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Original article
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Fault tree analysis in the R programming environment. Treatmentof common cause failures

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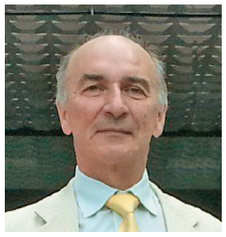

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Abstract. **Aim.** *This paper is the continuation of [1] that proposes using the R programming language for fault tree analysis (FTA). In [1], three examples are examined: fault tree (FT) calculation per known probabilities, dynamic FT calculation per known distributions of times to failure for a system'selements. In the latter example, FTA is performed for systems with elements that are described by different functional and service models. Fault tree analysis (FTA) is one of the primary methods of dependability analysis of complex technical systems. This process often utilizes commercial software tools like Saphire, Risk Spectrum, PTC Windchill Quality, Arbitr, etc. Practically each software tool allows calculating the dependability of complex systems subject to possible common cause failures (CCF). CCF are the associated failures of a group of several elements that occur simultaneously or within a short time interval (i.e. almost simultaneously) due to one common cause (e.g. a sudden change in the climatic service conditions, flooding of the premises, etc.). An associated failure is a multiple failure of several system elements, of which the probability cannot be expressed simply as the product of the probabilities of unconditional failures of individual elements. There are several generally accepted models used in CCF probability calculation: the Greek letters model, the alpha, beta factor models, as well as their variations. The beta factor model is the most simple in terms of associated failures simulation and further dependability calculation. The other models involve combinatorial search associated events in a group of n events, that becomes labor-consuming if the number n is large. Therefore, in the above software tools there are some restrictions on the n, beyond which the probability of CCF is calculated approximately. In the current R FaultTree package version there are no above CCF models, therefore all associated failures have to be simulated manually, which is not complicated if the number of associated events is small, as well as useful in terms of understanding the various CCF models. In this paper, for the selected diagram a detailed analysis of the procedure of associated failures simulation is performed for alpha and beta factor models. The* **Purpose***of this paper consists in the detailed analysis of the alpha and beta factor methods for a certain diagram, in the demonstration of fault tree creation procedure taking account of CCF using R's FaultTree package.* **Methods.** *R's FaultTree scripts were used for the calculations and FTA capabilities demonstration.* **Conclusions.** *Two examples are examined in detail. In the first example, for the selected block diagram that contains two groups of elements subject to associated failures, the alpha factor model is applied. In the second example, the beta factor model is applied. The deficiencies of the current version of FaultTree package are identified. Among the main drawbacks we should indicate the absence of some basic logical gates.*

Keywords*: fault tree, fault tree analysis, CCF, total cause failure, independent failures, dependent failures, antithetic events, alpha factor, beta factor.*

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Introduction

This paper is the continuation of [1] dedicated to the overview of the capabilities of the FaultTree package developed for the R programming environment. R is a programming language for statistical processing of graphics, as well as a free open-source programming environment developed as part of the GNU project. R supports a wide range of statistical and numerical methods and a large number of extension packages. Packages are libraries that support specific functions and subprograms or special applications. The paper continues the analysis of the capabilities of the package for creation, calculation and output of fault trees, the FaultTree package, in terms of the common cause failures (CCF).

Fault tree analysis (FTA) is a method of complex systems dependability analysis, in which the system failures are analyzed using the methods of Boolean algebra, summarizing the sequence of the subordinate events (low level failures) that cause the failure of the entire system. Sequences of random events are identified that may cause the system to fail, ways of reducing risks are defined and the rates of system failures are determined. In the most simple cases the fault trees form independent events. However, situations are possible when failures occur due to common causes, i.e. depend on a certain internal or external factor. Internal factors include general design, process and other internal causes, external factors include the effects of natural phenomena and/or human activity [2-4].

Calculations of CCF probabilities commonly involve various mathematical models that establish linear connection between the probabilities of dependent failure of a subset of elements affected to CCF with the probability of failure due to total causes. Failure due to total cause is essentially a complete group that includes independent failures of each element, CCF of two, three, etc. elements. The sufficiently simple, from the implementation point of view, beta factor model implies that in a set of elements exposed to CCF the failures can only be of two types: independent single failures of elements and dependent CCF of the entire group occurring simultaneously or almost simultaneously. In this case these events can be easily introduced into the fault tree manually. It should be taken into consideration that they must be incompatible, i.e. the connecting logical operations must make allowance for this fact. Under relatively low probabilities of failure, operator "or" can be used, while the calculation error is small.

The beta factor model is a special case of the more common Greek letters and alpha factor models. Let us note that the latter has several modifications. The basic difference between the generalized models and the beta factor model is that dependent failures can affect any subsets out of a set of elements affected by CCF. The choice of such subsets must be substantiated by the fact that their combination must cause system failure. It is clear that in this case we are dealing with a combinatorial enumeration of such situations, that, in case of small size of the set (two, three elements) can be done manually. However, if the set is large, computer technology has to be used, more precisely specialized software products: Windchill PTC, Risk Spectrum, Arbitr, etc. In the software tools there are some restrictions on the size of sets, beyond which the calculations are conducted approximately. That is due to the fact that as the size of the set of elements affected by CCF grows, the computational costs increase incommensurably.

As to the FaultTree package, its current version does not yet have CCF calculation models, therefore in the generalized models all enumerations have to be performed manually. That causes other problems associated with a deficiency in the required logical operations and/or event categories thatwill be covered in this article.

Let us examine some basic CCF capabilities supported by FaultTree.

Treatment of common cause failures

For the purpose of demonstrating the CCF capabilities, let us consider four different models: beta factor, alpha factor (with staggered and non-staggered tests) and the Greek letters model [5-7]. As the initial scheme let us consider the circuit shown in Figure 1 as per [1].

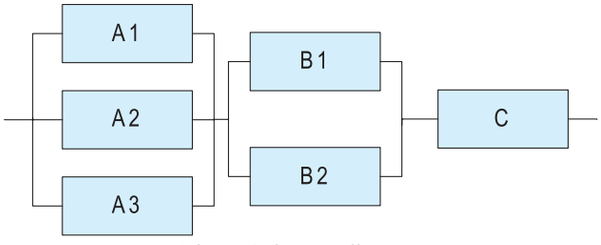

Figure 1. System diagram

Let us assume that the elements of group A (A1, A2, A3) and the elements of group B (B1, B2) may fail due to common causes. Let us introduce the following designations:

$I_1(A)$, $I_2(A)$, $I_3(A)$ are independent (single) failures of the elements of group A;

$C_{12}(A)$, $C_{23}(A)$, $C_{13}(A)$ are the CCFs of exactly two elements of group A;

$C_{123}(A)$ are CCFs of all thee elements of group A;

$I_1(B)$, $I_2(B)$ are independent failures of elements of group B;

$C_{12}(B)$ are CCFs of all the elements of group B;

$F(C)$ is the failure of element C.

The basic parametric model of CCF analysis determines the following events:

$$\begin{aligned} 1_t(A) &= I_1(A) + C_{12}(A) + C_{13}(A) + C_{123}(A): \\ 2_t(A) &= I_2(A) + C_{12}(A) + C_{23}(A) + C_{123}(A); \\ 3_t(A) &= I_3(A) + C_{13}(A) + C_{23}(A) + C_{123}(A); \\ 1_t(B) &= I_1(B) + C_{12}(B); \\ 2_t(B) &= I_2(B) + C_{12}(B). \end{aligned} \quad (1)$$

For instance, the first event will indicate a failure due to total causes related to the failure of the first element of group A. Let us designate the probabilities of such events:

$$\begin{gathered} Q_t(A)=\Pr(1_t(A))=\Pr(2_t(A))=\Pr(3_t(A)); \\ Q_1(A)=\Pr(I_1(A))=\Pr(I_2(A))=\Pr(I_3(A)); \\ Q_2(A)=\Pr(C_{12}(A))=\Pr(C_{13}(A))=\Pr(C_{23}(A)); \\ Q_3(A)=\Pr(C_{123}(A)); \\ Q_t(B)=\Pr(1_t(B))=\Pr(2_t(B)); \\ Q_1(B)=\Pr(I_1(B))=\Pr(I_2(B)); \\ Q_2(B)=\Pr(C_{12}(B)). \end{gathered} \quad (2)$$

Equations (2) are substantiated by that fact that hypothetically all elements of the same group are identical and are operated under identical conditions, and, therefore, their dependability indicators are identical as well.

Due to the incompatibility of events in the right part of each equations (1), we obtain:

$$\begin{gathered} Q_t(A)=Q_1(A)+2Q_2(A)+Q_3(A); \\ Q_t(B)=Q_1(B)+Q_2(B). \end{gathered} \quad (3)$$

The probabilities of the right parts of equations (3) are determined differently depending on specific models.

Greek letters model

Thus, for the Greek letters model the following assumption is true:

$$Q_k^{(m)}=\left(\frac{1-p_{k+1}}{C_{m-1}^{k-1}}\prod_{i=1}^{k}p_i\right)Q_t,\ p_1=1,\ldots,p_{m+1}=0. \quad (4)$$

In our case if we designate: $p_2=\beta$, $p_3=\gamma$, from (4) easily follows:

$$\begin{gathered} Q_1^{(3)}(A)=\left(1-\beta(A)\right)Q_t(A); \\ Q_2^{(3)}(A)=\frac{1}{2}\beta(A)\left(1-\gamma(A)\right)Q_t(A); \\ Q_3^{(3)}(A)=\beta(A)\gamma(A)Q_t(A); \\ Q_1^{(2)}(B)=\left(1-\beta(B)\right)Q_t(B); \\ Q_2^{(2)}(B)=\beta(B)Q_t(B). \end{gathered} \quad (5)$$

Alpha factor model (not-staggered testing)

In this case the general formula for the probabilities is as follows:

$$Q_k^{(m)}=\left(\frac{k\alpha_k^{(m)}}{C_{m-1}^{k-1}\alpha_t}\right)Q_t,\ \text{where}\ \alpha_t=\sum_{k=1}^{m}k\alpha_k^{(m)}. \quad (6)$$

For groups of 3 and 2 events, we thus obtain:

$$\begin{gathered} Q_1^{(3)}(A)=\frac{\alpha_1^{(3)}}{\alpha_t^{(3)}}Q_t(A); \\ Q_2^{(3)}(A)=\frac{\alpha_2^{(3)}}{\alpha_t^{(3)}}Q_t(A); \\ Q_3^{(3)}(A)=\frac{3\alpha_3^{(3)}}{\alpha_t^{(3)}}Q_t(A);\ \text{где}\ \alpha_t^{(3)}=\alpha_1^{(3)}+2\alpha_2^{(3)}+3\alpha_3^{(3)}; \\ Q_1^{(2)}(B)=\frac{\alpha_1^{(2)}}{\alpha_t^{(3)}}Q_t(B); \\ Q_2^{(2)}(B)=\frac{2\alpha_2^{(2)}}{\alpha_t^{(2)}}Q_t(B);\ \text{где}\ \alpha_t^{(2)}=\alpha_1^{(2)}+2\alpha_2^{(2)}. \end{gathered} \quad (7)$$

Alpha factor model (staggered testing)

In this case the general formula for the probabilities is as follows:

$$Q_k^{(m)}=\left(\frac{\tilde{\alpha}_k^{(m)}}{C_{m-1}^{k-1}}\right)Q_t,\ \text{where}\ \sum_{k=1}^{m}\tilde{\alpha}_k^{(m)}=1. \quad (8)$$

For groups of 3 and 2 events, we thus obtain:

$$\begin{gathered} Q_1^{(3)}(A)=\alpha_1^{(3)}Q_t(A); \\ Q_2^{(3)}(A)=\frac{1}{2}\tilde{\alpha}_2^{(3)}Q_t(A); \\ Q_3^{(3)}(A)=\tilde{\alpha}_3^{(3)}Q_t(A)\ where\ \ \tilde{\alpha}_1^{(3)}+\tilde{\alpha}_2^{(3)}+\tilde{\alpha}_3^{(3)}=1; \\ Q_1^{(2)}(B)=\tilde{\alpha}_1^{(2)}Q_t(B); \\ Q_2^{(2)}(B)=\tilde{\alpha}_2^{(2)}Q_t(B)\ where\ \tilde{\alpha}_1^{(2)}+\tilde{\alpha}_2^{(2)}=1. \end{gathered} \quad (9)$$

Beta factor model

One of the simplest CCF models is as follows:

$$Q_k^{(m)}=\begin{cases}(1-\beta)Q_t, & k=1; \\ 0, & 1<k<m; \\ \beta Q_t, & k=m.\end{cases} \quad (10)$$

In our case we obtain:

$$\begin{gathered} Q_1^{(3)}(A)=\left(1-\beta(A)\right)Q_t(A); \\ Q_2^{(3)}(A)=0; \\ Q_3^{(3)}(A)=\beta(A)Q_t(A); \\ Q_1^{(2)}(B)=\left(1-\beta(B)\right)Q_t(B); \\ Q_2^{(2)}(B)=\beta(B)Q_t(B). \end{gathered} \quad (11)$$

It is not difficult to show that by substituting (5), (7), (9), (11) into (3) an identical equation is obtained: $Q_t(A)=Q_t(A)$, $Q_t(B)=Q_t(B)$, however, this will be definitely true under large m as well. Thus, the difference between the approaches employed by the models consists only in the different understanding of the correlations between the probabilities $Q_1^{(m)},Q_2^{(m)},\ldots,Q_m^{(m)}$. Frequently, different models may provide sufficiently close results. For that purpose transfer equations can be used [5] (see Table A-2-A-4 of annex A). In addition, [4] (Table 5.11, p. 75) provides reference statistical information of the parameters $\tilde{\alpha}_k^{(m)}$ for the alpha factor model (8). Thus, for parallel series of two elements B1, B2 sample medians of the parameters (50% of point) are equal respectively

$$med\left(\tilde{\alpha}_1^{(2)}\right)=0,953,\ med\left(\tilde{\alpha}_2^{(2)}\right)=0,047. \quad (12)$$

For subseries A of three elements A1, A2, A3

$$\begin{gathered} med\left(\tilde{\alpha}_1^{(3)}\right)=0,9500,\ med\left(\tilde{\alpha}_2^{(3)}\right)=0,0242, \\ med\left(\tilde{\alpha}_3^{(3)}\right)=0,0258. \end{gathered} \quad (13)$$

Let us take these numbers as the values of the parameters of model (8). Probabilities (9) will be as follows

$$\begin{aligned} Q_1^{(3)}(A) &= 0,9500 \cdot Q_t(A); \\ Q_2^{(3)}(A) &= 0,0121 \cdot Q_t(A); \\ Q_3^{(3)}(A) &= 0,0258 \cdot Q_t(A); \\ Q_1^{(2)}(B) &= 0,953 \cdot Q_t(B); \\ Q_2^{(2)}(B) &= 0,047 \cdot Q_t(B). \end{aligned} \quad (14)$$

Flow tables can be used, but it is not difficult to guess, that in model (5)

$$\beta(A) = 0,05, \gamma(A) = \frac{0,0258}{\beta(A)} = 0,516, \beta(B) = 0,047.$$

In the alpha factor model (staggered testing), a simple transformation provides the following result:

$$\alpha_1^{(3)} = 0,95, \alpha_2^{(3)} = 0,0121, \alpha_3^{(3)} = 0,0086, \alpha_t^{(3)} = 1,$$

$$\alpha_1^{(2)} = 0,953, \alpha_2^{(2)} = 0,0235, \alpha_t^{(2)} = 1.$$

Under the deduced values of the parameters the results of both the alpha factor and Greek letters models will provide identical results. For the sufficiently rough, yet simpler beta factor model the results will be different, since the beta factor model uses only one input parameter. Nevertheless, let us take it identical to the corresponding Greek letter, 0.05.

Now let us proceed to the calculations. In order to simplify the fault tree let us avoid using different dependability models for different elements, but assume that the probabilities of failure of elements A, B and C are respectively

$$Q_t(A) = 0.3, Q_t(B) = 0,2, Q_t(C) = 0,1. \quad (15)$$

The probability of failure without regard to the CCF will be equal to:

$$Q_S = 1 - \left(1 - Q_t^3(A)\right)\left(1 - Q_t^2(B)\right)\left(1 - Q_t(C)\right) = 0,1593. \quad (16)$$

Let us perform calculations taking the CCF into account. The circuit will fail under the following combinations of events presented as eight minimum sections:

$$\begin{gathered} \{I_1(A) \cap I_2(A) \cap I_3(A)\}, \{I_1(A) \cap C_{23}(A)\}, \\ \{I_2(A) \cap C_{13}(A)\}, \{I_3(A) \cap C_{12}(A)\}, \{C_{123}(A)\}, \\ \{I_1(B) \cap I_2(B)\}, \{C_{12}(B)\}, \{F(C)\}. \end{gathered} \quad (17)$$

Let us compose the calculation script. Unlike in the the specialized packages mentioned above, in the current version of the package under consideration CCF is not taken account of, therefore all the events of (17) have to be developed and introduced manually. Let us note that in (17) there is a group of incompatible (thus dependent) sections, for example, the first and the second, the first and the third, etc. There is also a group of independent sections, for example, $\{I_1(A) \cap I_2(A) \cap I_3(A)\}$ and $\{C_{12}(B)\}$, i.e. sections belonging to different CCF groups. Correct calculation of the probabilities of failure of this group requires using the specialized logic node "or" that calculates the probability of a sum of antithetical events. On the other hand, an additional type can be introduced for the group of incompatible events contained in one CCF group. Probably, the optimal solution consists in the development of a module for taking account of CCF, that, probably without a graphic representation in the fault tree, would automatically and correctly calculate the dependability indicators when highlighting CCF event groups and selecting the appropriate model. Unfortunately, such capabilities are not yet implemented in R. Therefore, in the calculation we will be using regular "or".

Example 1. CCF. Alpha factor model

```
library(FaultTree)
tree4 <- ftree.make(type="or", name="Example
4.", name2="CCF")
tree4 <- addLogic(tree4, at=1, type="and",
name="I1(A)*I2(A)*I3(A)")
tree4 <- addLogic(tree4, at=2, type="inhibit",
name="Independent", name2="failure Ai")
tree4 <- addProbability(tree4, at=3,
prob=.95, name="Parameter", name2="models")
tree4 <- addProbability(tree4, at=3, prob=.3,
name="Failure Ai", name2="(total)")
tree4 <- addDuplicate(tree4, at=2, dup_
id=3)
tree4 <- addDuplicate(tree4, at=2, dup_
id=3)
tree4 <- addLogic(tree4, at=1, type="and",
name="Ii(A)*Cjk(A)")
tree4 <- addDuplicate(tree4, at=12, dup_
id=3)
tree4 <- addLogic(tree4, at=12,
type="inhibit", name="CCF", name2="failure
Aj, Ak")
tree4 <- addProbability(tree4,
at=16, prob=.0121, name="Parameter",
name2="models")
tree4 <- addProbability(tree4, at=16, prob=.3,
name="Failure Ai", name2="(total)")
tree4 <- addDuplicate(tree4, at=1, dup_
id=12)
tree4 <- addDuplicate(tree4, at=1, dup_
id=12)
tree4 <- addLogic(tree4, at=1,
type="inhibit", name="CCF C123(A)",
name2="failure A1,A2,A3")
tree4 <- addProbability(tree4,
at=33, prob=.0258, name="Parameter",
name2="models")
tree4 <- addProbability(tree4, at=33, prob=.3,
name="Failure Ai", name2="(total)")
tree4 <- addLogic(tree4, at=1, type="and",
name="I1(B)*I2(B)")
```

```
  tree4 <- addLogic(tree4, at=36,
type="inhibit", name="Independent",
name2="failure Bi")
  tree4 <- addProbability(tree4,
at=37, prob=.953, name="Parameter",
name2="models")
  tree4 <- addProbability(tree4, at=37,
prob=.2, name="Failure Bi", name2="(total")
  tree4 <- addDuplicate(tree4, at=36, dup_
id=37)
  tree4 <- addLogic(tree4, at=1, type="inhibit",
name="CCF C12(B)", name2="failure B1,B2")
  tree4 <- addProbability(tree4,
at=43, prob=.047, name="Parameter",
name2="models")
  tree4 <- addProbability(tree4, at=43, prob=.2,
name="Failure Bi", name2="(total)")
  tree4 <- addProbability(tree4, at=1,
prob=.1, name="Failure C", name2="(total)")
  tree4 <- ftree.calc(tree4)
  ftree2html(tree4, write_file=TRUE)
  browseURL("tree4.html")
```

We will provide no detailed comments regarding this script. Let us focus on lines nos. 4, 11, …. When a logical elements is added, an inhibitory gate is used. As it is known [5-7], in this case the output event occurs, if both input events occur, one of which is a restraint event. The role of condition is performed by the coefficient of the alpha, beta factor or Greek letters model, as these coefficients really play the role of conditional probabilities.

It would appear that calculating the beta factor model two insignificant corrections would suffice. In the 12-th line the probability of 0 and in the 17-th line the probability of 0.05 would need to be specified. However, in this case the fault tree calculation results in an error due to the fact that one of the probabilities is equal to 0. Most probably, in the future this error will be corrected. For now, at least two approaches are possible. One of them consists in specifying zero probability as extremely low. The other one is to remove the branches with a zero probability. The following example demonstrates this exact approach.

Example 2. CCF. Beta factor model

```
  library(FaultTree)
  tree4 <- ftree.make(type="or", name="Example
4.", name2="CCF")
  tree4 <- addLogic(tree4, at=1, type="and",
name="I1(A)*I2(A)*I3(A)")
  tree4 <- addLogic(tree4, at=2, type="inhibit",
name="Independent", name2="failure Ai")
  tree4 <- addProbability(tree4, at=3,
prob=.95, name="Parameter", name2="models")
  tree4 <- addProbability(tree4, at=3, prob=.3,
name="Failure Ai", name2="(total)")
  tree4 <- addDuplicate(tree4, at=2, dup_
id=3)
  tree4 <- addDuplicate(tree4, at=2, dup_
id=3)
  tree4 <- addLogic(tree4, at=1,
type="inhibit", name="CCF C123(A)",
name2="failure A1,A2,A3")
  tree4 <- addProbability(tree4, at=12,
prob=.05, name="Parameter", name2="models")
  tree4 <- addProbability(tree4, at=12, prob=.3,
name="Failure Ai", name2="(total)")
  tree4 <- addLogic(tree4, at=1, type="and",
name="I1(B)*I2(B)")
  tree4 <- addLogic(tree4, at=15,
type="inhibit", name="Independent",
name2="failure Bi")
  tree4 <- addProbability(tree4,
at=16, prob=.953, name="Parameter",
name2="models")
  tree4 <- addProbability(tree4, at=16,
prob=.2, name="Failure Bi", name2="(total")
  tree4 <- addDuplicate(tree4, at=15, dup_
id=16)
  tree4 <- addLogic(tree4, at=1, type="inhibit",
name="CCF C12(B)", name2="failure B1,B2")
  tree4 <- addProbability(tree4,
at=22, prob=.047, name="Parameter",
name2="models")
  tree4 <- addProbability(tree4, at=22, prob=.2,
name="Failure Bi", name2="(total)")
  tree4 <- addProbability(tree4, at=1,
prob=.1, name="Failure C", name2="(total)")
  tree4 <- ftree.calc(tree4)
  ftree2html(tree4, write_file=TRUE)
  browseURL("tree4.html")
```

Let us conduct calculations analytically. First, let us calculate the alpha factor and Greek letters models. By fitting model coefficient we obtained identical results. By virtue of (2) and independence of events, the precise probability of failure due to all causes (both common causes, and independently) will be equal to

$$Q_{S(CCF)} = 1 - Pr\left(\overline{A} \cap \overline{B} \cap \overline{C}\right) = 1 - Pr\left(\overline{A}\right) Pr\left(\overline{B}\right) Pr\left(\overline{C}\right), \quad (18)$$

where events $\overline{A}$ ={elements of group A did not fail}, $\overline{B}$ = {elements of group B did not fail}, $\overline{C}$ = {elements of the group C did not fail}.

Since the independent failures and common cause failures are incompatible, thus mutually dependent, then

$$\begin{cases} Pr\left(\overline{A}\right) = 1 - Q_1^3(A) - 3Q_1(A)Q_2(A) - Q_3(A), \\ Pr\left(\overline{B}\right) = 1 - Q_1^2(B) - Q_2(B). \end{cases} \quad (19)$$

Numerical value $Q_{S(CCF-\alpha)}$ = 0.170350.Calculated approximate value $Q_{S(CCF-\alpha)}$ = 0.16981 (see Fig. 2).The figure shows the incomplete fault tree with a number of "collapsed" branches due to its awkwardness.

