) is countered in one of the 4 elements that can be regarded both as channels and, for instance, separate CMOS transistors.

A broader interpretation of such configuration requires the following redundancy

$$(r+1)^2. \quad (4)$$

In this case failures (faults) are countered in r channels out of possible $(r+1)^2$.

The probability of no-failure $P(t)$, if voting is not required, is as follows:

$$P_{(r)from(r+1)^2}(t)=\sum_{i=0}^{r} C_{(r+1)^2}^{i}\left\{e^{-\left[(r+1)^2-i\right]\cdot\lambda\cdot t^{\alpha}}\cdot\left(1-e^{-\lambda\cdot t^{\alpha}}\right)^{i}\right\}. \quad (5)$$

Let us examine formulas (1) to (5) taking into account the special features of various implementations of redundancy.

Theoretical part

In case of a "2-out-of-3" majority voted redundancy ($r = 1$) we have three channels and majority elements (ME) and obtain the structure diagram of dependability (Fig. 1).

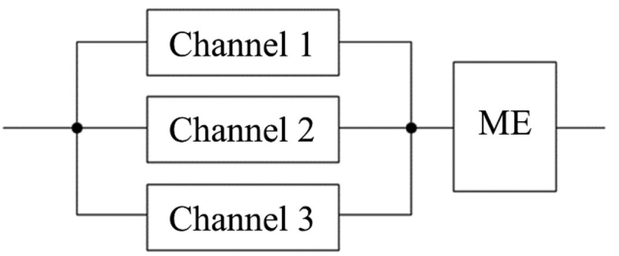


Figure 1. "2-out-of-3" majority voted redundancy

Given that the channel has n elements (e.g. transistors) and the complexity of ME is 12 transistors we obtain [7]:

$$P_{*3}=\left(3e^{-2\cdot(n)\cdot\lambda\cdot t^{\alpha}}-2e^{-3\cdot(n)\cdot\lambda\cdot t^{\alpha}}\right)e^{-(12)\cdot\lambda\cdot t^{\alpha}}. \quad (6)$$

For the purpose of countering failures (faults) in ME, let us obtain the structure diagram of dependability (Fig. 2).

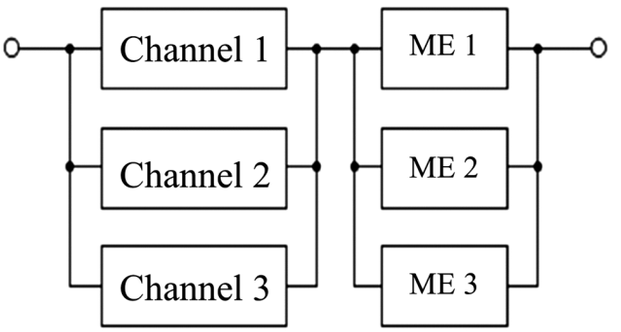


Figure 2. Majority voted redundancy

In this case we obtain:

$$P_{*33}=\left(3e^{-2\cdot(n)\cdot\lambda\cdot t^{\alpha}}-2e^{-3\cdot(n)\cdot\lambda\cdot t^{\alpha}}\right)\cdot\left(3e^{-2\cdot(12)\cdot\lambda\cdot t^{\alpha}}-2e^{-3\cdot(12)\cdot\lambda\cdot t^{\alpha}}\right). \quad (7)$$

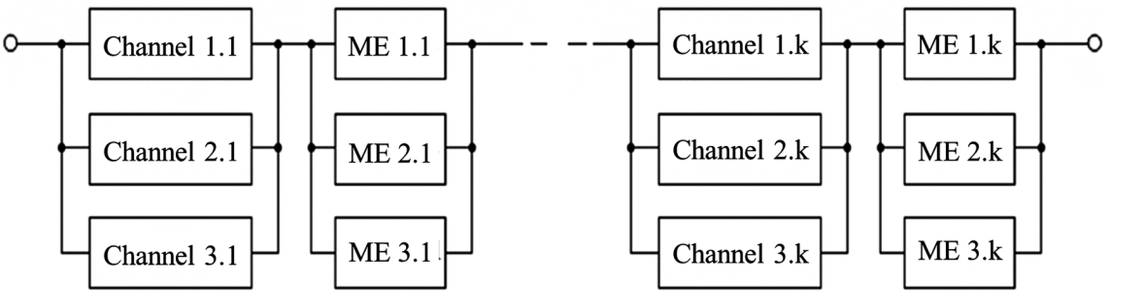


Figure 3. Deep majority voted redundancy

Furthermore, three power supplies are required. Thus, either the failure of one power supply, or the failure of one channel, or the failure of one majority element is countered.

"3-out-of-5" majority voted redundancy. Accordingly, five "3-out-of-5" majority elements are required:

$$P_{mvr}^{3\ oo\ 5}(t)=e^{-5\cdot\lambda\cdot t^{\alpha}}+5e^{-4\cdot\lambda\cdot t^{\alpha}}\left(1-e^{-\lambda\cdot t^{\alpha}}\right)+10e^{-3\cdot\lambda\cdot t^{\alpha}}\left(1-e^{-\lambda\cdot t^{\alpha}}\right)^{2}\cdot$$
$$\cdot\left[\begin{array}{c}e^{-5\cdot\lambda_{me.3/5}\cdot t^{\alpha}}+5e^{-4\cdot\lambda_{me.3/5}\cdot t^{\alpha}}\left(1-e^{-\lambda_{me.3/5}\cdot t^{\alpha}}\right)+\\+10e^{-3\cdot\lambda_{me.3/5}\cdot t^{\alpha}}\left(1-e^{-\lambda_{me.3/5}\cdot t^{\alpha}}\right)^{2}\end{array}\right]. \quad (8)$$

Majority voted redundancy that enables operation with one channel. In this case the system is capable of rearranging itself into a doubled configuration and further into a single-channel configuration, if necessary. That requires more complex additional equipment. Taking into account the additional equipment for reconfiguration (the failure rate is $\lambda_д$) we will obtain:

$$P_{mvr1}=\left[1-\left(1-e^{-\lambda\cdot t^{\alpha}}\right)^{3}\right]\cdot\left[3e^{-2(\lambda_{me}+\lambda_{o})t^{\alpha}}-2e^{-3(\lambda_{me}+\lambda_{o})t^{\alpha}}\right]. \quad (9)$$

Formula (9) does not take into consideration the probability of "oversight" in case real-time testing does not detect the failed channel.

The so-called **deep majority voted redundancy** involves "splitting" channels into k parts (Fig. 3).

Let us assume that λ, the failure rate of the entire channel, is split into k identical parts, then we obtain

$$P_{dm}=\left[3e^{-2\cdot n\frac{\lambda}{k}t^{\alpha}}-2e^{-3\cdot n\frac{\lambda}{k}t^{\alpha}}\right]^{k}\cdot\left[3e^{-2\cdot 12\cdot t^{\alpha}}-2e^{-3\cdot 12\cdot t^{\alpha}}\right]^{k}. \quad (10)$$

If n elements are quadrupled ($r = 1$), we obtain:

$$P_{4}(t)=\left[e^{-4\cdot\lambda\cdot t^{\alpha}}+4e^{-3\cdot\lambda\cdot t^{\alpha}}\left(1-e^{-\lambda\cdot t^{\alpha}}\right)\right]^{n}. \quad (11)$$

However, formula (10) only holds for restriction $(r+1)^2 \le q$ in connection with the Mead-Conway requirements [8] on the maximum number of series-connected transistors r in a circuit that cannot be more than q (before and after quadrupling).

Let n be the number of transistors (while observing the Mead-Conway restriction) and m be the number of the circuit's outputs. Then for $r = 1$ by comparing the quadrupling and triplication, we will obtain:

$$4n \le 3n+12m. \quad (12)$$

Otherwise, if the following formula is correct

$$1 \le 12\frac{m}{n} \quad (13)$$

quadrupling is not "costlier" than triplication.

In the case of channel quadrupling "3-out-of-4" voting is required, therefore we will obtain:

$$P_{4}(t)=\left[e^{-4\cdot n\cdot\lambda\cdot t^{\alpha}}+4e^{-3\cdot n\cdot\lambda\cdot t^{\alpha}}\left(1-e^{-n\cdot\lambda\cdot t^{\alpha}}\right)\right]^{n}\cdot$$
$$\cdot\left[e^{-4\cdot\lambda\cdot t^{\alpha}}+4e^{-3\cdot\lambda\cdot t^{\alpha}}\left(1-e^{-\lambda\cdot t^{\alpha}}\right)\right]^{m}. \quad (14)$$

Experimental part

With no regard to the probability of no-failure of the majority element we obtain the probability of no-failure of a majority system P_{mvr}^{2oo3} with a "2-out-of-3" selection:

$$P_{м.с}^{2\ из\ 3}=p^{3}+3p^{2}(1-p)=$$
$$=1-(1-p)^{3}-3p\left(1-p^{2}\right)=3p^{2}-2p^{3}. \quad (15)$$

Thus, for example, if $P = 0{,}9$ we obtain a significant increase:

$$P_{mvr}^{2oo3}(t)=3(0.9)^{2}-2(0.9)^{3}=0.972. \quad (16)$$

A "3-out-of-5" majority voted redundancy improves the dependability even more:

$$P_{mvr}^{3oo5}(t)=P^{5}+5P^{4}(1-P)+10P^{3}(1-P)^{2}. \quad (17)$$

For example,

$$P_{mvr}^{3oo5}(t)=(0.9)^{5}+5(0.9)^{4}(0.1)+10(0.9)^{3}(0.1)^{2}=0.99144. \quad (18)$$

With no regard to this additional equipment and majority elements, that can also be triplicated, in the case of majority voted redundancy that enables operation with one remained channel, we will obtain:

$$P_{mvr1}=P^{3}+3P^{2}(1-P)+3P(1-P)^{2}=1-(1-P)^{3}. \quad (19)$$

In this case the probability of no-failure reaches the value

$$P_{mvr1} = 1 - (0.1)^3 = 0.999. \quad (20)$$

Let us obtain in MathCad the time curves of comparison of the formulas for the probability of no-failure for a single-channel digital system $e^{-\lambda t}$ with majority voting redundancy of "2-out-of-3" (5) and "3-out-of-5" (7) (Fig. 4).

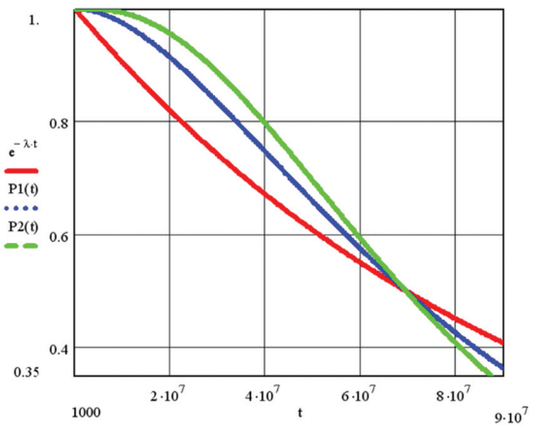


Figure 4. Comparison of a single-channel digital system $e^{-\lambda t}$ with a majority voted redundancy: "2-out-of-3" ($P_1(t)$, blue line), "3-out-of-5" ($P_2(t)$, green line) if $\lambda = 10^{-8}$, $\alpha = 1$

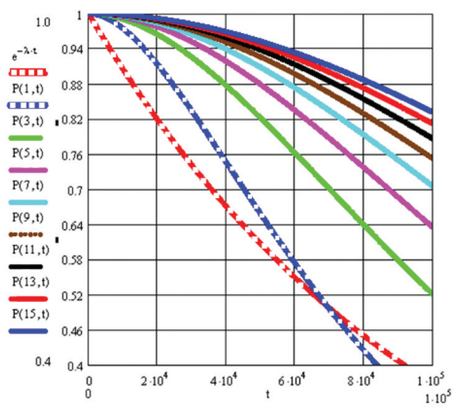


Figure 5. Probability of no-failure curves of a system without majority voted redundancy $e^{-\lambda t}$, with majority voted redundancy $P_1(t)$ and deep majority voted redundancy $P_k(t)$ (k layers, $k = 3, 5, 7, 9, 11, 13, 15$) if $\lambda = 10^{-8}$

We see that the majority voting redundancy "raises" the exponential curve beyond the point that corresponds to approximately a third of the time axis, but this causes a "slack" in the last third. After a certain value of time the probability of no-failure becomes less than 0.5 an the non-redundant configuration becomes better that a redundant one. It is clear that such probability should not be allowed to happen. Let us evaluate the deep majority voted redundancy (Fig. 5).

We can see that the deep majority voted redundancy considerably improves the dependability as the number of layers k grows.

If $\lambda = 10^{-5}$, $\lambda_{me} = \frac{\lambda}{\alpha_1}$, $\alpha_1 = 10$ we obtain the optimum for $k = 12$, $t = 10^4$ (Fig. 6, a). If $\lambda = 10^{-3}$, $\lambda_{me} = 10^{-5}$ we obtain the optimum for k = 100 (Fig. 6, b).

The cost of the system increases in comparison with ordinary majority voted redundancy:

$$C_m = 3(C_\lambda + C_{me} + C_{ps}), \quad (21)$$

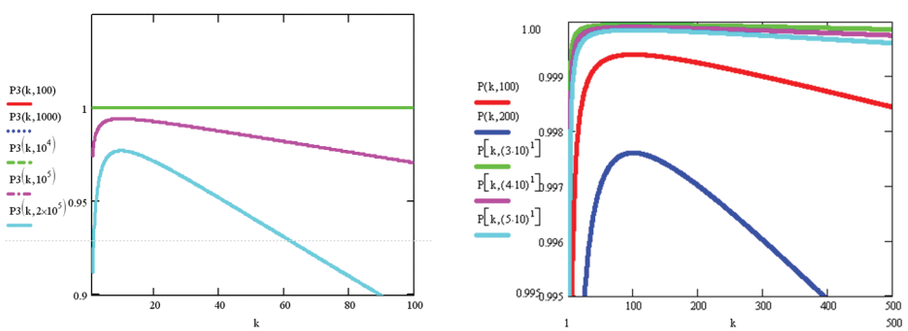
where C_λ is the cost of one channel, C_{me} is the cost of the majority element, C_{ps} is the cost of the power supply. The signal propagation delay only increases by the delay of one majority element τ_{me}. In (21), the growing complexity of routing is not taken into consideration. In case of deep majority voted redundancy, the costs are significantly higher:

$$C_{dm} = 3(C_\lambda + kC_{me} + C_{ps}), \quad (22)$$

while the signal propagation delay is increased by the delay k of the $k \cdot \tau_{me}$ majority elements. Normally, that is done if high dependability must be ensured, while the reduced performance is compensated by algorithmic methods.

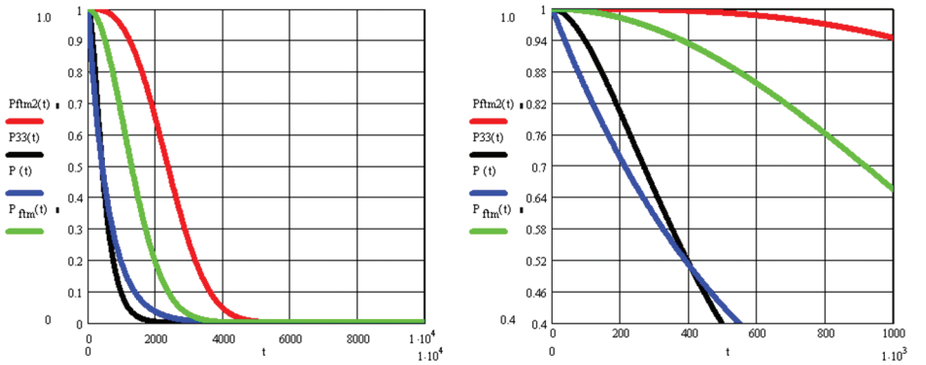
Let us obtain comparison graphs for transistor-for-transistor circuit quadrupling with majority voted redundancy. Countering a failure of any single transistor in each transistor configuration (each group of four transistors) requires quadruple redundancy [9] and is described with formula:

$$P_{fmt}(t) = e^{-(4)\lambda \cdot t} + 4 \cdot e^{-3 \cdot \lambda \cdot t}\left(1 - e^{-1 \cdot \lambda \cdot t}\right). \quad (23)$$



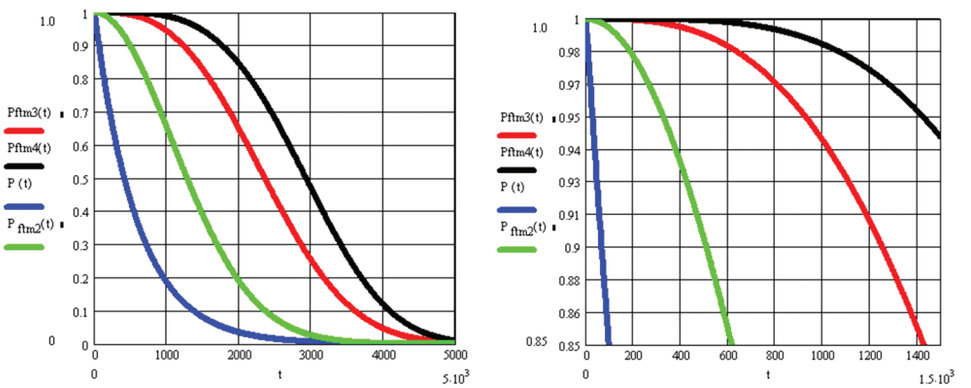
a) b)

Figure 6. Optimum of deep majority voted redundancy: a) $k = 12$, b) $k = 100$



a) b)

Figure 7. Change graphs of the probability of no-failure of a non-redundant circuit $P(t)$; a quadruple circuit that counters one failure $P_{ftm}(t)$; a triplicated circuit with three majority elements $P_{33}(t)$ and a circuit that counters two failures $P_{ftm}2(t)$ if the failure rate is 10^{-5} 1/h; a) within probability range from 1 to 0; b) within probability range from 1 to 0.4



a) b)

Figure 8. Change graphs of the probability of no-failure of a non-redundant circuit $P(t)$; a quadruple circuit that counters one failure $P_{ftm}2(t)$; a circuit that counters two failures $P_{ftm}3(t)$ and a circuit that counters three failures $P_{ftm}4(t)$ if the failure rate is 10^{-5} 1/h; a) within probability range from 1 to 0; b) within probability range from 1 to 0.4

Countering a failure of any two transistors in each transistor configuration requires nonuple redundancy and is described with formula:

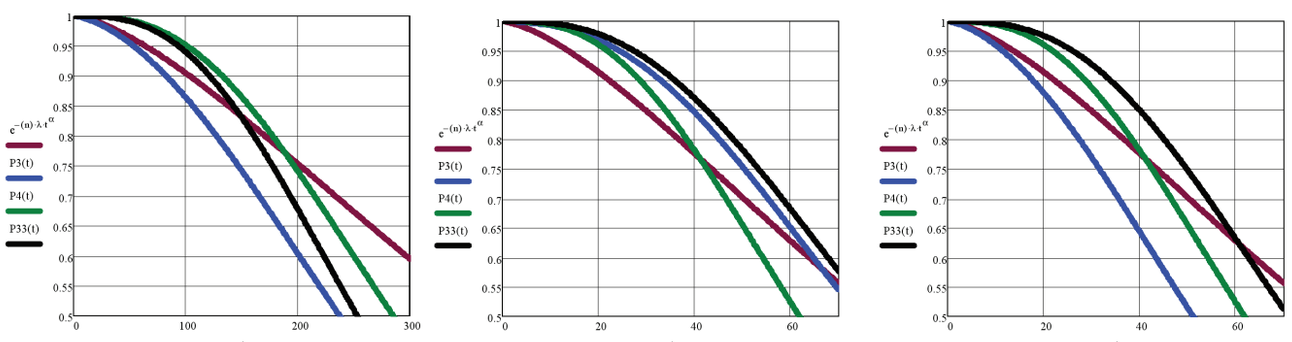
$$P_{fmt2}(t)=e^{-(9)\cdot\lambda\cdot t}+9\cdot e^{-8\cdot\lambda\cdot t}\left(1-e^{-1\cdot\lambda\cdot t}\right)+36\cdot e^{-7\cdot\lambda\cdot t}\left(1-e^{-1\cdot\lambda\cdot t}\right)^2. \quad (24)$$

The respective graphs are shown in fig. 7.

Countering a failure of any three transistors in each transistor configuration requires sixteen-fold redundancy and is described with formula:

$$P_{fmt3}(t)=e^{-(16)\cdot\lambda\cdot t}+16\cdot e^{-15\cdot\lambda\cdot t}\left(1-e^{-1\cdot\lambda\cdot t}\right)+$$
$$+120\cdot e^{-14\cdot\lambda\cdot t}\left(1-e^{-1\cdot\lambda\cdot t}\right)^2+560\cdot e^{-13\cdot\lambda\cdot t}\left(1-e^{-1\cdot\lambda\cdot t}\right)^3. \quad (25)$$

Change graphs of the probabilities of no-failure of a non-redundant circuit $P(t)$; a FCTLUT circuit that counters one failure $P_{ftm}2(t)$; a FCTLUT circuit that counters two failures $P_{ftm}3(t)$ and a FCTLUT circuit that counters three failures $P_{ftm}4(t)$ if n = 4 are shown in in fig. 8.



a) b) c)

Figure 9. Channel quadrupling: a) n = 10, m = 1; b) n = 100, m = 1; c) n = 100, m = 10

Comparison of channel quadrupling $P_4(t)$ with a non-redundant circuit and triplication $P_3(t)$; $P_{33}(t)$ is shown in fig. 9.

Conclusion

Quadrupling at transistor level is the most efficient solution in terms of designing radiation-resistant digital equipment. It enables higher probability of no-failure as compared to triplication throughout the timeframe. In some cases the redundancy of quadrupling is lower than that of triplication, if majority elements are taken into account. Countering any single failure in each transistor configuration requires quadruple redundancy. Countering any two failures in each transistor configuration requires nonuple redundancy that enables a higher probability of no-failure of a quadruple circuit, yet it is outperformed throughout the timeframe by a sixteen-fold redundant circuit that counters the failures of any three transistors in each transistor configuration whose implementation required sixteen-fold redundancy. Countering powers supply failures can be done by doubling it as part of a quadruple circuit, e.g. as it is proposed in [10].

