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# Model of item monitoring system under unreliable supervision

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**Abstract. Aim.** *The conducted research aims to develop an analytical model of item dependability for situations of technical state monitoring with constant inspection frequency and subject to inspection errors and failures of various types. The primary purpose of the model is the calculation and prediction of dependability indicators that depend on specified conditions.* **Methods.** *The model is based on the Markovian process theory. Models of two types are used, i.e. the continuous-time discrete process model and semi-Markovian model. The mathematical operations involved in the model implementation were performed in matrix form. An items' operation is presented in the form of recurrent cycles separated from each other by the recovery state. A continuous-time model allows obtaining state probabilities within the periods between inspections, mean active state times and state probabilities at the end of a period. The probabilities of entering states at the end of a period are a priori for the semi-Markovian model, using which the mean numbers of active states within one cycle were obtained.* **Results.** *The mean up and down time within a cycle were calculated using mean state frequency and mean time of active state. Based on those parameters, formulas were obtained for calculating the availability and non-availability coefficients. Out of the above model follows that the dependability indicators depend on the frequencies of explicit and hidden failures, inspection frequency and inspection errors. The paper sets forth the calculation data for the mean cycle duration and non-availability coefficient under various failure rates and various probabilities of inspection errors. It is shown that the mean cycle duration significantly depends on the probability of inspection errors of the I kind and practically does not depend on the probability of inspection errors of the II kind. However, the non-availability coefficient practically does not depend on the probability of inspection errors of the I kind, yet there is a strong dependence on the probability of inspection errors of the II kind.* **Conclusions.** *The presented model allows calculating and predicting dependability indicators taking into consideration explicit and hidden failures, as well as the monitoring system parameters. While designing new and improving the maintenance procedures of existing systems, the effect of various factors on the dependability level should to be taken into consideration.*

**Keywords:** *item technical condition monitoring, explicit and hidden failures, inspection frequency, inspection errors.*

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## Introduction

As it is known, an item's dependability depends not only on the kinds and parameters of failures, but also on the maintenance system, one of the components of which is the technical state monitoring that consist in supervising the item in order to obtain information on its technical state and operational characteristics. For this reason, research of dependability of items in view of technical state monitoring remains relevant.

In the course of operation, an item may be in various states, if used as intended, be submitted to various types of maintenance, including technical state inspections. From this perspective, an item's operation can be represented as three phases: intended use (operation), technical state inspection and recovery.

When an item is used as intended, its technical state is monitored, i.e. the item is observed in order to obtain information on its technical state and operational characteristics. The monitoring is implemented in the form of technical state inspection operations that are performed continuously or at intervals. Two technical states associated with failures are considered, i.e. the failure is detected or not detected at the moment of occurrence. In this context, explicit and hidden failures are distinguished. A monitoring system is intended for recurrent inspections, performance supervision, parameter measurements and – based on the above – identifying the presence of hidden failures.

## Source overview

Technical state monitoring is used in a number of technical fields with respective specificity. Thus, in the energy industry, one of the major problems is relay protection of power systems, where it is required to supervise such events as false operation of the monitoring system, functional failure, internal and external faults [22, 23]. An analytical functional model of relay protection of power systems that takes into consideration three kinds of failures and a performance monitoring system are examined in [19]. The model allowed obtaining failure rates, predicting the system availability and identifying the required frequency of relay protection system technical state inspection.

Telecommunication network equipment is classified as long-term use systems, within which various sections of the network are submitted to continuous and recurrent monitoring, which allows establishing the required network availability taking into consideration equipment redundancy and recovery characteristics [2].

Monitoring simulation enables the research, design and improvement of technical systems. For that purpose, the discrete Markovian continuous and discrete-time process theory is sued. Both in Russia, and abroad various research activities are conducted in this area.

Many researchers examine transitions between states in continuous time. Such transitions are described with a system of differential equations. This approach was used in [13, 15, 17] while generating dependability models of complex systems. In [11], based on a system of differential equations, a number of technical systems were described.

Self-monitored systems have been studied by many authors. Thus, in [16], function accuracy control in restorable systems was examined. The model is based on the continuous-time Markovian process theory. The state transitions are described using a system of differential equations.

The research widely uses models based on semi-Markovian processes [12, 18]. In [10], the theory and application examples of semi-Markovian processes are provided. Embedded Markov chains were used to examine the characteristics of nonstationary processes, for instance, temporal characteristics in queueing systems.

In [13], the authors examine the effect of the completeness, depth and reliability of inspections on the simulation of the dependability of redundant systems. Models of standard dependability structures were developed. The simulation results allow making substantiated requirements for the monitoring system characteristics.

In [21], based on analytical methods of monitoring, failure and damage detection and diagnostics models were developed for complex systems. Specific research activities associated with the frequency of preventive maintenance are set forth in [15].

The monitoring system is strongly associated with the matters of operational tests that are a reliable source of information on the initial dependability characteristics [3, 14, 20]. Those characteristics are used in the construction of various models that reflect actual processes in technical systems. Rational organization of operational tests affects the reliability of obtained information and cost of the monitoring system.

## Conceptual model

In the course of operation, an item may be in two states: up and down. An item enters the down state as a hidden failure occurs and is not detected at the moment of its onset. Such failures are detected during technical state inspections as part of check operations.

Thus, in terms of technical state monitoring, an item's failures are divided into two types: hidden and explicit.

An item operates and is occasionally submitted to inspections. Between inspections, an item may fail, resulting in its transition from the up into the down state. The item is used as intended both in the up, and the down state. If an up item is inspected, then upon such inspection it is returned into operation. If a down item is inspected, it is submitted to recovery, upon which it is returned into operation.

An item is observed in operation in order to obtain information on its technical state in the following cases:

1) the item enters the down state as a hidden failure occurs and is detected by the next inspection;

2) upon the onset of an explicit failure, it is detected by the continuous monitoring system, upon which the item is submitted to recovery.

Explicit failures are detected by the continuous monitoring system at the moment of their onset, while hidden failures are detected during scheduled inspections. Therefore, the duration of the period between inspections may be:

1) specified, if no explicit failure occurred;

2) below specified, if an explicit failure occurred.