The logical node "or" does not take into consideration the fact of dependence of minimum sections in (17) and calculates $Pr\left(\overline{A}\right)$ and $Pr\left(\overline{B}\right)$ using the following formulas:

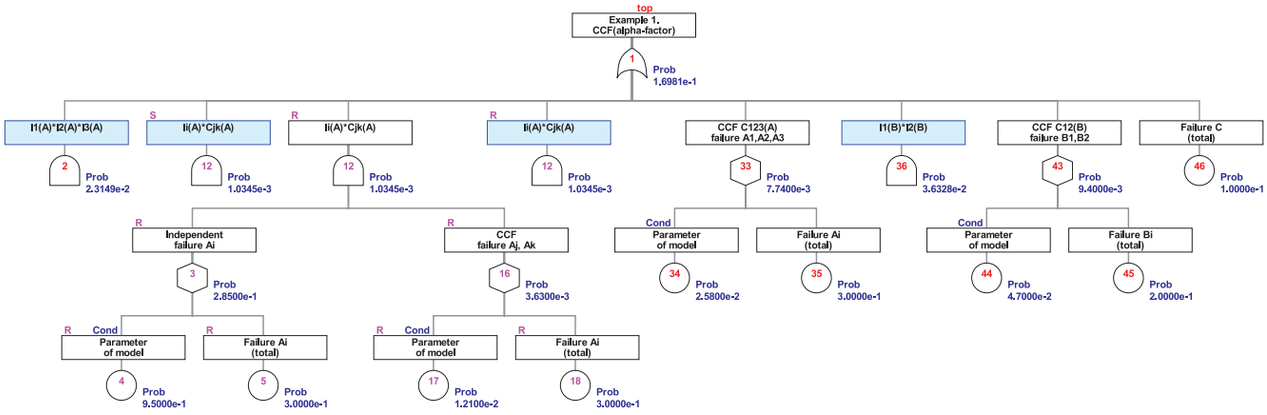

Figure 2. Fault tree for example 4 (alpha factor model)

$$\begin{cases} Pr\left(\overline{A}\right)=\left(1-Q_1^3\left(A\right)\right)\left(1-Q_1\left(A\right)Q_2\left(A\right)\right)^3\left(1-Q_3\left(A\right)\right), \\ Pr\left(\overline{B}\right)=\left(1-Q_1^2\left(B\right)\right)\left(1-Q_2\left(B\right)\right). \end{cases} \quad (20)$$

For the beta factor model (10) the precise formula of probabilities calculation $Pr\left(\overline{A}\right)$ and $Pr\left(\overline{B}\right)$ will be somewhat simpler:

$$\begin{cases} Pr\left(\overline{A}\right)=1-Q_1^3\left(A\right)-Q_3^*\left(A\right), \\ Pr\left(\overline{B}\right)=1-Q_1^2\left(B\right)-Q_2\left(B\right). \end{cases} \quad (21)$$

Approximation formula:

$$\begin{cases} Pr\left(\overline{A}\right)=\left(1-Q_1^3\left(A\right)\right)\left(1-Q_3^*\left(A\right)\right), \\ Pr\left(\overline{B}\right)=\left(1-Q_1^2\left(B\right)\right)\left(1-Q_2\left(B\right)\right). \end{cases} \quad (22)$$

In (21) and (22), $Q_3^*\left(A\right)=0.05Q_t\left(A\right)$.Precise and approximated values $Q_{S(CCF-\beta)}=0,17392$ and $0,17333$ respectively. The approximate probability matches the estimated one (see Fig. 3).

As expected, the beta factor model turned out to be more pessimistic.

Figure shows the fault tree with a number of "collapsed" branches due to its awkwardness.

In conclusion, it should be noted the current version of FaultTreehas several essential deficiencies of in terms of its applicability in complex systems dependability calculation.

The selection of logical operations (gates) for work with events is quite limited. Thus, there are no modules "mutually excluding or", "priority and", "negation", etc. This substantially limits the package's capabilities.

The package does not allow duplicating a basic event in different branches of a tree. The addDuplicate() script only simplifies the construction of complex event trees while duplicating branches, structure. Yet it is impossible to take into consideration the fact of dependence, incompatibility of events. It is not possible to "manually", with the help of the available logical operations, create a tree that would contain such events. This was covered above.

Additional scripts for different models (alfa, beta factor, Greek letters, etc.) could significantly help taking account of CCF.

The wide range of tools of the R language allows for more flexible setting of calculations and unlike the rigid schemes of specialized packages enables independently performing certain procedures with input data. And, certainly, the most important advantage of R is that unlike the specialized packages intended for the analysis of event tree only it provides by far more capabilities to perform data analysis procedures.

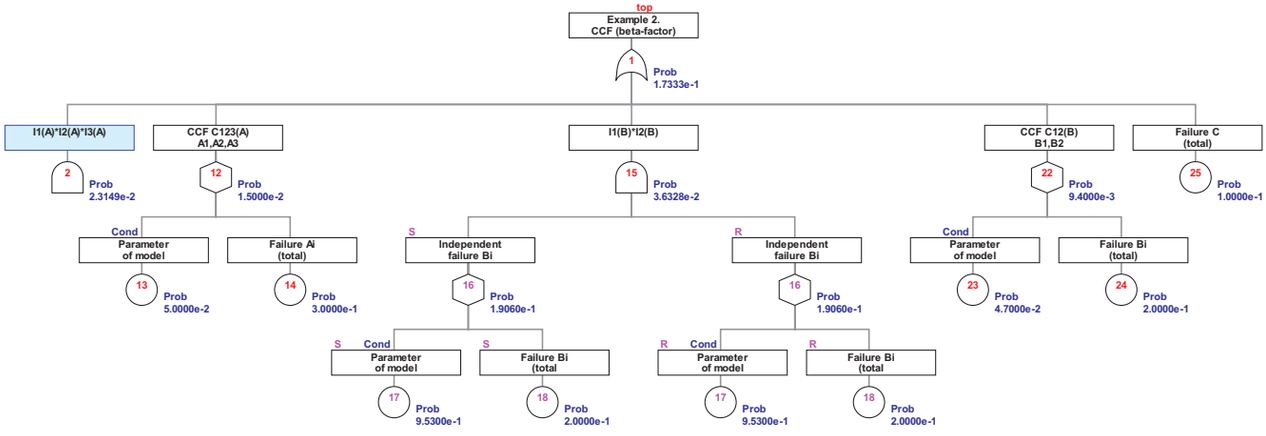

Figure 3. Fault tree for example 4 (beta factor model)

Thus, the vital improvement of FaultTree package aiming to eliminate the above shortcomings will indeed provide experts with a powerful tool for not only fault trees analysis, but also for more advanced statistical analysis. As to the further development of package, it should also be improved in terms of development of functionality related to the calculation of various importance factors according to Birnbaum, Fussell-Vesely, etc., uncertainty analysis.

Conclusion

This paper is dedicated to the demonstration of the fault tree construction and analysis capabilities of the actively developing statistical computing language R and its FaultTree package. Fault trees are used for dependability analysis of complex systems. The paper sets forth and analyses in detail some models of CCF management, two examples are given. In the first example, CCF is taken account of per alpha factor model. The second example is dedicated to the beta factor model. The deficiencies and optimal development strategy of the FaultTree package are identified.

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Simulation model of dependability of redundant computer systems with recurrent information recovery

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Abstract.*Today's digital nanotechnology-based information management systems are especially sensitive to highly-energized particles during operation in irradiated areas. This sensitivity is most often manifested in the form of intermittent soft errors, i.e. distortion of information bits in the system's memory elements with no hardware failure. The cause is in the afterpulses at the output of the logical elements that occur as the result of ionization of the gate area of the transistor's semiconductor after it is exposed to a highly-energized particle. In order to counter soft errors the system is equipped with self-repair mechanisms that ensure regular replacement of distorted data with correct data. If this approach to design is employed, the significance of dependability analysis of the system under development increases significantly. Since regular occurrence of soft errors is essentially normal operating mode of a system in conditions of increased radiation, dependability analysis must be repeatedly conducted at the design stage, as that is the only way to duly evaluate the quality of the taken design decisions. The distinctive feature of fault-tolerant hardware and software systems that consists in the presence of nonprobabilistic recovery process limits the applicability of the known methods of dependability analysis. It is difficult to formalize the behaviour of such systems in the form of a dependability model in the context of the classic dependability theory that is geared towards the evaluation of hardware structure. As it has been found out, the application of conventional methods of dependability analysis (such as the Markovian model or probabilistic logic) requires making a number of assumptions that result in unacceptable errors in the evaluation results or its inapplicability.* **Aim.** *Development of the model and methods of dependability analysis that would allow evaluating the dependability of hardware and software systems with periodic recovery.* **Results.** *A simulation model was developed that is intended for dependability evaluation of complex recoverable information management systems. The model is a network of oriented state graphs that allows describing the behaviour of a recoverable system subject to the presence of computation processes and recovery processes that operate according to non-stochastic algorithms. Based on the simulation model, a software tool for dependability analysis was developed that enables probabilistic estimation of dependability characteristics of individual system units and its overall structure by means of computer simulation of failures and recoveries. This tool can be used for comprehensive dependability evaluation of hardware and software systems that involves the analysis of recoverable units with complex behaviour using the developed simulation model, and their operation along with simple hardware components, such as power supplies and fuses, using conventional analytical methods of dependability analysis. Such approach to dependability evaluation is implemented in the Digitek Reliability Analyzer dependability analysis software environment.* **Practical significance.***The application of the developed simulation model and dependability analysis tool at the design stage enables due evaluation of the quality of the produced fault tolerant recoverable system in terms of dependability and choose the best architectural solution, which has a high practical significance.*

Keywords: *dependability model, simulation model, soft error, dependability theory, recoverable system.*

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Introduction

Out of [1–3] dedicated to the analysis of effects in semiconductor structures exposed to radiation follows that a highly-energized particle hitting a MOS transistor can cause the ionization of the gate area of the semiconductor. Due to that, the output of a gate that includes a transistor may produce as short false signal (voltage pulse), of which the duration is usually within 1 to 2 ns. In the context of today's nanotechnology-based integrated circuits such induced false pulses present a danger, since their characteristics are comparable with those of the useful signals and can cause distortions of information in the computer system.

If the false pulse changes the state of a trigger or another storage element, the event usually called soft error occurs. It consists in the fact that from the dependability point of view it can cause a failure, since a change in the internal state of system's memory affects its operation. At the same time, the equipment in this case remains operational, which means that the state of the system can be recovered by overwriting distorted data with correct ones.

Studies in the area of improvement of radiation durability of information management systems [4-6], including those conducted by a group of researchers of the St.Petersburg State Polytechnic University [7-11], show the introduction of periodic recovery facilities is the solution that enables a qualitative improvement of a system's resistance to soft errors.

The operation of such self-repairing systems has a number of distinctive features that affect the method of evaluation of their dependability and make the conventional methods of dependability analysis hardly applicable [12-16]. Dependability analysis for such systems is of utmost importance in the design process, as occasional soft errors are essentially part of their normal operation. Consequently, the design of this type of systems is impossible without detailed estimation of dependability that allows evaluating the quality of the structure under development. For this reason the development of new models and methods of dependability analysis that would cover the distinctive features of the self-repaired systems resistant to soft errors is now a relevant task.

Conventional analytical models of dependability of computer systems and their limitations

Over the years of dependability theory development many models and methods of dependability analysis were constructed. Most of them are geared towards the solution of the following practical problem: provided that a certain hardware system operates in stationary mode, when, with time, its individual components randomly fail, to estimate the system's time to failure and to identify the most structurally important components in terms of dependability.

However, when conducting dependability analysis, systems with periodic recoverythat operate in conditions of regular soft errors, the following features must be taken into consideration:

• the mechanism of memory state recovery implies that the distorted information bits are periodically rewritten. Obviously, recovery does not occur randomly, but at determined moments in time;

• the analyzed systems are hardware and software systems, in which the software component (computational process) often defines their operation. The hardware component, in turn, can be considered as a resource that must be in a operable state at the moment the computational process refers to it. Besides the primary computational process, there is a recovery process that at specific moments also requests access to the resource (memory).

Both of the above features complicate the requirements for the design of highly dependable systems. On the one hand, the designer must ensure the shortest possible period of recovery in each of the system's units. On the other hand, the recovery process must not block the resources required by the primary computational process. These contradictory requirements must be taken into consideration both during system design (synthesis) and it dependability analysis: having information on the operating algorithm of the primary computational process, the maximum permissible period of recovery in the units can be defined and dependability of the designed system can be estimated subject to the specified conditions. If the dependability requirements are not observed, as early as at the design stage the system architecture must be modified in favour of additional dependability improving solutions [7]. Under this approach the dependability analysis is the tool of a fault-tolerant system synthesis.

In practice, the following conventional analytical methods of dependability estimation are used:

1) combinatory estimation.

For a recoverable hardware unit with a fixed recovery period, the possible combinations of events (component failures) and the effects of such events on other connected components are analyzed. As the result, a probability function is constructed that connects the failure rates of the unit's components with the failure rate of the unit itself. For generic structures the formula is known in advance and it is sufficiently simple to substitute into it the parameters failure occurrence and moments of recovery [13]. This estimation procedure dictates a limited number of considered events occurring over the recovery period, in order to considerably reduce the number of analyzed combinations and thus simplify the final expression, which causes a growing error in the results.

2) Markovian model

If the combinations of component failures that occurred in the system are identified as system states, and all the failure and recovery events are associated with transitions between such states, the system can be represented

as a Markovian model. In this case the result is obtained by solving a system of Chapman-Kolmogorov algebraic equations[16]. The moments of all transitions must follow the exponential law of random distribution, which causes error that can be quite considerable [12]. Also, as the number of system components grows, the number of states in the model increases greatly.

3) logical and probabilistic method.

The logical and probability function of the system operability is constructed by well-known methods [17,18]. Its construction is also bound by limitations on the distribution law of failure and recovery moments typical to the application of the Markovian model.

Since all the above methods have limitations in terms of the analyzed systems, cause errors in estimation results, as well as are quite tedious in practice,it appears to be advisable to develop software tools that would enable automated dependability evaluation of systems with periodic recovery after soft errors.

Simulation model of dependability of a recoverable computer system

Since the analyzed systems have fairly complicated behaviour, it appears that simulation models, rather than analytical evaluation methods, are more applicable in their dependability assessment. At the same time, the use of general-purpose simulation models (such as the Petri nets) does not appear to be practically applicable, as it requires significant labour contributions from the user (system designer) in order to construct an adequate model. A specialized simulation model that would operate such dependability theory terms as "failure", "recovery", but would allow simulating a wide range of structures, seems to be appropriate. The software tools that operate this model must automatically calculate the desired dependability characteristics, such as the operability function and mean time to failure. This approach will enable quick modifications of the simulation model and recalculation of dependability characteristics subject to their changes, which is especially important at the design stage.

For this purpose the author has developed a dependability simulation model that is based on the representation of the system as an oriented state graph that contains the following basic elements:

• states that are defined by the set of failed components. Each state is classified as operable or inoperable (in this case states of "soft", i.e. recoverable error and unrecoverable error should be distinguished);

• transitions between states that usually occur in case of soft errors or unrecoverable failures or recoveries after soft errors.

Transitions between states may occur either at random or determined moments in time. Therefore, for each transition, a distribution law of the random value of occurrence (normal distribution, exponential distribution or determined moment of occurrence) and distribution characteristics (event rate) are defined. In the process of simulation, the events associated with the state (that occur a certain time upon transition into such state) and those not associated with a specific event must be distinguished. For example, the moment of recovery is not associated with the current state, as it occurs with a fixed rate independent of the moment of failure of any element that caused the system's transition into the current state. For the simulation of such events, a special entity called the Global Events Generator was introduced at model level. It contains the description of the rules occurrence of all events that do not depend on the current state of the system.

The analyzed system may contain a significant number of elements, and each state of the simulation model in general is based on the sum of the states of all of its elements. This causes a significant growth of the number of states and complication of the model. In order to solve this problem, the model may be described not as a single state graph, but in the form of a **network** consisting of multiple graphs. Transitions in each graph of this network may occur:

• due to an event associated with the current graph state;

• upon reception of signal from the Global Events Generator;

• upon occurrence of an event in another graph of the network (such events are called external).

In order to define the condition, under which the system is considered inoperable, in the model, parameter Health Function must be defined. The health function in the context of the simulation model is represented in the form of enumeration of graphs that must be in operable state for the system to be deemed operable.

The software tool developed by the author that operates this simulation model works as follows. The description of the simulation model (network of graphs) loads from xml files, after which the number of experiments specified in the models' parameters is performed. In the course of each experiment, the occurrence of random and determined events described in the model is simulated, and the time to system failure (moment, when at least one of the graphs enumerated in the operability function is inoperable) is measured. Since the experiment simulates random events, the estimate is also a random value. In order to evaluate the estimation error, the specified number of experiments (model parameter) is simulated, based on which the standard deviation of the estimate's random value is calculated. Provided the scope of statistics collected out of experiment results is sufficient, the probability function of system operability of time can be evaluated.

An example of application of the simulation model for dependability evaluation of a recoverable unit of a computer system

As an example, let us evaluate the time to failure of a unit of an information management system that operates with the clock cycle T and has the following structure:

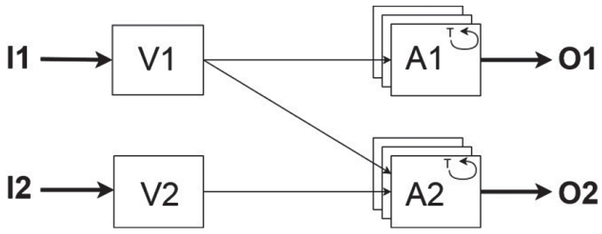

Figure 1. Analyzed unit of information management system

A1, A2 are functional modules, each of which is triplexed and majorized in order to improve the dependability, as well as have inbuilt mechanisms that ensure recovery of the module's state at each cycle (with the frequency 1/T). The modules ensure setting of output signals O1 and O2 respectively.

V1, V2 are voting components that ensure setting of correct input data I1 and I2 for components A1 and A2 per 2-out-of-3 voting rule.

O1, O2 are output signals of the unit, of which the correctness determines the operability of the whole unit. Since A1 and A2 are triplexed and majorized, the data of the corresponding outputs O1 and O2 become incorrect if 2 and more instances of modules A1 and A2 are inoperable. As long as only one instance is exposed to soft error, the module is in the degraded state, but this does not affect the system's operability in general.

The unit is affected by a flow of soft errors, as the result of which the triplexed instances of modules A1 and A2 randomly turn into inoperable state about every hundredth cycle (i.e. with the known frequency 1/100T). At the moment of recovery all the degraded instances A1 and A2 turn into the initial operable state. Majority elements are not affected by soft errors, since they do not have memory elements, of which the state can be distorted. However, they can be the source of short false pulses (with the known frequency 1/1000T) that, in turn, can cause soft errors in A1, A2.

The simulation model for this example has the following visual representation (Figure 2):

In Figure 2, individual graphs included in the simulation model are shown with dotted lines. Same-type graphs with identical structure (triplexed modules A1, A2) are grouped with the dual dotted line. In each graph, the thin contour circles designate operable states, the thick contour circles designate the inoperable states. The transitions between states are shown with arrows that connect the states. An arrow entering a transition designates the condition of such transition. It may be a transition that occurred in the current graph or a transition in another graph or Global Event Generator events (wide arrow). If a transition does not have incoming arrows, that means it only depends on the current state in the graph and is not governed by any external events.

Let us examine the model's operating principle using the example of the A1 unit. Primitive graph V1 that has the only state OK simulates the operation of voter V1 that is the source of error V1Fault that affects both the module A1 and A2. This transition, in turn, generates the event A1Fault. In graph O1 that simulates the state of the output line O1, transition to state DIST occurs, indicating that one of the triplexed instances of A1 is inoperable. Let us note that after this one of the instances of graph A1 that was affected by an error retains the inoperable state ERR and stops being the source of errors for O1. The occurrence of the recovery event REC transfers both the inoperable instance A1, and O1 into the state OK. The error in O1 will occur only if the event A1Fault occurs twice over the recovery period, in other words, if two dif-

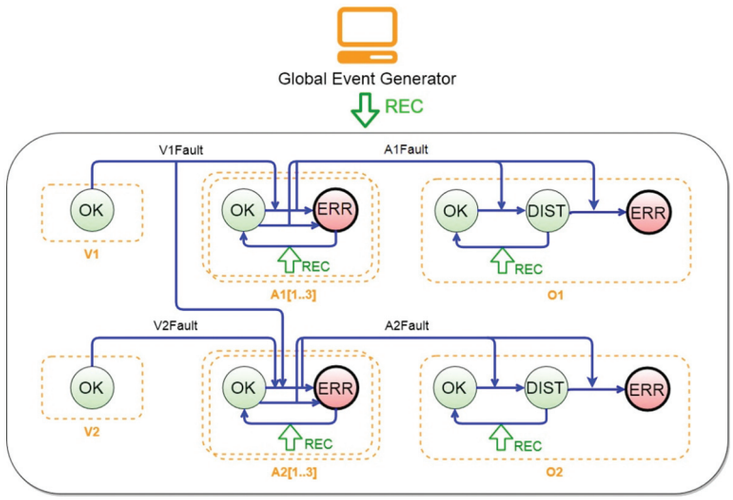

Figure 2. Visual representation of the simulation model

ferent instances of module A1 become inoperable during the recovery period. The event model for module A2 is built in the same way.

Obtaining numerical estimations requires specifying in the model the parameters of transitions and global events. In the text description of model (in the xml format) this is done as follows:

```
   <topLevelDescription>
      <globalEvents>
          <event eventName="REC" distribu-
tionType=
             "CONSTANT" intensity="1.0"/>
      </globalEvents>
      <healthFunction parameters="O1,O2"/>
      <graphs>
          <graph filePath="voter1.gr"
           graphName="V1"/>
          <graph filePath="voter2.gr"
          graphName="V2"/>
          <graph filePath="A1.gr"
          graphName="A1[1..3]"/>
          <graph filePath="A2.gr"
          graphName="A2[1..3]"/>
          <graph filePath="O1.gr"
          graphName="O1"/>
          <graph filePath="O2.gr"
          graphName="O2"/>
      </graphs>
  </topLevelDescription>
```

The globalEvents section describes the events generated by the global events generator. Each event (this applies not only to global events, but also to transitions in the graph) is defined by an "event" record that contains the following parameters:

• eventName, the name of the event in the model;

• distributionType, the distribution law of the random event of the moment of occurrence (CONSTANT, determined with specified frequency, EXPONENTIAL, exponential with specified intensity, GAUSSIAN, normal with specified intensity);

• intensity, specifies the intensity of the occurrence of the event distributed over the exponential and normal distribution laws. For deterministic events, the period between events is fixed.

HealthFunction defined the operability function. In its only parameter (parameters), separated by commas, are given the names of graphs that must be operable in order for the system to be deemed operable.

The graphs section specifies the list of graphs included in the simulation model. To each graph corresponds a record of the type graph with filePath parameters (path to the xml file that contains the graph description) and graphName (name of the graph). If a model contains several identical graphs (in the example at hand those are triplexed modules A1 and A2), structures of the type A1[1..3] can be specified as graph name, as the result of which the model will use 3 graphs with the names A1[1], A[2], A[3].

Given the fault parameters used in this example (soft errors rate of the A1 and A2 modules equals 1/100T), and taking the modules' operating cycle as the measurement unit, the description of graph A1 is as follows:

```
<description>
    <states>
        <state name="OK" isfail="false"
         initialProbability="1.0"/>
        <state name="ERR" isfail="true"
         initialProbability="0.0"/>
    </states>
    <links>
        <link firstNode="ERR"
         lastNode="OK" eventName="REC"/>
        <link firstNode="OK" lastNode=
         "ERR" eventName="V11Fault"
         generateBefore="A1Fault"/>
        <link firstNode="OK" lastNode=
         "ERR" intensity="0.01"
         distributionType="EXPONENTIAL"
         generateBefore="A1Fault"/>
    </links>
</description>
```

The description consists of a list of graph states and links. Each state has a name, an indication of operability (isFail) and probability of the graph being in this state at the start of simulation (sum of these probabilities for all graph states must be equal to 1). Each link has the same parameters as the Global Events Generator events. Additionally, outgoing (firstNode) and incoming (lastNode) states and the name of the external event that is additionally generated at the moment of this transition (in the generateBefore parameter, if the external event must be generated before the transition in the current graph, or in the generateAfter parameter, if the external event must occur after transition).The names of the states and events used in the description of the model correspond to those used on Figure 2.