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Problems of dependability and possible solutions in the context of unique highly vital systems design

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Aim. *The paper examines the problems caused by the conventional interpretation of dependability that prevent the practical use of dependability analysis (assessment) as a tool for engineers involved in the creation of unique highly vital systems and substantiates proposals for their resolution.* **Methods.** *The paper analyzes the problem of quantitative estimation of the dependability of unique highly vital systems without the use of probability statistical models. The view of dependability as a physical property of a product (as a result of changes in its internal state) allows – at the physical level – ensuring lasting capability to fulfil the required functions and quantitatively estimating the criteria of the required functions' performance, that can be defined by, for instance, specifying a set of parameters for each function that characterize the capability to perform, as well as the permissible limits of such parameters' variation. Such approach causes the requirement to take the origin of dependability into consideration and examine the causes of unlikely failures that are to be identified by means of additional analysis in parallel with calculations and experiments performed to support dependability. The solution to the problems of fuzzy terminology allows revealing the interrelation between the quality and the dependability, thus enabling – using the single information basis of design and process engineering solutions – the analysis, synthesis and assessment of the dependability of unique highly vital systems based on performance parameters without the use of probabilistic statistical models.* **Results.** *The solution of the above dependability-related problems allows ensuring dependability based on the physicality (causal connections) and physical necessity (consistency with the laws of nature) of the causes of failures. The dependability of unique highly vital systems must be ensured from the very early lifecycle stages based on consecutive execution of certain design, process engineering and manufacturing procedures, as well as application of engineering and design analysis of dependability, which also allows solving problems indirectly related to dependability, e.g. improving the quality and reducing the cost of the manufactured products.* **Conclusions.** *The paper shows that the application of design engineering methods for the dependability analysis (assessment) allows – within the framework of existing views, yet with certain corrections – solving dependability-related problems without the use of the mathematics of the classic dependability theory. High dependability can be achieved by the same ways as undependability comes about, i.e. through design and process engineering solutions. The analysis, substantiation of engineering solutions and specification of necessary and sufficient requirements for the manufacturing process allows achieving the target dependability by engineering means through higher quality of design and process engineering. If we regard dependability as a multiparametric property, parametric models of products can be developed that enable the evaluation of the temporal stability of parameter values using methods of individual design dependability and/or design engineering analysis of dependability. The principles of unity of the design concept and its implementation in manufacture enables the development of products and assessment of their dependability based on a single foundation, i.e. the design and process engineering solutions directly associated with the capabilities of a specific manufacturing facility.*

Keywords: *unique highly vital system, individual design dependability, design engineering analysis of dependability, ensuring dependability.*

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Introduction

There are two approaches to ensuring dependability of non-repairable products depending on the end goal of their use:

• some products are intended for failure-free operation during an indefinitely long period or for dependable performance of one-time operations/functions (their failure is undesirable or unacceptable);

• other products are intended to operate for a strictly defined time (warranty period), after which their operation *should be terminated* due to irreversible changes in the design or its parameters.

The first approach is used when creating highly vital unique products that are non-repairable or difficult to replace with new ones without serious financial and time costs, or the failure of which leads to a catastrophic breach of safety. Unmanned space vehicles or industrial nuclear facilities are examples of such products. The second approach is used when manufacturing single use (non-repairable) consumer goods (cars, household appliances, computers, gadgets, etc.) by programming their breakdowns (failures) immediately after the end of the warranty period in order to encourage sales. Some examples of programmable breakdowns are:

• an ordinary incandescent electric lamp should have an average warranty period of 1 000 hours, and today it is no secret that this is the result of a 1924 cartel agreement, when the largest manufacturers of electric lamps agreed for the first time to artificially limit the life of the incandescent lamps (they basically started manufacturing light bulbs of a degraded quality);

• at the same time, it is known that an experimental light bulb by Shelby Electric has been shining almost continuously since 1901 (more than 1.000.000 hours) at a fire station in Livermore, California, although its rated power of 60 W has since dropped to 4 W.

In the former case, when failures are unacceptable or undesirable, in order to ensure the required dependability, the products are made with structural reserve of working capacity. In the latter case, when failures are expected and allowed, a certain probability of maintaining the stability of the performance parameters by the end of the warranty period is ensured. In both cases, the dependability of products is characterized by failure-free operation, but it has a different physical meaning. In the former case, failures are not planned or implied, and in the latter case, they are not excluded, but rather planned, however they are allowed with a frequency of occurrence not exceeding a predetermined value.

For products that are considered only at the ultimate limiting state, these approaches differ in terms of choice of safety factors and safety margins that allow achieving the required dependability by varying them (programming breakdown or, on the contrary, making it unlikely). Strength calculations in the first approach are carried out by deterministic methods based on the mechanics of deformable solids, while in the second approach it is carried out by probabilistic statistical methods based on the probability theory and mathematical statistics.

If a product is in two or more limiting states, dependability calculations in second approach are carried out in probabilistic statistical setting using phantom elements method [1]. The modern dependability theory does not provide the answer to calculating dependability in the first approach, when a product can simultaneously be in several limiting states and at the same time should have dependability close to one, even though solving such problems in some cases is of critical practical importance, for example, for unique highly vital systems [2-8].

The paper examines the problems caused by the conventional view of the dependability that prevents the practical use of dependability analysis (assessment) as a tool for engineers involved in the creation of unique highly vital systems/products and substantiates proposals for their resolution.

Problem 1: How to calculate dependability without failure statistics? First of all, it should be noted that it is fundamentally impossible to create dependable products without studying certain characteristics and properties of materials, as well as units and components. Of course, it would be useful to have at least some failure statistics, if it is possible to obtain any. However, the question is whether it is necessary to conduct statistical tests before failure (without building probabilistic statistical models) in order to create products with specified dependability indicators.

Terminological definition apart, in regard to its semantic meaning dependability is something that will not let you down, something you can rely on for a long time. Fail-free operation speaks for itself, it is a manifestation of operation without accidents. There is no conceptual difference between dependability and fail-free operation with regard to non-repairable products: in both cases there should be *continuous operation without failures within a given time interval.* Now let us consider the terminological definition of GOST 27.002–2015, according to which dependability is the "ability of an object to fulfil the required functions in time…". With this definition of the term "dependability", a question (and even a problem) obviously arises, i.e. how to calculate *continuous fulfilment of the functions within a given time interval* (without failure), which (meaning functions) also need to be defined. For lack of anything better, the solution of a purely physical problem, i.e. the quantitative estimation of the property *to continuously fulfil specified functions over time,* was transformed through inversion into the solution of a mathematical problem, i.e. counting the events that reflect facts of not being able to fulfil the functions (failures). With this approach, it is not hard to register failures as events (without getting into the specifics of functional performance criteria or their number). Moreover, failures can be statistically analyzed, and the probability of their occurrence can be calculated

for any given time interval based on the statistical data acquired. Thus, instead of studying dependability as a physical property (as a result of changes in the internal state of an object), which ensures *continuous fulfilment of the functions within a given time interval,* dependability assessment has been reduced to studying *undependability,* a model in which failures are a priori possible (predefined). Eventually, studying actual causes of failures was reduced to studying their effects, i.e. failures as the results of events the causes of which are not always known. This approach is clear and convenient for mathematicians, but has neither sense nor value for engineers, since it is not clear how to use dependability calculations for making and analyzing real technical solutions.

As a result, a rather common notion appeared: dependability can only be quantitatively estimated by probabilistic statistical analysis of the failures of technology in operation, based on "reference data on the dependability of components and elements of an object, data on the dependability of similar objects ..." (GOST 27.002–2015). Meanwhile, the definition of the term "dependability" does not set any limitations on this matter. For example, according to the GOST there is no reason why dependability cannot be defined qualitatively (alternatively), if there is a way to ensure the "*ability to fulfil functions over time*" on the physical level and quantitatively estimate criteria of the required functions, which "*can be defined, for example, by setting for each function a set of parameters, characterizing the ability to perform it, and permissible limits for changing of these parameters' values*". After all, quantitative estimation of dependability is required when comparing different products with each other or a particular product with established development goals to evaluate their efficiency. However, this is not always necessary, for example, in the case of a unique production equipment, that cannot be compared to anything (the point here being to ensure the specified performance parameters during the service life). But without quality assurance of dependability (combined with specifying and justifying performance indicator values), it is impossible at the physical level to create a dependable product. At the same time, it is not always possible to accurately quantify dependability (logical and mathematical relations and dependences between quality assurance of dependability and its quantitative measure remain unknown without information on failure statistics). Meanwhile, the probabilistic statistical approach to dependability is firmly rooted in the GOST series Dependability in technics in the following forms: a restrictive list of products, to which statistical approaches can be applied, list of dependability indicators, standardized methods for determining (monitoring) dependability and dependability calculation methods etc. At the same time, it is quite obvious that any given quantitative requirement for dependability will be automatically met if the "*ability to fulfil functions over time…*" is provided on the physical level so that *the parameters characterizing the ability to perform them would certainly lie within the permissible limits of such parameters' variation* (as required by the GOST). Thus, the problem of calculating dependability as *continuous operation within a given time interval* centers around establishing the parameters of the structure's operation and justifying their values lying within permissible limits, not only (and not so much) around obtaining and processing statistical data on the products' behavior during operation.

Problem 2: Should the genesis of dependability be taken into account? The predominance of the probabilistic statistical approach in quantifying dependability resulted in a situation when, willingly or otherwise, "a blind eye is turned on" the genesis of dependability. Since the physical nature of any particular product's creation becomes somewhat unimportant, what is "important" is how its possible failures correspond to the chosen mathematical model. As a result, the focus of attention shifts from making and implementing specific engineering solutions to a model of products' behavior in operation (when it, unfortunately, becomes almost impossible to alter a poor decisions).

To fully realize how deeply the probabilistic statistical interpretation of dependability (or rather, undependability) is rooted in the regulatory documentation, let us take a look at GOST R 56526–2015, where an example of calculation of the dependability indicators of a single (small-batch) production unmanned space vehicle (USV) is preceded by the following hypothesis: "***It is assumed that*** *at the initial moment of time (the moment of the beginning of operating time calculation), the USV is in the up state...*". It is a rather strange situation: a highly vital product is made in only one copy, but instead of making sure that the product is 100% operational, it is **assumed** to be so with some probabilistic statistical behavior model (where would it come from for a one-of-a-kind product) with questionable distribution parameters being applied (operation is carried out in the space environment, and therefore it is, by definition, difficult to obtain experimental data with the necessary level of trust).

On the other hand, when an existing mathematical model has to be adjusted to a real physical object, assumptions and schematization of physical states and processes are always used and then are balanced out (adjusted) by selecting the model's parameters (that is the foundation engineering calculations). These parameters are selected based on a long-term observation and research practice. When it comes to unique highly vital products, for which there cannot be any reliable statistics, the assumption that the product is operational before the start of operation (i.e., that there are no fundamental errors in the technical documentation or manufacturing defects) is at least controversial. In the case of batch products that means "turning a blind eye" to the fact that the developer or manufacturer, like all people, can make mistakes. These mistakes lead to any product having a heredity of failures long before the start of operation, which can manifest itself in the

course of operation. Moreover, each stage of the product life cycle, starting with the preparation of the design and operational requirements, has a certain degree of criticality of hereditary factors due to the probability of loss of function, while the heredity itself is subject to the laws of realization. As shown in [5, 9], the conditional reliability of products defined by the failure heredity factors, has a tendency to accumulate before the end of the design stage, reaching its local maximum, and to spend starting from the stage of preproduction engineering, reaching a certain local minimum by the time of operation. That minimum should be taken as the initial conditions in the development of highly vital products.

It is important to understand that any development testing is a sort of quasi-operation (usually carried out under tougher conditions compared to normal operation) that is performed on a limited number of test objects (for financial and economic reasons). This suggests that for the purpose of justifying the target reliability the sample size may simply not be sufficient for evaluation of the test results with the required level of confidence (even given the tough testing). That is due to the fact that in the course of operation a combination of product technical statеы, operating modes, external loads and effects may occur that was not covered or technically infeasible during simulation at the testing stage.

Hence is the task of identifying and eliminating the potential hazard of improbable failures at the early stages of unique highly vital systems development. That can only be achieved by considering the genesis of their dependability [5, 9].

Problem 3: How to prevent improbable failures? The conclusion that the performance demonstration during testing does not guarantee the absence of failures during operation directly follows from the total probability formula

$$R(t)+Q(t)=1. \qquad (1)$$

Obviously, the dependability function $R(t)$ in formula (1) is defined by the up state of an object, while the failure (undependability) function $Q(t)$ is defined (similarly to the dependability function) by the *fallible state* of the object. If not proven otherwise, an object by default can simultaneously be in two states at any moment in time: up state and fallible state. For some reason, this obviously and important fact is not reflected in the dependability terminology (the concept of "*fallible state"* is not used in the regulatory documentation).

An important conclusion follows from (1): any methods for performance parameter calculation and product testing with limited sampling provide only a certain extremum of the dependability function $R(t)$ (which is not known in advance). This is a consequence of the ever-present uncertainty of the total probability's second component, the failure function $Q(t)$ that characterizes the occurrence of improbable events. For example, failure statistics for USV deployable structures [9] shows that, in practice, the existing modern computational and experimental methods allow achieving a dependability level of no more than 0.996 (while the acceptable requirement is at least 0.999). Therefore, in no case dependability can be evaluated (even indirectly) based on positive results of computational and experimental testing. It can only be argued that, for example, the successful experimental development (including flight tests) showed that the product demonstrated its performance n times successively.

If the specified dependability level $R(t) > \underline{R}$ has to be demonstrated, objective evidence must be provided to prove that

$$Q(t) < 1 - \underline{R}. \qquad (2)$$

The fulfillment of condition (2) obviously cannot be confirmed only by computational and experimental identification of the performance parameters.

Thus, for highly vital systems, the *direct* methods of confirming the specified level of the failure function (non-dependability) (2) must be used in addition to the computational and experimental demonstration of the performance parameters. The easiest solution is to carry out dependability tests, however, for financial and economic reasons they are not acceptable for costly highly vital one-of-a-kind products. All that is left to do is perform additional analysis to identify improbable failures, which should be carried out in parallel with the computational and experimental performance assurance (preferably with the use of a single data base). That requires the appropriate methodological framework for such analysis, which is not yet provided for in the regulatory documentation on dependability.

Problem 4: Fuzziness of dependability terminology. We are not even talking about the term "dependability" (its functional and parametric definition [6, 9 – 11]) that did not become clearer with the introduction of the new standard GOST 27.002–2015. In view of the above, it is much more important and useful to consider the term "up state". It is the author's opinion that one of the main problems of dependability of unique highly vital systems lies in the fuzziness of this term's definition. Let us put aside the vague definition in the new standard and assume that its essence has not changed with the introduction of the notes (clarifications), and therefore we can use a clearer definition of the term from the repealed standard. Thus, up state is *"a state of an object, in which the values of all parameters characterizing the ability to fulfil the specified functions comply with the requirements of regulatory and technical and/or design (project) documentation"*. In other words, in order to identify the up state one must not only identify "*the values of all parameters…"*, but also make sure that each of these parameters complies with "*the requirements of regulatory and technical and/or design (project) documentation"*, which should be timely speci-

fied there in advance (not after the failures occur, but at the end of the documentation development).

Here, the author sees semantic inconsistencies at the system methodology level. It is quite clear that in order to manufacture and operate a product in accordance with the design documentation (this particular documentation, not some "other documentation", as the new standard GOST 27.002–2015 interprets, since *design documentation* ***alone*** can be the basis for the manufacture of a product), it should contain all the necessary and sufficient requirements. Moreover, in order to develop error-free design documentation, the engineer must determine all the necessary and sufficient design parameters that characterize the ability to fulfil the specified functions, demonstrate the values of the chosen parameters and establish necessary and sufficient requirements for the manufacture that strictly correspond to the chosen design parameters. Not being able to perform any of these actions and/or to establish their criteria may lead to failures. However, these highly important concepts (how to identify all the necessary and sufficient parameters and ensure that they are relevant to the established requirements) are not reflected in any way in the terminology or in other provisions of the "Dependability in technics" series of standards.

Moreover, it is clear that in order to fulfil the specified functions, the values of a structure's design parameters must lie within the permissible limits during operation, ensuring its up state. It is also obvious that a state when the parameters' values are at the boundaries of the permissible range is a limit state; and a state when the parameters' values are outside of the permissible range is beyond the limit (disabled state). The transition of the parameters' values across the boundaries of the permissible range is called a failure. Thus, the limit state is determined by the formula

$$X_{lim} = \begin{cases} \overline{X} \\ \underline{X} \end{cases}. \tag{3}$$

From (3) follows the formula of the up state:

$$\underline{X} \le X \le \overline{X}. \tag{4}$$

From (3) – (4) follows the formula of the disabled state, which leads to failure:

$$X \in \left\{ \left(X < \underline{X} \right) \vee \left(X > \overline{X} \right) \right\}. \tag{5}$$

Formulas (3) – (5) clearly show that the concept of "limit state" not only plays a key role in determining the durability property (as interpreted by modern dependability terminology), but it is also directly related to dependability in general and, first and foremost, to fail-free operation.

Problem 5: How quality and dependability are related. Today, there is a firm understanding – at the level of regulatory documents – that quality among other things is characterized by dependability indicators. In other words, dependability is an integral part of quality. However, this is not quite so [3, 9]. Quality, as well as all its lower level properties, is determined by the relations of things in the form of collocation, interconnections and interactions, i.e. in the current state. At the same time, these relations themselves have a tendency to change over time, and it is this property that we call dependability. It characterizes in time the quality of products and, accordingly, each of the properties of quality individually.

With the definition of the term "operation" (GOST 22487–77) being a process of manifestation of the required properties in accordance with a given algorithm, the expression (4) can be interpreted as a formula for the quality of a product in up state. Thus, the dependability formula is

$$\underline{X} \le X(t) \le \overline{X}. \tag{6}$$

In a parametric form, formula (6) can be written as follows:

$$X(t) \in D = \left\{ X_i(t) \middle| \underline{X}_i \le X_i(t) \le \overline{X}_i ; t \in \left[\underline{t}, \overline{t} \right]; \forall i = \left[1, \overline{n} \right] \right\}, \tag{7}$$

where D is the domain, inside which the general dependability parameter $X(t)$ lies.

Taking into account (6) – (7), full dependability can be calculated as follows[1]:

$$R(t) = P\left\{ X(t) \in D; t \in \left[\underline{t}, \overline{t} \right] \right\} \tag{8}$$

Formula (7) conforms with the definition of the term "dependability" according to GOST 27.002 (old and new editions), and formula (8) conforms with the conclusions of the general dependability theory for mechanical systems of V.V. Bolotin [12].

The connection between quality (4) and dependability (6) is naturally determined using the dependence [9]

$$X = \lim_{\Delta t \to 0} X(t + \Delta t). \tag{9}$$

Formula (9) shows that dependability is a continuous function of time, and quality is some kind of a point locus on a dependability function curve. There is no "frozen" quality (inherent to the product once and for all), it constantly changes over time due to physicochemical processes, and it is exactly in relation to this change that quality is characterized by dependability. Quality can be identified at any fixed moment in time, for example, by means of direct or indirect measurements of product parameters with non-destructive testing. Dependability cannot be measured, it can only be predicted based on calculations (8) or by identifying the probability of each of the parameters' values being within a given range (6)

$$R_i(t) = P\left\{ \underline{X}_i \le X_i(t) \le \overline{X}_i ; t \in \left[\underline{t}, \overline{t} \right] \right\}. \tag{10}$$

[1] R – Reliability (dependability); P – Probability

For products with a serial connection of critical elements (if their parameters are independent in terms of dependability), full dependability with regard to (10) is calculated using the formula

$$R(t) = \prod_{i=1}^{n} R_i(t). \quad (11)$$

Solutions to the considered problems of dependability. Formulas (6) – (11) allow analyzing and synthesizing dependability by performance parameters, which makes it possible to move away from probabilistic statistical approaches and move on to ensuring dependability based on physicality (laws of cause-and-effect relationships) and physical necessity (non-contradiction to the laws of nature) of failure causes.

Analysis and synthesis of dependability by performance parameters (at least for highly vital products) should be obviously carried out taking conditions (1) – (2) into account. In order to do so, a full parameterization procedure is performed, during which the drawing and technical documentation is presented in the form of column vector of performance parameters characterizing the full functionality of the product structure in the following form

$$X = \left(X_1, X_2, \ldots, X_i\right)^{\mathrm{T}} \ \forall i = \left[1, \overline{n}\right]. \quad (12)$$

Column vector (12) is the basis of the parametric representation of the structure (7) and does not take into account the differences in ranking (for example, the frequency of events: never, rarely, frequently) and/or in significance (for example, the severity of malfunction: significant, insignificant, critical, catastrophic) between possible failures as events not being able to fulfil specified or intended functions (this is the only way improbable failures can be identified). The construction of the column vector in practice is done by performing successively the following procedures of dependability engineering and design analysis (DEAD) [4, 7-9]:

• identify functions that ensure the performance of the structure, which must be taken into account when making engineering decisions, and identify failures as hypothetical situations that interfere with the fulfilment of each of the functions in question;

• identify causes, directly leading to failures, which occur, exist and develop in environmental conditions as a combination of environmental factors and operating modes, taking the worst possible combinations into account;

• determine the properties of critical structural elements, which make each of the failure causes impossible (the failure causes are countered by the prescribed properties of the corresponding critical elements);

• each of the properties of critical elements is quantified using parameters (indicators), which ultimately belong to the desired column vector (12).

After the column vector is determined, the D (7) domain is defined. For that purpose, each parameter (indicator) is assigned a range of its permissible values based on the development (product design from the customer's point of view, specified requirement) and structural design (product design from the developer's point of view, implied requirement) requirements specification.

Then, dependability is calculated by formula (8) or (11), using stochastic methods to evaluate whether parameters' values of the structure lie within the permissible range (for example, individual design dependability method [13], which takes into account individual statistical characteristics of the parameters' distribution under specific production conditions). The other way is to ensure performance parameters margin by design so that they would fall in a given range with a permissible confidence level (for example, DEAD [4, 7-9]). The dependability calculated in this way shows how much the selected performance parameters comply with the requirements of the technical specification for dependability (basically, this is the expected or design dependability).