In this model, the following conditions and assumptions are adopted:

1) during an item's operation, hidden and/or explicit failures may occur;

2) hidden and explicit failures occur at constant rates, i.e. failures occur at random moments in time, while the time to failure is distributed exponentially;

3) item state is supervised at fixed periods, at the same time, with each period starting with the beginning of operation upon recovery or next inspection;

4) is a failure is detected, the item is submitted to recovery, after which operation starts in the up state;

5) in the course of scheduled inspection, inspection errors of the I and II kind are possible;

6) the duration of inspections and recovery are assumed to be negligibly small.

The last assumption is for the purpose of simplifying the model. Such assumption allows estimating the effect of various factors in the "pure form". For instance, in accordance with the established norms, the availability coefficient is the probability of up state disregarding planned periods of no intended use of the item. If necessary, the model allows taking into consideration the final active time of supervision and recovery.

The Aim of the paper is to make a model of item dependability with constant periods between inspections taking into consideration the above conditions and limitations.

## Methods

The models set forth in this paper are based on the Markovian process theory. Models of two types are used, i.e. the continuous-time discrete process model and semi-Markovian model.

Using the continuous-time Markovian model, the state probabilities are found. The input is the rate of transition between states $\lambda_{ij}$ represented in the form of a transition rate matrix $\Lambda = \left\| \lambda_{ij} \right\|$ over a certain set of states. Out of matrix $\Lambda$, the image of the state probabilities in matrix form is found:

$$P(s) = (sE - \Lambda)^{-1} \quad (1)$$

where $s$ is the Laplace variable; $E$ is the identity matrix.

Using inverse Laplace transformation, the state probability matrix $P(t) \div P(s)$ is found, where matrix $P(t) = \left\| p_{ij}(t) \right\|$, element $p_{ij}(t)$ of such matrix is the probability that in the moment in time $t$ the process is in the $j$-th state, provided that the $i$-th state is the initial one. If the initial probability distribution $p(0)$ is known, the state probabilities can be represented as a string [4, 5]:

$$p(t) = p(0) \times P(t). \quad (2)$$

*Note.* Finding the state probabilities does not require composing and solving a system of differential equations. State probabilities are found using standard computer operations.

Further in this model, the relative frequency method is used that is based on the semi-Markovian process theory [4, 6]. The input parameters are the probabilities of passage. Probability of passage $q_{ij}$ is the probability of transition from the $i$-th state into the $j$-th state provided that the $i$-th state is exited.

Let $U$ be a certain set of nonexistent states. In the passage probability matrix, over set $U$, $Q_{UU}$, transitions are shown only between the states of set $U$. Out of matrix $Q_{UU}$, the relative frequency matrix $N_U$ on set $U$ is found:

$$N_U = \left\| n_U(i, j) \right\| = (E - Q_{UU})^{-1}, \quad (3)$$

where $n_U(i,j)$ is the average number of entries into the $j$-th state before leaving the set $U$ provided that the $i$-th state is the initial one when entering set $U$. Elements of the relative frequency matrix are referred to as the relative state frequencies.

If the initial probability distribution $q(0)$ is known, the relative state frequencies can be represented as string

$$n_U = \left\| n_U(j) \right\| = q(0) \cdot N_U. \quad (4)$$

Out of the relative state frequencies and continuous-time state probabilities, the item' dependability indicators are found. As part of the examined model, the following will be calculated:

– mean duration of the up and down states;

– mean recovery frequency;

– availability coefficient and non-availability coefficient.

The operations in the course of model development can be performed manually or in a computer mathematics system.

## State probabilities within one period

Within one period, both hidden, and explicit failures may occur. An explicit failure may occur both in the up state, and the down state. It should be taken into consideration that an explicit failure may occur after a hidden failure, however, a hidden failure cannot occur after an explicit failure, as an explicit failure is detected by the monitoring system at the moment of its occurrence and the item is submitted to recovery. Both hidden, and explicit failures occur within a continuous-time period.

Let the initial state of the period be up. The diagram of continuous-time single-period states is shown in Fig. 1, where 1U is the up state; 2H is the down state with hidden failure: 3HE is the state with two types of failures; 4E is the state only with an explicit failure. State transitions occur as the result of a hidden and explicit failures at a random moment in time at the rates of $\lambda_h$ and $\lambda_e$.

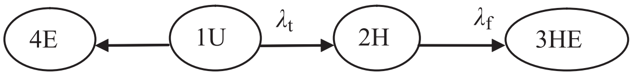


Fig. 1. Continuous-time single-period state diagram

The initial matrix of single-period transition rate:

$$\Lambda = \begin{pmatrix} -\lambda_h - \lambda_e & \lambda_h & 0 & \lambda_e \\ 0 & -\lambda_e & \lambda_e & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}.$$

Having performed the required transformations (1) and (2), we obtained the state probabilities within one period with the initial state 1 that are the elements of the first matrix row $P(t)$:

$$p_{11}(t) = \exp(-\lambda \cdot t);\ p_{12}(t) = \exp(-\lambda_e \cdot t) - \exp(-\lambda \cdot t);$$

$$p_{13}(t) = \frac{\lambda_c}{\lambda} + \frac{\lambda_e}{\lambda} \cdot \exp(-\lambda \cdot t) - \exp(-\lambda_e \cdot t);$$

$$p_{14}(t) = \frac{\lambda_e}{\lambda} - \frac{\lambda_e}{\lambda} \cdot \exp(-\lambda \cdot t), \tag{5}$$

where $\lambda = \lambda_h + \lambda_e$ is the total failure rate.

Obviously, $p_{11}(t) + p_{12}(t) + p_{13}(t) + p_{14}(t) = 1$. The probability of an explicit failure equals the sum of the state probabilities 3 and 4:

$$p_e(t) = p_{13}(t) + p_{14}(t) = 1 - \exp(-\lambda_e \cdot t). \tag{6}$$

It should be taken into consideration that states 1 and 2 are registered by the monitoring system at the end of the interval between inspections, while states 3 and 4 are registered at the moment of explicit failure.