By launching a calculation procedure for 1000 experiments we obtain the following result (in device operation cycles):

Mean time to failure = **1202.5 (cycles);**

Result error: **± 37.3 (cycles).**

Thus, the mean time to failure was estimated of a computer system unit that consists of recoverable structural blocks. The comparison of the quality of the results of dependability analysis of recoverable units obtained using a simulation model and conventional methods of dependability analysis is examined in [12].

The considered simulation model is applicable for the assessment of recoverable units with complex behaviour and recovery. It is incorporated into the Digitek Reliability Analyzer dependability analysis software [19]. At the same time, beside such units, a hardware and software system includes base blocks, such as batteries, clock speed generators, fuses, etc. The evaluation of such elements' effect on the dependability is more easily done

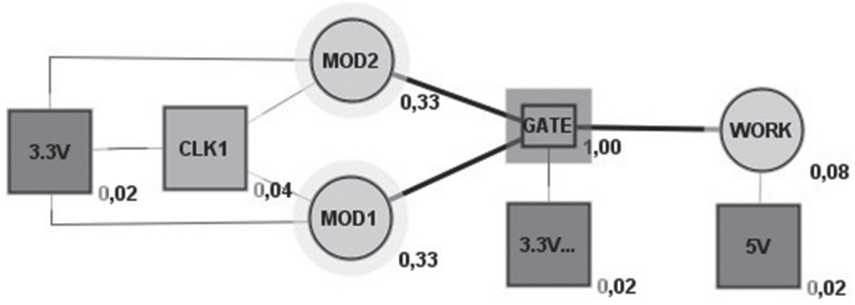

Figure 3. Structural diagram of information system dependability

by conventional methods. For that reason, when Digitek Reliability Analyzer is used, it is suggested analyzing complex recoverable units with the aid of a simulation model, then using a higher level dependability model that contains both the basic hardware elements and complex recoverable units represented as a "black box". The input parameters are the dependability characteristics of reliability previously calculated using the simulation model. Dependability calculation using the upper level model in Digitek Reliability Analyzer is performed logical and probabilistic methods and allows obtaining accurate analytical estimates.

As an example, let us examine a system containing a redundant recoverable unit (Figure 1), of which the dependability was evaluated above using a simulation model, and the connected hardware units. The structural diagram of the device's dependability developed in Digitek Reliability Analyzer is as follows (Figure 3).

The structural diagram (Figure 3) contains two instances of the previously analyzed recoverable unit (MOD1, MOD2) with connected power supply (3.3V) and system clock generator (CLK1). Outputs MOD1 and MOD2 are connected to the switch GATE that ensures correct data setting of the destination workstation (WORK) as long as at least one of the modules MOD1, MOD2 operates. The operation of the GATE element required a power supply (3.3 V...). The system is considered operable as long as workstation WORK operates, which requires the availability of undistorted data in the data line from the switch (GATE), operability of the 5 V power supply and absence of own internal failures.

For each of the elements of the structural diagram parameters of its own internal failures are set. For the elements MOD1 and MOD2 values re used that were calculated using a simulation model (mean time to failure of MOD1 and MOD2 equals 1202.5 cycles). The dependability of the system clock generator and power sources can be found in the respective technical specifications. Next, using DigitekReliability Analyzer the probability function of system operability $P(t)$ is automatically calculated. Its graph is shown in Figure 4 (time t is expressed in the number of cycles of modules MOD1, MOD2).

The vertical line in Figure 4 shows the mean time to system failure (approximately 725 cycles). In order to evaluate the contribution of individual components to this value, the software measures the structural significance of each of them. It is shown next to the right lower corner of the component (Figure 3), lies within the range from 0 (most insignificant components in terms of dependability) to 1 (most significant components in terms of dependability) and depends on the current time and input characteristics of units dependability. The greater is the value of structural significance, the greater "increase" in system dependability is ensured by the growth of such unit's dependability. For the example under consideration

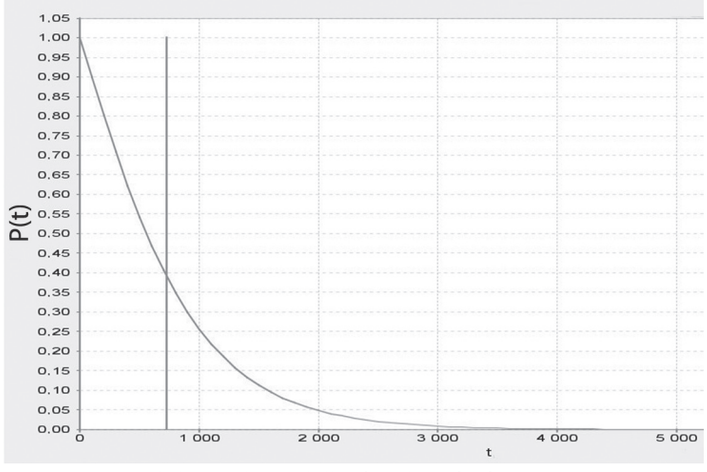

Figure 4. Calculated operability function of information system

(Figure 3) the switch (GATE) has the highest structural significance equal to 1. The recoverable modules MOD1, MOD2 have a structural significance three times smaller (0.33). This means that in order to further improve the dependability of the system, most likely, the fault tolerance of the switch should be increased first. After that, the dependability characteristics must be recalculated and the result evaluated: the mean time to failure must grow, while the structural significance of the units redistribute (the switch will cease to be the most important element). This information enables the designer to evaluate the quality of the current solution and choose the further direction to improved dependability through modification of system architecture.

Conclusion

The simulation model of structurally-complex systems dependability developed by the author enables automated evaluation of the dependability of recoverable hardware and software systems with complex operation algorithms. Its application is especially relevant in the process of design of information management systems that operate under conditions of regular soft errors (e.g. due to adverse radiation conditions).

The developed simulation model allows describing the system's reactions to random events, failures (non-recoverable and recoverable) in its components, as well as non-random events that occur in accordance with the computational algorithm or as the result of operation of the built-in self-repair mechanisms. The simulation model has a sufficient level of abstraction for the description of a wide range of systems. At the same time, its storage format allows developing user representations of the model that are more convenient for system designers.

The use of the simulation model for dependability evaluation of the most complex units alongside well-known analytical methods for dependability analysis of the overall system structure allows facilitating the design of highly dependable radiation resistant systems by incrementally providing the system developer with information required for the selection of the best architecture that meets the specified dependability requirements.

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On the assignment of dependability level

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Abstract. *The problem of assignment of optimum level of dependability is not new and has not yet been solved. The requirement of complete dependability is noted to be erroneous. However, insufficient dependability of buildings is fraught with significant social and economic losses. Hence is the problem of definition of the required, optimal level of dependability. In Russia, there are no quantitative guidelines for the dependability of buildings and structures. At the same time, the strengths of the materials of ferroconcrete structures are regulated by GOST 34028-2016 for rod reinforcement and GOST 18105-2010 for concrete, as well as by building regulations SP 63.13330-2012 Concrete and ferroconcrete structures. In this paper, the dependability of the "Loads – design" construction system is suggested to be defined using the total probability formula. We assume that the mechanical characteristics of a structure's materials and the loads are independent and joint random values: the emergence of one random value does not depend on the emergence of another one; change of load changes the stresses in the structural section. Probabilistic calculations showed that over the period of 10 years facilities designed in accordance with SP 38.13330.2012 for operation in the Gulf of Finland, will be destroyed almost with the 100% probability. For normal consequence class facilities (KS-2) the required dependability must tend to 3σ (0.99865). In order to ensure the required dependability of construction system of about 3σ, the probability of loads of 0.99865 should be attempted to be ensured. The application of SP does not always guarantee the required dependability of construction facilities. The application of probabilistic approaches in solving engineering problems can prevent emergency situations.*

Keywords: *probability, building, materials, loads, dependability, destruction, construction, building regulations, characteristics.*

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The problem of assignment of optimum level of dependability is not new and has not yet been solved [1]. The Russian version of the Hütte reference book [2] with a developed system of dependability coefficients was published in 1890. In 1926, professor M. Maier published the paper [3], in which he criticized the calculation on allowed voltage and proposed calculating structures assuming an disadvantageous combinations of loads and material resistances. In 1929, N.F. Khotsialov [4] elaborated upon M. Meyer's ideas. Noting the stochastic variability of mechanical and geometric parameters of structures, he proposed a new formula – "Building with a viable number of destructions" – instead of "Building without destructions, by all means". According to N.F. Khotsialov, engineering should take into account capital costs as well as possible "defects" and amount of losses that an accident brings to the state.

In 1945, in connection with the development of new forms of calculation and engineering standards, the Commission for calculation methods unification organized by Narkomtiazhprom (People's Commissariat of Construction of Heavy Industry), adopted a conventional scheme of estimated coefficients proposed by I.I. Goldenberg, M.G. Kostyukovsky and A.M. Popov. According to this scheme, the overall safety coefficient depended on uniformity, overload coefficients and operating conditions of the structure. In the future the proposed scheme was included in the calculation method for limit states. It was assumed that structures were to meet the relevant requirements with a reasonable level of risk.

The development of the dependability theory of engineering structures is related to a number of socio-economic issues. A.V. Gemmerling [5] noted the invalidity of the requirements of absolute dependability. He supposed that no matter which calculation methods were used, the real loads and strength characteristics always remain random values or functions. Therefore, there is a problem of determining the required dependability level.

A.R. Rzhanitsyn in [6] took into account the economic aspects of safety calculation. He determined a minimum of the mathematical expectation of costs related to building a structure and its possible damage over the life cycle, i.e. defined the minimum of function:

$$R = C + V \times D, \quad (1)$$

where C is the initial cost of the engineering structure; V is the probability of its damage; D are the losses caused by the damage, including renewal costs and loss caused by disturbed operation.

A.P. Sinitsin in his works noted the nonlinear relationship between the risk value and expected value and provided statistical data on the risk value for various industries. According to A.P. Sinitsin [7], the risk, characterized by the number of accidents 10^{-3} per person per year, is completely unacceptable. The risk level of 10^{-4} requires some measures and can be accepted only if there is no other solution.

For American conditions, the risk of car accidents can be as high as $2{,}8\times10^{-4}$. The risk level 10^{-5} corresponds to natural accident events, for example, accidents during swimming in the sea, for which the risk is estimated as $3{,}7\times10^{-5}$. Accidents with the risk of 10^{-6} belong to a low risk level as it is possible to avoid this risk by observing basic precautions.

Outside of Russia [8], the following formula for failure probability $Q(t)$ regulation became widespread:

$$Q(t) = 10^{-5}\,\xi_S\,T / L, \qquad (2)$$

where ξ_S is the coefficient of social significance (Table 1); T is the estimated lifecycle in years; L is the average number of people inside or around the building during the period for which the risk is assessed.

Table 1. Coefficient of social significance, ξ_S

Structure type	ξ_S
Public places, dam	0.005
Apartments, office and commercial buildings, industrial buildings	0.05
Bridges	0.5
Towers, pillars, offshore buildings	5

The required dependability on (2) for buildings with normal level of criticality is the following:

$1 - Q(t) = 10^{-5} \times 0.5 \times 50 / 50 = 0.999995$ or $0.9^5 5$.

Professor Ryush (Table 2) proposed to standardize structures dependability $P(t)$ based on their failure probability $Q(t)$, where $Q(t) = 1 - P(t)$.

Table 2. Standardization of ferroconcrete structures dependability

Failure type and characteristic	$Q(t)$
Failure without warning sign (brittle failure, buckling etc.)	10^{-7} ... 10^{-5}
Loss of carrying capacity with warning sign	10^{-4}
Inoperability with no loss of carrying capacity (similar to the 2-nd group of limit states)	10^{-3} ... 10^{-2}

In the Russian Federation, the significance of buildings and structures dependability is not quantified [9]. At the same time, the strengths of the materials of ferroconcrete structures are regulated by GOST 34028–2016 for rod reinforcement and GOST 18105-2010 for concrete, as well as by building regulations SP 63.13330-2012 Concrete and ferroconcrete structures. According to these documents, the dependability (reliability) of characteristic strength of materials is 0.95 (1.64σ), and the probability of calculated strength of materials is near 0.99865 (3σ): standard strengths are divided into dependability coefficients on materials that are above 1. Therefore, the dependability value is $P(A\times B) = 0.99865$ (A, B are random events; A is the structural carrying capacity and B is the loads) should be assigned to engineering structures with normal level of criticality.

The dependability of the "Loads – design" construction system is suggested to be defined using total probability formula (3). We assume that the mechanical characteristics of structure's materials and loads are independent and joint random values: the emergence of one random value does not depend on the emergence of another one; change of load changes the stresses in the structural section.

$$P(A\times B) = 1 - [P(A^{/}) + P(B^{/}) - P(A^{/})P(B^{/})], \qquad (3)$$

where $P(A^{/})$ and $P(B^{/})$ are the probabilities of opposite events of A and B: $P(A^{/}) = 1 - P(A) = 1 - 0.99865 = 0.00135$, $P(B^{/}) = 1 - P(B) = 1 - 0.95 = 0.05$.

Let us substitute the known values to formula (3) and define $P(A\times B)$:

$P(A\times B) = 1 - (0.00135 + 0.05 - 0.00135 \times 0.05) = 0.94872$.

To increase the system dependability to about 3σ, it is required to increase the non-exceedance probability of loads, for example, up to 0.99865. Then the system dependability will be as follows:

$P(A\times B) = 1 - (0.00135 + 0.00135 - 0.00135 \times 0.00135) = 0.9973$ or 2.78σ.

The low exceedance probability of loads for the Gulf of Finland is defined, for example, by SP 38.13330.2012 [11]:

$$F_{c,p} = 1.26\cdot10^3\, V\, h_d (m\, A\, k_b k_v R_c \rho\, \mathrm{tg}\gamma_)^{1/2} = 1.26\cdot10^3 \times \times 0.87 \times 1.002 \times (0.83 \times 330.75 \times 4.529 \times 3.18 \times \times 0.3 \times 1000 \times 2.7475)^{1/2} = 1.505\ MH, \qquad (4)$$

where V is the movement speed of the ice field; $V = 3\% \times 29\ m/s = 0.87\ m/s$; m is the shape factor of the supporting structure in plan view, $m = 0.83$; A is the maximum area of the ice field, m^2 that can affect the calculated structural element, identified through field observations or adopted depending on the lateral dimensions of the span as $A = 3l^2 = 3\times10.5^2 = 330.75$ (where l is the span); k_b and k_v are the factors 18 and 19 [11], respectively (according to tables): $k_b = 3.18$, $k_v = 0.3$; $R_c = 4.529\ MPa$; ρ is the water density, $\rho = 1000\ kg/m^3$; $\mathrm{tg}(70°) = 2.7475$.

According to [11] the load $F_{c,p}$, determined by formula (4), cannot be greater than the load $F_{b,p}\ MH$, determined by formula (5):

$$F_{b,p} = m\, k_b k_v R_c\, bh_d = 0.83 \times 3.18 \times 0.3 \times 4.529 \times \times 1.22 \times 1.002 = 4.386\ MH, \qquad (5)$$

where b is the lateral dimension of the supporting structure at the ice level, $b = 1.22\ m$.

According to [11], a lower value of the ice load should be adopted in calculations, 1.505 *MH*.

The wind speed for the entire observation period at the Saint Petersburg weather station is taken into consideration in formula (4). According to the Saint Petersburg weather station, the wind distribution is approximated by the Pearson curve type I [12]:

$$y = 1{,}13\left(1 + \frac{x}{-13{,}834}\right)^{-0{,}37}\left(1 - \frac{x}{37{,}466}\right). \qquad (6)$$

The value of the wind speed with the probability of 0.99 is 29 m/s. The average long-term value of the sum of the frost degree-day according to the Saint Petersburg weather station for the period between 1881 and 1980 is 775ºC.

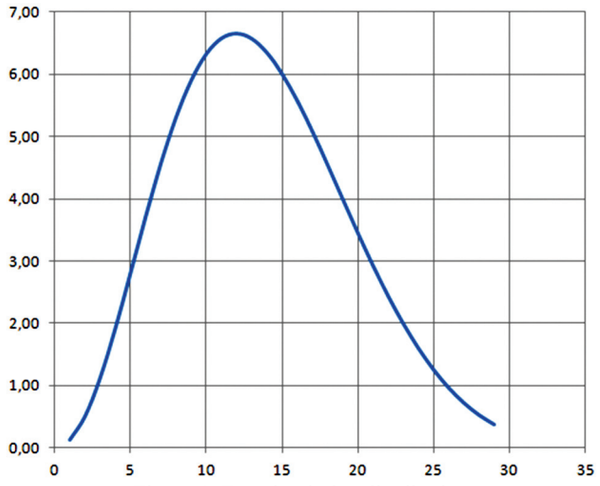

Figure 1. Freezing index distribution

Figure 1 shows the freezing index distribution for the Gulf of Finland. The freezing index distribution is also approximated by the Pearson curve type I. With the probability of 90% the freezing index is 983.9. Freezing indexes with the probability of 99% and 99.9% are 1274.2 and 1358.2 respectively.

The ice thickness is calculated using formula (7) after substitution of known values with the freezing index, R = 1358.2, with the probability of 99.9%:

$$h_d = 0.034nR^{1/2} = 1.002\ m, \quad (7)$$

where n is the coefficient of the local conditions; we take the larger value: n = 0.8.

The ice strength under compression, R_c, is calculated using formula (48) from [11]:

$$R_c = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(C_i + \Delta_i\right)^2} = 4.529\ MPa. \quad (8)$$

The ice load 1.505 *MH* calculated by the formula (5) causes the shearing load of the one pile relative to the foundation frame of the conventional leading mark 1.172 *MH*.

In 2013, several leading beacons, designed for the load of 1.505 *MH*, were destroyed as a result of shearing of 80% of piles relative to the foundation frames. Piles were reinforced 16∅25*A*500. The pile load capacity by the shearing, N_{sh}, with an average (not with calculated) resistance of steel was 2.104 *MH*. Let us assume that this is a shearing with an average value of the ice load.

The average value of the ice load is calculated using formula (9):

$$F_{c,pm} = N_{sh} / (1 - 3.25/14.7) = \\ = 2.104 / (1 - 3.25/14.7) = 2.701\ MH. \quad (9)$$

where 3.25 and 14.7 are the dimensions of the pile in *m* above the water surface and under water.

With the variation coefficient of 0.15 of the ice load the mean-square deviation will be as follows:

$$\sigma_{ice} = F_{c,pm} \times v = 2.701 \times 0.15 = 0.405\ MH. \quad (10)$$

As 80% of the pile was destroyed, the specified average value and the mean-square deviation of the ice load will be respectively: 2.701 + 0.405 = 3.106 *MH* and 3.106 × 0.15 = 0.466 *MH*.

Then the ice load with the probability of 0.99865 will be:

$$F_{c,p3\sigma} = F_{c,pm} + 3\sigma_{ice} = 3.106 + 3 \times 0.466 = 4.504\ MH. \quad (11)$$

Thus, the probability of the ice load calculated by [11] in the Gulf of Finland is:

$$t = [(1.505 - 4.504) / 0.466] = -6.44. \quad (12)$$

That means, that the facilities designed per [11] for the Gulf of Finland will be destroyed with the 100% probability within 10 years.

In our opinion, in [11] formula (50): $F_{c,p} = 1.26 \cdot 10^{-3}\ V\ h_d\ (m\ A\ k_b k_v R_c\ \rho\ \mathrm{tg}\gamma)^{1/2}$, should be modified.

Experience shows that the force, $F_{c,p}$, increases in direct proportion to the growth of the ice strength, R_c. Therefore, the variable R_c should be taken outside the radical sign.

The ice thickness is not homogeneous, therefore, $F_{c,p}$ has a hyperbolic dependence on variable h_d. Therefore, the variable h_d should be taken inside the radical sign.

The wind influence on the hydraulic structure should be taken into account with the ice massifs which in form of variable A and coefficient k_v are inside the radical sign in the formula (50) [11]. Therefore, the wind speed also should be taken inside the radical sign.

The variable of the water density (ρ = 1000 kg/m^3) practically doesn't change, so it should be removed from the formula (50). Then, the coefficient $1.26 \cdot 10^{-3}$ will change to 0.04: $1.26 \cdot 10^{-3} \times (1000)^{1/2} = 0.04$. This coefficient was used to determine $F_{c,p}$ in SNiP 2.06.04-82*.

After the transformations formula (50) in [11] will be as follows:

$$F_{c,p} = 0.04\ R_c\ (m\ k_b\ k_v\ A\ V\ h_d\ \mathrm{tg}\gamma)^{1/2}. \quad (13)$$

Then the force from the ice load, $F_{c,p}$, will more accurately correspond to the physical meaning, and its dimension $F_{c,p}$ will be: $ms/m^2 \times (m^2 \times m/s \times s \times m)^{1/2} = ms/m^2 \times m^2 = ms$. Using formula (50) [11] it is possible to obtain "at the output" the following dimension: $m/s \times s \times m \times (m^2 \times ms/m^2 \times ms/m^3)^{1/2} = ms \times (m)^{1/2}$.

The new value of the ice load $F_{c,p}$, determined by (13), will be:

$F_{c,p} = 0.04 \times 4.529 \times (0.83 \times 3.18 \times 0.3 \times 300 \times 0.87 \times 1.02 \times 2.75)^{1/2} = 4.538\ MH$.

The value $F_{b,p}$, determined by (5), is 4.386 *MH*. Thus, we obtain the comparable values of the ice load. For further calculations we will use not a lower ice load value, as recommended in [11], but a higher one, 4.538 *MH*.

The probability of the ice load will be:

$$P[(4.538 - 3.106) / 0.466 = 3.073] = 0.99894. \quad (14)$$

Conclusions. The problem of assignment of optimum level of dependability is not has not yet been solved. In order to ensure the dependability of construction system of about 3σ, the probability of loads of 0.99865 (3σ) should be attempted to be ensured.

The application of SP does not always guarantee the required dependability of construction facilities. The application of probabilistic approaches in solving engineering problems can prevent emergency situations.

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Analysis of the performance indicators of oil well sucker-rod pumps

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Abstract. *The paper notes that as the depths of operated wells grow, the application of cable and pulley mechanisms becomes preferable as compared to the existing pumpjacks. A generalized theoretical analysis of the kinematics of cable and pulley drives is set forth. The authors present the general theoretical analysis of the kinematics of the above mechanisms, as well as the results of computer calculations based of the developed equations for a number of cases. Further analysis of the results showed that the crank mechanisms of a rope pulley have "smooth" kinematics. The research resulted in a proposed invention of the design of mast-type oil well sucker-rod pump drive with lower steel intensity and power consumption that would allow increasing the performance of sucker-rod pumps. The* **Purpose** *of this article consists in finding a utility model of a pump for the well rod in order to ensure the environmental safety of the equipment. That is achieved by lightening the metal structure of the pump with rotary stem and energy consumption is reduced. In the context of this problem, some calculations were performed in order to prove the system's dependability. Based on the performed calculations it was established that the light structure can be used instead of the old heavy structure being its environmentally safe version. Experimental studies conducted by AzINMASH Research and Design Institute of Petroleum Engineering (Baku, Azerbaijan) indicate the feasibility of normal operation of sucker-rod pumps under the condition that n·S = 54÷60 m/min. The authors examined the dependence between the peak output Q and the number of strokes n for various standard pumpjack sizes. The analysis of the parameters shown that the value of the product n·S in the existing pumpjacks is below the recommendations based on experimental data, i.e. there is a tangible opportunity of increasing the productivity by extending the stroke of the rod hanger center, since well pump barrels may be as long as 6 to 7 meters. Estimates show that while studying the kinematics of long-stroke drives the changes in the length of the rope may be practically disregarded due to the displacement of the rope-to-pulley contact point. This simplifies the formulas that describe the kinematics of this type of long-stroke drives. Using the resulting formulas, comparative computer calculations for various cases were performed. It is shown that cable and pulley mechanisms have "softer" kinematics. The calculations confirmed the advisability of modification of the pump's design that ensured reduced pollution of environment and energy savings. The future world will need renewable sources of energy, more power-efficient oil and gas production, minimal or zero pollution of the environment, thus the proposed solution appears to be of relevance. The authors propose a more productive design of sucker-rod pump that is easy to install and maintain at oil and gas production facilities. That can be achieved based on the calculations mentioned above.*

Keywords: *pumpjack, cable and pulley mechanism, deep well sucker-rod pump drive, long-stroke drive, drive link, crank, kinematic calculation, rod hanger center, displacement, speed, acceleration.*

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Introduction. As it is known, one of the mechanical methods of oil extraction is the use of sucker-rod pumps (SRP). Currently, the most commonly used deep well sucker-rod pump drive (DWSRPD) in the world are balanced pumpjacks. Over the past few years, the design of the pumpjack has remained almost unchanged due to its relative simplicity, ease of maintenance, operational characteristics, and reliability. However, in recent years, there was significant progress in the implementation of new design solutions of DWSRPD drives that is due to the intense development of oil production equipment and technology. The aim of this paper is to research the improvement of the DWSRPD drive design, aimed at reducing steel intensity of the existing drives and increasing SRP efficiency.