It should be noted that with a proper choice of the performance parameters margins (when DEAD is used), the expected dependability is $R(t) \equiv 1$. In order to translate this dependability into practice, error-free design and technical documentation should be developed, and critical defects should be eliminated at the production stage. For that purpose, DEAD provides certain procedures for verification of parameters' compliance with specified requirements in regulatory, design and technical documentation, as well as compliance control procedures. Dependability calculations are adjusted based on the results of these procedures, and final conclusions on the compliance with the dependability requirements are made [4, 7-9].

Thus, not only the dependability problems listed above are solved, but also some problems beyond the dependability.

Problem 6: Why doesn't the quality management system always guarantee quality and dependability? A quality management system (QMS), for example, ISO 9001 is a set of procedures (methods of carrying out activities), which allow converting drawing and technical documentation into an end product during the manufacture in strict accordance with the established requirements.

QMS can be visualized as millstones. If you add grain, you get flour; if you add garbage, you get the same garbage. The reason is that there are no formalized procedures that would separate (sort the "grain" from the "garbage") correct (sufficient) requirements from incorrect (insufficient) ones. Obviously, technical quality management procedures (that are rarely mentioned in the present day) should be applied together with the QMS procedures formalized in the ISO 9001 standards.

The DEAD procedures, namely parameterization (12); substantiation of parameters' values being within the permissible range (4) and (6); regulatory and technical documentation requirements definition; verification of parameters' compliance with specified requirements, fulfil a function of technical quality management [4; 7-9].

Problem 7: How does dependability affects development costs? It is generally believed that the development costs directly depend on the values of the specified dependability indicators (it is assumed that heavy expenses are the price paid for high dependability). This seemingly obvious connection is in fact a delusion in some way. If we proceed from mathematics, then everything seems to be true. According to the classic concepts of the dependability theory [14], the lower one-sided confidence limit for estimating the probability of failure-free operation when conducting a series of tests without failures is calculated by the formula:

$$\hat{P}_{н} = (1-\gamma)^{1/n}. \qquad (13)$$

From (13) it follows that, for example, with a dependability confidence level of $\gamma = 0.9$, the demonstration of no-failure operation $P = 0.9$ will require a minimum of $n = 22$ independent tests of homogeneous products; if $P = 0.99$ $n = 230$; if $P = 0.999$ $n = 2302$; if $P = 0.9999$ $n = 23025$. Hence the conclusion that with each "extra" nine the development cost should increase by an order of magnitude. However, such "accounting approach" is not always reasonable in real life, because, according to (6) – (12), future production costs can be significantly and effectively reduced at the earliest stages of the life cycle by developing error-free design documentation (with mandatory use of DEAD) and organizing defect-free manufacturing by QMS methods, for example, ISO 9001.

Moreover, this early stage failures prevention technology is fully consistent with the well-known "tenfold cost rule" (if there is an error at one of the stages of the product life cycle, which was detected at the next stage, fixing it will cost 10 times more than if it was detected on time).

Conclusion

The application of design methods for the dependability analysis (assessment) allows – within the framework of existing views, yet with certain corrections – solving dependability-related problems without the use of the mathematics of the classic dependability theory. High dependability can be achieved by the same ways as non-dependability comes about, i.e. through design and process engineering solutions. The analysis, substantiation of engineering solutions and specification of necessary and sufficient requirements for the manufacturing process allows achieving the target dependability by engineering means through higher quality of design and process engineering.

If we regard dependability as a multiparametric property, parametric models of products (statistical, mathematical, physical, virtual or digital) can be developed that enable the evaluation of the temporal stability of parameter values using methods of individual design dependability [13] and/or DEAD [4, 7-9]. The principles of unity of the design concept and its implementation in manufacture enables the development of products and assessment of their dependability based on a single foundation, i.e. the design and process engineering solutions directly associated with the capabilities of a specific manufacturing facility.

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Refinement of the engineering practice of evaluation of the wear rate of excavator implement components

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Abstract. *The existence of humankind on Earth largely depends on the energy at its disposal. It is mostly generated by processing minerals extracted from the Earth's crust by open-cut mining. The quality and low cost of extraction are largely defined by the dependability of employed machines and mechanisms, plants and process engineering solutions. Various types of excavators are the backbone of a mining machine fleet. Their parts that principally interact with the environment (rock) are components of implements, i.e. primarily the buckets and components of bucket(s). It must be noted that in the process of interaction with the environment (rock) the excavator implements and their components are exposed to so-called abrasive wear. Since abrasive wear of implement components (most frequently excavator bucket teeth) causes their recurrent replacement, this inevitably affects the performance of the excavator as a whole and those process flows it is part of. Occasional interruptions of operation and repairs reduce the availability factor, the most important complex indicator of equipment dependability. Given the above, the aim of this paper is to refine the previously known formula proposed more than thirty years ago in VNIISDM (Reysh A.K.) for evaluation of the rate of abrasive wear of excavator bucket teeth. For the first time, with a sufficient accuracy we examined the multitude of operating modes of mining equipment, i.e. operation of excavators in various conditions, e.g. on different soils. Additionally, we extended Reysh's approach from single-bucket machines to continuous operation multi-bucket ones. For that purpose, the authors used a method of data integration from known sources, method of full-scale experiment under the operating conditions of a specific excavator and method of mathematical simulation (a form of the Monte Carlo method). All of that allowed revising the values of the parameters in the Reysh formula. The refined formula that we obtained can now be used for the dependability evaluation of machines operating under varying conditions, as well as for the purpose of appointing the time of preventive inspections.*

Keywords: *wear, wear rate, bucket wheel excavator, bucket teeth, mine rock, operating modes.*

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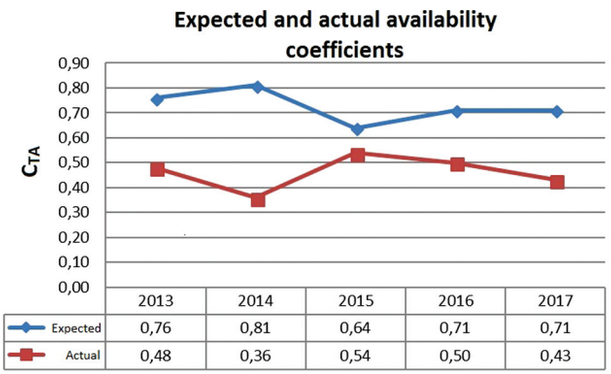
Relevance and state of the art. Stable development of Russia's fuel and energy industry directly depends on the reliable and productive operation of the existing manufacturing chains, starting from single mining machines to plants and ultimately high technology power station equipment. The primary task of open pit mining was and is to ensure convenient, complete and cost-efficient access to mineral resources. For that purpose, various machines, plants and processes are used.

For the sake of specificity, this paper considers the SRs(k)-4000 continuous operation bucket wheel excavator (Germany) in operation for many years in Krasnoyarsk Krai (Nazarovskoe brown coal field).

Figure 1 shows the graph of the expected C_{TA} availability coefficients of the above equipment. It is evident that the actual dependability indicator does not reach the expected value, which indicates the requirement to develop and implement measures to as quickly as possible correct this negative situation.

It is known that the availability of machines for use in time is largely ensured by reliable operation of all units and mechanisms [1 – 5 and many others]. Failure analysis shows that most idle hours of any excavator (including the one under consideration) are associated with the recovery of the implements, more specifically the replacement of worn-out bucket teeth. That is confirmed by Fig. 2. The main factor causing failures of bucket teeth (Fig. 3) and their components is abrasive wear (Fig. 4).



	2013	2014	2015	2016	2017
Expected	0,76	0,81	0,64	0,71	0,71
Actual	0,48	0,36	0,54	0,50	0,43

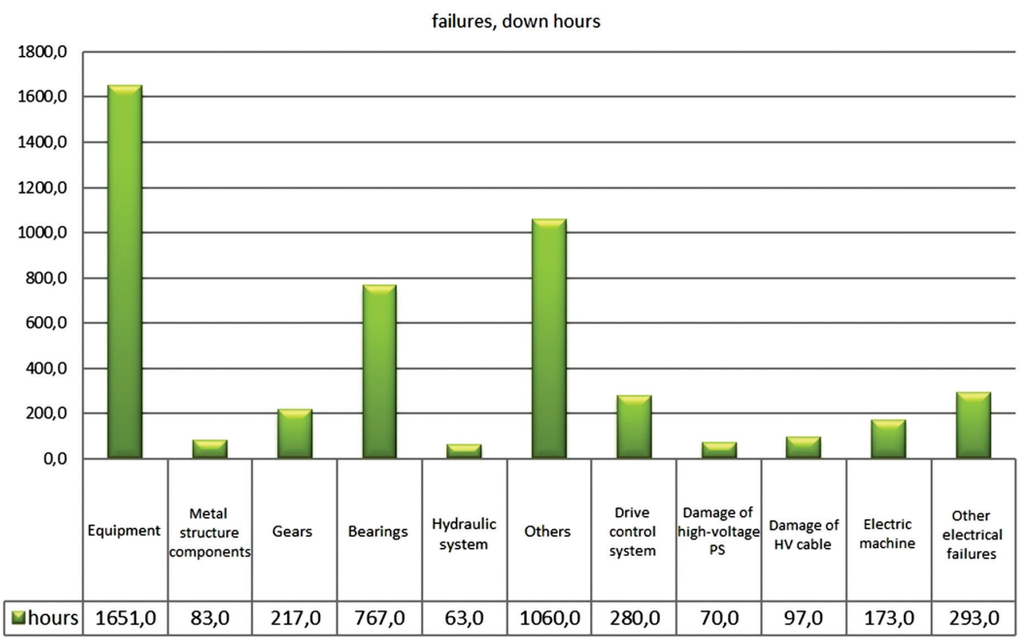
Figure 1. Expected and actual availability coefficients of the SRs(k)-4000 excavator

Abrasive wear is the subject of many research papers (a sufficiently good pre-1980 study can be found, for example, in [6]).

The works of Khrushchiov M.M. [7 and many others], Kragelsky I.V. [8 and many others], Drozdov Yu.N. [9 and many others] and Kostetsky B.I. [10 and many others] are now considered among the most fundamental studies of abrasive wear.

Figure 3. Bucket of a bucket wheel excavator

As regards mining and construction vehicles, the following well-known experts were involved with this subject



	Equipment	Metal structure components	Gears	Bearings	Hydraulic system	Others	Drive control system	Damage of high-voltage PS	Damage of HV cable	Electric machine	Other electrical failures
hours	1651,0	83,0	217,0	767,0	63,0	1060,0	280,0	70,0	97,0	173,0	293,0

Figure 2. Diagram of failure distribution of excavator components in 2013 – 2017

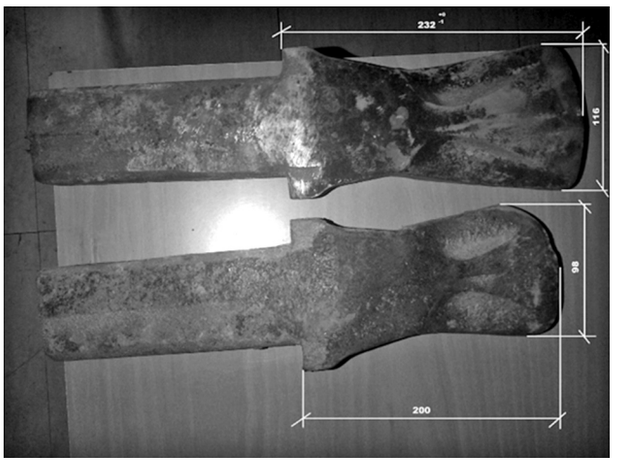


Figure 4. SRs excavator tooth before (above) and after (below) use

matter in its various aspects and in different time periods: Abezgauz V.D. [11 and others], Akilev S.A., Banatov P.S., Baron L.I., Bogolyubov B.N. [12 and others], Valova L.S., Vetrov Yu.A. [13 and others], Vinogradov V.N., Glatman L.B., Goryushkin N.N., Grinberg N.A., Dombrovskaya I.K., Evdokimov Yu.A., Zimin A.I. [14 and others], Zorin V.A., Ikramov U. [6, 15 and others], Kabashev R.A., Kovalchuk V.A., Kolesov V.G., Kokh P.I., Larionov V.P., Leshchiner V.B., Lifshits L.S., Lvov P.N., Metlin Yu.K., Novikov I.V., Papić L. [16 and others], Petrov I.V., Pristaylo Yu.P., Reysh A.K. [17 and others], Smorodinov M.I., Solod G.I., Sorokin G.M., Tenenbaum M.M. [18 and others], Tkachiov V.N. [19 and others], Toropov V.A., Faddeev B.V., Frolov P.T., Kharach G.M., Chudakov K.P., Shreyner L.A., Yampolsky G.Ya. [20] and many others.

However, despite extensive research conducted in the area of abrasive wear, many practically important problems are yet to be resolved.

Thus, still unsolved is the problem of evaluation of wear rate of excavator implement components, i.e. bucket teeth and their components [see for example, 17, 21 – 26 and many others].

In [17], written over thirty years ago, its author proposes an empirical formula to estimate the wear rate of excavator teeth. However, due to the large number of empirical coefficients whose values were not known to the author, it was impossible to be used (out of all practically interesting approaches that we know of this one appears to be the most advantageous).

This paper is dedicated to changing this negative situation.

Theoretical foundations. On the refinement of the Reysh formula [17]. In [17], the author proposed a formula for estimation of a bucket tooth service life as follows:

$$t_{\text{H}} = \frac{U_D}{\gamma}, \qquad (1)$$

where U_D is the allowed wear of the tooth (for the purpose of engineering calculations it is normally recommended to take this parameter as half or its working length); γ is the wear rate that was proposed to be estimated using an empirical formula as follows:

$$\gamma = (A \cdot P \cdot C_{p0} \cdot C_{vp0} \cdot f \cdot s \cdot t_{\text{D}} \cdot C_{\text{y}} \cdot C_{\text{ABR}} \cdot \frac{1}{C_{\text{WEAR}}}) \cdot C_{t20}, \qquad (2)$$

where A is the proportionality factor; P is the pressure on the tooth's working surface; C_{p0} is the coefficient that takes into account the effect of changing pressure; C_{vp0} is the coefficient that takes into account the effect of the frequency of pressure change; f is friction coefficient; s is the tooth's rubbing path; t_D is the duration of digging; C_U is the coefficient that takes into account tooth dulling; C_{ABR} is the soil abrasion factor; C_{WEAR} is wear resistance coefficient; C_{t20} is the coefficient that takes into account the ambient temperature.

As formula (2) shows, its successful application requires a significant amount of experimental data. A part of this data is known with sufficient accuracy for engineering calculations (P, f, s, t_{D}, C_{U}, C_{ABR}, C_{WEAR}, C_{t20}) [2, 6-19, 22-26 and many others], for some parameters only the possible ranges of values are known (C_{p0}, C_{vp0}), while for parameter A no data is known as of today (that the author of [17] openly states).

Thus, understandably common engineers cannot use formula (2) (let us note that the author of this formula also allowed an unfortunate inaccuracy in the dimensionality). A research is to be done in order to identify the values coefficient A can take (to at least understand the order of magnitude).

For that purpose, we propose to rewrite formula (2) in a more convenient, in our opinion, form:

$$\gamma = A \cdot C_1 \cdot C_2 = A \cdot \prod_{j=1}^{m} C_j \cdot \prod_{i=1}^{k} C_i, \qquad (3)$$

where $C_1 = \prod_{j=1}^{m} C_j$ is the first generalized wear coefficient not depending on the machine's operating mode that, obviously, equals to the product of a number of coefficients (f, C_{ABR}, C_{WEAR} and C_{t20}); $C_2 = \prod_{i=1}^{k} C_i$ is the second generalized wear coefficient that depends the machine's operating mode that also obviously equals to the product of a number of other coefficients (P, C_{p0}, C_{vp0}, s, t_{D}, C_{U}).

This new notation allows, if necessary, considering individually the behavior of groups of empirical coefficients and more accurately take into account the operational specifics of the individual excavators.

Let us note that for the above-mentioned excavator we know both the range of values of teeth wear and the extreme values of the coefficients of equation (2) for specific operating conditions.

Then, using the previously conducted experimental research, we will estimate the possible values of coefficient A in accordance with the obvious formula:

$$A = \frac{\gamma}{C_1 \cdot C_2}. \qquad (4)$$

Table 1. Coefficients among the second generalized wear coefficient

C_p0	$C_{vp}0$	s, m	t_D, s	C_U*	P, MPA
1	2	3	4	5	6
0.6 – 3	0.6 – 1.54	5 – 10	3600	1.088 – 1.132	0.1 – 2.0

* this parameter is identified using formula [17]: C_U=1+0,44·U, where U is the projection of wear surface (normally from 0.2 to 0.3 m).

Table 2. Coefficients among the first generalized wear coefficient

f	C_{ABR}	C_{WEAR}	C_t20
1	2	3	4
0.25 – 0.8	0.7 – 6.6	1.0 – 2.1	C_{t20}=(0.05…0.08) ·t_F*

* the t_F parameter is the actual temperature within the range from -60 to +50 degrees Celsius (in our opinion it must be modulo, excluding the value equal to zero).

Table 3. Distribution of excavator operation time per type of soil and some of their characteristics

Type of soil	Average portion of operation time, p_i	Specific weight of soil, ρ, t/m^3	Friction coefficient, f	Ground abrasion factor, C_{ABR}
1	2	3	4	5
Peat	0.15	0.8 … 1.2*	0.25	0.7
Loams	0.25	2.04	0.30	1.66
Silt	0.1	1.8 … 2.0*	0.25	1.0
Aleurolites	0.1	2.04 … 2.15	0.50	1.0
Clay	0.15	2.03	0.35	1.2
Argillaceous sandstone	0.25	2.4	0.30	6.6
	Σp_i=1,0**			

* the precise value significantly depends on the humidity.

Tables 1 and 2 show the initial data for calculation.

Accounting for operation in different modes. Some of the above coefficients depend on the type of soil. In order to more accurately take account for this factor subject to a specific excavator's operating conditions based on its operational dependability data we created the so-called generalized series that takes into consideration the multi-mode nature of the product's operation. That is due to the fact that during the period of operation in question the SRs(k)-4000 bucket wheel excavator worked on various soils.

Table 3 contains a number of characteristics of the operating conditions of the excavator in question that are required for the creation of the above generalized series. We made it based on the expert estimations and analysis of known literature.

Let us note that data per the coefficients were collected for each of the modes.

Further, for each i-th mode, using formula (3) individual wear rate γ^i was identified taking into account the data from the tables. Since wear-related degradation damage accumulates all operating modes, applying the above formulas requires estimating the average wear rate $\overline{\gamma}$ taking into account the generalized series information from the tables.

The average rate $\overline{\gamma}$ is expressed as the quotient of the total distance by the total time, while the distance U_Σ is the amount of total wear, mm:

$$\overline{\gamma} = \frac{U_\Sigma}{T} = \frac{1}{T}\sum_{i=1}^{k}\gamma^i \cdot T \cdot p_i = \sum_{i=1}^{k}\gamma^i \cdot p_i, \qquad (5)$$

where T is the total operation time; k is the number of operating modes under consideration.

Let us note that while deriving formula (5) we used obvious formulas of the form t_i=T·p_i, where t_i is the operation time in the i-th mode and $U_\Sigma = \sum_{i=1}^{k} U_i = \sum_{i=1}^{k}\gamma^i t_i$.

Thus, it can be stated that the average wear rate under time-specific apportionment of operating modes is the arithmetical value of the modes subject to portions p_i.

Regarding coefficient *A*. Under the time T, h, known from the full-scale experiment the possible numerical values of the proportionality coefficient A are identified based on the above formulas and tables.

Our average estimate of the coefficient was: $A = 8.1\cdot10^{-8}$ 1/(PA·h) provided that γ has the dimensionality of m/h.

Nevertheless, as the dependability theory goes [27, 28 and many others] point estimation alone does not suffice. In order to estimate the confidence intervals per parameter A, assuming that all the required parameters (some of which, let us remember, are within the above ranges) that, obviously, generally are stochastic, have normal distribution

with average values corresponding with the middles of the intervals and given variation coefficients, let us use the Monte Carlo method [29 and many others] (an example is given in [30]).

As the result, in calculating the distribution of constant A with 90% variation for several variables the confidence interval for A under the assumption of normal distribution of the values from the above tables according to preliminary calculations is $6{,}8\cdot10^{-8}$… $1{,}2\cdot10^{-8}$.

The calculations were performed in the R programming environment [35]. An example of application is in [36].

Conclusion. Based on both the experimental data we obtained regarding the operation of a bucket wheel excavator under various operating conditions over a long period of time and taking into account out analysis of the available literature we estimated the coefficient in the formula used for calculation of the wear rate.

At the same time, we evaluated the accuracy of the results.

In conclusion, we can state that now the Reysh formula can be successfully used in the assignment of inspections, repairs and replacements, as well as for the analysis of the effect of the operational factors (optimization goals can be set in a way similar to that described in [31], in particular, taking into account the economic criteria).

Additionally, now we can set and subsequently successfully solve the problem of spare parts and tools optimization in respect to mining excavators and in individual repair units, for example in the way proposed in [32].

Obviously, the applicability of the Reysh formula is a significant contribution to the design of the method of prediction, maintenance and, as far as possible, improvement of the dependability of quarry mining machines ([33] can be cited as an example).

In conclusion let us note that although the study was conducted on a specific excavator operated under specific conditions, the generality of the findings will not be lost as the conditions of the Nazarovsky mine and Krasnoyarsk Krai as a whole are quite typical in terms of such machines' operation in Russia. The conditions of Ukraine or Kazakhstan and other regions will possibly require the data presented in this paper to be refined.

We will continue the respective activities both in terms of further refinement of the values of coefficient A and examination of other types of excavators. The methods of collection and processing of expert information will also be essentially improved (based, for example, on [34 and many others]).