If state 2 is normal, then

$$p_{21}(t) = p_{24}(t) = 0;\ p_{22}(t) = \exp(-\lambda_e \cdot t);$$

$$p_{24}(t) = 1 - \exp(-\lambda_e \cdot t). \tag{7}$$

Let us introduce a parameter that we will name the reduced failure rate:

$\rho_h = \lambda_h \cdot T, \quad \rho_e = \lambda_e \cdot T, \quad \rho = \lambda \cdot T$. The reduced failure rate is the average number of failures within period $T$: $\rho_h$ and $\rho_e$ are the reduced rates of hidden and explicit failures, $\rho$ is the reduced total rate of hidden and explicit failures. Using one parameter instead of two allows simplifying the formulas and calculations.

The state probabilities at the end of the period will be expressed in terms of reduced rates. If the initial state is 1:

$$p_{11}(T) = \exp(-\lambda \cdot T) = \exp(-\rho);$$

$$p_{12}(T) = \exp(-\lambda_e \cdot T) - \exp(-\lambda \cdot T) =$$
$$= \exp(-\rho_e) - \exp(-\rho) = \exp(-\rho_e) \cdot (1 - \exp(-\rho_h));$$

$$p_{13}(T) = \frac{\lambda_h}{\lambda} + \frac{\lambda_e}{\lambda} \cdot \exp(-\lambda \cdot T) - \exp(-\lambda_e \cdot T) =$$
$$= \frac{\rho_h}{\rho} + \frac{\rho_e}{\rho} \cdot \exp(-\rho) - \exp(-\rho_e);$$

$$p_{14}(T) = \frac{\lambda_e}{\lambda} - \frac{\lambda_e}{\lambda} \cdot \exp(-\lambda \cdot T) =$$
$$= \frac{\rho_e}{\rho} + \frac{\rho_e}{\rho} \cdot \exp(-\rho) = \frac{\rho_e}{\rho} \cdot (1 - \exp(-\rho)). \tag{8}$$

If the initial state is 2:

$$p_{21}(T) = p_{24}(T) = 0;$$

$$p_{22}(T) = \exp(-\lambda_e \cdot T) = \exp(-\rho_e);$$

$$p_{23}(T) = 1 - \exp(-\lambda_e \cdot T) = 1 - \exp(-\rho_e). \tag{9}$$

A period my start with an up or down state and end with any state. Therefore, a period can be characterized by the initial or final state. The model under consideration may involve 6 types of periods shown in Table 1. Shown in Table 1 are: U and D are the up and down states of the item, HF and EF are hidden and explicit failures.

**Table 1. Types of periods between consecutive inspections**

| Type of period | Initial state | Events within period | Final state | Period designation | Probability of period |
|---|---|---|---|---|---|
| 1. Up period | U | – | U | UU | $p_{uu}$=$p_{11}(T)$ |
| 2. Period with HF | U | HF | H | UH | $p_{uh}$=$p_{12}(T)$ |
| 3. Period with EF and HF | U | HF and EF | HE | UHE | $p_{uhe}$=$p_{13}(T)$ |
| 4. Period with EF | U | EF | E | UE | $p_{ue}$=$p_{14}(T)$ |
| 5. Down period | D | – | D | DD | $p_{dd}$=$p_{22}(T)$ |
| 6. Down period with EF | D | EF | E | DE | $p_{de}$=$p_{23}(T)$ |

**Table 2. Probabilities of up and down states within periods of different types ($t\in[0;T]$)**

| Type of period | State transitions | Probabilities of states up | Probabilities of states down |
|---|---|---|---|
| 1. UU | U→U | $p_u(t)=1$ | $p_d(t)=0$ |
| 2. UH | U→H | $p_u(t)=\exp(-\lambda_h\times t)$ | $p_d(t)=1-\exp(-\lambda_h\times t)$ |
| 3. UHE | U→H→E | $p_u(t)=\exp(-\lambda_h\times t)$ | $p_d(t)=\frac{\lambda_h}{\lambda_h-\lambda_e}\cdot\left(\exp(-\lambda_e\cdot t)-\exp(-\lambda_h\cdot t)\right)$ |
| 4. UE | U→E | $p_u(t)=\exp(-\lambda_e\times t)$ | $p_d(t)=0$ |
| 5. DD | D→H | $p_u(t)=0$ | $p_d(t)=1$ |
| 6. DE | D→E | $p_u(t)=0$ | $p_d(t)=\exp(-\lambda_e\times t)$ |

## State durations within one period

Let the type of the period be known from the initial and final state. That means that the state transitions within a period occurred as specified in accordance with the conceptual model. The state transitions and probabilities of the state, in which the item is up or down, are shown in Table 2.

*Note*. In the up state there are no failures, in the down state there is only a hidden failure.

For an UHE period, the state probabilities

$$p_{11}(t)=\exp(-\lambda_h\cdot t);$$

$$p_{12}(t)=\frac{\lambda_h}{\lambda_h-\lambda_e}\cdot\left(\exp(-\lambda_e\cdot t)-\exp(-\lambda_h\cdot t)\right);$$

$$p_{13}(t)=1-\frac{\lambda_h\cdot\exp(-\lambda_e\cdot t)-\lambda_e\cdot\exp(-\lambda_h\cdot t)}{\lambda_h-\lambda_e}. \quad (10)$$

An inspection shows that $p_{11}(t)+p_{12}(t)+p_{13}(t)=1$, while with the probability $p_{13}(t)$ at the moment in time $t$ the period will be interrupted, as an explicit failure is detected at the moment of its occurrence, while the probability that, at the moment $t$, the period continues will be

$$p_{11}(t)+p_{12}(t)=\frac{\lambda_h\cdot\exp(-\lambda_e\cdot t)-\lambda_e\cdot\exp(-\lambda_h\cdot t)}{\lambda_h-\lambda_e}. \quad (11)$$

It is obvious that the durations of states, as well as the duration of the period depend on the type of the period. An explicit failure is detected by the continuous monitoring system at the moment of its occurrence, upon which the item is submitted to recovery. For this reason, explicit failures reduce the duration of the period, however, hidden failures do not.

The average time of the item being in the $j$-th state, if the initial state is the $i$-th, within one period is calculated according to formula:

$$\theta_{ij}=\int_0^T p_{ij}(t)\mathrm{d}t. \quad (12)$$

The mean up time ($\theta_u$) and down time ($\theta_d$) within the periods of each type, as well as the mean durations of the periods, are calculated by integrating the respective probabilities. Those durations are shown in Table 3.