The main quality of SRP is its efficiency that depends on the following basic standard parameters:

1) stroke length of the rod hanger center (plunger);

2) number of double strokes per minute of the rod hanger center;

3) diameter of plunger.

In order to find the most advantageous pumping mode, it is required to choose the correct combination of these indicators.

The first two indicators depend on the design of the deep well sucker-rod pump drive. The field experience of deep well pumps operation has shown that increasing the pump performance by increasing the number of plunger strokes is impractical, since with a number of strokes greater than 15 per minute the frequency of sucker rod breakage increases significantly.

The formula of the daily capacity of a pumping plant is as follows:

$$Q = 1440 K_p f_a n S \left(\frac{1}{\cos \frac{\pi n H}{30 a}} - \frac{\lambda}{S} \right),$$

where Q is the plant capacity, m^3/day; K_p is the pump delivery coefficient; n is the number of double strokes of the rod hanger center (RHC); S is the length of RHC stroke, m; H is the pump running depth, m; λ is the total static deformation of pumps and rods under the load of the liquid mass, m; f_a is the cross sectional area of the plunger, m^2; a is the sound speed in rods, m/s.

The results of experimental studies conducted by AzINMASH Research and Design Institute of Petroleum Engineering (Baku, Azerbaijan) indicate the feasibility of normal operation of sucker-rod pumps under the condition that $n \cdot S = 54 \div 60$ m/min.

Let us examine the dependence between the peak output Q and the number of strokes n for various standard pumpjack sizes (Table 1).

Analyzing the table parameters we can see that the value of the product $n \cdot S$ in the existing pumpjacks is below the recommendations based on experimental data, i.e. there is a tangible opportunity of increasing the productivity by extending the RHC stroke, since well pump barrels may be as long as 6 to 7 meters.

Let us examine the following example to prove the statement regarding the applicability of the long stroke in increasing the plant capacity.

Figure 1 shows two dependences of the sucker-rod pump capacity on the number of RHC strokes – $Q = f(n)$.

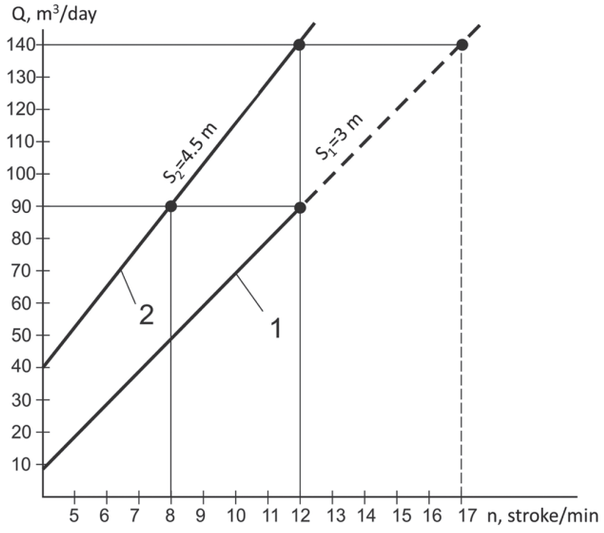

Figure 1. Performance to number of RHC strokes dependence graph

For the first dependence, the following standard parameters of the SKD8-3-4000 pumpjack are chosen: the

Table 1. SKD-type pumpjack technical parameters

Pumpjack standard size	Parameters				
	Diameter of pump d_n, mm	Length of motion S, m	Number of RHC double strokes, n	Pump output Q, m^3/day	n·S
SKD 3-1.5-710	68	1.5	15	84.9	22.5
SKD 4-2.1-1400	93	2.1	15	225.8	31.5
SKD 6-2.5-2800	93	2.5	14	245.8	35
SKD 8-3-4000	93	3	12	250	36
SKD 10-3.5-5600	93	3.5	12	291	42
SKD 12-3-5600	93	3	12	236.7	36

number of double strokes per minute of the rod hanger center is n = 12; the stroke length of RHC is S_1 = 3 m; the deep well pump with the diameter of d_p = 57 mm is hung at a depth of H = 980 m; pumps diemeter is 73 mm; the structure of stem rod is three-stage and consists of rods with diameters of 19 mm, 25%, 22 mm, 40% and 25 mm, 35%. The capacity is determined on the basis of computer calculations (Appendix 1) and is as follows: Q_1 = 90 m^3/day; $n{\cdot}S$ = 36.

The second dependence corresponds to the stroke length S_2 = 4.5 m, the capacity of Q_2 = 140 m^3/day (Appendix 2), $n{\cdot}S$ = 54 and other equal parameters.

Considering the fact that the dependence of the capacity on the number of strokes is close to the straight line law, the diagram shows that if capacity S_1 increases for the dependece 1 to the value of S_2 = 140 m^3/day, the number of double strokes per minute of the rod hanger center increases to 17.

Such number of double strokes per minute of the rod hanger center is unacceptable, since in addition to the increasied number of sucker-rod brackage, the number of strokes cannot provide the required capacity. The positive aspect of increasing the RHC stroke length to 4.5m is that in order to obtain the capacity of S_2 = 140 m^3/day, the number of double strokes per minute of the rod hanger center decreases up to 8, which should reduce the frequency of the sucker-rod brackage, as the diagram shows. In this case, the real possible capacity due to the increase of the stroke length will be at $S_2 - S_1$ = 140 – 90 = 50 m^3/day greater.

If the long-stroke DWSRPD drive is developed on the basis of the kinematic parameters of the SKD-type pumpjack, it must be taken into account that the overal dimension as well as the pumpjack mass will increase, since the length of all parts – k_1, k, l, r, pole distance p, and, consequently, column height and frame length will increase. Additionally, the electric motor power N_{em} also grows (Table 2). The mechanism's dynamics deteriorate as well.

Estimates show that while studying the kinematics of long-stroke drives the changes in the length of the rope may be practically disregarded due to the displacement of the rope-to-pulley contact point. This simplifies the formulas that describe the kinematics of this type of long-stroke drives. For this purpose, let us assume in the calculation scheme in the Figure 2 that the contact point is fixed, i.e. the point A_o coincides with the point A. Then, in the initial state of the machine (when the rod hanger center D starts to move upwards), the cable length from the crank to the pulley (minimum length) will be as follows:

$$l_o = AO_1 - R\text{, where } AO_1 = \sqrt{p^2 - r^2} \text{ or } l_o = \sqrt{x_o^2 + y_o^2 - r^2} - R.$$

After the crank rotation by some angle φ, the current length of this cable section will be:

$$l(\phi) = \sqrt{AC^2 + CB^2},$$

$$\text{where } AC = l_o + R(1 - \cos\phi);\ CB = R\sin\phi,$$

$$l(\phi) = \sqrt{\left[l_o + R\left(1 - \cos\phi\right)\right]^2 + R^2\sin^2\phi}.$$

The displacement amount of point D is determined in accordance with the following formula:

$$S(\phi) = l(\phi) - l_o =$$

$$= \sqrt{\left[l_o + R\left(1 - \cos\phi\right)\right]^2 + R^2\sin^2\phi} - \sqrt{p^2 - r^2} + R.$$

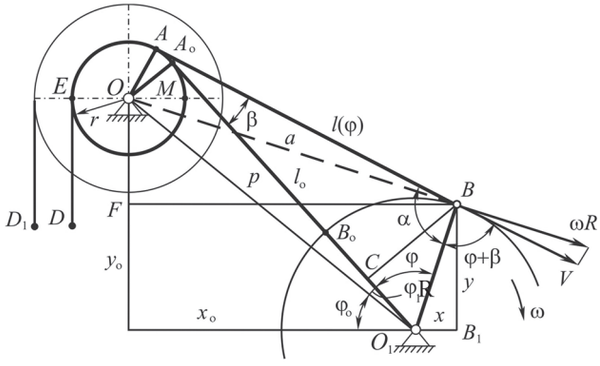

Figure 2. The calculation scheme of the crank cable and pulley drive of DWSRPD

The movement speed of this point is determined as the line speed projection of the cutpoint of the cable and crank on the cable direction:

$$V(\varphi) = \omega R\cos(\pi/2 - \varphi - \beta) = \omega R\sin(\varphi + \beta).$$

The acceleration of this point is determined as the derivative of the speed found with respect to time:

$$W(\phi) = \frac{dV(\phi)}{dt} = \frac{d\phi}{dt}\cdot\frac{dV(\phi)}{d\phi} = \omega\frac{dV(\phi)}{d\phi} = \omega^2 R\frac{d}{d\phi}\cos(\phi + \beta),$$

$$W(\phi) = \omega^2 R\left(1 + \frac{d\beta}{d\phi}\right)\cos(\phi + \beta).$$

Let us calculate the angle β(φ):

$$\beta(\phi) = \operatorname{arctg}\frac{CB}{AC} = \operatorname{arctg}\frac{R\sin\phi}{l_i + R\left(1 - \cos\phi\right)}.$$

To simplify calculations, let us expand the function arctg$x$ by formal power series provided that $|x| < 1$:

Table 2. Comparative table of SKD-type pumpjack and assumed long-stroke DWSRPD drive performance indicators

Type of DWSRPD drive	Indicators							
	S_o, mm	k_1, mm	k, mm	l, mm	r, mm	p, mm	N_{em}, kW	Q, m^3/day
SKD 8-3-4000	3	2	2.29	3	1.2	3,62	23.5	90
Long-stroke DWSRPD drive	4.5	3.43	3	4.52	1.8	5.43	35	140

$$\operatorname{arctg} x = \sum_{n=0}^{\infty} (-1)^n \frac{x^{2n+1}}{2n+1} = x - \frac{x^3}{3} + \ldots$$

Assuming that $\left| \frac{R \sin \phi}{l_o + R(1 - \cos \phi)} \right| < 1$ and, using just the first two expansion term with a high degree of accuracy, we obtain:

$$\beta(\phi) = \frac{R \sin \phi}{l_o + R(1 - \cos \phi)} - \frac{1}{3} \left[\frac{R \sin \phi}{l_o + R(1 - \cos \phi)} \right]^3.$$

The final formula for the acceleration $W(\varphi)$ will be:

$$W(\phi) = \omega_2 R \left\{ 1 + \frac{R(l_o + R)\cos \phi - R^2}{\left[l_o + R(1 - \cos \phi) \right]^2} \left\{ 1 + \left[\frac{R \sin \phi}{l_o + R(1 - \cos \phi)} \right]^2 \right\} \right\} \times$$

$$\times \cos \left\{ \phi + arctg \left[\frac{R \sin \phi}{l_o + R(1 - \cos \phi)} \right] \right\}.$$

For the differential pulley, in order to obtain values $S(\varphi)$, $V(\varphi)$ and $W(\varphi)$ for the point D_1, the abovementioned formulas should be multiplied by gear ratio $\lambda = r_1/r$.

On the basis of the obtained formulas, the computer simulation was performed and comparative computer calculations for the long-stroke drives were made based on a conventional double-arm balanced pumpjack with the stroke length of the rod hanger center $S = 8$ m and drive on the scheme in Figure 3 with the same stroke length.

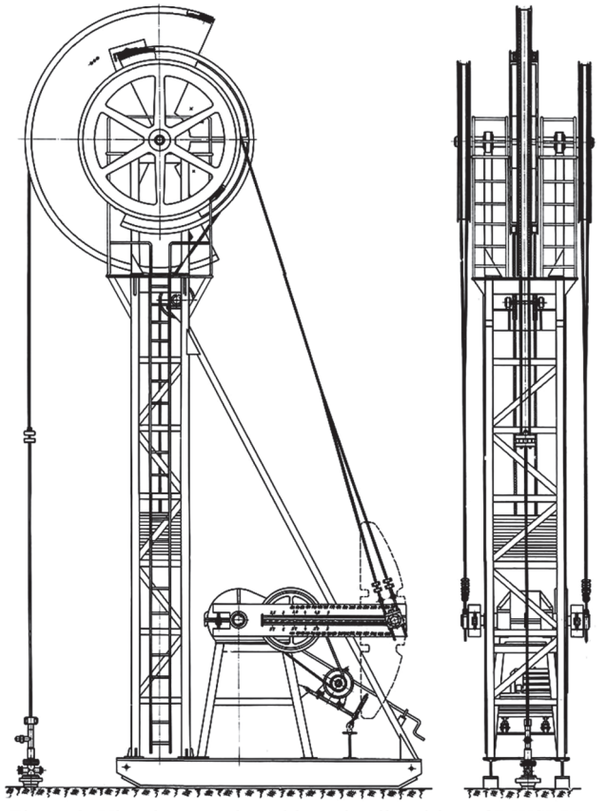

Figure 3. Ultra-long-stroke cable and pulley drive of DWSRPD (Azerbaijan)

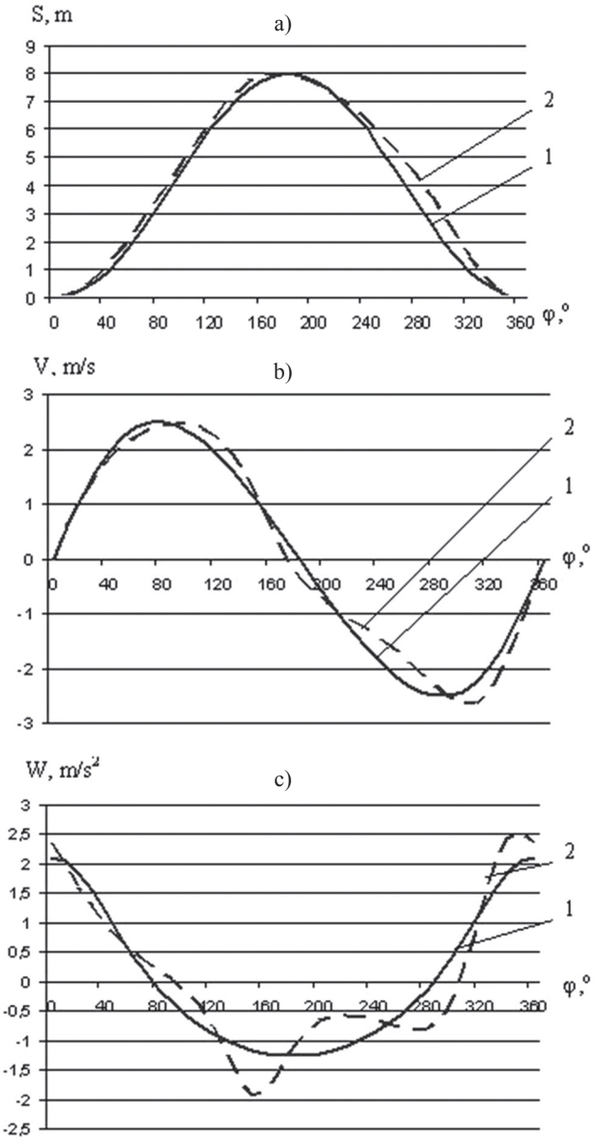

Figure 4. The diagrams of change of displacement (a), speed (b) and acceleration (c) of RHC SRP:
The 1-st is the cable and pulley drive of DWSRPD;
the 2d is the off-center pumpjack

The calculation of the pumpjack was carried out according to the well-known conventional formulas for a modern off-center SKD-type pumpjack produced with the off-center angle $\theta = 9°$. The ratio of the crank radius r to the lengths of the tail half of walking beam k and rocker l were equal to $r/k = 0{,}6$ and $r/l = 0{,}4$ respectively, in accordance with the moderm design practice. The ratio of the length of the front arm of the walking beam k_1 to the length of tail half of walking beam k was equal to $k_1/k = 1.4$. In accordance with the stroke length S = 8 m, the obtained dimensions of the pumpjack are as follows: the length of the front arm of the walking beam is $k_1 = 6.1$ m; the length of the tail half of the walking beam is $k = x_o = 4.36$ m; the length of the

rocker is $l = y_o = 6.54$ m; the length of the pole distance is $p = 7.86$ m; the crank radius is $R = 2.62$ m.

The dimensions of the machine according to the diagram in the Figure 2 are as follows: the radius of the large pulley is $r_1 = 2.5$ m; the radius of the small pulley is $r = 1.5$ m; the radius of the crank is $R = 2.4$ m; the radius of the length $x_o = 1.5$ m; $y_o = 9.2$ м; the radius of the pole distance is $p = 9.3$ m. The calculation of this option was carried out in accordance with the abovementioned formulas for the differential pulley.

Figure 4 shows the results of the comparative kinematic calculation, where the curves 1 correspond to the cable and pulley drive, and curves 2 correspond to the conventional double-arm off-center pumpjack.

Since the dynamics of the downhole equipment operation and, consequently, the strength load of the drive and transmission largely depend on the machine kinematics and mainly on acceleration, the presented comparative schemes allow concluding that the main performance indicators of the crank cable and pulley mechanism of the SRP drive for the oil extraction are better.

To create long-stroke DWSRPD drives that allow increasing the capacity of SRP, reducing steel intensity and power consumption in comparison with the existing long-stroke drives, the design of mast-type oil well sucker-rod pump drive was proposed as an invention [2].

Conclusion

Comparative calculations of the performance of SRPS allowed making a conclusion regarding the applicability of long-stroke SRP.

The paper sets forth basic dependences of the kinematics of long-stroke drives, on which comparative calculations and graphs of movement, speed and acceleration of the rod hanger center of SRP rope and pulley drive and eccentric pumpjack were based showing the superior basic performance of the rope and pulley mechanism.

The research resulted in a proposed invention of the design of mast-type SRP drive with lower steel intensity power consumption that would allow increasing the SRPS performance.

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Reliability of forecast of successful flight training based on professional psychological selection

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Abstract. *Today's military aviation imposes ever increasing requirements on the pilots' professional qualities, thus complicating the problems related to the improvement of the quality of professional selection and training of military pilots. The research conducted by V.A. Ponomarenko and V.A. Bodrov introduced the term "prolonged selection" into aviation psychology, meaning professional psychological support of flight training. The forecasting of successful training at the early stage is an important part of this support and is the focus of this paper.* **Methods.** *The aim of the study was to verify the forecast of successful flight training based on the professional psychological selection (PPS) at early stages of professional training and feasibility of such forecast in the form of integral estimation. For that purpose the authors used the academic progress estimates, the results of piloting skills development using flight simulators, the dynamics of professionally important qualities (PIQ) of cadets during the first two years of training in comparison with those indicators obtained during the PPS. The sample included 143 cadets. The test subjects were surveyed at their admission to the flight school and in the first two years of the course according to programs prescribed by the regulatory documents of the Russian Ministry of Defense and command of the Aerospace Forces. The survey is an obligatory condition for enrollment in a flight school and the subsequent flight training and does not contradict today's ethical standards of scientific research. The surveyed cadets were distributed into two groups per categories of professional aptitude based on the results of PIQ survey conducted during the professional psychological selection: the 1-st group (55 people), the "fit" with good professional aptitude indicators, and the 2-nd group (88 people), the "conditionally fit" with acceptable professional aptitude indicators. Statistical analysis was carried out with Microsoft Office 2007 Excel descriptive statistics, Student's t-test criterion for unpaired samples.* **Results.** *The survey showed that the "fit" group, as compared to the "conditionally fit" are better adapted to the conditions of military service, have higher indicators of cognitive mental processes and sensorimotor abilities. They master course content and simulator training better. At the same time, in terms of their physiological and physical qualities the cadets of the two surveyed groups are indistinguishable and all show good results, which is confirmed by their grades in physical education and shows their good physical development and fitness.* **Conclusions.** *The forecast of successful flight training made at the stage of professional psychological selection as a category of professional aptitude is confirmed at the initial stages of the cadets' training during professional psychological support activities. The integral estimation composed of the results of academic progress, psychological, psychophysiological inspection survey data, results of simulator training can be used in subsequent flight training as the input for individual professional training programs. In order to improve the reliability of training, integrated automated methods are planned to be developed for the purpose of diagnosing current flying PIQs, as well as methods of their improvement and development [4].*

Keywords: *professional psychological selection, professionally important qualities, professional training, professional aptitude, forecast of successful flight training, professional psychological support of flight personnel training.*

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Introduction. Today's military aviation is characterized by the rapid development of aviation technology and the nature of flight operations becoming more complicated. In these conditions, the requirements for the pilots' professional qualities are increasing and the system concept of reliability and safety of flights is becoming more and more complex [1, 7]. In this context, the problems related to the improvement of the quality of professional selection and training of military pilots arise. At the initial stages of training in the flight school the professional psychological selection (PPS) specialists continue to dynamically observe the indicators of the professional aptitude level (category) and update the initial forecast of successful flight training. The study of the changes in the socio-psychological, psychophysiological and other characteristics (and traits) of the future pilot during the training in the flight school was carried out at the end of the last century by the well-known scientists V.A. Ponomarenko and V.A. Bodrov. They complemented PPS with the term "prolonged selection" as the implementation of the principles of dynamic, differentiated forecasting of the professional aptitude during the flight training process [2, 9, 10]. In today's conditions the "prolonged selection" is called professional psychological support of flight training. It includes the assessment of the dynamics of professionally important qualities (PIQ) of cadets, updating the structure and compensation of PIQ during their professional development, aggregation of individual recommendations, preparation of psychological profiles, optimal assigning of cadets to flight professions [3, 6, 8]. The professional psychological support of flight training in the flight school is carried out by specialists of the research department (professional psychological selection and professional psychological support of flight training). It effectively improves the quality of professional flight training and is constantly developing.

Thus, in order to optimize recommendations for the cadets' flight training, the development of an integrated assessment of forecast of successful flight training at the initial stages of training studies are being conducted. The study sets the following tasks:

- Whether the flight training is confirmed to be successful at the initial stages of the training of cadets as predicted during PPS?

- Whether the forecast of the successful flight training can be presented as an integral assessment including academic and simulator-based learning results as well as psychological and psychophysiological examination findings?

In order to achieve the objectives of the study, the academic progress estimates, the results of piloting skills development using flight simulators, the dynamics of professionally important qualities of cadets during the first two years of training (the sample included 143 cadets) were compared with those indicators obtained during the PPS.

Methods. The following psychological and psychophysiological examination methods were used: to assess personal PIQ, the multifactorial personality questionnaire "Adaptability", "Risk Propensity", "Motivation to Success", "Motivation to Avoid Failure", "Level of Subjective Control", "Level of Aspiration" were used; to assess intellectual PIQ, "Working Memory", "Correction Task", "Red and Black Tables", "Regularity Test", "Audio-Verbal Memory", "Visual Memory", "Spatial Thinking", "Visual Thinking" were used. Sensorimotor characteristics were evaluated using simple sensorimotor reaction, complex sensorimotor reaction (lability of nervous processes) and reaction to a moving object tests. The physiological characteristics were assessed using Stange-Gench and Ruffier functional tests [5].

Statistical analysis was carried out with Microsoft Office 2007 Excel descriptive statistics, Student's t-test criterion for unpaired samples.

The surveyed cadets (n=143) were distributed into two groups per categories of professional aptitude based on the results of PIQ survey conducted during the professional psychological selection:

The 1-st group was named "fit" and had good professional aptitude indicators. It consisted of 55 people.

The 2-nd group was named "conditionally fit" and had acceptable professional aptitude indicators. It consisted of 88 people.

The survey showed that professional aptitude assessment during PPS directly correlated with the academic performance of the flight school cadets. Thus, there is a significant difference ($p<0.05$) between the "fit" and the "conditionally fit" groups in most academic courses taken during the first two years of the studies: the "fit" group was more successful in such principal subjects as mathematics, physics, computer science, mechanics, aerodynamics, aviation meteorology. The "fit" group was more successful at general subjects like national history, foreign language, health and safety, electronics and electrical engineering as well. There was no significant difference between the two surveyed groups in general tactics and philosophy.