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The effect of the structural composition on the resilience of pipeline systems to node damage

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Abstract. *The* **Aim** *of this paper is to study the effect of the structural features of pipeline systems on the development of emergency situations by the mechanism of progressive blocking of transportation nodes. The blocking of an individual point element of a system is considered as the result of simultaneous failure of all the pipelines converging into the node. The process of progressive blocking of a certain set of nodes of a pipeline system in random order is called a progressive blocking. The development of progressive blocking is associated with the disconnection of the consumers from the source of end product and is a dangerous scenario of emergency development. The system's resilience against progressive blocking is estimated by the resilience indicator F_x, the average share of the system's nodes whose blocking in a random order causes the disconnection of all consumers from the source of the end product.* **Methods of research.** *The values of $0 \le F_x \le 1$ were identified by means of computer simulation. After each fact of damage associated with a random blocking of an individual node, the connection between the source and consumers of the end product was established. The statistical characteristics of the process of progressive blocking were evaluated according to the results of repeated simulation of the procedure of damage of the analyzed network structure. In general, the structure of a pipeline system is characterized by a graph that describes the connections between point elements. The valence of an individual graph node is the number of edges that converge into it. Similarly, the valence of the respective network node is the number of converging linear elements (pipelines). Furthermore, an important characteristic of an individual node is the composition of the converging linear elements. Thus, the set of a system's linear elements includes the following varieties that ensure the connection between: the source and the consumer (subset G1), two consumers (subset G2), a consumer and a hub (subset G3), two hubs (subset G4), the source and a hub (subset G5).* **Results.** *The author analyzed and examined the effect of the structural characteristics on the ability of pipeline systems to resist the development of emergency situations through the mechanism of progressive blocking of nodes. It was established that with regard to structural optimization the most pronounces positive effect associated with the increase of the values F_x is observed as the valence of the source node grows and additional linear elements of subset G1 are included in the system.* **Conclusions.** *The process of progressive blocking of pipeline transportation system nodes is a hazardous development scenario of an emergency situation. The most efficient method of improving pipeline system resilience against progressive blocking consists in increasing the valence of the source node and inclusion of additional linear elements of subset G1 in the system. Structural optimization of pipeline systems should be achieved by defining the values F_x for each of the alternatives with subsequent adoption of a substantiated design solution.*

Keywords: *pipeline, system, resilience, damage, node, structure, blocking, optimization.*

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Introduction. Pipeline transportation systems are used in various industries for the purpose of delivering raw materials and end products to consumers [1-3]. The highest potential hazard is associated with the processing and delivery of toxic, flammable, explosive substances. Efficient operation, dependability and operational characteristics of such complex technical systems depend both on the properties of individual structural elements and the specificity of their interaction [4-7].

Transition into the state of non-operability of individual pipelines negatively affects the process capabilities of transportation systems and their operational efficiency [8]. The highest hazard to an operational system is associated with the process of node damage. That is due to the fact that normally several linear elements converge at a single node. In this context, damage (blocking) to a node means simultaneous failure of all the pipelines converging into it.

If in an emergency situation a system's nodes are progressively blocked in a random order, such scenario is called progressive blocking.

The development of emergency situations in the form of progressive blocking of nodes is associated with rapid degradation of the system's properties and can cause complete interruption of the end product's delivery to all consumers.

The ability of a system to resist the development of progressive blocking of nodes is characterized by the resilience indicator F_x [9]. Resilience indicator $0 \le F_x \le 1$ represents the average share of a transportation system's nodes whose blocking in a random order causes the complete disconnection of all consumers from the source of the end product. For the specified structure of a transportation system the value F_x is established by means of simulation [10]. The closer F_x is to one, the higher is the analyzed system's resilience against the development of progressive blocking.

The **Aim** of this paper is to study the effect of the structural features of pipeline systems on the development of emergency situations by the mechanism of progressive blocking of nodes.

Computer simulation of progressive damage to various network structures allows identifying the following specifics and patters of the process.

1. Any network structures of pipeline transportation systems with equal numbers of nodes and equal numbers of end product consumers are comparable regardless of the number of the linear elements they include.

2. The increasing number of linear elements in a system is associated with growing values of the resilience indicator F_x, however, this effect is manifested to different degrees and depends on the structural features of the analyzed object.

In the general case, the structure of a pipeline transportation system is described with a marked-out graph that clearly shows the existing connections between individual point elements. The number of edges that converge into a node is called valence that is a characteristic of each node [11]. Similarly, the number of pipelines converging into an individual transportation node is further considered to be its valence. Additionally, a system is characterized by the set of linear elements G that is divided into 5 subsets whose designations are shown in Table 1 [12].

As the blocking of an individual transportation node causes immediate transition into the state of non-operability of all connected pipelines, we should assume that the number of linear elements in the node is its characteristic that affects the development of the progressive damage process.

Table 1. Characteristic and designations of subsets of the transportation system's linear elements

Designation of subset of linear elements	Nodes of the transportation network connected by linear elements out of different subsets
$G1$	product source – consumer
$G2$	consumer – consumer
$G3$	consumer – hub
$G4$	hub – hub
$G5$	product source – hub

If, as part of solving the synthesis problem, an additional linear element is included in the system, such structural variation causes increased valence of two transportation nodes at once. Thus, a change in the valence of any node of the system in the process of structural synthesis should be

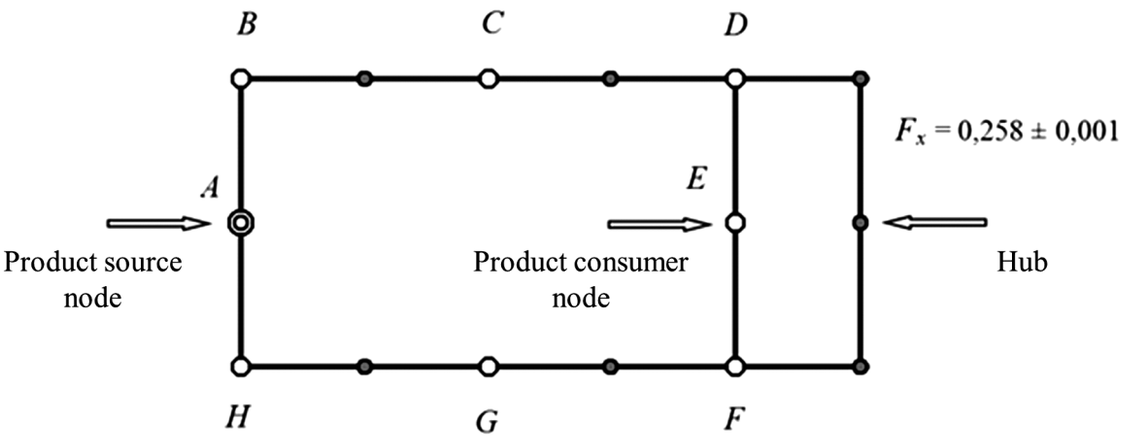

Figure 1. Structure diagram of a pipeline transportation system

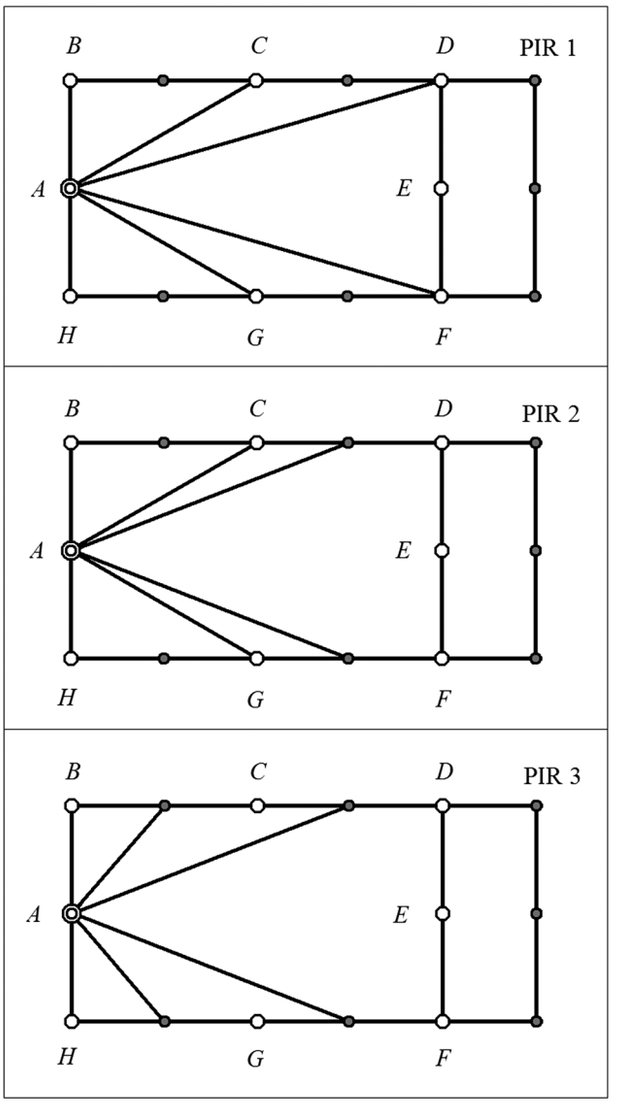

Figure 2. Derivative network structures with increased valence of the source node

examined subject to the observed changes in the valence of the other associated node.

The analysis of the effect of the valence of the transportation nodes on the resilience of network structures against the development of the progressive blocking process is of practical interest and requires additional research. Identifying such patterns involves selecting appropriate network structures and substantiating the associated computational schemes.

In this context, let us examine the basic structure diagram of a pipeline system shown in Figure 1. The analyzed facility includes the source of end product *A*, that is a point element with valence of 2, as well as 7 consumers of end product *B*, *C*, … *H*.

Let us increase the valence of the source node 3 times. For that purpose, let is include 4 additional linear elements into the basic object. The above elements may be part of subsets *G*1 and *G*5 and their inclusion in the system will increase the valence of not only the source node, but other nodes as well.

Structure diagram variants PIR1 to PIR3 with an increased valence of the source node *A* are shown in Figure 2. All the mentioned objects are comparable and their characteristic and results of calculation of the values of F_x are shown in Table 2. As we can see, the most pronounces positive effect associated with the increase of the valence of the source node is observed when linear elements of the subset G1 are added to the system. If the number of elements of subset *G*1 decreases at the expense of elements of subset *G*5, the value of the resilience indicator F_x decreases as well.

Thus, the valence of the source node should be increased primarily by including additional linear elements of the subset *G*1 into the system. In this case the achieved positive effect is most pronounced.

Now, using the base structure diagram, let us increase 3 time the valence of the consumer node *E* as it shown in Figure 3. The characteristics of derived structure diagrams designated PIR4 to PIR6, as well as the modeling results of progressive blocking of nodes are shown in Table 2. As we can see, the most pronounces positive effect associated with the increase of the valence of the source node is observed when linear elements of the subset *G*2 are added to the system. As they are gradually replaced with elements of subset *G*3 the system's resilience against progressive blocking of nodes decreases.

Table 2. Characteristics of derivative network structures

Network structure designation	Number of linear elements belonging to different subsets converging at the valence node 6, pcs					Resilience indicator, F_x	Correlation of values of F_x for the derivative and basic structures
	*G*1	*G*2	*G*3	*G*4	*G*5		
PIR1	6	0	0	0	0	0.374±0.001	1.45
PIR2	4	0	0	0	2	0.348±0.001	1.35
PIR3	2	0	0	0	4	0.339±0.001	1.31
PIR4	0	6	0	0	0	0.320±0.001	1.24
PIR5	0	4	2	0	0	0.316±0.001	1.22
PIR6	0	2	4	0	0	0.302±0.001	1.17
PIR7	0	0	0	6	0	0.294±0.001	1.14
PIR8	0	0	2	4	0	0.304±0.001	1.18
PIR9	0	0	4	2	0	0.307±0.001	1.19

Let us now examine the effect of the hub's valence on the resistance of a network object to progressive damage. For that purpose, let us increase 3 time the hub's valence using elements of subsets *G*3 and *G*4 as it is shown in Figure 4. The characteristics of thus synthesized structures are also shown in Table. 2. As we can see, the minimal increase in the values of F_x is observed when only elements of subset *G*4 converge at the hub.

Thus, based on the results of performed analysis is was established that there are three types of point elements of systems whose growing valence to different degree affects the increase in the values F_x.

Thus, the most pronounces positive effect associated with the increase of the valence of the source node is observed when linear elements of the subset *G*1 are added to the system.

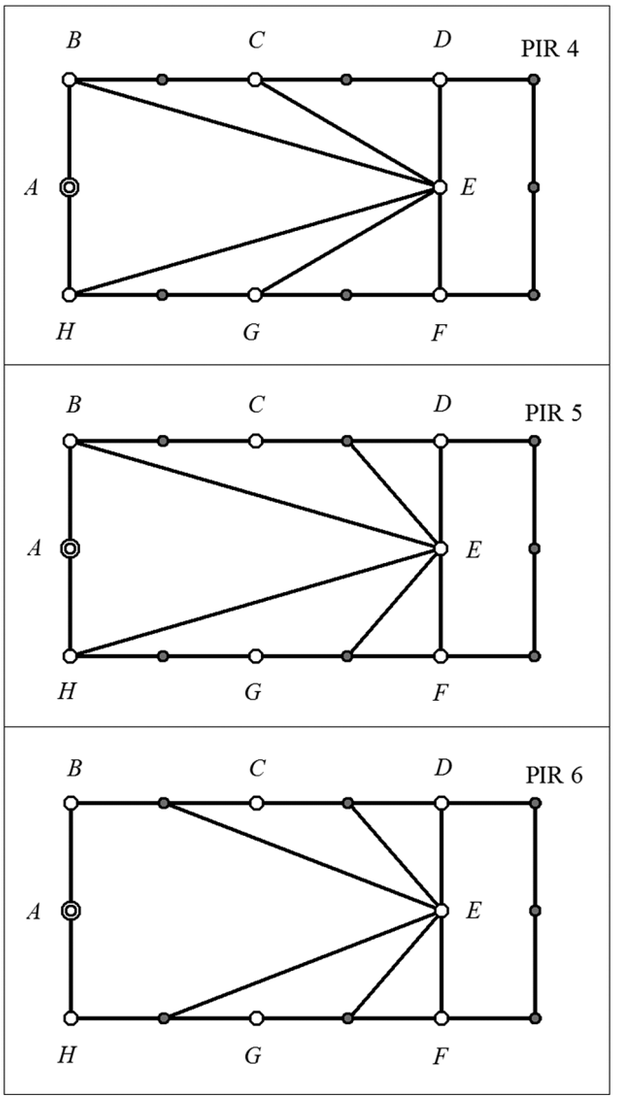

Figure 3. Derivative network structures with increased valence of the consumer node

The least increase of the values of F_x is observed as the valence of the hubs grows and additional linear elements of the subset *G*4 are included in the system.

The increasing valence of consumer nodes has an intermediate effect on the growth of the resilience indicators of network structures against the development of the progressive blocking process.

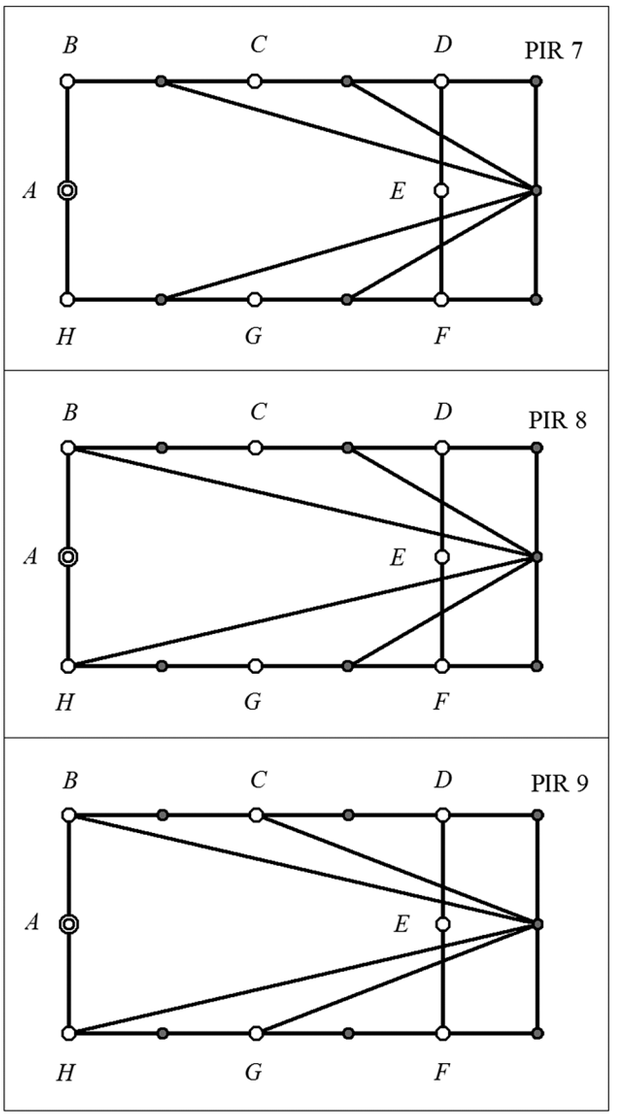

Figure 4. Derivative network structures with increased valence of the hub

Obviously, with regard to problems of structural synthesis the inclusion of additional pipelines into a system is always costly. Therefore, in practical terms, it is important to enable the required level of resilience of network structures to the development of the progressive blocking processes by adding the minimal possible number of linear elements into them.

Then, the most efficient method of improving pipeline transportation system resilience should consist in the inclusion of a small number of linear elements of the subset *G*1.

As an example, let us examine the structure diagram of a pipeline system designated TTR1 shown in Figure 5a.

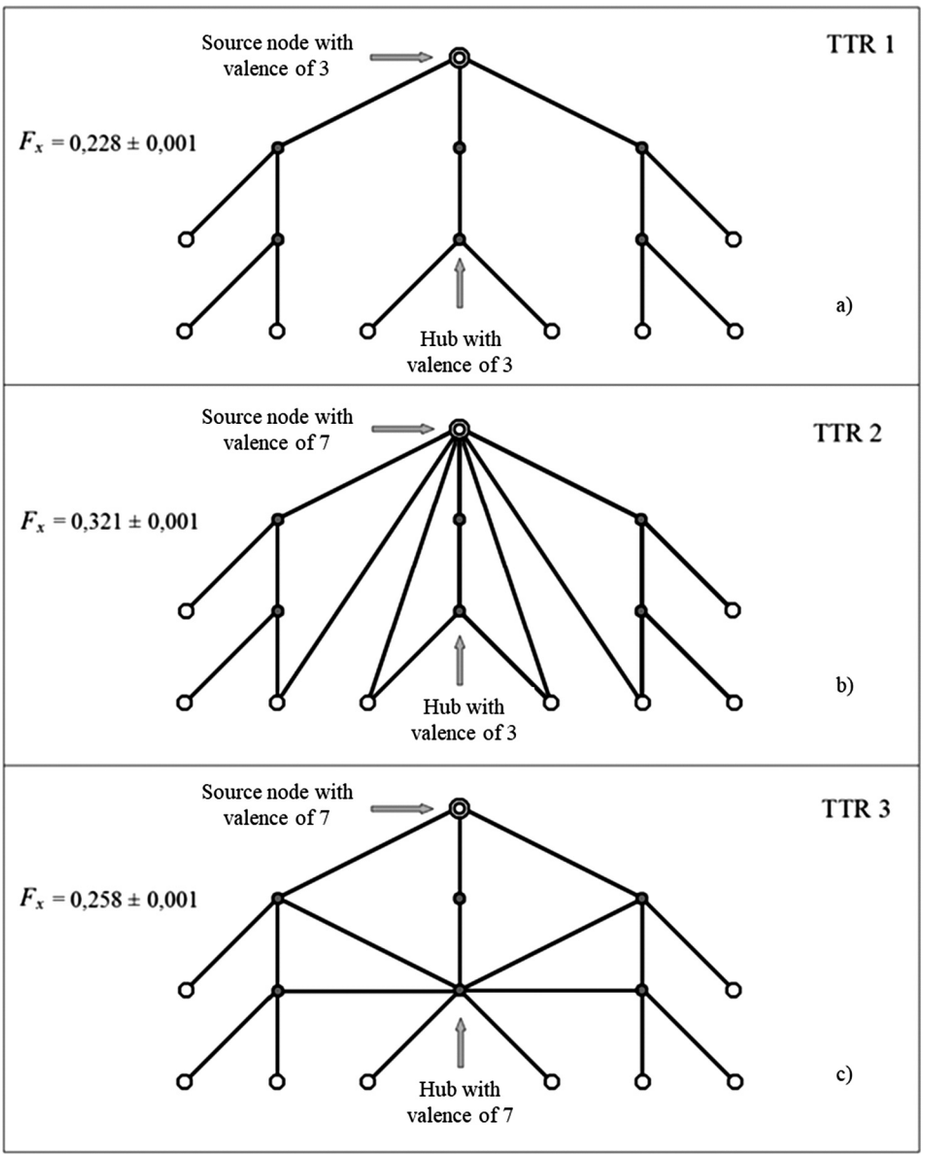

Figure 5. Structure diagram of a basic pipeline system (a) and derived structures with increased valence of the source node (b) and the hub (c)

Let us assume the solution of the synthesis problem is associated with planned inclusion of 4 linear elements into such base object. If the valence of the source node is increased by 4 out of elements of subset $G1$, thus synthesized structure diagram TTR2 will take the form shown in Figure 5b.

Now, let us increase the valence of the hub of TTR1 by adding 4 linear elements of subset $G4$. Thus, obtained derived structure TTR3 has the form shown in Figure 5c.

Taking into account the previously obtained results, it should be assumed that solution shown in Figure 5b will be close to the best, while the one shown in Figure 5c will prove to be one of the worst. The expected values of the resilience indicator for each of the above variants of derived network structures are shown in Figure 5.

As we can see, the value of F_x identified for the version shown in Figure 5b exceeds the value of the resilience indicator of the structure shown in Figure 5c approximately 1.24 times.

Thus, the results of the calculations confirm the earlier assumption regarding the expected properties of synthesized network structures.

Conclusions

1. The process of progressive blocking of pipeline transportation system nodes is a hazardous development of an emergency situation, as each fact of blocking is associated with the simultaneous transition to the state of non-operability of all the pipelines converging to the node.

2. The most efficient method of improving pipeline system resilience against progressive blocking of nodes consists in increasing the valence of the source node and inclusion of additional linear elements of the subset $G1$ in the system.

3. Structural optimization of pipeline systems should be achieved by defining the values of F_x for each of the alternatives with subsequent adoption of a solution that enables the highest level of resilience against the development of progressive damage processes.