The sum of the times $\theta_u$ and $\theta_d$ is the mean time of the period. The mean times $\theta_u$ and $\theta_d$ are calculated by

**Table 3. Mean time of up and down state within periods of different types**

| Type of period | $\theta_u$ | $\theta_d$ | Average period duration |
|---|---|---|---|
| 1. UU | $T$ | 0 | $T_{uu}=T$ |
| 2. RS | $\frac{1-\exp(-\rho_h)}{\rho_h}\cdot T$ | $\frac{\rho_h-\left(1-\exp(-\rho_h)\right)}{\rho_h}\cdot T$ | $T_{uh}=T$ |
| 3. UHE | $\frac{1-\exp(-\rho_h)}{\rho_h}\cdot T$ | $\frac{\rho_h\left(1-\exp(-\rho_e)\right)-\rho_e\left(1-\exp(-\rho_h)\right)}{\left(\rho_h-\rho_e\right)\cdot\rho_e}\cdot T$ | $T_{uhe}=\theta_c+\theta_и$ |
| 4. UE | $\frac{1-\exp(-\rho_e)}{\rho_e}\cdot T$ | 0 | $T_{ue}=\frac{1-\exp(-\rho_e)}{\rho_e}\cdot T$ |
| 5. DD | 0 | $T$ | $T_{dd}=T$ |
| 6. DE | 0 | $\frac{1-\exp(-\rho_e)}{\rho_e}\cdot T$ | $T_{de}=\frac{1-\exp(-\rho_e)}{\rho_e}\cdot T$ |

integrating the probabilities of up and down times within the respective period. The mean duration of a period of type UHE:

$$T_{\text{uhc}} = \theta_h + \theta_d = \frac{\rho_u^2 \cdot \left(1-\exp(-\rho_e)\right) - \rho_e^2 \cdot \left(1-\exp(-\rho_h)\right)}{\left(\rho_h - \rho_e\right) \cdot \rho_h \cdot \rho_e} \cdot T.$$

## State diagram

In accordance with the conceptual model, the item operation time consists of the period between inspections, the inspections themselves and the recovery. Fig. 2 shows the state diagram of operation. The states are numbered and designated with notional indexes: 1U is the up state of an item at the beginning of a period; 2UU is the up state of an item at the end of a period; 3UH is the state of an item at the end of a period with a hidden failure; 4UHE is the state of an item with a hidden and explicit failure; 5UE is the state of an item with a hidden and explicit failure; 6D is the down state of an item at the beginning of a period as the result of an inspection errors of the II kind; 7DD is the down state of an item at the end of a period; 8DE is the down state of an item with an explicit failure; 9IU and 10ID is the inspection of an up and down item at the end of a period; 11IE is the inspection of an item with an explicit failure (detection of explicit failure); 12R is item recovery.

Out of the above diagram follows that the up state is the initial one after recovery or latest inspection of an up item. The following period may be up (transition 1→2), with a hidden failure (transition 1→3) or with an explicit failure (transitions 1→4 and 1→5). Thus, up state 2 and down state 3 are the states at the end of a period, while states 4 and 5 are the states, whose duration is shorter that a period.

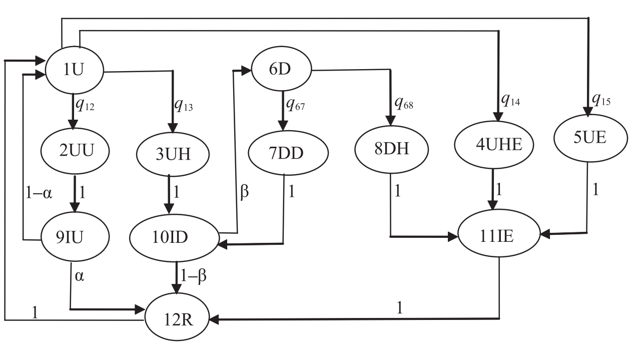


Fig. 2. State diagram of item operation

The diagram shows state transitions as the result of inspection errors: transition 9→12 as the result of an inspection error of the I kind with probability α and transition 10→6 as the result of an inspection error of the II kind with probability β. Transitions designated with probability 1 occur reliably.

After states 2 and 3, as part of technical state monitoring, the up and down items are inspected respectively. If the item is up, then, after the inspection, it is returned into operation with the probability 1 – α, while if it is down, it is submitted to recovery with the probability 1 – β. Upon recovery, the item is returned into operation in the up state.

The diagram shows the state transitions and the respective passage probabilities. The passage probability is a characteristic of the respective period:

$$q_{12} = p_{\text{uu}};\ q_{13} = p_{\text{uh}};\ q_{14} = p_{\text{uhe}};\ q_{15} = p_{\text{ue}};\ q_{67} = p_{\text{dh}};\ q_{68} = p_{\text{de}}. \quad (14)$$

State transitions are described using a passage probability matrix. A passage probability matrix at the whole set of states is as follows:

$$Q = \begin{pmatrix} 0 & q_{12} & q_{13} & q_{14} & q_{15} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & q_{67} & q_{68} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1-\alpha & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \alpha \\ 0 & 0 & 0 & 0 & 0 & \beta & 0 & 0 & 0 & 0 & 0 & 1-\beta \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

## Relative frequencies of states

Lest us divide the set of states into two subsets: $U = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11\}$, $V=\{12\}$. As the result of such division, an item's operation can be represented as in the form of sequential transitions between such subsets: $U \to V \to U \to V \ldots$ An item being in the states of subset $U$ followed by it being in the states of subset $V$ will be referred as a cycle. The diagram in Fig. 1 follows that subset $U$ always starts with state 1.

The passage probability matrix on subset $U$, $Q_{UU}$ is obtained by removing the 12-th row and 12-th column from matrix $Q$. Out of matrix $Q_{UU}$ the relative frequency matrix $N_U$ is calculated according to formula (3). As state 1 always is the initial one in transition $V \to U$, we will calculate only the first row of matrix $N_U$. The elements of inverse matrix $N_U$ can be calculated in a number of ways (it is recommended to use computer mathematics).