The assessment of the psychological characteristics and traits showed there is a significant difference ($p<0.05$) in adaptability between the "fit" and the "conditionally fit" cadets. The cadets from the "fit" group adapt faster and more easily to military service conditions, they have higher indicators of communicative qualities and are more stable emotionally. There was no significant difference in such personality traits as pursuit of success and achievements and tendency to avoid failure between the two groups: both "fit" and "conditionally fit" cadets are equally motivated to succeed and to avoid failure, have an equally moderate level of aspiration. Meanwhile, the cadets from the "fit" group have a significantly higher level of risk propensity, higher level of subjective control of their behavior and higher level of socializing ($p<0.05$).

The intellectual PIQ diagnostics showed that the "fit" cadets have significantly higher indicators of cognitive processes: attention, memory, thinking, perception, that is, verbal logical thinking, visual and short-term memory, imagery ability.

Some sensorimotor characteristics were evaluated: reaction time, accuracy, reaction to a moving object. The "fit" group has significantly ($p<0.05$) higher sensorimotor reac-

tion indicators: reaction time to simple and complex signals, stability of the reaction to a moving object, coordination of movements.

In terms of their physiological qualities the cadets of the two surveyed groups are indistinguishable. At the same time, the average values of the cardiorespiratory system's reserve capacity indicators (Bogomazov's index) and the exercise tolerance of the cardiovascular system (Ruffier Index) of both groups are at a high level. Such results were obtained in both the first and the second years of training.

The high level of physiological characteristics is confirmed by the high level of physical fitness of cadets in both groups: the mean grade in physical fitness of all cadets is 4.5[1] or higher. They also have good physical qualities, i.e. strength, speed, stamina, dexterity, since the integral assessment of physical fitness is a combination of different exercises: running, pull-ups, gymnastic exercises, etc.

The results of simulator-based training turned out to be the most evident confirmation of the predicted successful flight training. The "fit" cadets had a significantly greater scope of attention than the "conditionally fit" cadets (6.09±0.51 and 5.52±0.45 respectively), they perform better at ground training (5.95±0.46 with 5.24±0.39 for "conditionally fit"), operate aircraft equipment more competently (6.14±0.46 with 5.41±0.37 for "conditionally fit") and act more confidently in special situations (5.95±0.47 with 5.13±0.48 for "conditionally fit"), their flight skill is developed faster and is more stable (6.09±0.45 with 5.55±0.41 for "conditionally fit"). The "fit" cadets have a higher overall grade at simulator-based training than the "conditionally fit" cadets (6.18±0.45 and 5.5±0.41 respectively).

Results. The survey showed that the "fit" group, as compared to the "conditionally fit", are better adapted to the conditions of military service, have higher indicators of cognitive mental processes and sensorimotor abilities. They better master course content and simulator training. At the same time, in terms of their physiological and physical qualities the cadets of the two surveyed groups are indistinguishable and show good results, which is confirmed by their grades in physical education and shows their good physical development and fitness.

Conclusions. The obtained results suggest the following conclusions:

- the forecast of successful flight training made at the stage of professional psychological selection as a category of professional aptitude is confirmed at the initial stages of the cadets' training during professional psychological support activities;

- the forecast of successful flight training made at the initial stages of the cadets' training is confirmed by the results of their academic progress, psychological, psychophysiological inspection survey data, results of simulator training that can be used as components of the integral estimation. This integral estimation can be used in subsequent flight training as the input for individual professional training programs.

[1] By five-point numerical grading scale

Specific quantitative criteria for the integral estimation with the inclusion of the results of their academic progress, psychological, psychophysiological inspection survey data, results of simulator training, that still ae not defined in aviation psychology, will be defined in subsequent studies with the use of statistical analysis methods and implemented in the professional psychological support for flight crew training. The reliability of forecast of successful flight training at the initial stages of the training was confirmed, however the applicability of the used PPS professional success forecasting methods to the training with the next generation aircrafts is in question.

To address these issues, PC-based integrated automated methods are planned to be developed for the purpose of diagnosing current flying PIQs, as well as methods of their improvement and development [4].

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On an approach to the evaluation of the latent risk of expert assessment of roadbed seismic stability[1*]

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Abstract. *The paper aims to examine the problem of integration of the opinions of a group of experts regarding a certain probabilistic distribution for the purpose of its evaluation by an analyst. It is implied that the decision-maker will use the result to evaluate the target risks and take according decisions. This problem may arise in many areas of risk analysis. For the purpose of this paper, the stability of various structures (buildings, railways, highways, etc.) against external mechanical effects, e.g. earthquakes, is chosen as the application object domain. As the primary research tool it is suggested to use the probabilistic method of decision-making risk calculation associated with involving experts into the analysis of risk of roadbed and other structures destruction in case of earthquakes. The evaluation of the seismic stability of rail structures using expert opinions is based on the Bayesian approach. The proposed method of estimation by analyst of the probabilistic distribution (fragility curve) on the basis of the opinions of a group of experts allows, using the obtained results, formalizing and explicitly expressing the latent risk of expert assessment. The procedure developed subject to a number of limitations allowed obtaining an explicit expression for the latent risk of expert assessment. The theoretical constructs presented in this paper can be easily implemented as software that will enable interactive input of parameters and data of the model under consideration and obtaining the desired distribution and the value of "risk in risk". Such system, on the one hand, will allow verifying some intuitive assumptions regarding the behavior of results depending on the variation of parameters, and on the other hand, will be able to be used as the tool of expert assessment automation and analysis of its quality that helps making grounded decisions under risk. Further development of the proposed method may involve the elimination of the dependence of the value of "risk in risk" from the expert assessment. Implicitly, this dependence is present in the final expression, while ideally this risk is to be determined only by the expert ratings. The proposed approach can serve as the foundation of some practical optimization problems, e.g. the selection of the best group of involved experts from the point of view of minimization of this share of risk in cases of restricted funding of expert assessment (obviously, the higher the expert's competence, the more accurate his/her estimates are and, subsequently, the lower is the risk, yet the higher is the cost of such expert's participation). An associated problem can be considered as well. It consists in the optimal selection of experts for the purpose of minimization of assessment costs under the specified maximum allowable level of "risk in risk". As a whole, the proposed method of evaluation of an unknown distribution and calculation of risk is sufficiently universal and can be used in the context of mechanical stability of structures, but also a wide class of problems that involve the assessment of a certain probabilistic distribution on the basis of subjective data about it.*

Keywords: *latent risk of expert assessment, Bayesian approach, fragility curve, quantiles.*

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Introduction

When analyzing various risks using probabilistic approaches, one often deals with events, of which the frequency is extremely low, e.g. various catastrophic phenomena. In addition, experimenting on real objects is normally either impossible in principle (usually, in cases of natural disasters), or extremely costly. Consequently, analysts have to deal with the situation of acute shortage, inconsistency or sometimes complete absence of direct experimental data. This forces the decision-makers (DMs or analysts) to construct risk analysis procedures solely on the basis of specifically invited subject matter experts, i.e. individuals who possess specific knowledge.

That causes the problem of optimal consideration and integration of all presented opinions obtained using different methods that probably contradict each other. Naturally, the DM must somehow classify the experts depending on the degree of trust. Additionally, he/she must be able to evaluate how close to reality the obtained result is, i.e. how satisfactory the conducted expert assessment is. In other words, while involving experts into the process of risk analysis, he/she must have an idea of the magnitude of the risk of wrong results and what possible negative consequences their use might have. This latent risk of expert assessment, i.e. the risk associated with the very fact of experts' involvement in the risk analysis is the main focus of this paper. The aim is to create the perfect tool for its assessment. Naturally, it is not supposed to appear out of nowhere, but be based on some procedure that transforms the information obtained from the experts into the final aggregated DM opinion. Further, a specific problem will be formulated, of which the solution will form the foundation of a practical method of calculation of the latent risk of expert assessment.

The purpose of the above procedure would be to solve the problem of integration of the opinions of a group of experts regarding a certain probabilistic distribution for the purpose of its evaluation by an analyst. It is assumed that the DM will subsequently use the result to evaluate the target risks and take according decisions.

This problem can arise in many areas of risk analysis. For the purpose of this paper, the stability of various structures (buildings, railways, highways, etc.) against external mechanical effects, e.g. earthquakes, is chosen as the application object domain. It is described with the so-called fragility curves (per [1]). According to the definition, the indicator of fragility of a structure or its component is the probability of its destruction (or failure) under the specified value of the parameter that characterizes an external effect (e.g. in case of an earthquake this parameter is the peak horizontal acceleration of ground). Thus, the fragility curve can be considered as the distribution function (integral) of a random value that reflects the ability of a structure to withstand mechanical stress with this parameter as the argument.

In order to formalize the concept of "expert opinion", the so-called quantile approach was used that is described, for example, in [2] and consists in the following. A certain finite set of distribution function values is defined. The experts are to express their opinion regarding under what values of the variable the distribution function is equal to each of the proposed values. These values of the variable are the distribution quantiles that correspond to the specified probabilities.

Several alternative methods were proposed for the solution of the problem. In this case, taking into account the initial goal, i.e. the definition of the concept of "latent risk of expert assessment", the Bayesian approach should be chosen, as it is based on the idea that experts are in principle imperfect sources of information, and attempts to take this imperfection into consideration. As part of this approach, each estimate received from an expert is interpreted as a result of an experiment and, therefore, is considered a random value that is specifically the main object of analysis.

The theoretical foundations of the Bayesian approach were laid in the mid-1970's to early 1980's ([2-5]), after which the practical applications started to develop in different areas, including the one at hand ([6-8]). In order to ensure the consistency of the presentation of the proposed method of evaluation of the fragility curve, it will start with the Bayes' theorem that, at the same, will be described briefly in the aspects that were earlier described in literature.

Bayesian formula

As part of the chosen approach, the opinions of the experts are considered input data, point estimates of the quantile that have an effect of the DM's "state of knowledge" of the Bayesian distribution:

$$\pi\left(x^t \mid E\right) = k^{-1} L\left(E \mid x^t\right) \pi_0\left(x^t\right), \qquad (1)$$

where the following designations are used:

$\pi\left(x^t \mid E\right)$ is the DM's a posteriori notion of the distribution (specifically, the value of the variable corresponding to one quantile or another) after studying the expert opinions E (here, distribution density is involved);

$\pi_0\left(x^t\right)$ is the DM's initial (a priori) notion of the unknown distribution before studying the expert opinions;

E is the experts' opinion on the distribution;

$L\left(E \mid x^t\right)$ can be called "plausibility function" of the input data E provided that the true value of the unknown (estimated) quantity is x^t; the meaning of this formula will be clarified below[1*];

k^{-1} is the normalization constant.

Thus, the problem comes down to the estimation of the a priori distribution $\pi_0\left(x^t\right)$ and plausibility function $L\left(E \mid x^t\right)$. The latter is the key element and its correct interpretation

[1*] In the object domain under consideration (mechanical resistance of structures) the fact that the unknown quantity equals x^t means that the structure will be destroyed with the probability 1 under the maximum value of vertical acceleration equal to xt. The superscript "t" here means "true".

is vital to the understanding of the whole method. For the simplest case of one expert and one assessment of quantile x_1 we have:

$$\pi\ \left(x^t \mid x_1\right) = k^{-1} L\left(x_1 \mid x^t\right) \pi_0\left(x^t\right).$$

In this expression the quantity $L\left(x_1 \mid x\right) dx_1$ is a subjectively estimated by the analyst probability that the value received from the expert will be between x_1 and $x_1 + dx_1$ provided that the true value of the variable corresponding to the quantile equals x^t. Obviously, this notion is true for the case of several experts. Thus, the plausibility function is in some way the measure of accuracy of the expert's opinion from the point of view of the DM who uses it to construct his/her own subjective model of the former's ability to give a quantitative evaluation of an unknown quantity.

As to the a priori knowledge of the analyst, in this paper it will be described with a uniform distribution. That was done for the sake of simplicity and corresponds to the situation when before receiving the expert assessments the DM does not have any information on the nature of the desired distribution. In this case from his/her point of view the probability of the unknown quantity being between x^t and $x^t+\Delta x^t$ does not depend on x^t, which exactly corresponds to the absence of any knowledge.

Limitations of the model

The problem of construction of the desired probabilistic distribution based on experts' opinions is in general extremely complicated. Therefore, in order to obtain a practically applicable result, some simplifying assumptions must be made regarding both the nature of the distribution itself and the properties of the plausibility unction.

First, it will be assumed that the desired distribution belongs to the lognormal family, i.e. its density is defined by two parameters, и and щ:

$$f\left(x\right) = \frac{1}{\sqrt{2\pi}\ \omega\ x} \exp\left\{-\frac{1}{2}\left[\frac{\ln x - \theta}{\omega}\right]^2\right\}. \qquad (2)$$

Accordingly, the fragility curve is determined by integral of (2). Taking into account the selected subject field, this assumption is completely valid. A number of research programs dedicated to the study of real fragility curves (e.g. see [1]) indicate that the integral of the function (2) approximates them with good accuracy.

In the context of this assumption the problem of finding the distribution is significantly simplified and is reduced to the estimation of its parameters. Bayes's theorem is rewritten as follows:

$$\pi\left(\theta, \omega\ \mid E\right) = k^{-1} L\left(E \mid \theta, \omega\right)\ \pi_0\left(\theta, \omega\right). \qquad (3)$$

Under known distribution of parameters, the final estimate of the fragility curve, i.e. a specific pair of parameters, must be chosen. It appears that the most logical choice is the most probable distribution. Its parameters are found from the maximum condition based on the parameters of a posteriori distribution density $\pi\left(\theta, \omega\ \mid E\right)$ and are, therefore, the roots of the system:

$$\begin{cases} \dfrac{\partial \pi\ \left(\theta, \omega\ \mid E\right)}{\partial \theta} = 0, \\ \dfrac{\partial \pi\ \left(\theta, \omega\ \mid E\right)}{\partial \omega} = 0. \end{cases} \qquad (4)$$

The second hypothesis concerns the input data that are the set of estimates:

$$E = \left\{\ x_{ij},\ i = \overline{1,\ N};\ j = \overline{1,\ M}\right\},$$

where x_{ij} is the estimate by the i-th expert for the j-th quantile. It will be assumed that the estimates for all quantiles given by all experts are mutually independent. Certainly, this is a very strong assumption that can only be approximately true, and even then under a small number of quantiles. However, in the simple model under consideration it provides satisfactory results. Accounting for the dependences between the estimates, while radically increasing the inconvenience of calculations and reducing the illustrative qualities of the model, does not always have a significant effect on the result.

Subject to the second assumption, the general plausibility function is simply the product of the individual ones:

$$L\left(E \mid \theta, \omega\right) = \prod_{i=1}^{N} \prod_{j=1}^{M} L_{ij}\left(x_{ij} \mid \theta, \omega\right) \qquad (5)$$

where $L_{ij}\left(x_{ij} \mid \theta, \omega\right) \Delta x_{ij}$ is the probability that the estimate of the value of the variable corresponding to the j-th quantile by the i-th expert will fall into the small interval $\left[x_{ij},\ x_{ij} + \Delta x_{ij}\right]$ provided that the parameters of true distribution are equal to и and щ.

And finally the last assumption concerns the description of the analyst's expectations regarding the result obtained in the process of the expert opinion formation. There are two models of experts (additive and multiplicative), in which the probability of the deviation of the expert's opinion (from the DM's point of view) about the unknown value from the true value is explicitly expressed, i.e. the basic idea of the Bayesian approach to accounting for the inaccuracy of the information obtained from the expert is implemented. In this paper, the multiplicative model will be used. It is briefly presented below.

According to this model, the analyst examines the i-th expert's estimate of the value of the variable corresponding to the j-th quantile as random variable X_{ij} that is the product of two terms:

$$X_{ij} = x_j^t B_{ij},$$

where x_j^t is the true value (defined by the unknown parameters of the lognormal distribution), while B_{ij} is the random variable that corresponds to the error. Taking the logarithm, we will obtain:

$$\ln X_{ij} = \ln x_j^t + \ln B_{ij}.$$

Assuming that random variable $\ln B_{ij}$ is distributed over the normal law with the mathematical expectation $\ln b_{ij}$ and dispersion σ_{ij}^2, we will obtain, as it is easy to show, the lognormal distribution of the expert estimate:

$$L\left(x_{ij}|\theta,\omega\right)=\frac{1}{\sqrt{2\pi}\sigma_{ij}x_{ij}}\exp\left\{-\frac{1}{2}\left[\frac{\ln x_{ij}-\left(\ln x_j^t+\ln b_{ij}\right)}{\sigma_{ij}}\right]^2\right\}. \quad (6)$$

This function well describes the behaviour of experts and is widely used. This is that "building block" (since it is the plausibility function for the case of one estimate given by one expert) that will be the foundation for the construction of the general aggregated plausibility function that is in equation (1).

One additional hypothesis is accepted in this paper: experts are considered to be sufficiently competent in their subject area to not make systematic errors. Therefore, in equation (6), the calculations will assume that

$$\ln b_{ij}=0,$$

which corresponds to the absence of systematic shift. Thus, as part of the general idea of taking account of the inevitable inaccuracies in the obtained information, only one type of errors will be considered, the random ones. As the result, formula (6) is rewritten as follows:

$$L_{ij}\left(x_{ij}|\theta,\omega\right)=\frac{1}{\sqrt{2\pi}\,\sigma_{ij}x_{ij}}\exp\left\{-\frac{1}{2}\left[\frac{\ln x_{ij}-\ln x_j^t}{\sigma_{ij}}\right]^2\right\}. \quad (7)$$

Now, subject to the above assumptions, an a posteriori distribution of parameters $\pi\left(\theta,\omega\mid E\right)$, and, therefore, the desired estimation of the fragility curve can be constructed on the basis of experts' opinions.

Construction of the distribution

Let us first express the individual plausibility function that is defined by (7). The method of evaluation of the dispersions of estimationσ_{ij}^2 will be presented below. The true value of the variable that corresponds to the *j*-th quantile can be found using the assumption (2) of the true curve being part of the lognormal family. This value is associated with the lognormal distribution parameters as follows:

$$\ln x_j^t=\omega\, Z_j+\theta, \quad (8)$$

where Z_j is the value of the standard normal distribution variable (with zero mathematical expectation and the unit dispersion) corresponding to this quantile. Thus, formula (7) transforms into:

$$L_{ij}\left(x_{ij}|\theta,\omega\right)=\frac{1}{\sqrt{2\pi}\,\sigma_{ij}x_{ij}}\exp\left\{-\frac{1}{2}\left[\frac{\ln x_{ij}-\left(\omega Z_j+\theta\right)}{\sigma_{ij}}\right]^2\right\}. \quad (9)$$

Now, by assumption of mutual independence of all expert assessment, by substituting (9) into (5), and further (5) into (3) by virtue of the hypothesis of the uniformity of a priori distribution we will obtain:

$$\pi\ \left(\theta,\omega\ \mid E\right)=k_1^{-1}\exp\left\{-\frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{M}\left[\frac{\ln x_{ij}-\left(\omega Z_j+\theta\right)}{\sigma_{ij}}\right]^2\right\}.$$

This is the desired distribution of the lognormal distribution parameters. However, in this form it is inconvenient to examine it to the maximum on и and щ. By squaring the expression under the summation sign and extracting perfect squares by parameters, after sufficiently simple, yet tedious calculations we will obtain:

$$\pi\left(\theta,\omega|E\right)=K^{-1}\exp\left\{-\frac{1}{2}\left[\left(\frac{\omega-\Omega}{\sigma_\omega}\right)^2+\left(\frac{\theta-\Theta(\omega)}{\sigma_\theta}\right)^2\right]\right\}, \quad (10)$$

where

$$\Omega=\frac{\left(\sum_{ij}\sigma_{ij}^{-2}\right)\left(\sum_{ij}\sigma_{ij}^{-2}Z_j\ln x_{ij}\right)-\left(\sum_{ij}\sigma_{ij}^{-2}\ln x_{ij}\right)\left(\sum_{ij}\sigma_{ij}^{-2}Z_j\right)}{\left(\sum_{ij}\sigma_{ij}^{-2}\right)\left(\sum_{ij}\sigma_{ij}^{-2}Z_j^2\right)-\left(\sum_{ij}\sigma_{ij}^{-2}Z_j\right)^2}, \quad (11)$$

$$\sigma_\omega^2=\frac{\sum_{ij}\sigma_{ij}^{-2}}{\left(\sum_{ij}\sigma_{ij}^{-2}\right)\left(\sum_{ij}\sigma_{ij}^{-2}Z_j^2\right)-\left(\sum_{ij}\sigma_{ij}^{-2}Z_j\right)^2}, \quad (12)$$

$$\Theta(\omega)=\frac{\sum_{ij}\sigma_{ij}^{-2}\ln x_{ij}-\omega\sum_{ij}\sigma_{ij}^{-2}Z_j}{\sum_{ij}\sigma_{ij}^{-2}}, \quad (13)$$

$$\sigma_\theta^2=\left(\sum_{ij}\sigma_{ij}^{-2}\right)^{-1}, \quad (14)$$

while K^{-1} is the proportionality coefficient that does not depend on и and щ.

By substituting (10) in the system of equations (4) and solving it we will obtain the parameters of the most probable distribution:

$$\begin{aligned}\omega_m&=\Omega,\\ \theta_m&=\Theta\ (\Omega).\end{aligned} \quad (15)$$

Thus, the desired distribution density function (the integral of which is the fragility curve) subject to all the above assumptions is as follows:

$$\pi\ (x)=\frac{1}{\sqrt{2\pi}\ \Omega\, x}\exp\left\{-\frac{1}{2}\left(\frac{\ln x-\Theta(\Omega)}{\Omega}\right)^2\right\}.$$

We should mention another type of expressions for ω_m and θ_m that will demonstrate the contribution of each expert assessment into the final result. By regrouping the terms in the sums we obtain:

$$\theta_m = \sum_{ij} c_{ij}^{\theta} \ln x_{ij}, \quad (16)$$

$$\omega_m = \sum_{ij} c_{ij}^{\omega} \ln x_{ij}, \quad (17)$$

where

$$c_{ij}^{\theta} = \frac{\sigma_{\theta}^2 \sigma_{\omega}^2}{\sigma_{ij}^2} \left[\left(\sum_{ij} \sigma_{ij}^{-2} Z_j^2 \right) - \left(\sum_{ij} \sigma_{ij}^{-2} Z_j \right) Z_j \right], \quad (18)$$

$$c_{ij}^{\omega} = \frac{\sigma_{\theta}^2 \sigma_{\omega}^2}{\sigma_{ij}^2} \left[\left(\sum_{ij} \sigma_{ij}^{-2} \right) Z_j - \left(\sum_{ij} \sigma_{ij}^{-2} Z_j \right) \right]. \quad (19)$$

It is apparent that the contribution of the estimation of the *j*-th quantile given by the *i*-th expert is proportional to the value $\frac{\ln x_{ij}}{\sigma_{ij}^2}$. This fact will be used subsequently.

In the formulas that describe the resultant distribution there are values σ_{ji}^2, dispersions in the multiplicative model of errors that are part of the expression of plausibility function. The approach used for their estimation is also based on certain assumptions.

First, for one expert the dispersions of assessment for different quantiles are taken equal to each other. That means that the amount of random deviation of the estimate from the true value expected by the analyst does not depend on the quantile, but is defined only by the general degree of trust the DM has for this experts' opinion:

$$\sigma_{ij} = \sigma_i, \quad j = \overline{1, M}, \; i = \overline{1, N}. \quad (20)$$

These standard deviations of the opinions of each expert are to be estimated. To that effect, the concept of weight (or rating) w_i assigned to experts is introduced in this model. The value of this parameter determines the general degree of the analyst's trust in the *i*-th expert's opinion, the expected margin of error in the quantitative assessments he/she provides. Naturally, the higher is an expert's rating compared with the rest, the better the obtained distribution must correspond to his/her assessment.

As it is obvious from formulas (16)-(19), the terms are proportional to σ_{ji}^{-2}. Therefore, it appears to be natural to associate the dispersions with the weights in this way, i.e. taking into account (20),

$$w_i = \frac{\gamma}{\sigma_i^2},$$

where r is proportionality coefficient.

It should be noted, that, as it follows from (11) and (13), when identifying the parameters of the most probable distribution, only the relative values σ_i^2 matter, as in both formulas both the numerator and the denominator are dispersion-homogeneous and the degree of uniformity is identical. The absolute values affect the values σ_{θ}^2 and σ_{ω}^2, as it follows from (12) and (14). Thus, the scale of the weights of experts (under identical relationships among them) reflects only the quality level of the produced expert assessment, i.e. the expected probability that the obtained curve will be sufficiently close to the true fragility curve.