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Method of improving the functional dependability of the control systems of an unmanned aerial vehicle in flight in case of failure in the onboard test instrumentation

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Abstract. *The* **Aim** *of this paper consists in the development of a method of improving the functional dependability of the control systems of unmanned aerial vehicles (UAV CS) affected by electromagnetic effects in flight and failures within the functional component of the onboard test instrumentation (OBTI).That is achieved through the identification of the failed functional element, the functional component of OBTI, the capability of performing the target objective of the UAV CS and decision-making regarding the initiation of the flexible operation algorithm. The existing and future UAV CS under development use binary reliability models, i.e. two states are distinguished: up and disabled. Therefore, each in-flight failure is classified as the UAV CS failure regardless of the current mission. If we regard a CS as a multifunctional system, it becomes obvious that the failure of not any UAV CS functional element causes flight termination.* **Methods.** *Solving the problem involved the use of a CS diagnostic model in the form of binary relations between the control actions and combinatorial subsets of functional elements, risk of losses estimation method as part of improving the functional dependability of UAV CS in flight, decision theory and combined branch-and-bound method. The mission performance probability is used as the efficiency criterion. This criterion is applicable when changes in a UAV CS' characteristics cause only partial reduction of the functional efficiency.* **Results.** *The purpose of OBTI self-supervision is failure location with the depth that allows determining its ability to perform the basic operations with the probability not lower than required by the customer, as well as the allowed set of elementary checks (EC) in this case. Based on the current results of elementary self-checks (ESC), one of the following decisions can be taken: stop the checks and discard OBTI; continue location; stop failure location and continue UAV CS mission per modified algorithm. At each stage of failure location in OBTI, based on the results of ESC, the area of covering check (ACC) and part of set suspected of failure (PSSF) are analyzed, which includes verifying the ACC for sufficient coverage of the PSSF, based on which appropriate decisions are taken. The following areas are formed: the area of observable data (processes of changes in the ACC and PSSF areas), within which the decision is taken to continue the checks, and the area, within which it is finally decided to terminate the checks. If it is decided to continue the failure location, another ESC is selected, which is associated with the risk of loss. The probability of false discarding of OBTI due to ESC selected out of ACC is taken as the risk of loss. The moment of termination of OBTI self-supervision depends not only on the set of decisions, but their sequence as well. Thus, the task at hand comes down to designing the optimal ESC strategy that minimizes the probability of false discarding. The idea of combined branch-and-bound method (CBBM) as part of the design of the optimal OBTI self-supervision algorithm consists in the consecutive selection at each stage of ESC implementation process, out of the subset of minimum risk checks of the next ESC till a one-element subset is obtained and/or the corresponding decision is taken.* **Conclusions.** *The developed method allows continuing the performance of the target objectives of a UAV CS in flight when affected by failures in OBTI.*

Keywords: *unmanned aerial vehicle, control system, self-supervision, combinatory subsets of elements, part of set suspected of failure, binary diagnostic model, probability of false discarding, combined branch and bound method, risk of loss.*

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Introduction

In terms of the employed technological solutions, today's unmanned aerial vehicles (UAV) can be described as complex technical systems. The inclusion of a control computer (CC) into the control system (CS) enabled a significant extension of UAV functionality and missions. Not only the supervision and diagnostics functions were implemented onboard, but the flight of UAV was made completely automatic. Successful application of UAV depends on the reliable operation of all onboard systems. UAVs often operate in adverse electromagnetic environments caused by the presence of many characteristic external and internal factors [1, 2, 3]. That caused increased failure rate in UAV CS. The UAV CS [4, 5] consists of onboard test instrumentation (OBTI), its self-supervision system (SSS) and onboard mission equipment (OBE). The existing and future UAV CS under development use binary reliability models, i.e. two states are distinguished [4, 5]: up and disabled. Therefore, each in-flight failure is classified as the UAV CS failure regardless of the current mission. In this case the UAV interrupts mission performance and returns to the launch site (airfield) for the purpose of identification and replacement of the failed component. The replacement addresses either the failed unit or a line replacement unit.

However, if we regard a CS as a multifunctional system, it becomes obvious that the failure of not any UAV CS functional element [6, 7, 8] causes the impossibility of further mission performance. Thus, the unequal significance of the failures of different functional elements of UAV CS in terms of mission performance allows, by changing the CS operation algorithm, increasing the efficiency of UAV deployment. The flight plan can be modified based on the principle of exclusion of damaged areas with subsequent continuation of operation using the remaining functions. Since the completion of every task requires the fulfillment of a certain set of control and supervision operations implemented by the respective technical facilities, the CS OBTI includes supervisory equipment (SE) for up state supervision (USSE), operation (OSE) and emergency flight mode (EFMSE) of a UAV [7, 9].

The aim of this paper consists in the development of a method of improving the functional dependability of UAV CS affected by electromagnetic effects in flight and failures within the functional component of OBTI. That is achieved through the identification of the failed functional element, the functional component of OBTI, the capability to perform the target objective of the UAV CS and decision-making regarding the initiation of the flexible operation algorithm.

Definitions used in the method

In [10], it is proposed to use a binary hierarchical model (BHM) of UAV CS. It involves the subdivision of the CS into local functional components, which is caused by the requirement to evaluate their effect on the final results of UAV CS mission performance in flight and the capability to modify its operation algorithm. Each operation is implemented by its own set of elements that in the general case overlap [9, 11]. The overlapping of such elements subdivides the OBTI into non-overlapping combinatorial subsets of elements (CSE) each of which implements a precise set of elementary operations.

Definition 1. Elementary operation (EO) is the maximum set of operations on signals constant in all tasks (implemented completely with the execution of any task) performed under the control of a computer and/or human operator.

Definition 2. Elementary check (EC) is a set of EOs required and sufficient for the verification of an individual parameter (attribute) of the object of supervision.

Definition 3. Elementary self-check (ESC) is a set of EOs required and sufficient for the verification of an individual parameter (attribute) of the OBTI in the course of its self-supervision.

Definition 4. Supervised part of set (SPS, $\mathfrak{A}_i$) is a subset of OBTI CSE covered by the *i*-th EC (ESC)

$$\{b_1, \ldots, b_i\} \in \mathfrak{A}_i.$$

Definition 5. Part of set suspected of failure (PSSF, $\mathfrak{C}$) is an area of CSE(a) formed by the overlapping of the $\overline{\mathfrak{A}}_i$ of the *i*-th ESC, in which a failure has been identified with $\mathfrak{A}_j$ of previous ESCs

$$\{b_j\} \in \overline{\mathfrak{A}}_i \cap \mathfrak{A}_j \in \mathfrak{C},$$

where $\overline{\mathfrak{A}}_i$ is the SPS of the *i*-th ESC in which a failure was identified,

$\mathfrak{A}_j, j = \overline{1, i-1}$ is the SPS of ESC performed before the *i*-th ESC that returned "OK".

In the course of ESC as part of OBTI self-supervision it may occur that $\mathfrak{A}_j = \varnothing$, i.e. PSSF is the same as the SPS of the *i*-th ESC.

Definition 6. ESC (π_i) is essential to $\mathfrak{C}_\gamma$, if simultaneously $\mathfrak{C}_i \cap \mathfrak{C}_\gamma \neq \mathfrak{C}_\gamma$ and $\mathfrak{C}_i \cup \mathfrak{C}_\gamma \neq \varnothing$.

Definition 7. Elementary checks (EC) that ensure UAV CS, control in emergency flight mode called basic.

The remaining ECs are auxiliary. Each EC corresponds with an ESC.

Problem definition

There is a UAV CS that consists of an OBTI, OBE and SSS. The components of this system are represented with a binary diagnostic model (BDM) [10]. For each functional element of the BDM there are known failure rates represented with row vectors.

Using EC (ESC), the operability of all CSEs of CS OBE (OBTI CSE) is supervised, therefore the EC (ESC) can have two definitive outcomes, i.e. "OK" and "not OK". The reliability of UAV CS must be ensured with the required probability P^*. The time of the latest supervision of CS OBE and self-supervision of OBTI is known. EC overlap per OBTI elements. Each EC is associated with an ESC in the course of self-supervision. The OBTI has a failure belonging to one CSE that does not allow executing a part of the EC (set of ECs) of CS OBE.

The purpose of OBTI self-supervision is the failure location with a depth that allows identifying its ability to perform the primary operations with the probability not lower than P^* and the allowed set of ECs in this case.

The π_γ (γ-th EC) returned "not OK". In this case the entire set $\boldsymbol{\Pi}$ of ECs (ESCs) is divided into two non-overlapping subsets (if $\gamma \neq 1$ and $\gamma \neq \mathcal{M}$):

$\boldsymbol{\Pi}_1 = \{\pi_1, \ldots, \pi_\gamma\}$ is the subset of implemented ECs (ESCs),

$\boldsymbol{\Pi}_2 = \{\pi 1, \ldots, \pi\gamma\}$ is the subset of non-implemented ECs (ESCs).

The following were defined: PSSF ($\mathfrak{C}$) that includes $\{\bar{b}_j\}$ CSEs of BTI and ACC ($\mathfrak{S}$), i.e. area of EC (ESC) that covers the PSSF. $\mathfrak{S} \subseteq \boldsymbol{\Pi}_2$ is sufficient for the failure location. In terms of functionality, ECs (ESCs) can be basic and auxiliary.

Based on the current ESC results a decision can be taken out of the following options:

– decision 1: stop the checks and reject the OBTI,

– decision 2: continue failure location,

– decision 3: stop the failure location and continue execution of UAV CS flight plan per modified algorithm.

At the final stage of OBTI self-supervision the second decision degenerates into the first or the third one. Due to that the set $\mathfrak{D}$ contains two basic elements: d_c, decision to continue the failure location and d_s, decision to stop the failure location. The second and third decisions define the depth of OBTI self-supervision.

At each stage t_i of failure location in OBTI, based on the results of ESC, the ACC and PSSF are analyzed, which includes verifying the ACC for sufficient coverage of the PSSF ($\mathfrak{C} \subseteq \mathfrak{S}$), based on which the appropriate decisions are taken. In this case areas $\mathfrak{G}_c^\phi$, $\mathfrak{G}_\psi$: $\mathfrak{G}_c^\phi(t_i)$ are formed, i.e. the area of observable data (processes of changes in the areas $\mathfrak{C}$, $\mathfrak{S}$), within which the following decisions are taken

$$d_c = \left(d_c^{11},\ d_c^{10}\right) \text{ and } d_c^\phi,$$

where d_c^{11} is the decision to continue the failure location, as in PSSF there are $\{b_j\} \in$ SE, OBTI EFMSE,

d_c^{10} is the decision to continue the failure location, as in PSSF $\{b_j\} \in$ OBTI SE, provided $P_{MP} < P^*$,

P_{MP} is the mission performance probability used as the criterion of UAV CS efficiency. It is applicable when changes in an object's characteristics cause only partial reduction of the functional efficiency. We understand this indicator [7] as the a posteriori probability of absence of failures in the CS equipment required and sufficient for successful completion of UAV CS mission.

$d_c^{\phi i}$ is the decision to next implement the i-th ESC,

$_\psi(t_i)$ is the area within which final decisions are taken

$$d_s = \left(d_s^{01},\ d_s^{10}\right),$$

where d_s^{01} is the decision to stop the checks and discard the OBTI, as in PSSF there are only $\{b_j\} \in$ OBTI EFMSE,

d_s^{10} is the decision to stop location and allow OBTI to continue the mission per a modified functional program of CS, since in PSSF $\{b_j\} \in$ SE and $P_{MP} \geq P^*$.

Decision $d(t_i) = \delta_{t_i}\left(\mathfrak{C}^{t_i}, \mathfrak{S}^{t_i}\right)$ that conform to the general sequential rule $\delta = \left\{\delta_{t_i}\left(\mathfrak{C}^{t_i}, \mathfrak{S}^{t_i}\right), \mathfrak{C}, \mathfrak{S} \in \mathfrak{G}(t_i), i \geq 0\right\}$ with planning of observations, has the form

$$\delta_{t_i}\left(\mathfrak{C}^{t_i}, \mathfrak{S}^{t_i}\right) = \begin{cases} d_s^\varphi \ if\ \mathfrak{C}^{t_i}, \mathfrak{S}^{t_i} \in \mathfrak{G}_s^\varphi(t_i), i \geq 0, \\ d_\psi \ if\ \mathfrak{C}^{t_i}, \mathfrak{S}^{t_i} \in \mathfrak{G}_\psi(t_i), i \geq 0. \end{cases} \quad (1)$$

If it is decided to continue the failure location, another ESC is selected, which is associated with the risk of loss [11, 12]. The probability of false discarding of OBTI due to ESC selected out of ACC is taken as the risk of loss. It is identified according to formula

$$P_{FD}^*(i) = P_{FD}(i) + P_{PP}(i)\hat{P}_{FD}^{\max}(M - i), \quad (2)$$

where $\hat{P}_{FD}^{\max}(M - i)$ is the estimation of the probability of false discarding in the course of remaining ESCs,

$P_{PP}(i)$ is the probability that as the result of implementation of the i-th ESC, in C there will be both elements of SE and EFMSE.

$P_{FD}(i)$ is the probability of false discarding of OBTI in the course of the i-th ESC.

The moment of termination of OBTI self-supervision depends not only on the set of decisions $\mathfrak{D}$, but their sequence as well

$$\tau\left(\delta_{t_i}\right) = \inf\left\{\tilde{\gamma}\left(\delta_{t_i}\right) : d(t_i) \in \mathfrak{D}_n\right\}$$

and is a random value.

Thus, the task at hand comes down to designing the optimal ESC strategy that minimizes the probability of false discarding

$$\bar{\gamma}(\delta) = min\, P_{FD}^*(i)\ \ if\ P_{MP} \geq P^*. \quad (3)$$

Description of the solution method

We assume that there is one failed CSE within the OBTI. Based on the properties of the binary diagnostic model of the OBTI the initial PSSF and ACC are generated. They are then analyzed using the obtained results. For the ACC it consists in the definition of the functional composition of the ESC that can be basic and auxiliary, while for the PSSF it leads to the corresponding decision d_c or d_s. If the results of analysis fell within the area $\mathfrak{G}_s^\phi$, the next ESC is selected out of the initial ACC. The application of the i-th ESC for failure location in OBTI can be regarded as the subdivision of the PSSF set into two subsets $\mathfrak{C}_j$ and $\bar{\mathfrak{C}}_i$, with the result of π_i implementation of the i-th ESC unambiguously defining the belonging of the failed CSE to one of these subsets: subset $\mathfrak{C}_j$ if the result is "OK" and subset $\bar{\mathfrak{C}}_i$ if the result is "not OK". Further failure location, obviously, can only involve ESCs essential to the current PSSF. Therefore, in the process of selection of the i-th ESC the ACC is specified, where upon the implementation of such ESC only essential ones must remain. The selection of the next ESC is based on the

Table 1. Components of the model of BTI failure location in the course of self-supervision

Numbers of graph nodes	ESC classification			ESC result hypothesis		PSSF-SPS			Solution		$P_{\text{FD}}(i)$	$P_{\text{PP}}(i)$	$Q_{EFSME}(M-i)$	$P_{\text{FD}}(i)$
	δ_1	δ_2	1-δ_2	H	$\bar{\text{H}}$	δ_3	δ_4	δ_5	δ_6	δ_7				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
8.4	1	0	1	1	0	1	-	0	1	0	0	$P_{EFSME_i} R_{EFSME_i}$	0	0
8.5	1	0	1	1	0	1	-	0	0	1	0	0	0	0
8.6	1	0	1	1	0	0	-	1	1	0	0	$P_{EFSME_i} R_{EFSME_i}$	$1-e^{-\sum\lambda_{\text{EFMSE}}t}$	$P_{EFSME_i} R_{EFSME_i}\times$ $\times Q_{\text{EFMSE}}(M-i)$
8.1	1	0	1	0	1	-	-	-	0	0	0	0	0	0
8.2′	1	0	1	0	1	1	-	0	0	0	$P_{\text{EFMSE}_i}(1-R_{\text{EFMSE}_i})$	0	0	$P_{\text{EFMSE}_i}(1-R_{\text{EFMSE}_i})$
8.2′′	1	0	1	0	1	0	-	1	0	0	$P_{\text{EFMSE}_i}(1-R_{\text{EFMSE}_i})\times$ $\times \Phi^*_{\text{EFMSE}}$	0	$1-e^{-\sum\lambda_{\text{EFMSE}}t}$	$P_{\text{EFMSE}_i}(1-R_{\text{EFMSE}_i})\times$ $\times \Phi^*_{\text{EFMSE}}$
8.7	0	1	0	0	1	-	-	-	1	0	0	$1-P_{\text{SE}_i}$	0	0
8.8	0	1	0	0	1	-	-	-	0	1	0	0	0	0
8.12	0	1	0	0	1	1	0	0	1	0	0	$P_{\text{SE}_i}(1-R_{\text{SE}_i})$	0	0
8.13	0	1	0	0	1	1	0	0	0	1	0	0	0	0
8.15	0	1	0	0	1	0	0	1	1	0	0	$P_{\text{SE}_i}(1-R_{\text{SE}_i})\times$ $\times(\Phi^*_{\text{EFMSE}}(1-\Phi^*_{\text{SE}})+\Phi^*_{\text{SE}})$	0	0
8.16	0	1	0	0	1	0	0	1	0	1	0	0	0	0
8.9	0	1	0	0	1	0	1	0	1	0	0	$P_{\text{SE}_i}(1-R_{\text{SE}_i})$	0	0
8.10	0	1	0	0	1	0	1	0	0	1	0	0	$1-e^{-\sum\lambda_{\text{EFMSE}}t}$	0
8.19	0	1	0	1	0	1	0	0	1	0	0	$P_{\text{SE}_i} R_{\text{SE}_i}$	0	0
8.20	0	1	0	1	0	1	0	0	0	1	0	0	0	0
8.21	0	1	0	1	0	0	0	1	1	0	0	$P_{\text{SE}_i} R_{\text{SE}_i}$	$1-e^{-\sum\lambda_{EFM}t}$	$P_{\text{SE}_i} R_{\text{SE}_i}\Phi^*_{\text{EFMSE}}\times$ $\times Q_{\text{EFMSE}}(M-i)$
8.18	0	1	0	1	0	0	1	0	0	0	$P_{\text{SE}_i} R_{\text{SE}_i}\Phi^*_{\text{EFMSE}}$	0	$1-e^{-\sum\lambda_{\text{EFMSE}}t}$	$P_{\text{SE}_i} R_{\text{SE}_i}\Phi^*_{\text{EFMSE}}$
8.22-8.25	0	0	1	0	1	-	-	-	1	0	0	$P_{\text{EFMSE}_i}+P_{\text{SE}_i}-$ $-2P_{\text{EFMSE,SE}_i}+$ $+P_{\text{EFM,SE}_i}\times$ $\times(1-R_{\text{EFMSE}_i})$	$1-e^{-\sum\lambda_{\text{EFMSE}}t}$	$(P_{\text{EFMSE}_i}+P_{\text{SE}_i}-$ $-2P_{\text{EFMSE,SE}_i}+$ $+P_{\text{EFMSE,SE}_i}\times$ $\times(1-R_{\text{EFMSE}_i}))\times$ $\times Q_{\text{EFM}}(M-i)$
8.28	0	0	1	1	0	1	0	0	1	0	0	$P_{\text{EFMSE,SE}_i}\times$ $\times R_{\text{EFMSE,SE}_i}$	0	0
8.29	0	0	1	1	0	1	0	0	0	1	0	0	0	0
8.27	0	0	1	1	0	0	1	0	0	0	$P_{\text{EFMSE,SE}_i}\times$ $\times R_{\text{EFMSE,SE}_i}$ Φ^*_{EFMSE}		$1-e^{-\sum\lambda_{\text{EFMSE}}t}$	$P_{\text{EFMSE,SE}_i}\times$ $\times R_{\text{EFMSE,SE}_i}$ Φ^*_{EFMSE}
8.30	0	0	1	1	0	0	0	1	1	0	0	$P_{\text{EFMSE,SE}_i}\times$ $\times R_{\text{EFMSE,SE}_i}$	$1-e^{-\sum\lambda_{\text{EFMSE}}t}$	$P_{\text{EFMSE,SE}_i}\times$ $\times R_{\text{EFMSE,SE}_i}\times$ $\times Q_{\text{EFMSE}}(M-i)\times$ $\times \Phi^*_{\text{EFMSE}}$

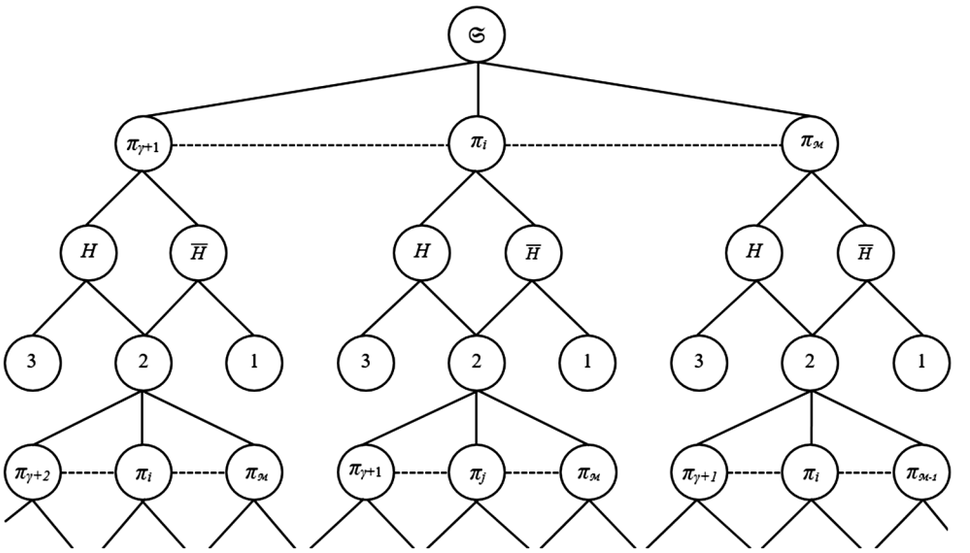

Figure 1. Graph of the failure location process in the course of OBTI self-supervision

prediction of the risk of loss from its implementation. The probability of false discarding of OBTI per the i-th ESC is taken as the risk of loss [9, 11, 12]. $P^*_{\text{FD}}(i)$ is calculated based on the procedure of risk of loss identification is part of improving the functional dependability of UAV CS in flight [9, 11] according to formula (2). The implementation of the next ESC in the course of OBTI self-supervision may cause a probability of its false discarding. For that reason this probability is estimated for each ESC that make the ACC of the current step of location. In formula (2) $\hat{P}^{\max}_{FD}(M-i)$ can be estimated through the probability of failure of the self-supervision facilities of the functional component of the OBTI EFMSE per the remaining ESCs of the ACC. In this case formula (2) is as follows:

$$P^*_{FD}(i) = P_{FD}(i) + P_{PP}(i) Q_{EFMSE}(M-i), \qquad (4)$$

where $Q_{EFSME}(M-i)$ is the probability of failure of self-supervision facilities of the functional component of the OBTI EFSME.