Let us express the passage probabilities in terms of reduced rates:

$$q_{12} = p_{\text{uu}} = \exp(-\rho);\ q_{13} = p_{\text{uh}} = \exp(-\rho_e) - \exp(-\rho);$$

$$q_{14} = p_{uhe} = \frac{\rho_h \cdot \left(1-\exp(-\rho_e)\right) - \rho_e \cdot \left(\exp(-\rho_e) - \exp(-\rho)\right)}{\rho} = $$

$$= \frac{\rho_h + \rho_e \cdot \exp(-\rho) - \rho \cdot \exp(-\rho_e)}{\rho};$$

$$q_{15} = p_{ue} = \frac{\rho_e \cdot (1-\exp(-\rho))}{\rho};$$

$$q_{67} = p_{\mathrm{dd}} = \exp(-\rho_e);\ q_{68} = p_{\mathrm{dh}} = 1-\exp(-\rho_e). \quad (15)$$

Let us reduce the elements of the first row of matrix $N_U$ by expressing them in terms of the passage probabilities and reduced rates:

$$n(1,1) = \frac{1}{\Delta 1};\ n(1,2) = \frac{q_{12}}{\Delta 1} = \frac{\exp(-\rho)}{\Delta 1};$$

$$n(1,3) = \frac{q_{13}}{\Delta 1} = \frac{\exp(-\rho_e)-\exp(-\rho)}{\Delta 1};$$

$$n(1,4) = \frac{q_{14}}{\Delta 1} = \frac{\rho_h \cdot (1-\exp(-\rho_e)) - \rho_e \cdot (\exp(-\rho_e)-\exp(-\rho))}{\rho \cdot \Delta 1};$$

$$n(1,5) = \frac{q_{15}}{\Delta 1} = \frac{\rho_e \cdot (1-\exp(-\rho))}{\rho \cdot \Delta 1};$$

$$n(1,6) = \frac{\beta \cdot q_{13}}{\Delta 1 \cdot \Delta 2} = \frac{\beta \cdot (\exp(-\rho_e)-\exp(-\rho))}{\Delta 1 \cdot \Delta 2};$$

$$n(1,7) = \frac{\beta \cdot q_{13} \cdot q_{67}}{\Delta 1 \cdot \Delta 2} = \frac{\beta \cdot (\exp(-\rho_e)-\exp(-\rho)) \cdot \exp(-\rho_e)}{\Delta 1 \cdot \Delta 2};$$

$$n(1,8) = \frac{\beta \cdot q_{13} \cdot q_{68}}{\Delta 1 \cdot \Delta 2} = \frac{\beta \cdot (\exp(-\rho_e)-\exp(-\rho)) \cdot (1-\exp(-\rho_e))}{\Delta 1 \cdot \Delta 2};$$

$$n(1,9) = \frac{q_{12}}{\Delta 1} = \frac{\exp(-\rho)}{\Delta 1};$$

$$n(1,10) = \frac{q_{13}}{\Delta 1 \cdot \Delta 2} = \frac{\exp(-\rho_e)-\exp(-\rho)}{\Delta 1 \cdot \Delta 2};$$

$$n(1,11) = \frac{q_{14}+q_{15}}{\Delta 1} + \frac{\beta \cdot q_{13} \cdot q_{68}}{\Delta 1 \cdot \Delta 2} = \frac{1-\exp(-\rho_e)}{\Delta 1} + \frac{\beta \cdot (1-\exp(-\rho_h)) \cdot (1-\exp(-\rho_e)) \cdot \exp(-\rho_e)}{\Delta 1 \cdot \Delta 2}, \quad (16)$$

where $\Delta 1 = 1-(1-\alpha)\cdot q_{12} = 1-(1-\alpha)\cdot \exp(-\rho)$; $\Delta 2 = 1-\beta \cdot q_{67} = 1-\beta \cdot \exp(-\rho_e)$.

In order to ensure a better understanding of the obtained results, let us refer to some formulas that confirm the correctness of the above findings:

1) the product of the first row of matrix $N_U$ and matrix $(E-Q_{UU})$ equals the row, whose first element is equal to 1, the remaining elements are equal to 0;

2) active states 1 are distributed between states 2, 3, 4, 5: $n(1,2)+n(1,3)+n(1,4)+n(1,5) = n(1,1)$;

3) a state with an explicit failure within one cycle originates from states 4, 5, 8: $n(1,4)+n(1,5)++n(1,8)=n(1,11)$.

## Item dependability indicators

Let us proceed to calculating the dependability indicators taking into consideration the adopted conditions and assumptions. In accordance with the conceptual model, the mean up and down time within one cycle is defined by such times in states 2, 3, 4, 5, 7, 8.

The mean up time within one cycle:

$$t_u = \left[ \begin{array}{c} n(1,2)+n(1,3)\cdot \dfrac{1-\exp(-\rho_h)}{\rho_h} + n(1,4)\cdot \\ \cdot \dfrac{1-\exp(-\rho_h)}{\rho_h} + n(1,5)\cdot \dfrac{1-\exp(-\rho_e)}{\rho_e} \end{array} \right] \cdot T. \quad (17)$$

The mean down time within one cycle:

$$t_d = \left[ \begin{array}{c} n(1,3)\cdot \dfrac{\rho_h - (1-\exp(-\rho_h))}{\rho_h} + n(1,4)\cdot \\ \cdot \dfrac{\rho_h (1-\exp(-\rho_e)) - \rho_e (1-\exp(-\rho_h))}{(\rho_h-\rho_e)\cdot \rho_e} + \\ + n(1,7)+n(1,8)\cdot \dfrac{1-\exp(-\rho_e)}{\rho_e} \end{array} \right] \cdot T. \quad (18)$$

The mean cycle duration:

$$t_c = t_u + t_d. \quad (19)$$

Availability coefficient $C_{\mathrm{a}}$ and non-availability coefficient $C_{\mathrm{na}}$

$$\mathrm{C}_a = t_u / t_c;\ \mathrm{C}_{na} = t_d / t_c. \quad (20)$$

## Results

Set forth below are the calculation data for the mean cycle duration and non-availability coefficient under various failure rates and various probabilities of inspection errors. Those calculations are presented in table form with specific numerical values. Tables show the changes in the dependability indicators and predicted values of dependability indicators.