In order to obtain specific numerical estimations of the risk of involving experts, this scale, i.e. some "single", reference level of risk with which all values will be associated, must be identified at the beginning. There are problems that involve the minimization of the risk with some limitations, and in their context its magnitude is of no significance as regards the choice of the optimal solution. However, in some decision-making problems the value of latent risk of expert assessment is in itself an important indicator.

In this paper the scale will be identified as follows. Let us assume that w_i are known and let us examine the coefficient r. The "reference" value of dispersion (that corresponds to the weight of an expert's opinion equal to 1) can be evaluated by purely empirical methods.

Let us examine the graph of the lognormal distribution function (that describes the experts' errors) with the parameters y and *b* (Figure 1).

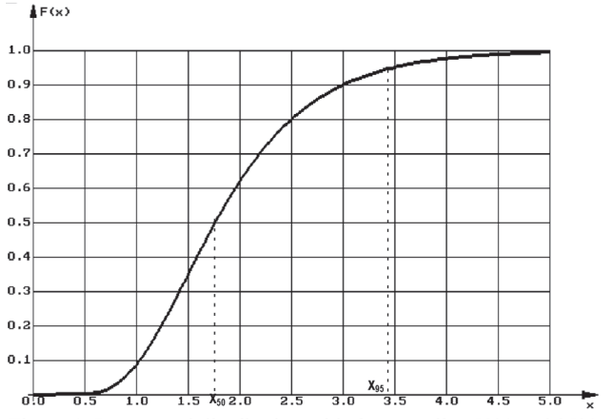

Figure 1. Lognormal distribution with the quantiles 50% and 95%

Let us find two values of the variable for quantiles with the probabilities 50% and 95%. They can be expressed with the corresponding values of the variable of the standard normal distribution and parameters (equation (8)):

$$x_{50} = \exp\left\{\sigma Z_{50} + b\right\},$$

$$x_{95} = \exp\left\{\sigma Z_{95} + b\right\}.$$

The value $\ln x_{95} - \ln x_{50}$ must characterize the internal scatter of the lognormally distributed random variable, and, therefore, its standard deviation as well. For tentative estimation of the latter let us assume that

$$\frac{x_{95}}{x_{50}} \approx 2,$$

i.e.

$$2 \approx \frac{\exp\left\{\sigma Z_{95} + b\right\}}{\exp\left\{\sigma Z_{50} + b\right\}} = \exp\left\{\sigma \left(Z_{95} - Z_{50}\right)\right\},$$

out of which the desired "reference" standard deviation is:

$$\sigma = \frac{\ln 2}{Z_{95} - Z_{50}} \approx \frac{\ln 2}{1,645} \approx 0,421$$

(out of tables we know that $Z_{50} = 0$, $Z_{95} = 1.645$).

This value will be used in dispersions calculation:

$$\sigma_i^2 = \frac{0,421^2}{w_i} = \frac{0,177}{w_i} .$$

Identification of the latent risk of expert assessment

As it is known, the risk is defined by two factors: the probability of a certain adverse event and the expected losses caused by its realization. As part of the approach under consideration, a discrete model of a posteriori situation is adopted: the building has either collapsed or not, i.e. there are no intermediate options. Therefore, the expected magnitude of losses is the same, which allows disregarding it completely and equating the risk with the probability of destruction. Of course, that is just an approximation, and in more complex models the degree of destruction, among other things, can be considered as well, yet that is beyond the above described method.

The main point of the proposed method of evaluation of the latent risk of expert assessment consists in the following. For each value of the parameter that characterizes external effects, the local, "differential" risk is calculated, after which it is summed over this parameter subject to its distribution (in other words, the mathematical expectation is calculated). Naturally, that requires knowing this distribution (in the subject area under consideration that is the prediction of seismic situation that reflects the dependence of the probability of earthquake from its strength). Let us assume that it is known and designate it $f_0(x)$. The problem now is to obtain the expression for evaluation of the local risk given x.

The source of the latent risk of expert assessment associated with the involvement of experts is the probabilistic nature of the parameters estimation of the fragility curve that causes the possibility of its deviation from the actual situation, which ultimately leads to incorrect assessment of the initial risk that defined by the fragility curve itself. The probability of structure destruction, i.e. the value of the fragility curve in point x, should be considered the differential measure of the initial risk in that point. The local estimation of the latent risk of expert assessment, due to its nature, should be based on the value and probability of curve deviation (defined by the obtained distribution of lognormal distribution parameters) from the true value in point x.

It must be understood that unlike the estimation of the initial risk, the consequences of deviation in different directions are essentially different from each other. The fact that the curve obtained as the result of expert assessment is below the true one means that the experts underestimated the risk in this point. That is fraught with the destruction of the building with a higher probability, i.e. the latent risk of expert assessment is of the same type as the initial one. In the opposite situation, when the experts overestimate the risk, in terms of permission, there seems to be no negative consequences, yet if preventive measures are taken in order to reduce the residual risk to the acceptable level, overexpenditure may occur, which is also undesirable. Obviously, the consequences in different cases must be taken into consideration differently. However, sufficiently approximate estimation of the latent risk of expert assessment can be done uniformly, while it is most convenient to perform calculations using the first procedure, which will be done below (Figure 2).

To estimate the local risk in point x, let us compare the true (unknown) fragility curve, the lognormal distribution function $p(x;\theta',\omega')$, shown in Figure 2 with a dotted line, with the curve obtained with a certain probability as the result of expert assessment (solid line in Figure 2). According to the above described method, the probability of one or another position of the expert assessment of the fragility curve is defined by a posteriori distribution of parameters $\pi(\theta,\omega \mid E)$, and the solid line reflects one of these possible positions. In this case the experts underestimated the risk of destruction in point x: instead of the real probability $p(x;\theta',\omega')$ they predicted a lower one, $p(x;\theta,\omega)$. In this context it appears to be quite logical to examine the risk associated with the involvement of experts as a share of the total risk.

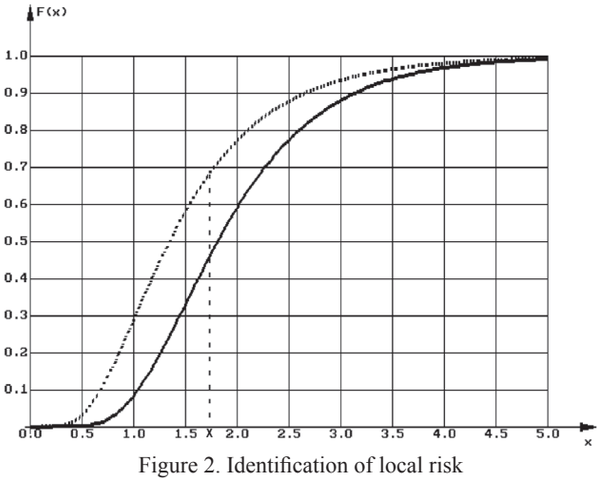

Figure 2. Identification of local risk

Thus, its quantity can be directly expressed as the difference between these probabilities. In Accordance with the chosen symmetrical approach to the assessment of deviations of unlike signs, in general, the module of this difference should be considered. Further, taking into consideration the probabilistic nature of the curve obtained as the result of analysis of the expert opinions, the local infinitely small risk in point x can be calculated as the mean module of difference with respect to the parameters:

$$d\tilde{R} = \iint_{\theta,\omega} \left| p(x;\theta,\omega) - p\left(x;\theta',\omega'\right) \right| \pi(\theta,\omega|E)\, d\theta\, d\omega\, dx. \quad (21)$$

The tilde in this expression means that this is not the final formula. Its presence here has two reasons. First, as it was mentioned above, the parameters by the true fragility curve are unknown. However, taking into consideration the assumption of the absence of a systematic shift in the expert assessments (according to the error model), its good approximation for the purpose of averaging of the difference module is the most probable distribution with the parameters defined in (15) that was obtained above. Second, expression (21) does not reflected the fact that x is also a random variable with the distribution density $f_0(x)$. These two factors taken into consideration, the local risk writes as follows:

$$dR = \left\{ \iint_{\theta,\omega} \left| p(x;\theta,\omega) - p(x;\theta_m,\omega_m) \right| \pi(\theta,\omega|E)\, d\theta\, d\omega \right\} f_0(x)\, dx,$$

and, respectively, the risk associated with the involvement of experts in the analysis of the fragility curve, is defined by the expression:

$$R = \int_x \left\{ \iint_{\theta,\omega} \left| p(x;\theta,\omega) - p(x;\theta_m,\omega_m) \right| \pi(\theta,\omega|E)\, d\theta\, d\omega \right\} f_0(x)\, dx.$$

This value should be compared with the total risk of structure destruction predicted by the experts. It is defined by the formula:

$$R_0 = \int_x p(x;\theta_m,\omega_m)\, f_0(x)\, dx.$$

If $R << R_0$, the quality of the expert assessment must satisfy the analyst. With a sufficient certainty, he/she can analyze the various possible developments and make grounded decisions, e.g. as regards the advisability of facility construction or the development of preventive measures for reduction in the possible losses. But if value of the latent risk of expert assessment is comparable with the total risk (say, differs less than three to five times), the quality of the expert assessment does not allow considering its results as sufficient grounds for any decision making. This means that more competent experts must be involved or other methods be used for additional analysis.

This method of calculation of the latent risk of expert assessment examination, certainly, is not universal. It has limitations caused by the assumptions that were used to ensure logical transitions as part of distribution estimation. They substantially simplified the computations, yet at the same time reduced the method's applicability. One must be fully aware of what conditions must be fulfilled in order to obtain satisfactory results.

The first hypothesis concerns the chosen model of the experts' behavior when assessing the quantiles of the distribution, according to which they do not make systematic errors, while the random value is defined by one parameter (dispersion) directly associated with the expert's rating. In more complex models, in case of many expert assessments, the expected value of systematic shift can be statistically estimated and subsequently taken into consideration. Here, it is assumed that the subject area experts are sufficiently experienced to not allow it.

Further, an assumption, possibly, the strongest of all, is made regarding the mutual independence of all expert assessments for all quantiles. It can be performed only with a certain degree of approximation. On the one hand, the information sources used by the experts are largely common, which leads to the correlation of the opinions of different experts. On the other hand, usually they look at the distribution as a whole, and as the result the assessments made by the same expert for different quantiles begin to depend on each other. This effect is most apparent with an increasing number of quantiles, therefore in order to guarantee at least an approximate fulfillment of conditions of independence one must restrict oneself with just a few.

Another important aspect of the estimation is the requirement of the true distribution belonging to the parametric family. Although there are no restrictions on the nature of the family and number of parameters, i.e. in this sense a very wide spectrum of problems is covered, this condition is necessary, and in cases where for some reasons it is not possible to indicate the only family, this method is not applicable.

As a whole, the proposed method of evaluation of an unknown distribution and calculation of risk is sufficiently universal and can be used in the context of mechanical stability of structures, but also a wide class of problems that involve the assessment of a certain probabilistic distribution on the basis of subjective data about it.

Conclusion

The paper suggests a risk calculation method associated with involving experts into the analysis of risk of destruction of various structures (buildings, railways, highways, etc.) in case of earthquakes. The source of this particular latent expert assessment risk is the imperfection of experts as sources of information that causes uncertainty in the obtained results. It determines the additional risk caused by inadequate ideas of the possible development of the situation in case of materialization of unfavorable factors.

The Bayesian approach was chosen in order to take account of this uncertainty as it is best suited for its description. Based on a number of works, in which it was developed, as well as subject matter research, a method was proposed for the estimation by an analyst of the probabilistic distribution (fragility curve) on the basis of the opinions of a group of experts that allows, using the obtained results, formalizing and explicitly expressing the latent risk of expert assessment. The described method is based on some additional assumptions given above, therefore this definition of the latent risk of expert assessment is not universal and can only be used only in the context of problems of the same type with the same limitations.

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On traffic safety incidents caused by intrusion of derailed freight cars into the operational space of an adjacent track[1]

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Aim.*Derailments of rolling stock units (cars, locomotive units) of freight trains cause damage to roadbed and rolling stock, as well as possible loss of transported cargo. Of special interest are cases when derailed rolling stock units intrude into the operational space ofan adjacent track. This, for instance, happened in the case of the Moscow – Chi in u train at the Bekasovo I – Nara line on May 20, 2014, when as a result of the derailment of freight cars with subsequent intrusion into the operational space of an adjacent track 6 people were killed as the result of collision with an opposing train. In some cases intruding units may collide with an opposing freight train, which may cause the death of that train's crew and derailment of its cars, which in case of transportation of hazardous loads (e.g. oil and gasoline) may have catastrophic consequences. Intrusion into the operational space ofan adjacent track also interrupts the traffic in both directions. In this context, evaluating the probability of derailed cars intruding into the operational space of an adjacent track is extremely important in order to maintain the tolerable level of risk in railway transportation, while the aim of this paper is to construct functional dependences between the probability of derailed cars intruding into the operational space of an adjacent track and various factors.* **Methods.** *Probability theory and mathematical statistics methods were used: maximum likelihood method, logistic regression, probit regression, Cauchy regression.* **Results.***For each of the groups of incidents: derailments due to faulty cars/locomotive units, derailments due to faulty track, using the classic binary choice model an estimation was constructed of the probability of at least one derailed freight car intruding into the operational space of an adjacent track. This estimation turned out to be dependent upon the train loading and number of derailed units. As the number of derailed units is a priori (before the derailment) unknown, it was suggested to construct the probability of intrusion by at least one derailed freight car into the operational space of an adjacent track using a parametric model of dependence between the average number of derailed units and various traffic factors. The resulting dependences were compared. A numerical example was examined.* **Conclusions.***There is a significant direct correlation between the random values that characterize intrusion by at least one unit into the operational space of an adjacent track and the number of derailed freight train units. A direct dependence between the train loading and intrusion by derailed units into an adjacent track was established. In case of derailment due to faulty track, for loaded trains the probability of at least one derailed unit intruding into the operational space of an adjacent track is extremely high.*

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Introduction

According to 2013-2016 Russian transportation incident records, there were 37 cases of rolling stock derailment out of switches when at least one of derailed freight train unit intruded into the operational space of an adjacent track. As the result of such derailments, 6 collisions with moving or stationary opposing trains (including 1 passenger train) took place, which caused 8 deaths in opposing trains, as well as damage to cars/locomotive units of opposing trains, some of which had to be excluded from the inventory fleet. The average service delay for the adjacent track was about six and a half hours. As it follows from the given data, the problem of freight train units derailment and subsequent intrusion into the operational space of an adjacent track is extremely relevant. However, the problem related to the prediction of intrusion by derailed units into the operational space of an adjacent track remained unresearched both in Russia and abroad.

Among the publications dealing with the subject matter of this paper a special attention should be given to the following: in [2-4] using Poisson streams the risk of side collision between a passenger train and a shunting consist caused by signal violation by one of them was calculated; [5] inquired how much the traffic density must be reduced in order to bring the probability of traffic incidents to the European level. In [6], an indicator for the estimation of a factor's effect on the frequency of transportation incident was developed, while in [7] a one-sided confidence interval was constructed for the conditional probability of a certain event subject to a certain factor. In [8], the technical availability coefficient of a line section subject to its partial operability was estimated. In [9] the effect of thedistance travelled by a gondola car on the failure of various components. In [10], the probability of train derailment was estimated that depended on the class of track, length of the train and number of cars, distance travelled, yet did not take into consideration, for instance, the track geometry. In [11], the distribution series of the number of derailed units was estimated that depended on a number of geometrical features of the track and train movement parameters.

Since only two outcomes of rolling stock derailment are possible, i.e. the operational space of an adjacent track will be either intrudedor not, then the random value that characterizes the intrusion into the operational space of an adjacent track has a Bernoulli distribution with the parameter of the desired probability of the derailed units intruding into the operational space of an adjacent track. This value can be estimated with the sample estimate of probability [12], however such estimate will be quite rough, as it considers neither the geometric features of the track nor train movement parameters. For a more precise estimation, some functional dependences between the probability and various factors should be sought, which is enabled by the maximum likelihood method that is used further. In cases when a random value that produced the sample has a Bernoulli distribution, the maximum likelihood method yields a binary choice problem [13]. In the context of railway transportation the binary choice was examined, in [14] in particular as part of the problem that involved finding the probability of derailment caused by broken rail. In [15], using a logistic regression, a functional dependence was constructed between the probability of collision between trains and automotive vehicles at a random level crossing over a certain period of time.

This paper examines the problem related to the estimation of the functional dependence between the probability of at least one derailed rolling stock unit intruding into the operational space of an adjacent track and various factors. For this purpose, various binary choice models are considered: logistic regression, probit regression, Cauchy regression. The resultant dependences are analyzed. An example of the use of the obtained formulas is given.

Preliminary data analysis

Let us identify three groups of derailments. The first group will include derailments of cars out of switches caused by car or locomotive unit malfunction. The second group will include derailments of rolling stock units outside of switches caused by faulty malfunction. The third group will include all other derailments, i.e. derailments at switches, derailments caused by violations of locomotive operating conditions, etc. Let us analyze how often car derailments cause their intrusion into the operational space of an adjacent track for different groups of incidents based on the 2013-2016 records.

Let us note that the sum of the number of incidents when derailed freight cars intruded or did not intrude intothe operational space of an adjacent track is not equal to the number of derailments. This is due to the fact that some records do not contain information on intrusion or non-intrusion intothe

Table 1. Frequency of car derailments with and without intrusions by at least one derailed unit into the operational space of an adjacent track

Group of events	Number of derailments	Number of encroachments on adjacent track clearance	Number of non-encroachments on adjacent track clearance
1	150	22	90
2	38	15	9
Total	188	37	99

operational space of an adjacent track, while some incidents occurred in single-track lines.

As it follows from Table 1, the relative frequency of derailments with intrusion by the derailed units into the operational space of an adjacent track is significantly higher in the case of derailments due to faulty track. At the same time, the number of derailments with intrusion by the derailed units into the operational space of an adjacent track is higher in the case of derailment due to faulty cars/locomotive units. Therefore, both groups of incidents should be studied in order to estimate the parametric dependence of the probability of intrusion into the operational space of an adjacent track and various operational conditions.

Primary designations

In the j-th group of incidents out of n_j transportation incident records involving freight train cars derailment during train operation, let us examine a certain i-th record. For the purpose of this record, let

c_{ij} be the total number of derailed units of rolling stock (locomotive units and cars);

χ_{ij} be a coefficient that characterizes the number of tracks at the location of derailment that equals zero if the derailment occurred at a single-track line, and equals one if otherwise;

y_{ij} be a coefficient that characterizes the intrusion by at least one unit (locomotive units and cars) into the operational space of an adjacent track that equals one if at least one derailed unit intruded into the operational space of an adjacent track, and equals zero if otherwise;

k_{ij} is the counting number (from the head of the train) of the first derailed unit;

v_{ij} be the speed of the train at the moment of derailment, km/h;

l_{ij} be the number of wagons in the train;

l_{ij}^L be the number of locomotive units in the train;

w_{ij} be the weight of the train, t;

$æ_{ij}$ be the rate of curve at the place of derailment (value inversely proportional to the curve radius; for tangents the rate of curve is taken to be equal to zero), m^{-1};

γ_{ij} be the track profile at the place of derailment measured in promille having the minus sign if the gradient is downward and the plus sign if the gradient is upward.

As in [11], let us introduce another auxiliary variable function $\tilde{\mu}(w,l)$ that characterizes the loading factor of the train that depends on the train weight and the number of transported cars that is calculated using formula

$$\tilde{\mu}(w,l) = \frac{w}{69l} - \frac{1}{3}.$$

Also, as in [1], let us introduce an auxiliary variable $c^{\max} = l^L + l - k + 1$ that is the realization of a certain random value $C^{\max} = l^L + l - K + 1$, where K is the random value that characterizes the number of the first derailed unit. Further, we will call random value $C^{\max}$ the remaining length of the train.

Since it is impossible to intrude into the operational space of an adjacent track on a single-track line, further we will consider only those derailments that occurred on lines with more than one track, i.e. those that have $\chi_{ij} = 1$. Let us renumber according to the respective dates the records of incidents remaining after the exclusion of the records of incidents in the single-track lines. Let $\overline{n}_j$ records remain for the j-th group of incidents.

Let us note that, as in the case of construction of regression between the number of derailed cars and various factors in [11], in this paper there also is the problem of missed data. Records that miss at least one of the parameters required for the construction of a dependence of the probability of intrusion into the operational space of an adjacent track from various factors will not be considered.

Problem definition and method of solution

Let us consider the j-th group of transportation incidents. Let Y_j be a random value that characterizes the intrusion by at least one freight train unit intruding into the operational space of an adjacent track after derailment that equals one if the derailed units intruded into the operational space of an adjacent track, and equals zero if otherwise. Random variable Y_j can take values 0 and 1 with the probabilities $1–p_j(\cdot)$ and $p_j(\cdot)$ respectively, where $p_j(\cdot)$ is a function that contains the speed of the train at the moment of derailment v, length of the train l and other parameters. Therefore,

$$Y_j \mid C = c, C^{\max} = c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma \sim Bi(1, p_j(c, c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma)).$$

Since the true function $p_j(\cdot)$ is unknown, we will seek its estimate $\hat{p}_j(\cdot)$. The simplest estimate $\hat{p}_j(\cdot)$ of the unknown function $p_j(\cdot)$ is the realization of the sample probability estimate, i.e.

$$\hat{p}_j(\cdot) = \frac{\sum_{i=1}^{\overline{n}_j} y_{ij}}{\overline{n}_j}.$$

However, this function does not allow taking into consideration either the track geometry or the train movement parameters.

In order to take account of the various train movement parameters we will seek function $\hat{p}_j(\cdot)$ as the function of train speed at the moment of the derailment v, train length l, rate of curve æ at the location of derailment, the constants $a_{1j}, a_{2j}, \ldots, a_{m_j j}$ to be determined, as well as other parameters using the method of maximum likelihood. For convenience of notation, let us introduce the designation $a_j \stackrel{\text{def}}{=} (a_{1j}, a_{2j}, \ldots, a_{m_j j})^{\mathrm{T}}$. For function $\hat{p}_j(\cdot)$ the following formulas are true

$$P\{Y_j = 0 \mid C = c, C^{\max} = c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma\} = \\ = 1 - \hat{p}_j(a_j, c, c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma), \quad (1)$$

and

$$P\{Y_j = 1 \mid C = c, C^{\max} = c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma\} = \\ = \hat{p}_j(a_j, c, c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma), \quad (2)$$

while

$$M[Y_j \mid C = c, C^{\max} = c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma] = \\ = \hat{p}_j(a_j, c, c^{\max}, w, l^L, l, \tilde{\mu}(w,l), æ, \gamma).$$

By virtue of (1) and (2) the log-likelihood function is as follows:

$$\overline{L}_j(a_j, y_{ij}, c_{ij}, c_{ij}^{\max}, w_{ij}, l_{ij}, l_{ij}^L, \tilde{\mu}_{ij}, æ_{ij}, \gamma_{ij}, i = \overline{1, n_j}) = \\ = \sum_{i=1}^{\bar{n}_j} (1 - y_{ij}) \ln(1 - \hat{p}_j(a_j, c_{ij}, c_{ij}^{\max}, w_{ij}, l_{ij}, l_{ij}^L, \tilde{\mu}_{ij}, æ_{ij}, \gamma_{ij})) + \\ + y_{ij} \ln(\hat{p}_j(a_j, c_{ij}, c_{ij}^{\max}, w_{ij}, l_{ij}, l_{ij}^L, \tilde{\mu}_{ij}, æ_{ij}, \gamma_{ij})).$$

Let us set the problem of finding the maximum likelihood estimates of parameters a_j:

$$a_j^* \overset{def}{=} (a_{1j}^*, a_{2j}^*, \ldots, a_{m_j j}^*)^T = \\ = \arg \max_{a_j \in R^{m_j}} \overline{L}_j(a_j, y_{ij}, c_{ij}, c_{ij}^{\max}, w_{ij}, l_{ij}, l_{ij}^L, \tilde{\mu}_{ij}, æ_{ij}, \gamma_{ij}, i = \overline{1, n_j}). \quad (3)$$

On the maximum likelihood estimate a_j^* of parameters a_j we have

$$\overline{L}_j^* = \overline{L}_j(a_j^*, y_{ij}, c_{ij}, c_{ij}^{\max}, w_{ij}, l_{ij}, l_{ij}^L, \tilde{\mu}_{ij}, æ_{ij}, \gamma_{ij}, i = \overline{1, n_j}).$$

Solution of the problem

The solution of problem (3) significantly depends on the choice of the structure of function $\hat{p}_j(\cdot)$. The structure of function $\hat{p}_j(\cdot)$ can be chosen, for example, according to the classic binary choice model: classic regression, probit regression, Cauchy regression that will be further used in this paper.