The components of formula (4) are calculated based on the procedure of risk of loss identification as part of improving the functional dependability of UAV CS in flight [9, 11] and is shown in Table 1. The selection of the i-th ESC itself and construction of the optimal strategy of failure location is based on the application of the combined branch-and-bound method (BBM). When the combined BBM is used, for the purpose of constructing optimal conditional self-supervision programs the sequential use of ESCs in the process of self-supervision is considered as a multistage process, and the application of any ESC at a random stage is considered as the subdivision of the set of the states of OBTI allowable at such stage into two parts, to one of which belongs the true state.

The idea of combined BBM as part of the design of the optimal OBTI self-control algorithm consists in the consecutive selection at each stage of ESC implementation process, out of the subset $\mathfrak{S} = \{\pi_{\gamma+1}, \ldots, \pi_{\mathcal{M}}\}$ per the minimal $P^*_{\text{FD}}(i)$ of the next i-th ESC till a one-element subset is obtained and/or the corresponding decision is taken.

This process is represented by a graph in Figure 1 where the apexes of the corresponding subset $\mathfrak{S} = \{\pi_{\gamma+1}, \ldots, \pi_{\mathcal{M}}\}$ are the results of ESC implementation, corresponding decisions, while the arcs are the logical connections between the apexes. Decisions 2 and 3 correspond to the ESC result "OK", while the decisions 1 and 2 correspond to the result "not OK". Let us examine the left branch of the graph. Let us assume that based on the analysis of the initial ACC per the minimal $P^*_{\text{FD}}(\gamma+1)$ the $(\gamma+1)$-th ESC was selected. Its implementation can return "OK" or "not OK", but decision d_c was taken, i.e. continue failure location. On this basis the ACC is specified and in this case $\mathfrak{S}^{t_1} = \{\pi_{\gamma+2}, \ldots, \pi_{\mathcal{M}}\}$.

At stage t_1 of failure location $P^*_{\text{FD}}(i)$ is calculated, $i = \gamma + 2, \overline{M}$, i-th ESC of $\mathfrak{S}^{t_1}$, and per the minimal $P^*_{\text{FD}}(i)$ the next ESC is selected for implementation. The branching process continues until decision 1 or 3 is taken.

Conclusion

The method of improving the functional dependability of UAV CS allows defining the strategy of in-flight UAV application:

a) if the failure belongs to OBTI EFMSE, abort the UAV mission and bring it back to LS.

b) implementing the procedure of modification of the UAV CS algorithm, if the failure belongs to OBTI SE; location in the course of the self-supervision must have the optimal depth.

If it is decided to continue the failure location, another ESC is selected, which is associated with the risk of loss. The probability of false discarding of OBTI due to ESC selected out of ACC is taken as the risk of loss.

The paper proposes a BBM-based solution that consists in sequential selection at each stage of ESC implementation

process, out of the ACC subset per minimal $P^{*}_{FD}(i)$ of the next ESC till a one-element subset is obtained and/or the corresponding decision is taken.

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Physical factors affecting the reliability of rail crane operators

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Abstract. *As it is known, load-lifting rail cranes of various models employed as part of Russian Railways repair and recovery trains are high-risk facilities. They normally have large dimensions and powerful engines that generate significant thrust and high energy. The paper examines the effects of harmful occupational factors of physical nature, i.e. industrial noise and vibration on the performance and health of rail crane operators.* **Aim.** *Based on the analysis of the causes of incidents that occurred in the course of operation of rail cranes, generalizing the experimental findings regarding the effects of industrial noise and vibration on crane operators and identifying the correlation between the clinical signs of distress in this category of workers and the levels of the above harmful physical industrial factors.* **Methods.** *Experimental studies and the subsequent evaluation of the effect of industrial noise and vibration generated by the mechanisms of cranes were conducted with the use of an Assistant Total+ noise and vibration analyzer in the course of operation of rail cranes of various models when handling cargo, as well as when crane engines idle. Measurements were conducted at workstations where the operator is to be at during the operation and maintenance of the crane, i.e. the control cabins, operator seat, control handles, near the crane engine.* **Results.** *The paper provides a classification of sources of noise and vibration that affect crane operators, experimental findings regarding the levels of industrial noise, general and local industrial vibration for various models of cranes. Clinical signs of distress are identified, a list is set forth of the most typical occupational health problems for this category of workers.* **Conclusions.** *The paper concludes that the reduction of industrial noise and vibration caused by the mechanisms of rail cranes is a relevant engineering and socioeconomic problem. From the socioeconomic point of view the solution to this problem will allow improving the working conditions of crane operators, while in terms of engineering it will enable higher technical and operational characteristics of crane mechanisms.*

Keywords: *working conditions, harmful occupational factors, rail crane, industrial noise, local industrial vibration, general industrial vibration, sources of industrial noise, sources of industrial vibration.*

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As it is known, load-lifting rail cranes employed as part of repair and recovery trains are high-risk facilities. They normally have large dimensions and powerful engines that generate significant thrust and high energy. These circumstances largely define the high levels of the factors of operating conditions and workflow at the workstations of crane operators.

Rail crane operators' work is not associated with excessive physical activity, however, it requires significant nervous and emotional effort, tension in the visual and auditory analyzers. The causes of accidents associated with the operation of cranes, along with the technical failures and "physical fatigue" of crane structural components, include the "human factor", i.e. errors by crane operators associated with reduced productivity and fatigue in the course of the working shift. That is due to the powerful and lasting vibration and noise affecting the operator and generated by the crane's mechanisms in the course of operation. These effects cause reduced performance during the work shift, while if such effects are lasting and recurring there is a risk of occupational health problems [1-4].

The sources of noise affecting rail crane operators should be divided into several groups:

– noises produced by the crane moving along the track. Despite the fact that the crane does not move fast when handling cargo, the operation is associated with the interaction between the rough surfaces of the wheel and rail, impacts within automatic coupling devices between the crane and flatcars. In this case the noise is nonstationary stochastic pulse processes.

– noises generated by main equipment (diesel generator, traction motor, speed transformer). As it is known, tear and wear of cogged wheels causes a significant increase of vibration in the speed transformer and traction motor frame.

– noises generated by auxiliary equipment (electrical machines and rectifying installation cooler fans, air conditioning system of the cabin). The sound power level of a fan is in complicated dependence with its parameters. For instance, as the blade speed increases the aerodynamic noise grows more rapidly than mechanical one, therefore a well-designed fan predominantly produces aerodynamic noise.

Depending on the design of rail cranes the level of noise they produce may differ. The paper cites the findings of experimental studies of the levels of noise for various models of cranes.

Thus, for the KZh-1572A hydraulic crane intended for recovery, construction and installation, maintenance and loading operations on 1520 mm gauge tracks, the primary sources of noise are the carriage and pivoting frames connected with a 360-degree rotation crown installed on two four-axle bogies fitted with a hydraulic travelling mechanism, as well as the crane's engine. The measurement data of the noise levels at the workstations where the operator is to be at during the operation and maintenance of the crane are given in Table 1.

The measurements were taken using an Assistant Total+ noise and vibration analyzer in the course of operation of rail cranes when handling cargo.

The DGKu railcar is one of the models of rail crane. Its design includs a load-lifting crane. It is intended for loading, unloading and transportation of loads, including 25-meter rails on its own platform or coupled flatcar, transportation of workers to work sites, conducting shunting operations in station tracks. The measurement data for the DGKu railcar in cargo handling mode are given in Table 2.

It should also be noted that when the operator is in the control cabin even if the engine idles, the noise can be as high as 52 to 63 dBA, or 61 to 78 dBA if the operator is communicating with the dispatcher via the radio. Thus, among the harmful physical factors affecting crane operator workstations noise stands out as a persistent high-intensity factor whose prolonged effect causes easy fatiguability, hearing loss, reduced performance.

The effects of noise on the human body are not limited to the auditory organ. Through the fibers of auditory nerves the stimulation is transmitted to the central and autonomic nervous systems and thus affects the internal organs and causes significant changes in the functional

Table 1. Levels of noise at the workstations of track machine operators, KZh-1572A rail crane

Measurement point	Center frequency band, Hz									dBA
	31.5	63	125	250	500	1000	2000	4000	8000	
RC	95	95	87	81	78	75	73	71	69	80
control cabin	104	105	88	86	83	78	76	82	76	83
engine platform	107	110	110	104	105	101	95	95	90	84

Table 2. Levels of noise at the workstations of track machine operators, DGKu rail crane

Measurement point	Center frequency band, Hz									dBA
	31.5	63	125	250	500	1000	2000	4000	8000	
RC	95	95	87	81	78	75	73	71	69	80
transport mode	96	96	88	85	82	82	76	74	68	86
operating mode	95	92	90	88	83	80	74	71	61	84

state of the body and the mental condition of the person creating the feeling of anxiety and irritation. The effect of noise on the central nervous system causes the increase of the latent period of visual motor reaction, leads to reduced mobility of nervous processes, changes in the electroencephalographic indicators, disrupts the bioelectric activity of the brain accompanied by overall functional changes in the body (starting with noise of 50 to 60 dBA), substantially changes the brain potentials, their dynamics, causes biochemical changes in the brain structures. Changes in the functional state of the central and autonomic nervous systems occur much earlier and at lower levels of noise than those causing reduced auditory sensitivity [5 – 7]. The above negative effects of noise cause crane operators to make errors and develop occupational health problems.

Crane operators are also affected by general and local vibration. The general vibration is felt under the feet and on the seat of the operator, local vibration affects the control handles. Vibration is generated by the running engine that sends it to the operator's cabin via the rigid frame. During a crane's operation vibrations occur both in the vertical and horizontal planes. The bouncing of the crane's mechanisms has the frequency range of 1.5 to 8.0 Hz. The cross shake that is imparted to the control cabin as the load swings has the frequency range of 0.2 to 1.0 Hz.

Given that the resonance frequency of human organs is within the range of 1 to 15 Hz, the operator is exposed to vertical oscillations of the most unfavorable range.

Vibration is also a physical factor of high biological activity. In case of lasting exposure it causes chronic occupational health problems, the hand-arm vibration syndrome disease that is the second on the list of railway personnel occupational health problems. General vibration primarily affects the supporting-motor apparatus and causes pains in the lower back, extremities, joints, muscles, tendons and around the stomach. The hand-arm vibration syndrome is manifested as systemic abnormalities with vascular tone disorder, absence of appetite, insomnia, irritability, easy fatiguability and pain sensitivity. Workers affected by vibration experience vertigoes, decomposition of movement, symptoms of motion sickness. Shock vibration is especially hazardous as it causes microtraumatization of various tissues with subsequent changesin them. Changes in metabolic processes, blood chemistry values are observed. General vibration with frequencies lower than 0.7 Hz (rocking) causes sea sickness as the result of disrupted vestibular system activity [5]. Vibration measurements made in the cabins of KZh-1572A and DGKu cranes showed that the levels of vibration (on the floor) are between 100 and 116 dB which exceeds the maximum permissible values by up to 9 dB (per vibration velocity levels) [8 – 11].

Thus, reducing the noise and vibration is a relevant technical and economic task whose solution will allow improving the technical and operational characteristics, as well as the working conditions of crane operators [12].

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Improving the reliability of professional psychological selection of aviation specialists

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Abstract. Aim. *The paper examines one of the possible ways of improving the reliability of professional psychological selection of aviation specialists using the method of assessment of their behaviour strategy in conflict situations in order to prevent failures of interaction within aircraft crews and air traffic control shifts.* **Methods.** *The research used the Thomas-Kilman Conflict Mode Instrument (TKI) (more specifically, TKI-R, the Russian adaptation by N.V. Grishina) psychodiagnostic procedure to assess the behaviour strategy in conflict situations, as well as the Buss-Durkee Inventory to determine the tendency of subjects to various forms of aggressive behaviour. Statistical processing of the findings was done using the Bravais-Pearson correlation coefficient and Pearson's χ^2 criterion.* **Results.** *At the first stage of the multipurpose experiment 48 student dispatchers were surveyed, at the second stage the total of 603 subjects were surveyed (students of the Saint Petersburg State University of Civil Aviation and the Institute of Philology, Foreign Languages and Media Communications of the Irkutsk State University), i.e. while emphasizing operator professions in order to improve the validity of the experiment the sample was significantly extended to include, among others, students of the humanities. It was found that the results of the Buss-Durkee Inventory have an inverse correlation with the tendency to an adaptation strategy and direct correlation with the tendency to rivalry and collaboration strategies. According to Pearson's χ^2 fitting criterion, there are significant differences in the manifestation of such behaviour styles as rivalry and avoidance between pilot and humanities students, while for the samples of males and females the differences are in the manifestation of such behaviour stiles as rivalry, avoidance and compromise. Females are significantly less inclined to rivalry and somewhat more inclined to avoidance and compromise as compared to males. There are also no observable crucial differences between the intercorrelations of the TKI-R results of the first and second stages of the experiment. The authors' findings were compared with the published results of the survey of the students of the Tuvan State University and Yaroslavl State Medical University, as well as with the results of surveys of athletes and business owners.* **Conclusions.** *By generalizing own findings and those set forth in other authors' publications, we can conclude that uncooperative behaviour of all tested students is dominated by average manifestation of strategies of competing, collaborating, compromising, avoiding and accommodating, which indicates the ability of the subjects of this age for flexible behaviour in conflict situations subject to the specific conditions of interaction. That means that students, unlike the success-seeking business owners, while prioritizing collaboration and compromise in conflict situations, flexibly use other behaviour strategies. This must be taken into consideration when planning measures aimed at improving the reliability of professional psychological selection in commercial aviation. It appears that in view of the above reasons, the application of the TKI-R procedure in the professional psychological selection of aviation specialists is unviable.*

Keywords: *commercial aviation, professional psychological selection, psychological assessment, dependability, conflict, behaviour strategy.*

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Introduction. Professional psychological selection (PPS) is a set of measures aimed at ensuring quality staff selection in an organization based on compliance assessment of the level of relevant psychophysiological (individual) qualities and characteristics of individuals with the professional requirements [1].

In most cases, such professional psychological selection involves an assessment of the level of some individual psychological and personal characteristics of candidates for specific professions that determine the success of their professional activity, in order to identify their compliance with the requirements of a specific profession [1], which, of course, includes aviation. Currently, in the Russian civil aviation the PPS is conducted in accordance with the Guidance [2].

It is well known that most flight accidents are associated with the human factor. Therefore, the problem of its negative impact will remain most important and urgent for many years. In order to reduce it, it is required to improve the reliability of professional psychological selection of aviation specialists [3, 4].

The authors have already pointed out in their papers, as for example in [5], the significant weakness of the current PPS [2]. In some papers, such as [6-10] and others, the authors considered various possible ways to increase its reliability. In this paper, the authors also intend to point out another aspect of this issue.

Problem definition. Failed interaction within the crew is one of the primary or associated causes of all plane crashes that made the headlines over the last few years. As a rule, such failures of interaction are followed by conflicts of varied intensity. An example of such conflict is the An-148 crash in the Moscow region, when "the captain was trying to obtain higher readings (authors' note: critically low speed displayed by the instruments) by nosediving, while the co-pilot was opposing such actions. At the same time, the interaction between crew members was affected by psychoemotional stress, pilots were swearing according to the voice recorder" [11]. A similar direct conflict was the reason of the Tu-134 crash near Ivanovo, when "virtually, the captain alone was piloting the plane, and didn't accept any information from the crew members" [12]. "Probably, co-pilot's and air navigator's mistakes made during landing approach in the Mineralnye Vody Airport were the reason for increasing tension between captain and crew members. The captain's comments could be the key factor in determining the style of the crew's future behaviour during the flight back to Ivanovo" [12]. When a Tu-134 crashed in Petrozavodsk, on the contrary, the air navigator was the leader in the situation. Investigators noted that one of the causes of the crash was "unsatisfactory interaction among crew members and crew resource management (CRM) on the part of the captain of flight 9605 during landing. The captain was following the air navigator's instructions, who was very active and under the influence of alcohol, and, in fact, while the co-pilot removed himself from the process at the final stage of the accident flight" [13]. Similarly, the investigation of the Yak-42 crash [14] near Yaroslavl identified "uncoordinated actions of the crew during the last stage of the run" and heated debates with the use of strong language. The crashes near Kazan [15] and Perm [16] were characterized by conflicts between the onboard crew and air traffic controllers, as well as general perplexity, when both crew members avoided accepting responsibility for the aircraft control and "during the turn maneuver the crew were complaining about the dispatcher" [15, p. 232]. Similarly, "the dispatcher's instructions to seek guidance made the crew members, the captain in particular, extremely annoyed, which as confirmed by the instrumental analysis of speech (paragraph 1.16.6, time 22:51:40)" [16, p. 128]. Pointing out the current altitude, the dispatcher asked whether the aircraft was descending, which caused "a strong reaction of the captain, who emotionally asked to "Tell the altitude! Tell the altitude!". That question, as well as the captain's constant errors (call sign, frequency, flight levels) showed that his psychoemotional state and situation awareness were far from optimal" [16]. The perplexity and avoidance of responsibility are evident "at 23:08:55, when the left bank angle was 30°, and the speed was less than V_{ref}, (authors' note: target speed of landing) the co-pilot asked the captain to take control ("…take it, take it, take it…!"), obviously being conscious of his own inability to control the aircraft". However, by that time the captain was also unable to assume control the situation ant the aircraft: "Take what (non-printable words), I can't do that either" [16, c. 147].

All the above examples of in-flight conflicts (and we only examined a few) show that improving the reliability of professional psychological selection of aviation specialists, especially pilots, it requires the research of the tendency of flight school applicants to conflicts, as well the behaviour strategies employed in conflict situations, if such arise. Let us take a closer look at this problem.

Behaviour in conflict. "A conflict is understood as the most acute way to resolve significant contradictions that arise in the course of interaction that consists in based on opposition between the parties to the conflict and is accompanied by negative emotions" [17]. The necessary and sufficient condition of a conflict is the opposite motives or judgements of the subjects of social interaction [17]. The so-called interpersonal conflicts most often occur during flight. "An interpersonal conflict is a confrontation between interacting parties on the basis of the arisen contradictions, which include opposite aims that are not compatible in some specific situation. An interpersonal conflict can arise in the course of interaction between two or more people. In interpersonal conflicts the parties confront each other and sort out their relations face to face. This is one of the most common types of conflict" [18]. In other words, "an interpersonal conflict is a confrontation between parties perceived and experienced by them (or, at least, one of them) as a significant psychological problem, which requires its resolution and causes the activity of the parties, aimed at overcoming the contradiction and resolving the situation in the interest of one or both parties" [19].

"The strategy (authors' note: or style) of behaviour in conflict is an orientation of a person towards a conflict and towards certain forms of behaviour in a conflict situation" [20].

"In the early 1970's Ralph H. Kilmann and Kenneth W. Thomas, using the theoretical model by Robert Blake and Jane Mouton, proposed an instrument to measure the manifestation of five main behaviour types in interpersonal conflict: competing, collaborating, compromising, avoiding and accommodating. That is called "Management-of-Differences Exercise" or MODE [21]. Similarity of the abbreviation with the term "mode" led to the fact that the authors of this instrument started calling it the "Thomas – Kilmann Conflict Mode Instrument (TKI)" meaning the conflict management tool. Using this instrument, it became clear that this is a powerful tool for managing interpersonal conflicts" [22]. (In Russian psychological literature the Russian-language version of the TKI-R test is more commonly known as the "K.Thomas test adapted by N.V. Grishina" [23]. This version was used by the authors in this paper). Usually, the so-called Thomas-Kilmann model is used to interpret the TKI test [24, 25] (Figure 1).

Tendency towards aggression. A large number of scientific publications are dedicated to the problem of conflict and the factors that influence the emergence and development of such conflict. It is logical to assume that tendency towards conflict and aggression should be connected with a positive correlation. In [26], the authors note that "based on the collected data it can be concluded that individuals, who choose ineffective strategies of behaviour in conflict situations, have a higher level of aggression, which may be associated with conflicts and disputes that satisfy their own interests in conflicts". Unfortunately, the authors of [26], while using TKI-R to assess the behaviour style, made further analysis of the results difficult by using non-standard terms. In particular, the authors write that "while evaluating the degree of realization of the interests by opponents and conflict resolution quality using a specific strategy in conflict, we should talk about the efficiency of a behaviour strategy in a conflict. Efficiency is assessed based on two criteria: satisfaction and productivity. Based on these criteria collaborating and compromising were defined as effective behaviour strategies (EBS) because if they are used, the interests of counter-parties will be satisfied to a greater extent; competing and accommodating were defined as ineffective behaviour strategy (IEBS) because if they are used, the interests of only one party will be satisfied; avoiding is a neutral behaviour strategy (NBS), because in this case the interests of both parties are not satisfied" [26]. (From the authors' point of view this is a strange classification. We suppose, if the strategies are ranked from the best to the worst, they will be presented as follows: collaborating, compromising, accommodating, competing and avoiding. According to the authors, the in-nobody's-favour solution, when resolving the conflict is impossible, is the least effective strategy of all).