Table 4 shows the expected values of such indicators under various values of inspection error probability and reduced rates $\rho_h = 0.005$ and $\rho_e = 0.05$ and inspection frequency $T = 1$ hour, while Table 5 shows similar calculations under $\rho_h = 0.05$; $\rho_e = 0.005$; $T = 1$ hour.

The above calculations show that the mean cycle duration significantly depends on the probability of inspection errors of the I kind, as this probability defines the average number of up periods, i.e. the higher is the probability of inspection errors of the I kind, the lower is the average number of periods within one cycle. The calculations clearly indicate that

**Table 4. Values of the non-availability coefficient if $\rho_e = 0.005$; $\rho_e = 0.05$; $T = 10$ h.**

| β<br>α | | 0 | 0.001 | 0.01 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
|---|---|---|---|---|---|---|---|---|---|
| 0 | $t_c$ | 18.7 | 18.7 | 18.7 | 18.7 | 18.7 | 18.7 | 18.8 | 18.8 |
| | $C_u$ | $1.3\cdot10^{-5}$ | $2.2\cdot10^{-5}$ | $1.1\cdot10^{-4}$ | $1.0\cdot10^{-3}$ | $2.2\cdot10^{-3}$ | $3.9\cdot10^{-3}$ | $6.0\cdot10^{-3}$ | $8.9\cdot10^{-3}$ |
| 0.01 | $t_c$ | 15.9 | 15.9 | 15.9 | 15.9 | 15.9 | 15.9 | 16.0 | 16.0 |
| | $C_u$ | $1.2\cdot10^{-5}$ | $2.2\cdot10^{-5}$ | $1.1\cdot10^{-4}$ | $1.0\cdot10^{-3}$ | $2.3\cdot10^{-3}$ | $3.9\cdot10^{-3}$ | $6.0\cdot10^{-3}$ | $8.9\cdot10^{-3}$ |
| 0.05 | $t_c$ | 9.9 | 9.9 | 9.9 | 9.9 | 99 | 9.9 | 10.0 | 10.0 |
| | $C_u$ | $1.2\cdot10^{-5}$ | $2.2\cdot10^{-5}$ | $1.1\cdot10^{-4}$ | $1.0\cdot10^{-3}$ | $2.3\cdot10^{-3}$ | $3.9\cdot10^{-3}$ | $6.0\cdot10^{-3}$ | $8.9\cdot10^{-3}$ |
| 0.1 | $t_c$ | 6.7 | 6.7 | 6.7 | 6.7 | 6.8 | 6.8 | 6.8 | 6.8 |
| | $C_u$ | $1.2\cdot10^{-5}$ | $2.2\cdot10^{-5}$ | $1.1\cdot10^{-4}$ | $1.0\cdot10^{-3}$ | $2.3\cdot10^{-3}$ | $3.9\cdot10^{-3}$ | $6.0\cdot10^{-3}$ | $8.9\cdot10^{-3}$ |
| 0.2 | $t_c$ | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 |
| | $C_u$ | $1.2\cdot10^{-5}$ | $2.2\cdot10^{-5}$ | $1.1\cdot10^{-4}$ | $1.0\cdot10^{-3}$ | $2.3\cdot10^{-3}$ | $3.9\cdot10^{-3}$ | $6.0\cdot10^{-3}$ | $8.9\cdot10^{-3}$ |
| 0.3 | $t_c$ | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |
| | $C_u$ | $1.2\cdot10^{-5}$ | $2.2\cdot10^{-5}$ | $1.1\cdot10^{-4}$ | $1.0\cdot10^{-3}$ | $2.3\cdot10^{-3}$ | $4.0\cdot10^{-3}$ | $6.0\cdot10^{-3}$ | $8.9\cdot10^{-3}$ |
| 0.4 | $t_c$ | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 |
| | $C_u$ | $1.2\cdot10^{-5}$ | $2.2\cdot10^{-5}$ | $1.1\cdot10^{-4}$ | $1.0\cdot10^{-3}$ | $2.3\cdot10^{-3}$ | $4.0\cdot10^{-3}$ | $6.0\cdot10^{-3}$ | $8.9\cdot10^{-3}$ |
| 0.5 | $t_c$ | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 |
| | $C_u$ | $1.2\cdot10^{-5}$ | $2.2\cdot10^{-5}$ | $1.1\cdot10^{-4}$ | $1.0\cdot10^{-3}$ | $2.3\cdot10^{-3}$ | $4.0\cdot10^{-3}$ | $6.0\cdot10^{-3}$ | $8.9\cdot10^{-3}$ |