For the logic regression function $\hat{p}_j(\cdot)$ is as follows

$$\hat{p}_j(\cdot) = \frac{1}{1 + \exp\{g_{1j}(\cdot)\}},$$

where $g_{1j}(\cdot)$ is a function linear in parameters a_j, dependent on parameters $c, c^{\max}, w, l, l^L, \tilde{\mu}, æ, \gamma$.

For probit regression

$$\hat{p}_j(\cdot) = \Phi(g_{2j}(\cdot)),$$

where $g_{2j}(\cdot)$ is a function linear in parameter a_j, dependent on parameters $c, c^{\max}, w, l, l^L, \tilde{\mu}, æ, \gamma$, while $\Phi(x)$ is a standard normal distribution function (Laplace function) that is determined by formula

$$\Phi(x) = \frac{1}{2\pi} \int_{-\infty}^{x} \exp\left\{\frac{-t^2}{2}\right\} dt.$$

For the Cauchy regression the following equation is true

$$\hat{p}_j(\cdot) = \frac{1}{\pi} \operatorname{arctg}(g_{3j}(\cdot)) + \frac{1}{2},$$

where $g_{3j}(\cdot)$ is a function linear in parameters a_j, dependent on parameters $c, c^{\max}, w, l, l^L, \tilde{\mu}, æ, \gamma$.

Now, for different groups of incidents, let us calculate the constraint force between random value $Y_j, j = 1, 2$ and various movement parameters: speed v, track plan æ andothers, as well as the residual length of train $C^{\max}$ and number C of derailed rolling stock units. We shall understand constraint force as the realization of the sample correlation coefficient in case when the analysis involves two random values, and the number calculated using the sample correlation coefficient realization formula if the analysis involves a random value and a non-random factor.

As it follows from Table 1 and Table 2, there is a significant positive correlation between the random vari-

Table 2.Constraint force between random value Y_1 that characterizes the encroachments by at least one derailed unit on adjacent track clearances in case of derailment due to faulty car and various factors.

Parameters	C	$C^{\max}$	v	w	$\tilde{\mu}$	æ	γ
Constraint force	0.518	0.034	-0.117	0.123	0.239	0.022	0.117
Sample size	112	109	107	110	110	102	88

Table 3. Constraint force between random value Y_2 that characterizesintrusions by at least one derailed unit into the operational space of an adjacent track in case of derailment due to faulty track and various factors

Parameters	C	$C^{\max}$	v	w	$\tilde{\mu}$	æ	γ
Constraint force	0.647	0.148	0.346	0.398	0.484	-0.277	0.127
Sample size	24	24	22	23	23	23	19

Table 4. Comparison of various models for prediction of intruding by at least one unit into the operational space of an adjacent track in case of derailment due to faulty car/locomotive unit (based on 110 observations)

Regression	Dependence	$\overline{L}_1^*$	Likelihood ratio	Significance
Logit	$g_{11}(\cdot) = a_1$	-55.04	–	–
	$g_{11}(\cdot) = a_1 + a_2 c + a_3 \tilde{\mu}$	-40.15	29.78	$4 \cdot 10^{-7}$
Probit	$g_{21}(\cdot) = a_1$	-55.04	–	–
	$g_{21}(\cdot) = a_1 + a_2 c + a_3 \tilde{\mu}$	-40.71	28.66	$6 \cdot 10^{-7}$
Cauchy	$g_{31}(\cdot) = a_1$	-55.04	–	–
	$g_{31}(\cdot) = a_1 + a_2 c + a_3 \tilde{\mu}$	-34.32	41.44	10^{-9}

Table 5. Comparison of various models of prediction of intruding by at least one unit into the operational space of an adjacent track in case of derailment due to faulty track (based on 23 observations)

Regression	Dependency	$\overline{L}_2^*$	Likelihood ratio	Significance
Logit	$g_{12}(\cdot) = a_1$	-15.395	–	–
	$g_{12}(\cdot) = a_1 + a_2 c + a_3 \tilde{\mu}$	-6.55	17.69	$1{,}4 \cdot 10^{-4}$
Probit	$g_{22}(\cdot) = a_1$	-15.395	–	–
	$g_{22}(\cdot) = a_1 + a_2 c + a_3 \tilde{\mu}$	-6.43	17.93	$1{,}3 \cdot 10^{-4}$
Cauchy	$g_{32}(\cdot) = a_1$	-15.395	–	–
	$g_{32}(\cdot) = a_1 + a_2 c + a_3 \tilde{\mu}$	-7.779	15.23	$5 \cdot 10^{-4}$

ables Y_1, Y_2 and C. There is also dependence between the intrusion by at least one unit into the operational space of an adjacent track and the train loading. Thus, functions $g_{kj}(\cdot)$ must contain parameters $c$and $\tilde{\mu}$, $k = \overline{1,3}$, $j = \overline{1,2}$. In the case of derailment due to faulty track, a positive constraint force between the intrusion by at least one unit into the operational space of an adjacent track and the speed can also be noted, however, due to the small number of observations, the effect of speed on the probability of intrusions into the operational space of an adjacent track will not be researched.

Let us compare different types of regression based on the likelihood ratio for the best (out of those constructed) functions $p_j(\cdot)$ in terms of the value of log-likelihood function.

As it follows from Tables 4 and 5, when predicting the intrusion by at least one unit into the operational space of an adjacent track in case of derailment due to faulty rolling stock it is advisable to use the Cauchy regression, while in case of faulty track probit regression should be used. For both groups of events the significance level of the model is close to zero. That means that the obtained estimate $\hat{p}_j(\cdot)$ of function $p_j(\cdot)$ is sufficiently good. Among the disadvantages of the constructed model is the fact that the number of derailed units is a priori (before the derailment) unknown. For this reason, estimating the probability of intruding into the operational space of an adjacent track some estimates of the number of derailed units, e.g. average as in [11], can be used. For example, for the 2-nd group of incidents we obtain

$$\hat{P}\{Y_2 = 1 \mid C = c, C^{\max} = c^{\max}, w, l, l^L, \tilde{\mu}(w,l), æ, \gamma\} =$$
$$= \Phi(a_1 + a_3 \tilde{\mu} + a_2 M[C \mid C^{\max} = c^{\max}, w, v, l, \tilde{\mu}(w,l), æ, \gamma]),$$

where $a_1 = -2{,}43$, $a_2 = 0{,}19$, $a_3 = 1{,}87$ (found while solving problem (3)), while

$$M[C \mid C^{\max} = c^{\max}, w, v, l, \tilde{\mu}(w,l), æ, \gamma]) =$$
$$= M[C \mid C^{\max} = c^{\max}, v, \tilde{\mu}(w,l)]) =$$
$$= 1 + \exp\{-6{,}04 + 1{,}01\tilde{\mu} + 0{,}68 \ln(v) + 1{,}48 \ln(c^{\max})\}$$

(found in [11]). Since the counting number of the rolling stock unit that derails first is a priori unknown, according to the formulas of multiplication of probabilities and composite probability [16] we conclude that

$$\hat{P}(A) = \chi \sum_{i=1}^{l^L + l} \Phi(-2{,}43 + 1{,}87\tilde{\mu}(w,l) + 0{,}19 M[C \mid C^{\max} =$$
$$= i, w, v, l, \tilde{\mu}(w,l), æ, \gamma]) P(C^{\max} = i \mid w, v, l, \tilde{\mu}(w,l), æ, \gamma), \quad (4)$$

where A is the event that consists in that in case of derailment due to faulty track at least one unit of the freight train encroaches on the adjacent track clearances provided the movement parameters of each unit are fixed: w, v, l etc., $P(C^{\max} = i \mid w, v, l, l^L, \tilde{\mu}(w,l), æ, \gamma)$ is the probability that in

case of derailment the realization of the residual length of the train is i rolling stock units, $i = \overline{1, l^L + l}$, while χ is the coefficient that equals one if the derailment occurred on a non-single-track line section, and equals zero if otherwise.

Example

Let the speed $v = 60$ km/h, train weight $w = 5400$ t, number of cars $l = 70$, number of locomotive units l^L=2, and traffic is not on a single-track line. A derailment due to faulty track occurs. Let us find the estimate of the probability that after this derailment at least one freight train encroaches on the adjacent track clearances.

We deduce

$$\tilde{\mu}(5400, 70) = \frac{5400}{69 \cdot 70} - \frac{1}{3} = 0,785.$$

For simplicity let us assume that

$$P(C^{\max} = i \mid w, v, l, l^L, \tilde{\mu}(w, l), æ, \gamma) =$$
$$= P(C^{\max} = i \mid l, l^L) = \frac{1}{l^L + l} = \frac{1}{2 + 70} = \frac{1}{72}, i = \overline{1, 72}.$$

Then, according to formula (4) we deduce that the estimate of the probability of the sought for event is

$$\hat{P}(A) = \frac{1}{72} \sum_{i=1}^{72} \Phi\left(\begin{array}{c} -2,43 + 1,87 \cdot 0,785 + 0,19 \cdot \\ \cdot \left(1 + \exp\{-6,04 + 1,01 \cdot 0,785 + \right. \\ \left. + 0,68 \cdot \ln(60) + 1,48 \cdot \ln(i)\} \right) \end{array} \right) = 0,822.$$

The number turns out to be quite significant, which means that measures must be taken to keep the track in working order or significantly restrict the speed of the given train in order to avoid the intrusion by at least one derailed unit into the operational space of an adjacent track.

Conclusion

The paper examines the problem of probability estimation of at least one derailed freight train unit intruding into the operational space of an adjacent track for various types of incidents: derailment due to faulty track, derailment due to faulty rolling stock. Dependences between the random value that characterizes the intrusions into the operational space of an adjacent track and various factors, including random ones, were analyzed. The paper sets forth estimations of the probability of at least one derailed freight train unit intruding into the operational space of an adjacent track in random location on a line based on the maximum likelihood method for various types of incidents.

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Algorithm of calculation and forecasting of functional safety indicators of railway power supply systems

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Abstract. Aim. *Uninterrupted transportation process is ensured by the highly dependable and safe power supply system of railway transport. In addition, the railway power supply system provides power to external consumers. A risk-oriented approach to railway transportation management requires an infrastructure risk management and safety system. The main purpose of risk management in this area is to improve the dependability and safety of railway infrastructure facilities [1, 2]. Additionally, given the growing numbers of intelligent information systems, as well as automated railway transportation management systems, the task of ensuring functional safety becomes very important. In most cases this problem is solved by introducing redundancy that is understood as an exceeding complexity of the system structure compared to the minimal values required for the performance of the specified task [3]. The simplest way of ensuring redundancy is by creating backup capabilities, particularly standby duplication within the system of functional units and components. In order to evaluate the safety of the railway transportation power supply systems it is required to calculate the functional safety indicators of their components and system as a whole taking into account the factor of redundancy. This approach will enable the optimal redundancy architectures and ensure compliance with the assigned level of general system safety. That requires taking into consideration the complex structure of the evaluated facilities: presence of diagnostics systems, right-side failures, wrong-side failures, as well as their random nature. The paper aims to develop an applied algorithm of calculation and prediction of functional safety indicators using the example of railway power supply systems that can be used in both manual and automated calculation.* **Methods.** *The power supply system evaluated for functional safety indicators is, from the functional point of view, a sequence of function implementations, while the failures of its components are random and some of them cause hazardous events. In this case, system analysis commonly involves Markovian and semi-Markovian methods, as well as graph methods. The advantage of these methods consists in the capability to evaluate the functional safety indicators of complex systems that go into many states, which is also typical for railway power supply systems.* **Result.** *This paper examines the application of graph semi-Markovian methods for calculation of stationary and non-stationary functional safety indicators for components of power supply systems taking into account redundancy and right-side failures. This algorithm allows calculating safety indicators using the example of power supply systems and includes a set of incremental actions aimed at constructing the state graph, calculation of the initial and intermediate graph factors. An example is provided of calculation of the functional safety indicators of a graph of a traction substation power transformer.*

Keywords: *functional safety, power supply systems redundancy, standby, Markovian and semi-Markovian processes, algorithm of calculation of functional safety indicators.*

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Introduction

Functional safety of power supply systems (PSS) is vital to uninterrupted operation of modern cities, as well as to the preparedness, response, recovery and mitigation of the consequences of hazardous events (failures, accidents). This problem is well-known and has its special features from country to country. For example, PSS of the Chinese railway transportation system are characterized by the threats of failure to ensure the dependability and functional safety of PSS under natural disasters (earthquakes) and terrorist attacks [4, 5].

Emergencies and failures of PSS can present danger not only to the workers who operate PSS, but to the environment as well. Interruptions of power supply can disrupt the functions of safety systems that rely on electric power. In railway transportation such systems include transportation safety and traffic safety facilities Another important example are life support systems in hospitals. Functions implemented by such systems are called safety functions. If a PSS failure causes a disruption in the operation of a safety function, such failure should be considered hazardous.

A safety function in this case is understood as a function implemented by a safety-related system or external risk reduction facilities (intruder detection, information security, etc.) designed to guarantee or maintain a safe state with respect to a specific hazardous event [6]. Today's PSS that cater to many consumers are characterized by a complex structure and a large number of tasks and operations that they perform. Increasing system complexity may cause the reduction of the probability of fault-free operation. The problem of ensuring the functional safety of PSS is so pressing, that the European Union has developed a series of standards aiming to establish harmonized approaches to ensuring functional safety of electrical systems. The first standard of these series is dedicated to general requirements for functional safety of electrical, electronic, programmable electronic safety-related systems [7]. Later, corresponding standards were developed for different industries, e.g. the processing industry [8].

Standard [7] establishes the requirement for evaluation of the probability of hazardous failure. Importantly, hazardous failures are sufficiently rare. According to international standards, the rate of hazardous functional failures is 2-4 orders of magnitude lower than the failure rate related to system dependability [6]. This is due to the fact that normally systems incorporate hardware-based dependability feature.

One of the methods of guaranteeing safety and dependability of PSS in railway transportation aimed at avoiding disruptions of traffic is structural redundancy that ensures the performance of safety functions in cases of failure of the backed-up system components. The matter of classification of structural redundancy itself is quite extensive as regards different systems. Depending on the PSS functionality, the following characteristics govern the selection of the type of redundancy: number of backup devices, possibility and parameters of recovery of failed devices; dependability of switching devices; duration of failures before detection by supervision facilities; allowable time of interruption of operation, etc. [9]. Despite the fact that non-fulfillment by a system component of its functions does not necessarily cause the whole system to fail, this event can be considered the failure of a specific component (object) or partial failure of the whole system. Depending on the chosen type of redundancy, in case of failure of one of the components the system may be either non-operable yet not allowing for hazardous failures and complete lasting interruption of operation, or operable in the case if redundancy does not provide for interruption of operation and performs the complete set of system functions. The problem of dependability of PSS is also examined in detail in [10]. Thus, when calculating PSS functional safety indicators, their redundancy and possibility of failure of both basic components performing vital functions, and the components of the system's structural redundancy must be taken into consideration.

The methods of calculation of dependability indicators are well known and examined in many sources. However, the situation with the functional safety evaluation methods is different. Standard [11] regulates 5 methods of defining the requirements for the safety integrity level (ALARP, quantitative method (fault tree), risk graph, layer of protection analysis, hazardous events gravity matrix).

Problem definition and choice of method of calculation of functional safety indicators of supply systems

The main problem in the calculation of functional safety indicators is the selection of the method that would allow calculating the most complete list of indicators based on a single set of initial data. While selecting the calculation methods, it must be taken into consideration that the condition of PSS is defined by the condition of its components, while the condition of the components, in turn, is defined by the effect on the capability by the consumers to perform their functions.

In accordance with [9], using Markovian models conditional probabilities of a system being in one state or another are evaluated by solving differential equations. The search for the equation corresponding to the condition diagram is a problem of its own. The same work allows using different methods for calculation of different indicators and does not demonstrate the potential applications of one method for evaluation of the whole list of required indicators. Among the most important drawbacksof this approach is the complexity of calculation, as well as the iterative collection of initial data required for different models.

[12] sets forth a method of using Markovian processes for identification of the dependability indicators

of systems consisting of restorable components as well as the application of this method in the context of PSS. This method is also based on the solution of systems of differential equations using the method of operators. Despite the detailed description of the method, its practical application for the analysis of complex technical systems is limited by the requirement to solve a system of differential equations, of which the number depends on the number of the vertices of the graph that simulates such system.

As the solution of the problem of the large dimensionality of algebraic equations and differential systems, [13] proposes a graph semi-Markovian method based on the decomposition of the initial graph model into component subgraphs that do not contain the identified vortices. The graph semi-Markovian method allows calculating over 10 functional safety indicators using the same pool of initial data and without using operator calculus. Along with the considered scientific studies in this area, the problem of selection of the method of indicators evaluation is also examined in foreign sources. Among the primary methods are the fault tree, Petri net, Markovian and graph semi-Markovian methods [14-16]. The majority of the considered studies come down to the selection of the application of the Markovian and graph semi-Markovian methods.

This paper examines the practical application of graph semi-Markovian methods that enable the evaluation of functional safety indicators taking into account the initial states the system might be in. A hazardous system failure shall be understood as a non-operable system state in which at least one safety function is not performed [7].

Calculation algorithm

For the purpose of calculating system functional safety indicators, it is proposed to use an algorithm (Figure 1) based on a graphsemi-Markovian method that defines the order of the stages of calculation of the primary functional safety indicators.

The algorithm reflects the order of actions associated with the calculation of the system of functional safety indicators, including the stages of generation of the set of states of the evaluated system, construction of the system state graph and procedure of application of formulas for calculation of dependability and safety indicators. The algorithm is designed in such a way as to allow intermediate

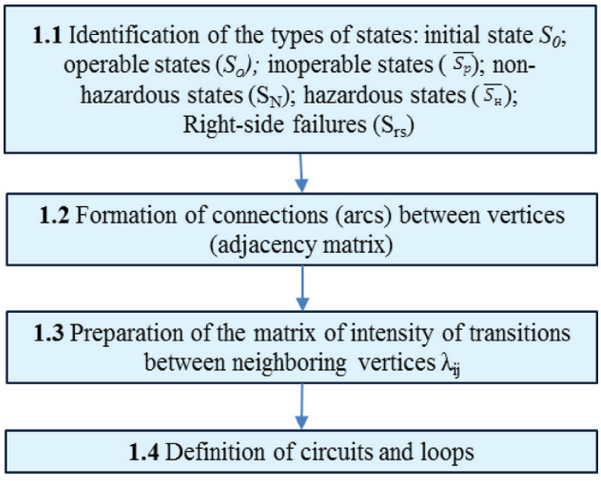


Figure 2. Procedure for implementation of the preparatory stage of calculation of functional safety indicators of complex technical systems using a graphsemi-Markovian method

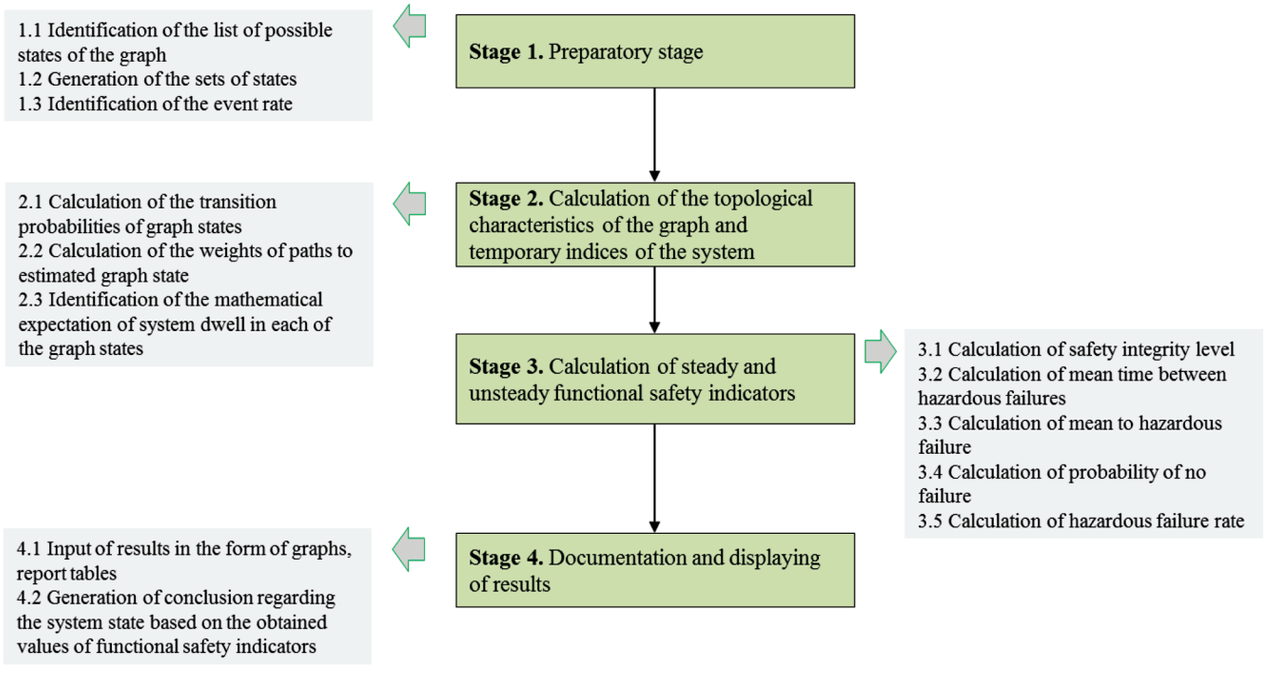


Figure 1. Algorithm of calculation of functional safety indicators of complex technical systems using a graphsemi-Markovian method

calculations to be used for evaluation of various indicators, which significantly reduces the time of comprehensive system analysis.

Preparation of application of agraphsemi-Markovian method of calculation of functional safety indicators of power supply systems

The input data for the application of a graph semi-Markovian method is an oriented graph of system states and intensity of transition between states. The implementation of the preparatory stage is shown in Figure 2. Importantly, the application of this method is possible both for the calculation of the indicators of whole system or its individual elements.

At the preparatory stage, the list is made of the system components that affect functional safety, as well as their possible states; the type of sets they are part of is identified. A set of states is understood as a set of significant properties of the system at the current moment of time [13, 17]. The following subsets of states are identified [7, 18]: subset of the operable states S_O, subset of the inoperable states $\overline{S_P}$, subset of the non-hazardous states S_N, subset of hazardous states $\overline{S_H}$ and the subset of safe states S_S. Let us examine each set in more detail.

The set of non-hazardous states of the system (S_N) is the operable or safe state of the system.

The set of safe states of the system (S_S) is the states of the system, in which the process functions are not performed, but all required safety functions are performed.

The set of hazardous states of the system ($\overline{S_H}$) is the non-operable system state, in which at least one safety function is not performed. The set of hazardous system states includes the states, in which safety functions implemented by the consumers are disrupted (e.g. impossibility to implement the functions of automated control of safe train movement).