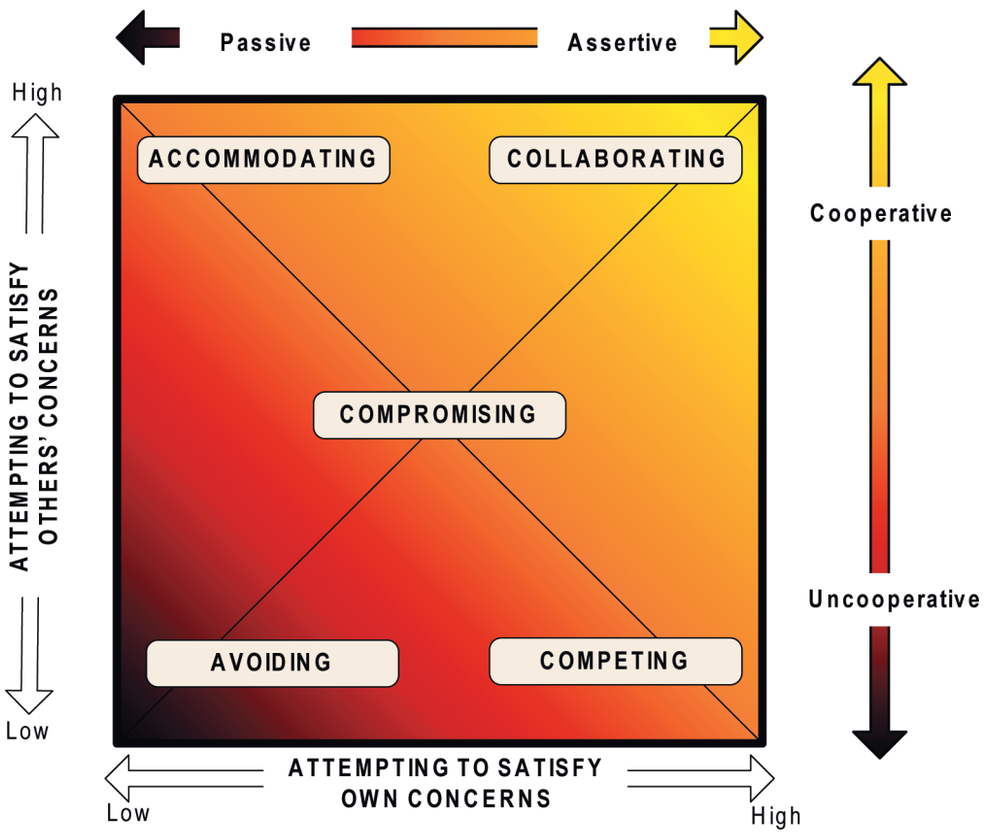

Figure 1. Thomas-Kilmann model

In [26], a comparison of the Buss-Durkee test results [23] (where A_P is physical aggression, A_{Ind} is indirect aggression, A_I an irritation, A_N is negativism, A_R is resentment, A_S is suspicion, A_{VA} is verbal aggression and A_A is autoaggression) for individuals with different behaviour strategies (Figure 1). "Adequate diagnostic indicators of aggressiveness include physical aggression, as well as emotional experiences associated with aggression, i.e. irritation, negativism, resentment, suspicion, hostility and guilt. Analysis of the research results of the students' level of aggression showed a relatively high level of suspicion in the NBS group with IEBS and EBS groups (Table 1). Probably, this is due to the fact that people, who prefer to avoid conflicts, are anxious, timid, avoidant. It is easier for such people to avoid conflict and remain neutral towards the source of the conflict. IEBS students have higher rates of irritation and negativism, they are characterized by impetuosity, emotionality, proactivity and therefore, only care about their own point of view and do not accept others' opinion, do not allow compromises and agreements" [26].

Table 1. Average values of aggressiveness and hostility indicators of students per the Buss-Durkee test, scores [26]

Indicators	IEBS	NBS	EBS
A_P	4.4±0.5	4.0±0.7	4.4±0.4
A_{Ind}	4.3±0.4	4.4±0.7	4.1±0.3
A_I	5.3±0.4	4.5±0.8	4.5±0.5
A_N	2.2±0.3	1.9±0.3	1.9±0.3
A_R	3.2±0.3	3.1±0.7	3.4±0.4
A_S	5.7±0.3*	6.6±0.5^{*+}	5.7±0.3^{+}
A_{VA}	6.4±0.4	6.6±0.5	6.0±0.8
A_A	6.3±0.4	6.5±0.5	5.9±0.3

Note: the data are given as arithmetic means (*M*) and their errors (*m*);
* is a significant difference between IEBS and NBS groups;
$^{+}$ is a significant difference between NBS and EBS.

Taking into consideration that, according to [26], the IEBS group includes people with "accommodating" behaviour style, the last sentence sounds strange indeed. In addition, individuals with an "avoiding" strategy, of course, try to avoid the conflict, and, first of all, its resolution.

Another example. As the author writes in [27]: "according to the research data of athlete student, being in a conflict situation, they apply such behaviour strategies as collaborating, compromising and competing. To a lesser extent they apply avoiding and accommodating behaviour styles. There are significant differences that were determined during detailed analysis of students' behaviour styles (Table 2)" [27].

Table 2. Indicators of athlete students' behaviour styles in conflicts (in scores) [27] per the TKI-R test

Behaviour style	Level of tendency towards conflict		
	High	Medium	Low
Competing	7.9±0.3	5.1±0.2*	1.8±0.2*
Collaborating	4.3±0.3	7.8±0.2*	7.3±0.5*
Compromising	5.1±0.3	6.5±0.3*	5.2±0.4
Avoiding	2.5±0.2	2.9±0.1	3.2±0.2
Accommodating	3.9±0.3	4.1±0.2	4.4±0.4

Note: *, $p < 0.05$, differences are reliable relative to indicators of students with high levels of tendency towards conflict

Results analysis. Let us compare the data with the results of our own experiments. In [6], we considered a group of 48 students (future air traffic controllers), but in somewhat different aspects. If we compare the sample from [6] with the sample from [26] (Figure 2), then it is obvious that in the sample of students of the Saint Petersburg State University of Civil Aviation (SPbSUCA) there are significantly more EBS students (according to the classification in [26]).

Table 3 shows the correlations between the K. Thomas and the Buss-Durkee tests on a sample of 48 student air traffic controllers. As it can be seen, there are few significant

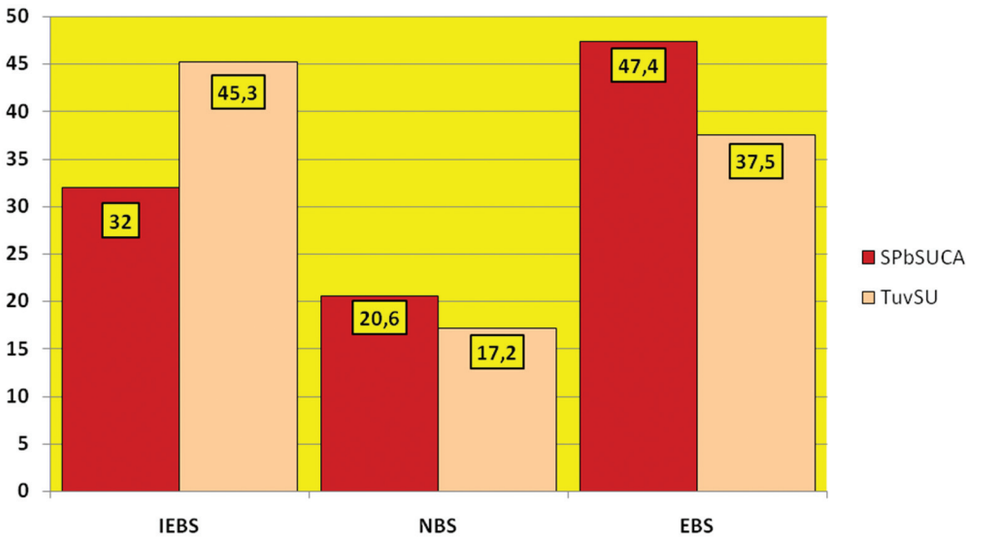

Figure 2. Comparison of the efficiency of behaviour strategies in a conflict situation identified among students of the Saint Petersburg State University of Civil Aviation (SPbSUCA) and the Tuvan State University (TuvSU)

Table 3. Correlation between K. Thomas and the Buss-Durkee test results on a sample of 48 student air traffic controllers

	Competing	Collaborating	Compromising	Avoiding	Accommodating
A_P	+0.1720	+0.1059	-0.1865	+0.1726	-0.2830
A_{Ind}	+0.2157	+0.1294	-0.1510	-0.0779	-0.1684
A_I	+0.0394	+0.2151	+0.2092	+0.0590	-0.3859*
A_N	+0.1374	+0.2227	-0.2594	-0.0039	-0.1094
A_R	-0.1533	+0.1010	+0.1390	+0.1353	-0.0889
A_S	+0.2387	-0.0729	+0.1059	+0.0605	-0.3809*
A_{VA}	+0.6146***	+0.1142	-0.2074	-0.0990	-0.5933***
A_A	-0.1612	+0.1134	-0.0431	+0.3318*	-0.1152

Note: Correlation significance (* is $p < 0.05$; ** is $p < 0.01$; *** is $p < 0.001$)

Table 4. Intercorrelation between TKI-R test results on a sample of 48 student air traffic controllers

	Competing	Collaborating	Compromising	Avoiding	Accommodating
Competing		-0.1626	-0.3803	-0.4262	-0.4985
Collaborating	$p \geq 0.05$		-0.2866	-0.2066	-0.0230
Compromising	$p < 0.05$	$p \geq 0.05$		+0.1121	-0.1944
Avoiding	$p < 0.01$	$p \geq 0.05$	$p \geq 0.05$		-0.2668
Accommodating	$p < 0.001$	$p \geq 0.05$	$p \geq 0.05$	$p \geq 0.05$	

Note: At the top right there are values of the Pearson correlation coefficient between performance indicators, and at the bottom left there are the characteristics of correlation significance

correlations between the results of these test methods. The fact that the Buss-Durkee test results negatively correlate with a propensity for the accommodating strategy is clear enough, as well as the fact that they almost all (excl. A_A and A_R) positively correlate with the propensity for competing strategy. But the fact that they also positively correlate with the propensity for the collaborating strategy is not quite clear. The strongest (+0.6146) and most significant ($p < 0.001$) correlation can be observed between the propensities for verbal aggression and competing strategy. Thus, some IEBS students (in the terminology of [26]), i.e. who are inclined to the competing strategy are also inclined to aggression, and another part of IEBS students are inclined to the accommodating strategy and are not inclined to aggression. That also shows the inexpediency of such classification of the efficiency of behaviour strategies in a conflict.

Table 4 shows the intercorrelations between TKI-R indicators obtained on the same sample. Significant intercorrelations are only between the tendency towards the competing and compromising, avoiding and accommodating strategies. Intercorrelations, as expected, are negative, but they don't reach an average strength of correlation. This suggests that there is no clear predominance of any style.

Figure 3 shows a similar conclusion on the absence of significant preferences in the selection of one or another strategy. There is no seeming inclination for any behaviour

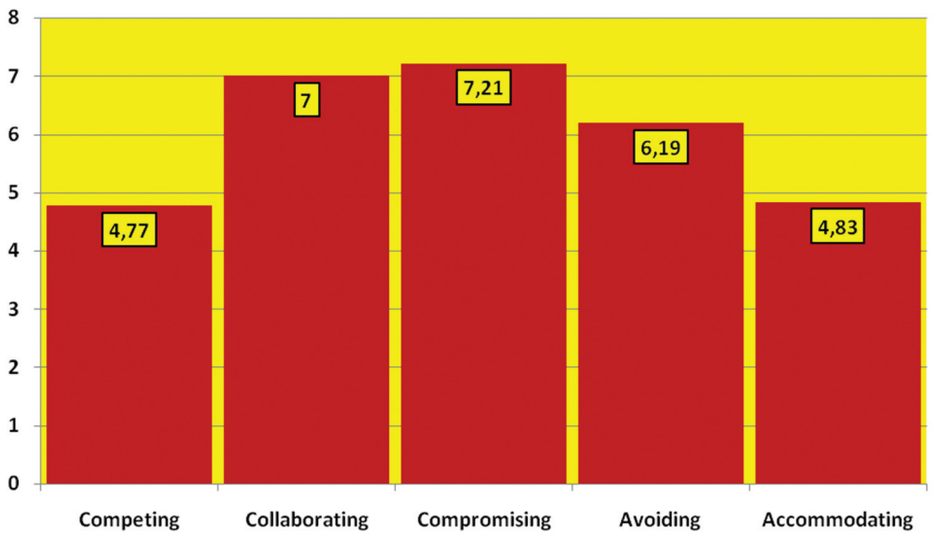

Figure 3. Indicators of average values of behaviour styles of student air traffic controllers in conflict situations per TKI-R in points (on a sample of 48 people from [6])

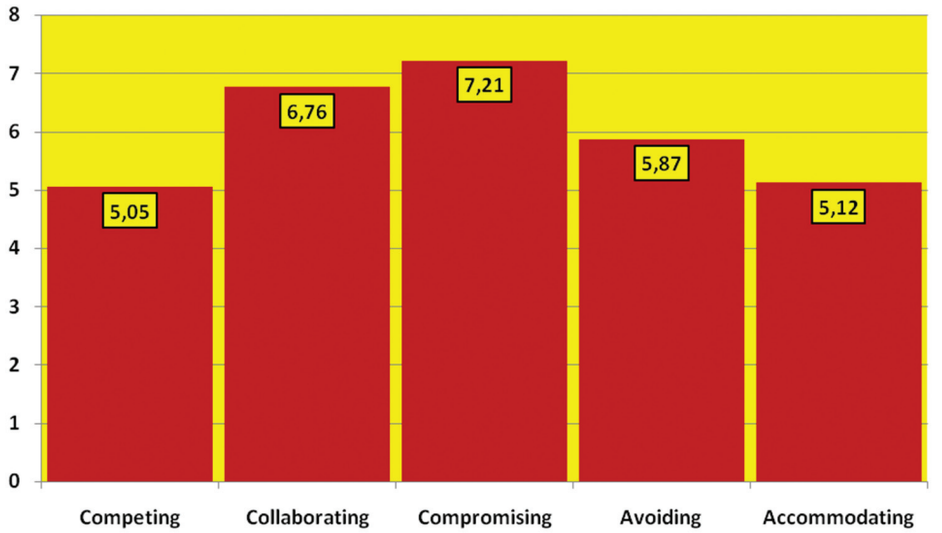

Figure 4. Indicators of average values of behaviour styles of SPbSUCA and PFLMC ISU students in conflict situation in accordance with TKI-R in scores (on a sample of 603 people)

style or its absence. Thus, according to the presented sample it can be noted that SPbSUCA students are most inclined to the collaborating and compromising strategies.

According to [27], "athlete students, being in a conflict situation, apply such strategies as collaborating, compromising and competing. To a lesser extent they apply the following 2 behaviour styles: avoiding and accommodating".

According to [28], female entrepreneurs mostly apply avoiding and competing strategies, while male entrepreneurs apply competing strategy.

The results in [20] are very interesting. The authors made a research on a sample of 129 students of the Yaroslavl State Medical University and noted that the first year students of the medical faculty use the compromising strategy (23.7%, the average score is 7.10) and avoiding strategy (23.6%, the average score is 7.07) approximately at the same degree, and in a lesser extent they use the competing strategy (15.4%, the average score is 4.62). "Therefore, for this group, it is important to focus on finding a mutually acceptable solution (temporary and intermediate) through concession. These respondents prefer to get at least something than to loose. At the same time, these students are inclined with the same extent to give up on their interests, but they are not ready to accommodate their partners. These respondents are less focused on the simultaneous realization of both their own interests and the partners' interests, they do not have the ability to explain the core of their interests and listen to their partner" [20]. First year students of the pediatric and dentistry faculties mostly use the compromising strategy (24.4%, the average score is 7.33, and 25.3%, the average score is 4.31), in a lesser extent they use the competing strategy (16.7%, the average score is 5.00, and 14.37%, the average score is 4.31), "therefore, first year students of all faculties are completely unwilling to come into confrontation or prioritize their own interests. Despite the fact that the compromising strategy is considered one of the most effective, the "doctor-patient" interaction process will not be fruitful, since it betrays the principles of both partners that is unacceptable during diagnostic and treatment processes. The avoiding strategy is ineffective at all for the medical profession. However, the first year students, obviously, do not have a clear vision of their future professional activity. Therefore, the identified dominant behaviour strategies in a conflict situation are characterized by individual and stylistic features to a larger extent than by the level of the professional qualities development" [20].

The authors of this paper conducted a multipurpose experiment on a large sample of SPbSUCA students (232 student pilots, 141 student air traffic controllers, 36 student air navigation specialists, 19 student advertisement and PR specialists, 53 student HR specialists). Additionally, in order to rectify the prevalence of students of technical faculties (although they were the focus of the research, since the PPS procedure generally concerns pilots and air traffic controllers) and conduct an objective analysis, with an active support of psychologist V.S. Kamenskaya form Irkutsk, the analysis results for 122 students majoring in Practice and Theory of Translation, Foreign Studies of the Institute of Philology, Foreign Languages and Media Communication of the Irkutsk State University (PFLMC ISU) were obtained. Thus, the total sample of experiment participants was 603 people. Figure 4 shows the distribution of average values of behaviour styles in conflict situations for the entire specified sample (SPbSUCA and PFLMC ISU students). Comparing Figure 3 and Figure 4, it is quite obvious that they are almost identical.

If we compare these 603 participants per individual samples, there are of course differences. There are highly-reliable ($p \leq 0.01$) differences in the manifestation of such behaviour styles as competing, compromising and avoiding between males (344 people) and females (259 people) according to the Pearson's χ^2 criterion. Females are significantly less inclined to the competing strategy and somewhat more inclined to avoiding and compromising as compared

Table 5. Intercorrelation between TKI-R results on a sample of 603 SPbSUCA and PFLMC ISU students of various specialties

	Competing	Collaborating	Compromising	Avoiding	Accommodating
Competing		-0.3188	-0.3783	-0.3924	-0.4847
Collaborating	$p < 0.001$		-0.1297	-0.1771	-0.0645
Compromising	$p < 0.001$	$p < 0.01$		-0.0211	-0.1972
Avoiding	$p < 0.001$	$p < 0.001$	$p \geq 0.05$		-0.1482
Accommodating	$p < 0.001$	$p \geq 0.05$	$p < 0.001$	$p < 0.001$	

Note: the values of Pearson correlation coefficient between efficiency indicators are located in the upper right; the characteristics of correlation significance are located in the bottom left

to males. This is to a certain extent consistent with the data of [20] that shows a significant difference in the maturity of competing strategy between female and male respondents (Mann-Whitney U-test, $U = 1003.5$ with $p = 0.036$): male students display a higher level than female students.

Student pilots (232 people) and students of humanities (194 people) also show highly reliable differences in the manifestation of such behaviour styles as competing and avoiding according to the Pearson's χ^2 criterion. Humanities students and student air traffic controllers (141 people) have highly reliable differences in the manifestation of the competing behaviour style.

Table 5 shows the intercorrelations between TKI-R results on a sample of 603 students of various specialties (SPbSUCA and PFLMC ISU). There are no fundamental differences between data in Table 4 and Table 5.

Conclusion. Thus, by generalizing the authors' findings and those set forth in other authors' publications [20, 26-29], we can agree with the conclusions of [29] in that "uncooperative behaviour of all tested students is dominated by average manifestation of strategies of competing, collaborating, compromising, avoiding and accommodating, which indicates the ability of the subjects of this age for flexible behaviour in conflict situations subject to the specific conditions of interaction". That means that students, unlike the success-seeking business owners [28], while prioritizing collaboration and compromise in conflict situations, flexibly use other behaviour strategies. This must be taken into consideration when planning measures aimed at improving the reliability of professional psychological selection in commercial aviation. It appears that in view of the above reasons, the application of the TKI-R procedure in the professional psychological selection of aviation specialists is unviable.

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Risk-based automated system for prediction of fire safety in railway facilities

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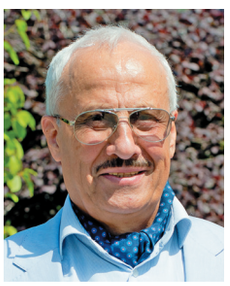
Igor B. Shubinsky

Aim.*The development of the Russian railway industry is associated with the growing number of operated buildings, rolling stock, more complex business processes of infrastructure maintenance and client service. In this context, JSC Russian Railways (JSC RZD) needs to manage the fire safety of more than ten thousand units of traction rolling stock and hundreds of buildings, where potential fires may cause harm to passengers or interruption of service. Fire safety management of both fixed and mobile railway facilities is performed at all lifecycle stages from design to disposal. Implementing the processes of fire safety diagnostics and prediction requires the development of a man-machine system whose core would be an automated fire risk control system (ACS) that allows – basedon the fire risk prediction – makingdecisions regarding the requirement for the repairs, replacement or maintenance of railway facilities and fire safety systems.* **Methods.***The methods of the automatic control theory, expert assessment were used. The study aimed to develop an algorithm of automated auditing of railway facilities fire safety.* **Results.***It is established that the majority fire safety control systems use gas concentration sensors to detect symptoms of hazard before flame development. This approach is hardly effective in terms of fire safety of railway facilities. For railway facilities whose actual state has an effect on the probability of fire a fire audit algorithm was developed that is based on the existing service and repair system, as well as statistical data on the states of railway facilities that precede fire. In order to enable systematic risk management measures in a large number of railway facilities, the paper proposes the structure of an automated fire risks management system that includes a fire safety management center and a mobile hardware and software system for fire safety auditing.* **Conclusions.** *It shows the importance of developing a proactive fire safety management system based on fire risk assessment. It was identified that information on the states preceding fires in railway facilities can be obtained from both the existing automated failure reporting and risk assessment systems and the diagnostic results of the actual state of objects as part of scheduled preventive maintenance. A method of automated assessment of fire hazard is proposed for systematic management of fire risks in many railway facilities.*

Keywords: *fire risk, automate dauditing algorithm, pro active fire safety management system, automated fire risk assessment*

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Introduction

The first fire detection sensors were developed in the XIX century and were based on temperature detection, i.e., according to current existing classification were heat-sensitive alarms [1]. Sensors are at the core of most automated supervision and control systems. With the development of information technology, ensuring safety is becoming progressively more simple, yet it requires complex algorithms. Among today's fire safety technology we can note automated fire safety management systems, as well as the intelligent and robotized fire alarm and suppression systems. The design of buildings with automatic fire suppression systems involves computer simulation of the evacuation process. Automation and application of information technology are evident in each aspect of fire safety both in the fire prevention systems and fire safety systems. At the foundation of such automation are technologies that enable collection of statistical information on the cases of fire, analysis, investigation and proposal of solutions to prevent repeated incidents.

In order to ensure fire safety of large facilities various hardware and software systems are integrated into a single automated fire safety management system. A research of the software architecture of safety-critical systems is done in [2]. An event-driven system has a number of advantages that are valuable in terms of fire safety, i.e. a system can be easily extended with a new component, the components can react to any events. However, such architecture does not guarantee a reaction to an event, therefore, the reaction to an event must be confirmed explicitly. That requires an interface to external systems, human operator or an automated decision support system.

This paper examines the task of constructing the functional structure of an automated railway facility fire safety management system based on fire risk assessment and enabling the prediction of the probability of fires using information on the results of railway facilities diagnostics.