**Table 5. Values of the non-availability coefficient if $\rho_e = 0.05$; $\rho_e = 0.005$; $T = 10$ h.**

| β<br>α | | 0 | 0.001 | 0.01 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
|---|---|---|---|---|---|---|---|---|---|
| 0 | $t_c$ | 18.7 | 18.7 | 18.7 | 18.9 | 19.1 | 19.5 | 20.0 | 20.0 |
| | $C_u$ | $1.2\cdot10^{-3}$ | $1.3\cdot10^{-3}$ | $2.2\cdot10^{-3}$ | $1.2\cdot10^{-2}$ | $2.5\cdot10^{-2}$ | $4.1\cdot10^{-2}$ | $6.2\cdot10^{-2}$ | $8.9\cdot10^{-2}$ |
| 0.01 | $t_c$ | 15.9 | 15.9 | 15.9 | 16.0 | 16.3 | 16.5 | 16.9 | 17.4 |
| | $C_u$ | $1.2\cdot10^{-3}$ | $1.3\cdot10^{-3}$ | $2.2\cdot10^{-3}$ | $1.2\cdot10^{-2}$ | $2.5\cdot10^{-2}$ | $4.1\cdot10^{-2}$ | $6.2\cdot10^{-2}$ | $8.9\cdot10^{-2}$ |
| 0.05 | $t_c$ | 9.9 | 9.9 | 9.9 | 10.0 | 10.2 | 10.3 | 10.6 | 10.9 |
| | $C_u$ | $1.2\cdot10^{-3}$ | $1.3\cdot10^{-3}$ | $2.2\cdot10^{-3}$ | $1.2\cdot10^{-2}$ | $2.5\cdot10^{-2}$ | $4.1\cdot10^{-2}$ | $6.2\cdot10^{-2}$ | $8.9\cdot10^{-2}$ |
| 0.1 | $t_c$ | 6.7 | 6.8 | 6.8 | 6.8 | 6.9 | 7.0 | 7.2 | 7.4 |
| | $C_u$ | $1.2\cdot10^{-3}$ | $1.3\cdot10^{-3}$ | $2.2\cdot10^{-3}$ | $1.2\cdot10^{-2}$ | $2.5\cdot10^{-2}$ | $4.1\cdot10^{-2}$ | $6.2\cdot10^{-2}$ | $8.9\cdot10^{-2}$ |
| 0.2 | $t_c$ | 4.1 | 4.1 | 4.1 | 4.2 | 4.2 | 4.3 | 4.4 | 4.5 |
| | $C_u$ | $1.2\cdot10^{-3}$ | $1.3\cdot10^{-3}$ | $2.2\cdot10^{-3}$ | $1.2\cdot10^{-2}$ | $2.5\cdot10^{-2}$ | $4.1\cdot10^{-2}$ | $6.2\cdot10^{-2}$ | $8.9\cdot10^{-2}$ |
| 0.3 | $t_c$ | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.1 | 3.2 | 3.2 |
| | $C_u$ | $1.2\cdot10^{-3}$ | $1.3\cdot10^{-3}$ | $2.2\cdot10^{-3}$ | $1.2\cdot10^{-2}$ | $2.5\cdot10^{-2}$ | $4.1\cdot10^{-2}$ | $6.2\cdot10^{-2}$ | $8.9\cdot10^{-2}$ |
| 0.4 | $t_c$ | 2.3 | 2.3 | 2.3 | 2.3 | 2.4 | 2.4 | 2.5 | 2.5 |
| | $C_u$ | $1.2\cdot10^{-3}$ | $1.3\cdot10^{-3}$ | $2.2\cdot10^{-3}$ | $1.2\cdot10^{-2}$ | $2.5\cdot10^{-2}$ | $4.1\cdot10^{-2}$ | $6.2\cdot10^{-2}$ | $8.9\cdot10^{-2}$ |
| 0.5 | $t_c$ | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 2.0 | 2.0 | 2.1 |
| | $C_u$ | $1.2\cdot10^{-3}$ | $1.3\cdot10^{-3}$ | $2.2\cdot10^{-3}$ | $1.2\cdot10^{-2}$ | $2.5\cdot10^{-2}$ | $4.1\cdot10^{-2}$ | $6.2\cdot10^{-2}$ | $8.9\cdot10^{-2}$ |

the average cycle duration changes by an order of magnitude in case of changes to the probability of errors of the I kind. It is also evident that the average cycle duration practically does not depend on the probability of error of the II kind, as the contribution of such error to down states is negligibly small as compared with the cycle duration. The explanation is simple. Down states as the result of inspection errors of the II kind can occur only after a hidden failure, while the probability of a hidden failure within a single period is a sufficiently small value. It should be noted that the mean cycle duration defines the recovery rate that can serve as the foundation for the calculation of the scope of recovery operations. The rate or percentage of false recoveries in the total scope of recovery activities.

Out of the above model follows that the non-availability coefficient practically does not depend on the probability of errors of the I kind, as the mean relative rates of all states are equally proportional to the parameter that depends on the probability of errors of the I kind (this parameter is designated $\Delta 1$). However, the non-availability coefficient significantly depends on the probability of inspection errors of the II kind. This indicator may vary several times and even 2 to 3 orders of magnitude in case of sufficient changes to the probability of errors of the II kind. That is due to the fact that the duration of down states may significantly vary subject to changes to the probability of errors of the II kind, although such values make up an insignificant part of the mean cycle duration.

The dependability level also depends on the correlations between the hidden and explicit failures, i.e. the higher is the share of hidden failures in the overall failure flow, the higher is the non-availability coefficient that may grow 1 to 2 orders of magnitude depending on this factor. Thus, the growing share of hidden failures may significantly reduce the dependability level.

## Discussion

The specificity of this model consists in the fact that the technical state inspections as part of the monitoring system are conducted with a constant frequency. In the analytical models used for describing technical system monitoring, random inspection frequency is often used. Using different ways of defining inspection frequency in models may have a significant effect on the expected values of dependability indicators. For instance, in [8], it is shown that the difference between the unavailability coefficient under different ways of defining inspection frequency may amount to several orders of magnitude under various failure rates.

Another particular trait of the above model consists in the fact that time count starts from the observed events that include explicit failures, technical state inspections, completed recovery. It should be noted that, within the monitoring system, time count from a hidden failure is impossible, as such event is not observable. In Markovian model-based research, it is assumed that the duration of states is random and is distributed exponentially with a constant strength. At the same time, such choice is rarely substantiated. The meaning of the "raty of state end" parameter is normally not explained.

The advantage of the model is its compatibility with computer simulation tools, e.g. Mathcad and Matlab. The use of matrix methods provides simple calculation algorithms in those systems.

## Conclusion

While designing new and improving the maintenance procedures of complex systems, explicit and hidden errors, inspection frequency, inspection errors are to be taken into consideration. At the same time, it is required to predict and calculate not only the availability or non-availability coefficients, but also the temporal characteristics associated with dependability. In actual monitoring systems, there is a great diversity in states, transitions and numeric values of input data. The presented model allows calculating and predicting such indicators subject to the influencing factors. For instance, the model allows analyzing the mean down time within one cycle and the components of this indicator that depend on the hidden failures and the probability of inspection errors of the II kind. The effect of explicit failures on the mean down time within one cycle can be taken into consideration as well.

Using the above model enables substantiated predictions of the dependability level taking into consideration the requirements for the monitoring system.

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## The author’s contribution

**Zelentsov B.P.** developed an analytical model of item dependability based on matrix methods for situations of technical state monitoring with constant inspection frequency and subject to inspection errors and of failures of various kinds in terms of detection features.

## Conflict of interests

The author declares the absence of a conflict of interests.