As an illustration of the method of functional safety indicators using graph semi-Markovian methods this paper cites the "railway 110 kV traction substation" power supply system with partial homogenous standby for the "power transformer" (PT-1) component. Partial homogenous standby in this case is an example of structural redundancy in the from of a standby power transformer (PT-2). The failure of a component like the power trans-

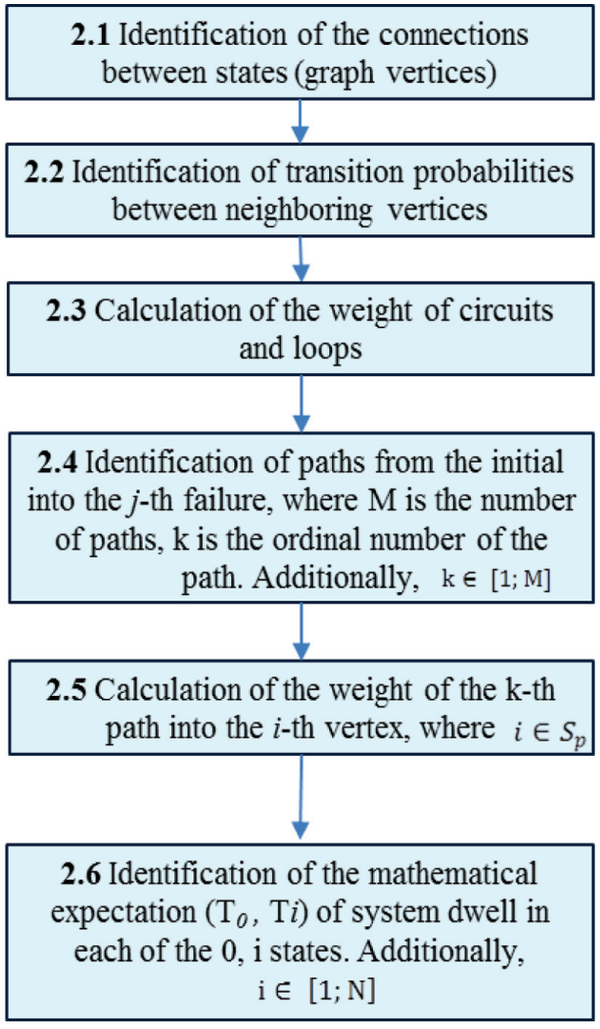


Figure 3. Stage 2 of the algorithm of calculation of functional safety indicators

Table 1. List of the dependability states of power transformer

System component	State of component (graph vertex)	Subset of states
PT-1 and PT-2	PT-1 and PT-2 are operable	S_R, S_N
PT-1	PT-1 insulation wear	S_R, S_N
PT-1	PT-1 bushings wear	S_R, S_N
PT-1	PT-1 switches wear	S_R, S_N
PT-1	PT-1 control equipment failure	S_R, S_N
PT-1	PT-1 external effect	S_R, S_N
PT-1	PT-1 mechanical or electrical damage	S_R, S_N
	PT-1 internal or turn-to-turn short circuit	S_R, S_N
PT-1	Detection of actual failure of PT-1	S_R, S_N
PT-1 and PT-2	PT-1 external effects protection tripping and transition to PT-2	S_P,
PT-1 and PT-2	PT-1 internal effects protection tripping and transition to PT-2	S_P, $\overline{S_P}$
PT-1 and PT-2	Hazardous failure. PT-1 and PT-2 are faulty	$\overline{S_H}$, $\overline{S_P}$

former in a "Traction substation" system entails serious consequences, including the interruption of service and provision of power to third-party users, which will lead to the disruption of business process. In turn, a hazardous failure of such facility may cause the non-fulfillment of the system's safety function, i.e. fire or explosion (for the oil-filled transformer). Such system is the perfect demonstration of the importance of fault-free and safe operation.

An example of the generation of the list of states for the "power transformer" component in accordance with the above definition is given in Table 1. Constructing a graph model requires a list of states (graph vertices). Here and below we will designate the main element, the "power transformers" as "PT-1", and the backup power transformer as "PT-2".

Calculation of the topological characteristics of the graph and temporal indicators of the power supply system

After the identification of the set of possible states, formation of connections between the vertices in the form of a connectivity matrix and matrix of intensities of the system component, the graph of the system component's dependability states is constructed. The result of this stage is the state graph of the system component with transition probabilities. The order of this stage's implementation is given in Figure 3.

Based on the selected states of the power transformer, connections between vertices are built that reflect the transition between states. When connections are built, its is important to remember to take into consideration the structural redundancy (presence of partial homogenous standby) that is normally implemented in the form of a standby power transformer. These connections ensure the transition of the system components into the operable state. Let us give an example of the generation of such connections. The first state of the power transformer is "PT-1 and PT-2 are operable". Later, in the process of operation emerges the state "Wear of PT-1 bushings". This transition is shown with a blue edge in Figure 4. "Wear of PT-1 bushings" can cause heating, flashovers, unequal voltage per phases, etc. The transformer can be in this state during a certain period of time. Some of these states cause mechanical or electrical damages to insulation, wire breaks, cracks. That means the transition into state "Mechanical or electrical damage of PT-1". Further developments may take two different courses: the malfunctions will be discovered and eliminated, i.e. system will return into the previous state or the damage is not eliminated in time, which will cause

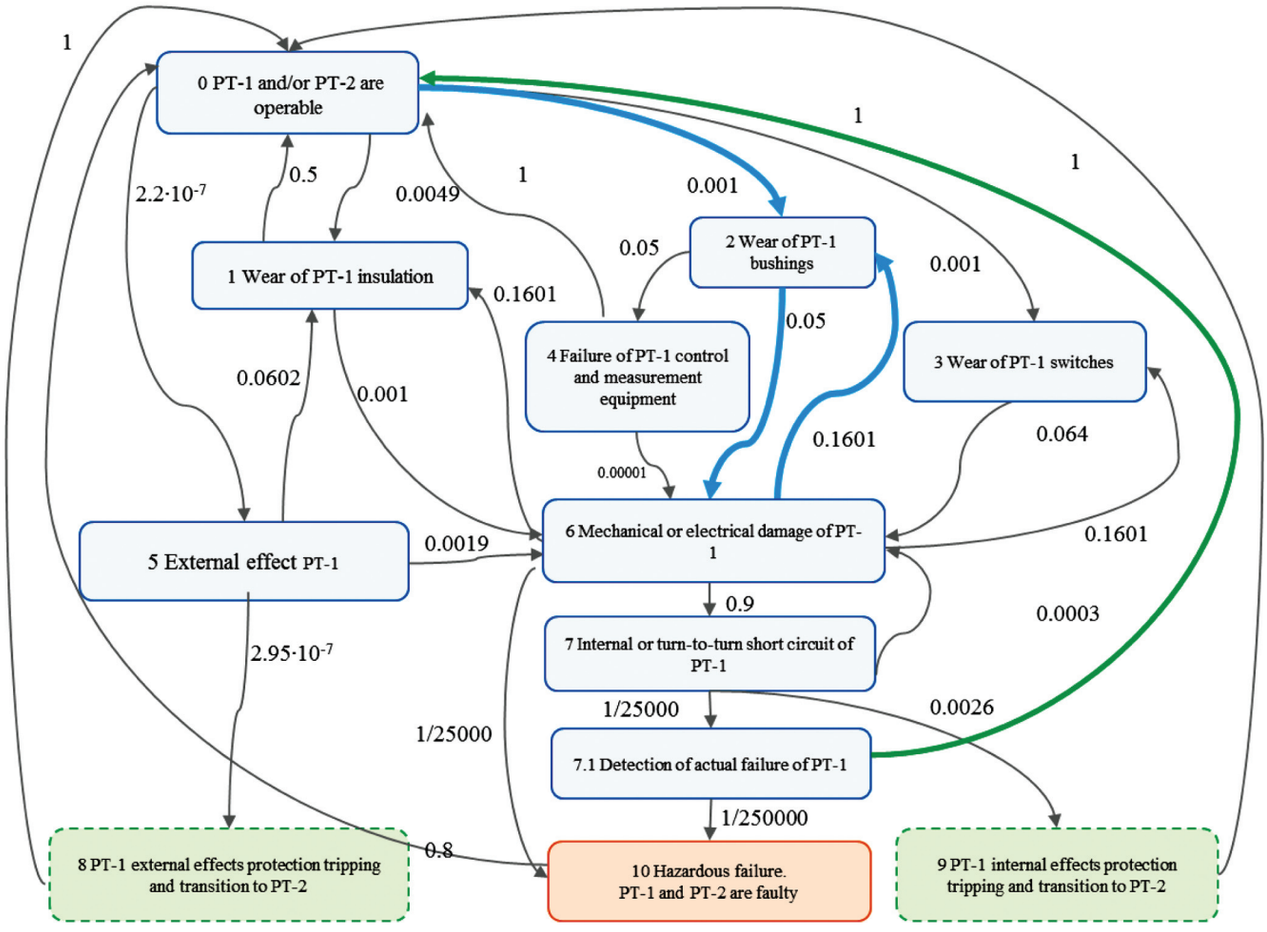


Figure 4. Graph of the sets of states of the component "Power transformer" of the system "Railway 110 kV traction substation"

short circuits or turn-to-turn short circuits. In turn, the state "Short circuit or turn-to-turn short circuits of PT-1" (graph vertex 7) will cause the loss of the capability by the transformer to perform its function. In that case, if the actual failure is discovered in time (graph vertex 7.1), the role of power transformer is taken by the redundant element, i.e. the backup power transformer. Then transition from state 7.1 to state 0 (edge shown in green) occurs. If that does not happen, for example, e.g. due to technical reasons, then the "Railway 110 kV traction substation" experiences a "Hazardous failure. PT-1 and PT-2 are faulty" (graph vertex 10). After the generation of the connections between the vertices, calculations are performed for the weights of the circuits, loops (formula 1) and paths of transition into the vertex (formula 2), as well as the mathematical expectation of the unconditional time of system being in each of the graph vertices (formula 3).

$$C_i = \prod_{i,r\in S} p_{ir} p_{ri} \quad (1)$$

where $p_{ir} p_{ri}$ is the probabilities of transition between neighboring vertices;

$$l_k^{0i} = \prod_{0,i,r\in S_p} p_{or} p_{ri} \quad (2)$$

$$T_i = \frac{1}{\sum_{r=1}^{n} \lambda_{ir}} \quad (3)$$

where λ_{ir} is the intensities of transitions between graph vertices.

Figure 4 shows the state graph of the power transformer. The numbers above the edges characterize the intensities of transition between the states of a system component.

Calculation of stationary and non-stationary functional safety indicators

After the calculation of the graph's topological characteristics, the functional safety indicators are calculated. Let us examine the calculation of one of the stationary indicators in the algorithm, the mean time to hazardous failure. For this system component, using the constructed graph the indicators from Table 2 can be calculated.

The set of non-hazardous states is the key aspect in the calculation of safety indicators. For the calculation of the mean time to hazardous failure of a safety-related system, the system is modeled with a state graph of a semi-Markovian stochastic process and a matrix of intensities of transitions is defined. The value of this indicator reflects the mathematical expectation of the object's time to first hazardous failure with the initial safe state, 0subject to known values of intensity of transition between states.

The proposed algorithm allows consecutively calculating the indicator for any hazardous failure. If this calculation method is used, the system's mean time to hazardous failure is identified according to the formula given in Table 2.

When mean time to hazardous failure is calculated, $G^0_{\overline{S_H}}$ is the weight of decomposition without the initial vertex 0 and the set of non-operable system states (graph vertices) $\overline{S_H}$ and associated edges; l_k^{0i} is the weight of the *k*-th path from the initial vertex 0to vertex *i*. A path is a chain of

Table 2. System safety indicators

№	Indicator	Notation	Calculation formula
1	Mean time to hazardous failure	$T_{\text{MT}}^{\text{haz}}$	$T_{\text{MT}}^{\text{haz}} = \frac{\dot{O}_0 \Delta G^0_{\overline{S_H}} + \sum_{(k)} \sum_{0,i} l_k^{0i} \Delta G_k^i T_i}{\Delta G_{\overline{S_H}}}$
2	Mean time between hazardous failures	T_0^{haz}	$T_0^{\text{haz}} = \frac{\sum_{i\in S_H} \Delta G^i \cdot T_i}{\sum_{i\in S_{H+}} \Delta G^i \cdot \sum_{j\in \overline{S_H}} p_{ij}}$
3	Safety coefficient	C_S	$C_S = \sum_{i\in S_p} \pi_i$
4	Dispersion of time to hazardous failure	$D_{\text{MT}}^{\text{haz}}$	$D_{\text{MT}}^{\text{haz}} = t_0^{-2} - (T_{MT}^{\text{haz}})^2$
5	Probability of hazardous failure	$\hat{Q}(t)^{\text{haz}}$	$\inf \hat{Q}(t)^{\text{haz}} < \hat{Q}(t)^{\text{haz}} < \sup \hat{Q}(t)^{\text{haz}}$
6	Probability of fault-free operation	$\hat{P}(t)^{\text{haz}}$	$1 - \sup \hat{Q}(t)^{\text{haz}} < \hat{P}(t)^{\text{haz}} < 1 - \inf \hat{Q}(t)^{\text{haz}}$
7	Hazardous failure rate	$\hat{\lambda}(t)^{\text{haz}}$	$\hat{\lambda}(t)^{\text{haz}} \in (\frac{-[\sup \hat{P}(t+\Delta t)^{\text{haz}} - \sup \hat{P}(t)^{\text{haz}}]}{\sup \hat{P}(t)^{\text{haz}} \Delta t}; \frac{-[\inf \hat{P}(t+\Delta t)^{\text{haz}} - \inf \hat{P}(t)^{\text{haz}}]}{\inf \hat{P}(t)^{\text{haz}} \Delta t})$

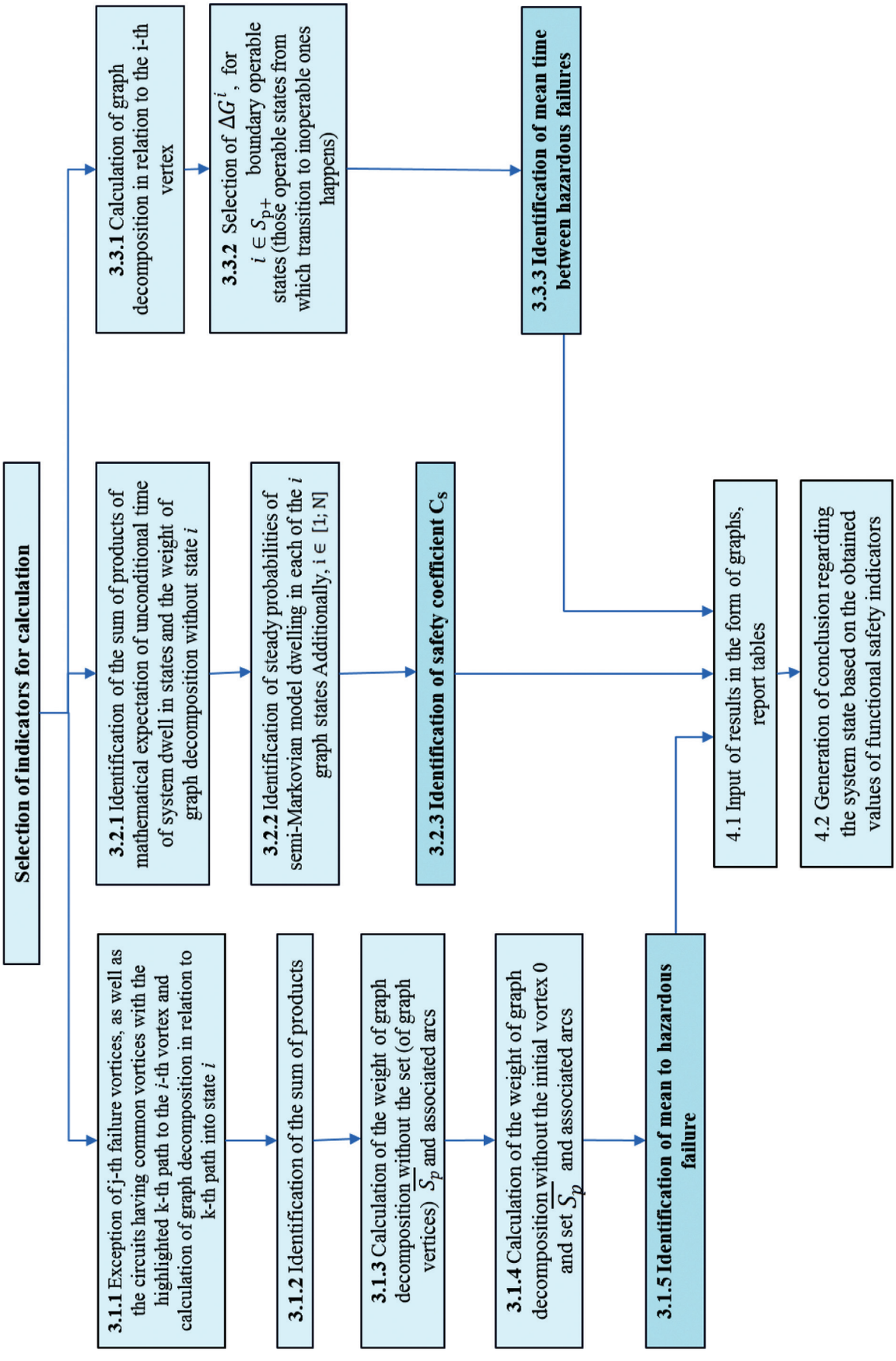


Figure 5. Stages 3 and 4 of the algorithm of calculation of steady functional safety indicators

series-connected unidirectional edges with the beginning in state *i* and the end in state *j*, $G_{\overline{S_H}}$ is the weight of the graph decomposition without the set of non-operable system states (graph vertices) $\overline{S_H}$ and associated edges.

Graph decomposition is a part the graph that does not contain the selected vertices and associated arcs. Graph decomposition is calculated using Mason's formula:

$$\Delta G = 1 - \sum_j C_j + \sum_{rj} C_r C_j - \sum_{irj} C_i C_r C_j. \quad (4)$$

The other stationary functional safety indicators are calculated in the same way. Thus, for instance, the safety coefficient is calculated as follows: according to the algorithm the stationary probabilities of containment of the semi-Markovian model in each of the graph vertices are calculated according to the formula:

$$\pi_i = \frac{\Delta G^i T_i}{\sum_{i \in S} \Delta G^i T_i}. \quad (5)$$

The advantages of this method include: applicability in calculation of the functional safety indicators of systems with a large number of states; absence of limitations on the structure of the examined system; no requirement to transform the initial state graph; operational calculus is not used.

The graph method also allows determining the strict lower (inf) and upper boundaries (sup) of the non-stationary functional safety indicators of safety-related systems. Values $\sup \hat{P}(t)^{\text{haz}}$ and $\inf \hat{P}(t)^{\text{haz}}$ are determined on the class of Erlang distribution functions:

$$f(t) = \begin{cases} t^{r-1} \cdot \dfrac{e^{-\frac{t}{T_{MT}^{haz}}}}{(T_{MT}^{haz})^r \, \Gamma(r)}, & t \geq 0, \\ 0, & t < 0. \end{cases} \quad (6)$$

where *r* is an integral parameter of distribution.

The failure rate will be within an interval, of which the boundaries are calculated using the formulas given in Table 2. In order to guarantee the specified calculation accuracy 1-*ε,* iterative calculations are performed, during which at each step Δt the observation interval is reduced up to the case when the following condition is true:

$|\inf\lambda(t) - \inf\lambda(t+\Delta t)| < \varepsilon$, $|\sup\lambda(t) - \sup\lambda(t+\Delta t)| < \varepsilon$,

Documentation and displaying of results

The documentation of results is an important part of the system states analysis. The application of the graph method described in the paper allows, using the results of the preparation stage, calculating a set of stationary and non-stationary functional safety indicators. When making the list of results, the following characteristics should be identified: name of indicator, designation, result of calculation, dimensionality (units of measurement). An example of the list of calculation results is given in Table 3.

The calculation results allow concluding on the high level of functional safety of the 110 kV railway traction substation system that features structural redundancy ensured by backing up the primary component, the power transformer. Indeed, statistically, hazardous failures of the power transformers that disable 110 kV traction substations and cause critical consequences are sufficiently rare as such systems are redundant.

Analysis of the power transformer functional safety indicators

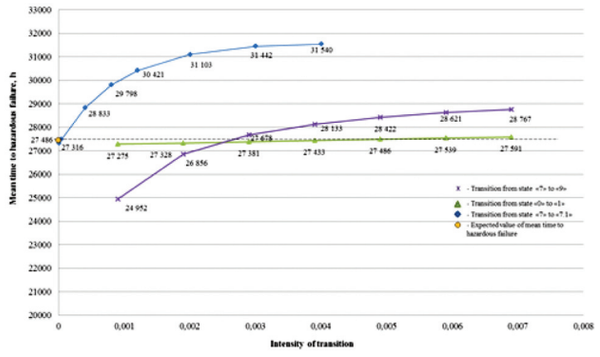
The application of the above algorithms enables variation calculations under different initial values of intensity of transition into the analyzed states. Such research allows making conclusions regarding the expected efficiency of the protection and redundancy systems, as well as the effect of the intermediate state elimination rate on the hazard rate.

Figure 6 shows the results of simulation of the dependence of the intensities of transition between intermediate graph states and the value of mean time to hazardous failure.

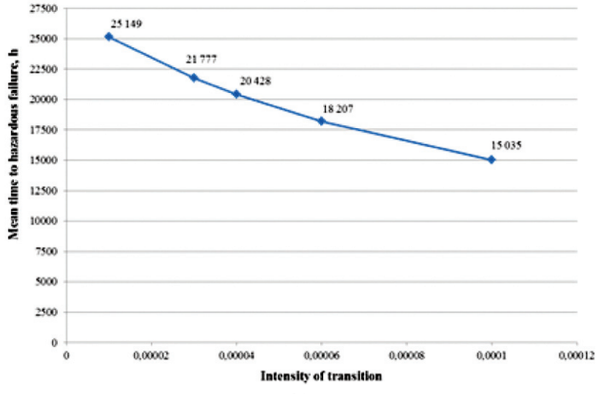
As graph 6a) evidently shows, the value of mean time to hazardous failure is most sensitive to changes in the intensity of transition from state 7, "PT-1 internal or turn-to-turn short circuit", into state 9, "PT-1 internal effects protection tripping and transition to PT-2". Also, as the intensity of transition for these states increases, the mean time to hazardous failure grows as well. This is due to the fact that state 1, "Wear of PT-1 insulation", 9, "PT-1 internal effects protection tripping and transition to PT-2", and 7.1, "Detection of actual failure of PT-1" have ways of transition into safe state 0, "PT-1 and PT-2 are operable" with higher intensity than the intensity of transition into hazardous state.

Table 3. Results of system component safety calculation

№	Name of indicator	Notation	Calculation result	Dimension
1	Mean time to hazardous failure	$T_{\text{MT}}^{\text{haz}}$	27 486	hour
2	Mean time between hazardous failures	T_0^{haz}	28 615 933	hour
3	Safety coefficient	C_{S}	$1\text{-}7 \cdot 10^{-4}$	
4	Probability of hazardous failure	$\hat{Q}(t)^{\text{haz}}$	$\hat{Q}(t)^{\text{haz}} < 3{,}64 \cdot 10^{-5}$	
5	Probability of fault-free operation	$\hat{P}(t)^{\text{haz}}$	$1 - 3{,}64 \cdot 10^{-5} < \hat{P}(T_{\text{MT}}^{\text{haz}})$	
6	Hazardous failure rate	$\hat{\lambda}_C(t)^{haz}$	$3{,}51 \cdot 10^{-4} < \hat{\lambda}_C(T_{MT}^{haz}) < 5{,}11 \cdot 10^{-4}$	



a)



b)

Figure 6. Graph of dependence of the mean time to hazardous failure and a) rate of transition from states "0→1", "7→7.1", "7→9"; b) under decreasing rate of transition into safe state and intensity of transition from state "7→7.1"

Figure 6b) shows the graph of dependence of the mean time to hazardous failure from the intensity of transition from state 7, "PT-1 internal or turn-to-turn short circuit", into state 7.1, "Detection of actual failure of PT-1". In this case the value of mean time to hazardous failure expectedly decreases as the intensity of transition into safe state grows.

Thus, the developed algorithm allows predicting the reduction of functional safety indicators and regulating the distribution of efforts aimed at maintaining the system's operable state,ensuring the redundancy of the system by increasing the intensity of transition into safe state or managing the maintenance and repair system by reducing the intensity of transition between system states.

Conclusion

The paper presents a step-by-step examination of the algorithm of calculation of functional safety indicators of railway PSS based on graph semi-Markovian methods. Using the example of functional safety indicators calculation of a "Railway 110 kV traction substation", the authors demonstrate the capabilities of the graph method and its universal applicability to systems of any configuration. The stages of system state graph construction and calculation of stationary and non-stationary functional safety indicators are examined in depth, their practical applicability is shown.

The paper also analyses the dependence of the estimated values under changing intensities of transition. The conclusion is made regarding the feasibility of decision-making subject to the values of functional safety indicators.

The method of functional safety indicators calculation considered in the paper has a potentially wide area of practical application, as it does not involve operational calculations, which substantially reduces the threshold of competence required for this method's application and can be interesting not only to academic, but the engineering community as well.

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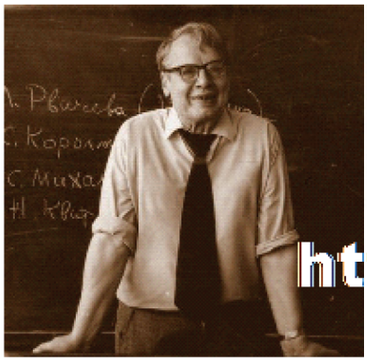

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