1. The problem of automated diagnostics of facility faults affecting fire safety

In accordance with the requirements of the code of practice [3] detecting the location of fire can be done using video cameras and matrix optical sensors with targeted indication of the source of fire, targeted automatic fire alarms, liquid flow detectors or sprinklers with start control. The efficiency of all actions following the detection of fire depends on the rate at which the alarm processes the incoming signals. For that purpose, various algorithms of processing the controlled ambient variables are in development [4]. Software dependability is another important factor. Matters of dependability of automated control systems, including those specific to fire safety, was examined by many researchers [5, 6, 7, 8]. In [9], the authors look at the problem of ensuring the protection of software from hardware faults, which is of special relevance in case of sensor-based systems. The high rate of sensor operation and dependability of automated systems components are essential, but not sufficient conditions of efficient fire safety management of complex technical facilities. Todays' systems must enable not only efficient suppression of detected fires, but prevent them as well. For this purpose, the fire alarm (FA) and public address and evacuation management system (PAEM) examined in [10] must be complemented with a circuit of early pre-fire detection of fire hazardous states (Fig. 1).

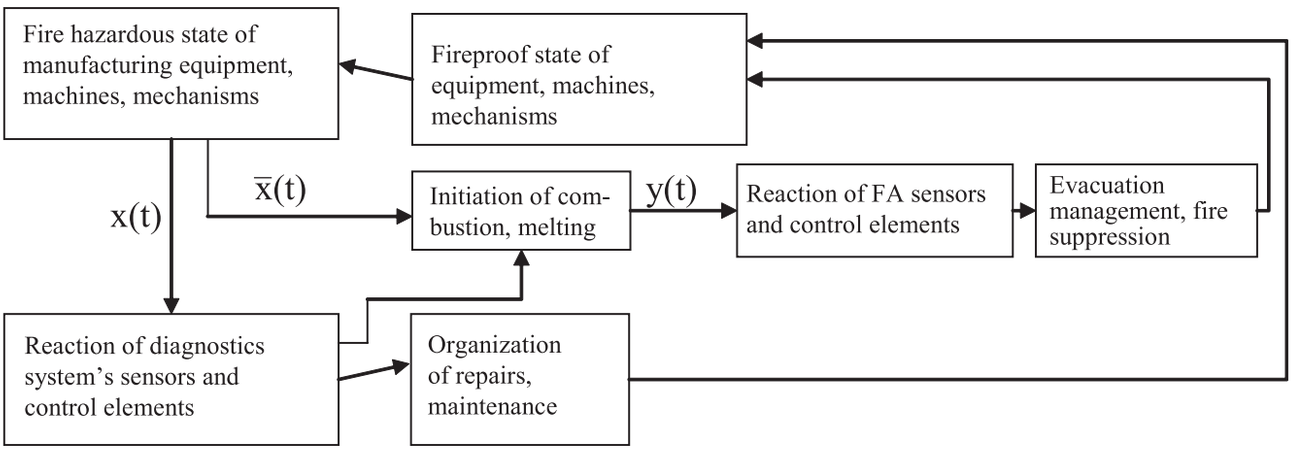

Figure 1. Operation diagram of FA and PAEM with a circuit of pre-fire detection of fire hazardous states

Table 1. Primary means of detection of pre-combustion signs of fire hazard

Facility	Technical facility	Controlled fire hazard state
Oil industry facilities [11]	Air pollution sensor	Dangerous level of explosive gas concentration
Sports facilities [12]	Combustible gases and ammonia vapors sensors	Dangerous level of explosive gas concentration, maximum acceptable concentration
Pipelines [13]	Pressure sensor	Elevated pressure
Peatlands [14]	Peat gas thermal probes	Temperature, gas concentration

Shown in Figure 1 are:

$x(t)$, the parameters of the object of evaluation (equipment/machine/mechanism) indicating the fire hazardous state of the facility, that can be identified by means of diagnostics, including, among other, human visual inspection of such facility,

$\overline{x}(t)$, the parameters of the object of evaluation (equipment/machine/mechanism) indicating the fire hazardous state of the facility, that cannot be identified by means of diagnostics, including, among other, human visual inspection of such facility,

$y(t)$, the environmental parameters registered by the fire alarm.

The majority of automated fire safety management systems contain only sensors that react to parameters $y(t)$. But currently, due to increasing costs of equipment, the requirement for round-the-clock operation, systems are needed that are capable of identifying signs of fire hazardous states before the appearance of fire. Such system will allow avoiding emergency interruption of manufacturing and business processes, as well as significantly reducing costs, including due to prevention of economic losses. Especially relevant is prevention of losses caused by emergency interruption of processes in railway transportation. Constructing a proactive fire safety management system requires designing methods and tools for diagnosing the parameters that indicate fire hazardous states of facilities. Based on the assessment of the fire risk of the identified states, the decision must be made regarding the modification of the state of the supervised facility before the onset of fire. Table 1 shows the technical facilities used for prediction of fire hazard in facilities before combustion

Today, proactive fire safety management systems are primarily used in the oil and gas industry and the primary parameter $x(t)$ they can observe is gas concentration. Gas alarm-based automated systems are also used in closed systems, e.g. submarines, warehouses. However, such diagnostics tools are not applicable in many other industrial facilities. That causes the requirement for the development of automated systems for monitoring faults affecting fire safety. This objective is especially important in the context of widespread automation of manufacturing and business processes and development of databases of actual states of facilities. For instance, JSC RZD operates an automated systems for recording technical facility failures [15], dependability and risks management systems [16]. Information from such systems should be used for purposes of various tasks. However, complete automation of diagnostics processes is not always necessary. Of high importance is the cost of sensors and other components, the availability of legacy manned facility inspection systems. The latter is especially important in case of facilities that undergo regular cycles of service and repair (S&R). In the railway industry, such facilities include: traction rolling stock, interlocking equipment, traction substations equipment, etc. In such facilities an efficient S&R system is already in place. The results of facilities diagnostics as part of S&R can be used in ensuring fire safety. It is obvious that the number of fire hazardous states of facilities is much smaller that the number of down or pre-failure states. For this reason, we should talk about fire audit of facilities whose criteria must be associated with the states that can actually cause a fire.

2. Diagnosing the faults of railway facilities that cause increased fire hazard

While auditing complex technical systems experts face two problems: limitations of human memory in terms of the number of the possible hazardous states of railway facilities (including "rote learning" of standard sets and ignoring the states outside of the expert's experience), as well as the time expenditures of coordination of the auditors' opinions. These problems are efficiently solved through the use of man-machine systems that enable real-time display of the list of auditing criteria for a specific technical system, recording the identified states, as well as using diagnostic tools.

Automated audit requires two modules, i.e. the module for railway facilities audit criteria and state classifiers development, the auditing module. The coordinated operation of these modules enables the algorithm of diagnostics of railway facility faults that cause increased fire hazard in facilities (Figure 2).

The module for audit criteria and state classifiers development must implement the following actions:

1. Source analysis for the causes of fire and results of EMERCOM inspections consisting in the composition of a list of fire safety violations identified as part of planned EMERCOM inspections, composition of a list of causes of fires.

2. Preparation of a list of standard fire hazardous states consisting in the statistics analysis of the fire safety violations and preparation of a list of typical violations, analysis of the causes of fire and composition of a list of typical fire hazardous states.

3. Ranking of typical fire hazardous states:

- preparation of the list of fire hazardous states of the 1-st category of hazard (states that cause fire),
- preparation of the list of fire hazardous states of the 2-nd category of hazard (states that lead to the onset of the causes of fire or states of facilities that were statistically sources of fire),
- preparation of the list of fire hazardous states of the 3-rd category of hazard (other states).

4. Agreement of the experts' opinions on the results of the ranking of fire hazardous states:

5. Quantitative estimation of the hazard of the 1-st category states:

- for the purpose of graph-based estimation of the fire probability, a graph and transition probability matrix are constructed,
- for the purpose of expert-based estimation of the fire probability, for each state the probability is estimated of the onset of fire hazardous events.

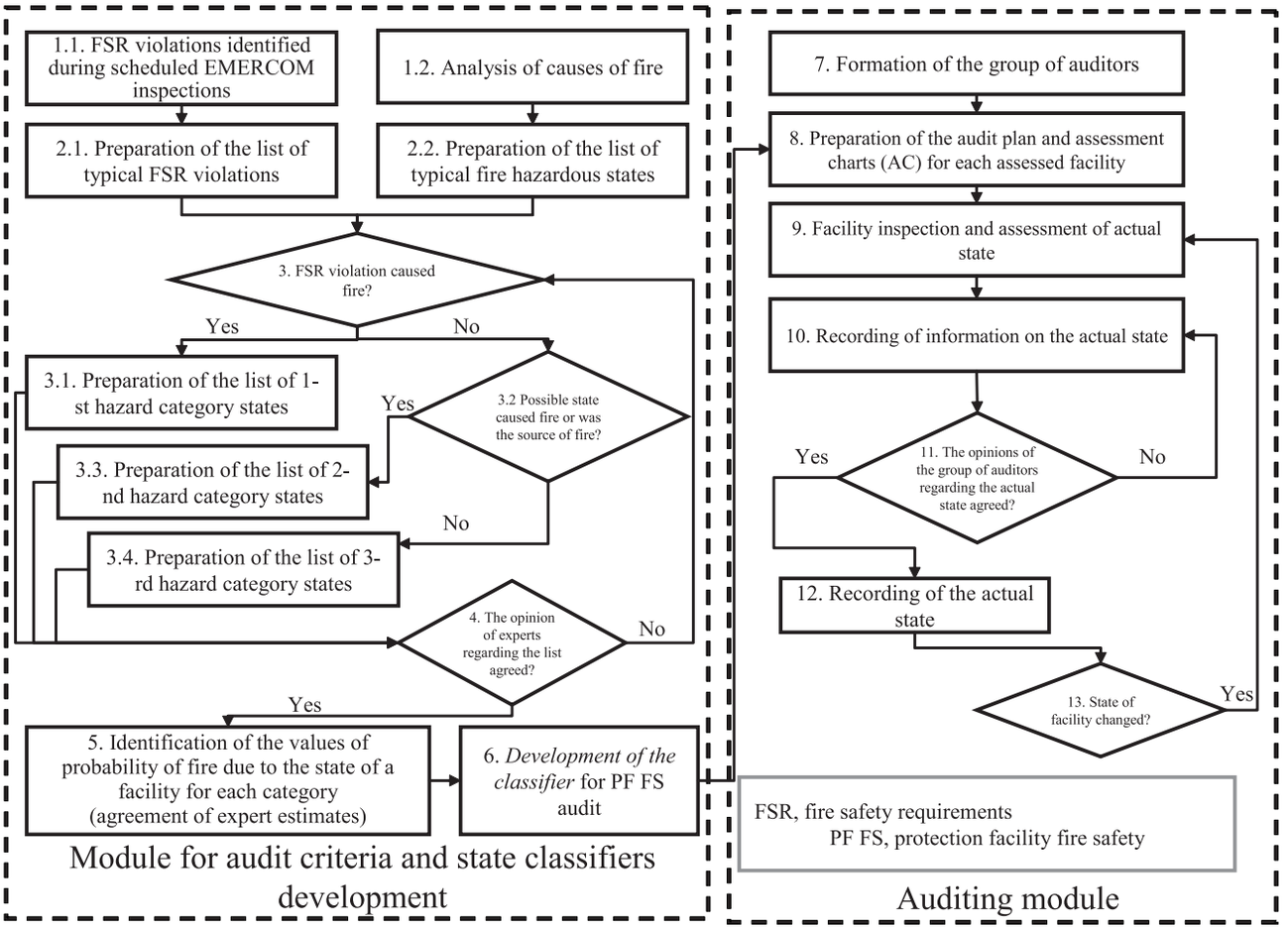

Figure 2. Algorithm of diagnostics of railway facility faults that cause increased fire hazard in railway facilities

6. Development of the classifier of fire hazardous states of fire safety auditing of railway facilities. The classifier includes the list of all possible states of a railway facility (taking into account the facility's design). The classifier, if necessary, indicates the tools that can be used to identify fire hazardous states. Using the developed classifiers, the auditing module operates and performs the following functions:

- formation of a group of auditors qualified in identifying fire hazardous states in railway facilities,
- preparation of the audit plan and assessment charts (AC) for each assessed facility. The audit plan describes the sequence of railway facility inspection. ACs contain a list of fire hazardous states that may be observed at the assessed facility. The AC also includes margins for notes on the actual state.

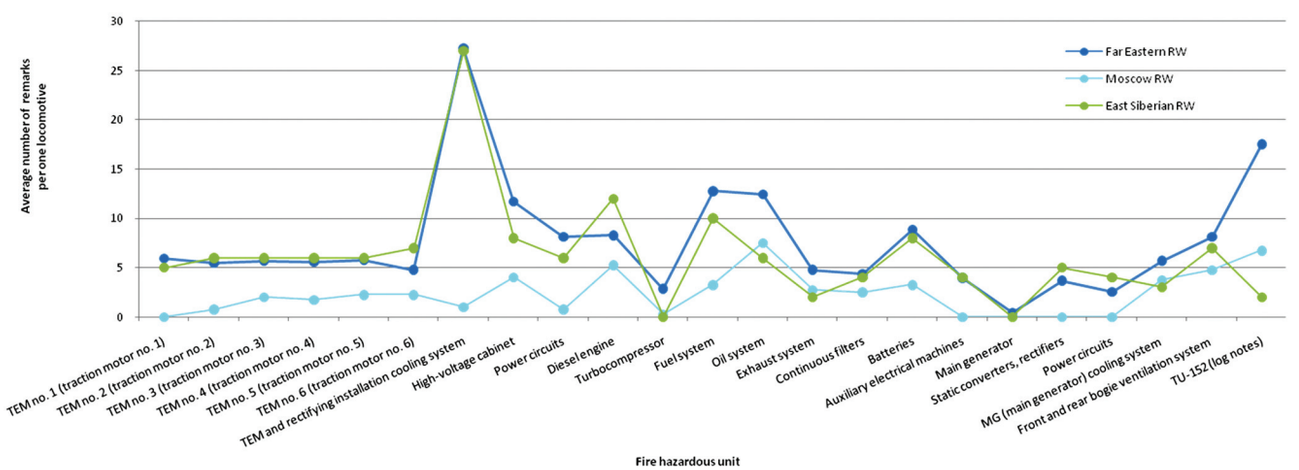

Figure 3. Fire hazardous state identification statistics in 3TE10-series traction rolling stock

7. Facility inspection, selection of the diagnostics tools, collection of data on the actual state.

8. Recording of information on the actual state.

9. Agreement of the auditors' opinions on the list of identified fire hazardous states

10. Registration of the facility's actual state.

11. Updating of the audit data in case of changes in the facility's state.

The algorithm shown in Figure 2 is iterated for each facility whose fire hazardous state is to be evaluated. Within the period of 2018 springtime inspection of the Far Eastern Traction Directorate 9761 fire hazardous states were identified in 221 units of TE10-series diesel-electric locomotives. Figure 3 shows data on the number of fire hazardous states identified as part of fire safety auditing of 3TE10-series locomotives of the Far Eastern, Moscow, East Siberian Traction Directorates.

3. Architecture of the automated railway facilities fire safety diagnostics and prediction system

Mathematical processing of the results of diagnostics railway facility defects that cause increased fire hazard are examined in [17, 18]. The result of such processing is the prediction of the fire risk of each assessed railway facility and decision-making regarding its clearance for operation. In order to enable systematic risk management measures in a large number of facilities an automated fire risks management system (AMS) is required. Such AMS must be developed taking into account the geographically distributed management system of the railway transportation. The following structure of the fire risks AMS in railway transportation will be efficient:

1) Fire safety supervision center that will collect information on the statistics of fires (e.g. through the integration with existing AMSs of JSC RZD). Such center must include the module for audit criteria and state classifiers development.

2) Mobile hardware and software system for fire safety auditing that enables the operation of the auditing module based on the data received from the fire safety supervision center.

Since the inspection of each facility requires visual monitoring, the use of mobile state recording systems will be optimal. Today, most sensors used in the diagnostics of the actual state of facilities (pressure, oil sensors, thermal imaging systems, etc.) are not part of a single network, therefore sensor readings must be taken individually. That is another argument in favour of mobile systems. Figure 4 shows the implementation diagram of the above method of railway facilities fire risk assessment.

The fire safety supervision center includes the central processor 1, whose inputs/outputs are directly connected

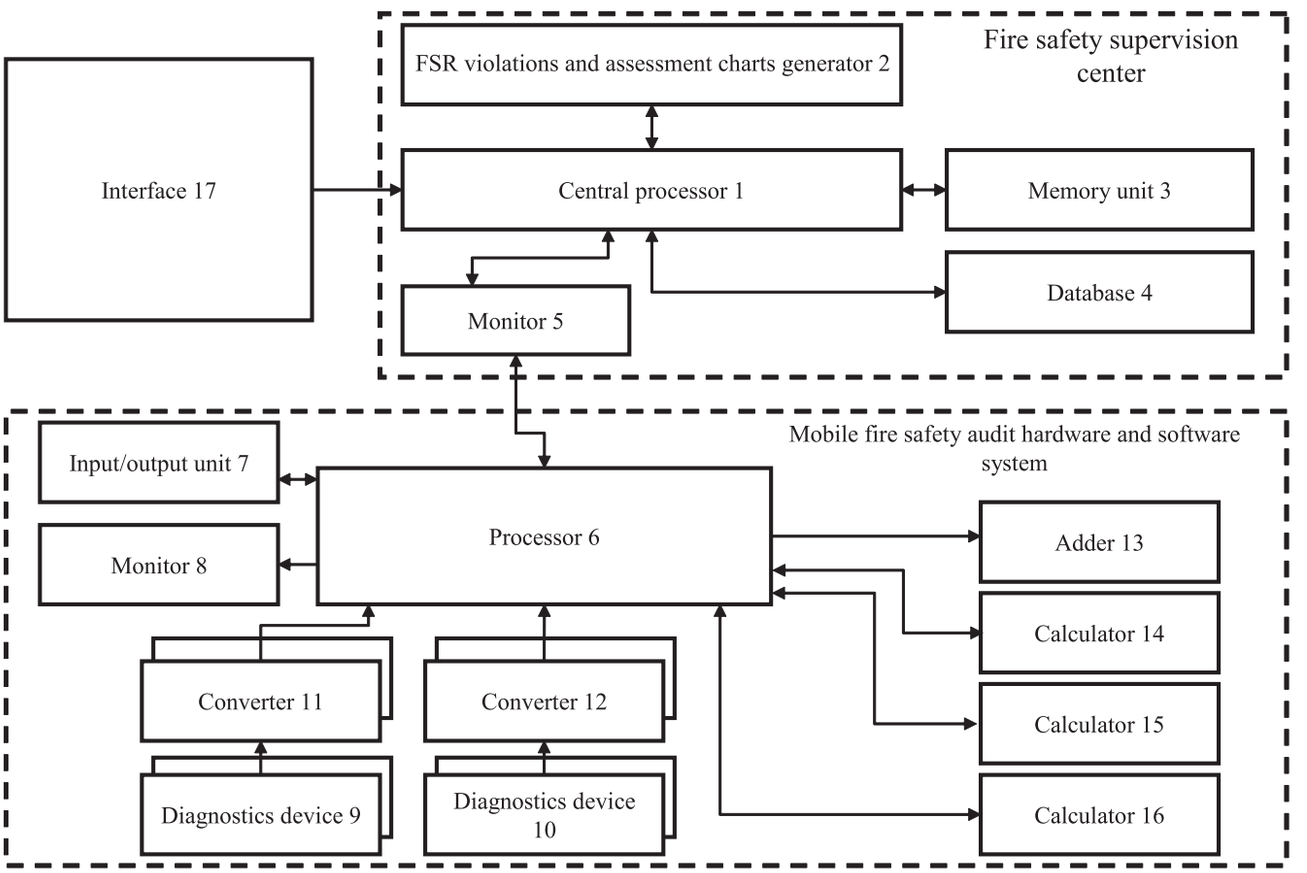

Figure 4. Implementation diagram of the above method of railway facilities fire risk assessment

directly to the outputs/inputs of the assessment chart generator 2 (module for audit criteria and state classifiers development), memory unit 3 and database 4, as well as the monitor 5. The mobile hardware and software system (MHSS) for fire safety auditing includes the processor 6 with the input/output unit 7 and monitor 8, diagnostic facilities in the form of appropriate supervision and diagnostics systems 9 and test instruments 10, converters 11 and 12, series-connected adder 13, first, second and third calculators 14, 15 and 16, the output of the latter of which is connected to the input of processor 6. The outputs of processor 6 are connected to adder 13 and communication interface 17 to ensure interaction of processor 6 with the central processor 1.

The output of each supervision and diagnostics system 9 and test instrument 10 through the appropriate converter 11 and 12 is connected to the input of processor 6, whose other inputs/outputs are connected to the outputs/inputs of calculators 14 and 15.

After the fire risk has been calculated using the data on the states of fire hazard submitted to MHSS, the elimination plan is developed taking into account the levels of risks created by such states. If the protected facility is cleared for limited operation, the elimination of fire hazardous states is done as part of scheduled S&R. If a facility is not cleared for operation, it is submitted to unplanned repairs.

Conclusion

The paper examines the problem diagnosing fire hazard states of railway facilities that precede fires. It shows the importance of developing a proactive fire safety management system based on fire risk assessment. It was identified that information on the states preceding fires in railway facilities can be obtained from both the existing automated failure reporting and risk assessment systems and the diagnostic results of the actual state of objects as part of scheduled preventive maintenance.

Selecting the parameters of facilities' actual states is proposed to be performed through an algorithm of diagnostics of railway facility faults that cause increased fire hazard allowing for the participation of a group of experts in the process of diagnostics. A method of automated assessment of fire hazard is proposed for systematic management of fire risks in many railway facilities. Taking into account the requirement of visual inspection of railway facilities, including the recording of the readings of geographically-distributed sensors, a mobile hardware and software system is proposed for auditing fire safety of facilities.

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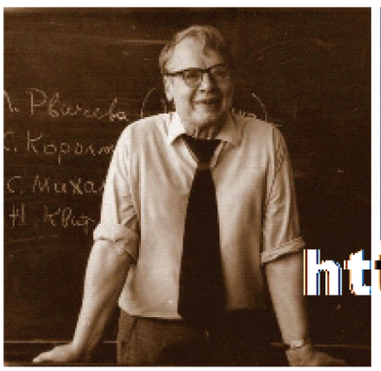

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