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# Dependability from a designer's standpoint

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**Abstract.** *The* **Aim** *of the paper is to let the reader look at dependability through the eyes of a designer who is to develop an entity with specified dependability requirements. The result of such work is not yet dependability as a property, but the ability proper to a structure, without which the required dependability cannot manifest itself. Designing highly dependable entities requires the use of formalized practices with specific operating procedures, that, on the one hand, do not contradict the provisions of the dependability theory, while, on the other hand, are to be useful, clear and easy-to-understand by any designer in order to ensure the required dependability.* **Methods.** *The paper examines the primary approaches that allow a designer, without violating the existing notions and terminology of dependability, solving problems of technical object dependability in the course of design and development based on engineering disciplines and design methods intended to ensure the dependability of products, starting with the very early life cycle stages. If such approaches to dependability research are employed, preventing failures only requires the application of the principles of physicality (causal connections) and physical necessity (consistency with the laws of nature) of the causes of failures.* **Results.** *The paper sets forth simple mathematical models that helped create a generalized parametric model of complex technical systems operation. Based on the cited models, it can be concluded that dependability calculation in terms of the known dependability indicators of components and elements can be replaced with dependability estimation in terms of the probability of performance by the components and elements of the required functions. This conclusion not only does not contradict the provisions of the dependability theory, but makes dependability an effective tool helping the designer ensure the specified dependability. The generalized parametric model of operation is solved using the method of design and process dependability analysis developed for the purpose of analyzing and assessing design solutions as part of high-dependability item design.* **Conclusion***. The concepts, approaches, models and methods suggested in the paper allow the designer to take dependability as operability expanded in time. Such dependability is always specific and takes into consideration all the distinctive features of an entity. In this case, the process of design and assurance of dependability becomes an integral part of the entity creation activities regardless of uniqueness, series production, availability of dependability indicators of components and elements. But most importantly, such approach to dependability, on the one hand, does not contradict the foundations of the modern dependability theory, and, on the other hand, relieves the designer of the impression that dependability is something foreign, not associated with the real design.*

**Keywords:** *dependability theory, highly dependable system design, dependability calculation, unique highly vital system, design engineering analysis of dependability (DEAD).*

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**Introduction.** Dependability requirements are to be set forth in the design specifications as it is required, for instance, in GOST 15.016–2016. Quantitative estimation of dependability is conventionally done based on the indicators defined through statistical testing (operation) of products or their components (elements) ([1], Annex (informative). Notes to the terms given in the standard). However, before such statistical testing is possible, at the stage of release of working design documentation, it is required to substantiate the ability of the employed engineering solutions to ensure the specified dependability requirements (normally, that involves dependability calculations according to GOST 27.301–95). As dependability is often understood as reliability, we should consider what exactly a designer is to do in order to ensure dependability if it (for simplicity) is defined through the probability of no failure[1].

In order to fulfil the design specification requirements in terms of specified probability of no failure, the designer, according to today's vision of dependability, is to develop the structure of the product (as a set of elements and relations between them) with known data on the dependability of its components and elements in the specified modes and conditions of operation. On the outside, it might look like putting Lego bricks together, creating a structure with a specified dependability out of components and elements with known dependability data. Whereby, if such data is not available, then, according to the modern dependability theory, they must be obtained through experimental means [2-4]. In practice, that is the design process of electronics with specified dependability that are based on electronic components with known dependability indicators [5]. Electronic components are mass-produced and they normally are sufficiently compact in order to enable in-laboratory production of statistical dependability information in specified application modes under extreme temperatures, temperature cycling, vacuum, radiation, corrosive environments, etc.

In the case of complex technical systems (entities) consisting of diverse components with different principles of operation: body parts, mechanisms, electromechanical devices, electronic assemblies, pyrotechnical devices, etc., Lego-like dependability development may become difficult. The collection of statistical data on the dependability of full-sized components of large-format entities (primarily, large deployable structures, complex mechanical and electromechanical devices, distributed structures made of composite materials, etc.) in unique operating conditions different from the normal environment of the Earth (deep underwater, in presence of high radiation, in outer space, etc.), will most probably be impossible for technical and economic reasons [6]. Certainly, there are available data on the dependability of similar items operating in slightly different modes and conditions, e.g. for spacecraft structures that are to be deployed in the orbit only once, as well as statistical data on land-based activations (if the project budget allows conducting the required number of uniform independent tests in order to confirm the specified dependability). However, it is not clear what to think of the reliability of dependability calculations (given that the land-based test conditions are different from the conditions of normal operation in space). It is even worse, if the product is one-of-a-kind (let alone unique), and there is no available dependability data on similar items, e.g. when it comes to landing vehicles of interplanetary spacecraft intended for traveling to a planet with a Venus-type atmosphere.

The situation might be more complicated, when reliability is defined by at least three nines after the decimal point (rounded to a smaller number of nines to improve the confidence). Formally, that does not rule out the possibility of failures, however in each particular case loss of functionality is not acceptable, as it can cause immeasurably more damage than the cost of development and manufacture of the failed product. A typical example is the deployment of structures of unmanned spacecraft in a near-Earth orbit. The failure of any of the deployment mechanisms may cause the loss of the satellite. For instance, due to the non-deployment of the solar panels in 2006, the 190-millon dollar Sinosat-2 communication satellite was lost, followed in 2019 by the 250-million dollar Chinasat-18. Besides direct damage due to the loss of spacecraft, such incidents bring costs associated with repeated manufacture of a replacement satellite and loss in goodwill. Additionally, in peacetime, the loss of a telecommunication satellite can cause faults in the global communication system with many risks of loss due to disrupted mobile communication, while in wartime it may cause a critical deterioration of (and even loss of) state security.

If it is impossible to follow the rules of the statistical dependability theory, the designer has to solve the problem of ensuring the specified dependability through non-formalized heuristic methods, that either do not imply dependability estimation, or allow dependability calculation with no regard for the design specificity of the respective entities. In any case, they do not answer the question of how exactly to achieve the dependability, under which failures due to certain causes are not allowable [7]. Then, all that remains is to hope for luck or use such design method that even without reliable statistical dependability data may prove to be useful, clear and easy-to-understand for any designer aiming to ensure the required dependability.

**Why making and calculating dependability are two different things.** Any calculation of performance parameters aims to substantiate the designer's decisions on the choice of materials, intermediate products, heat treatment, coatings, dimensions, tolerances, etc. Such calculations are based on the principle of redundancy for

[1] According to GOST R 50779.10-2000, probability is defined with a real number between 0 and 1 that is to reflect the relative frequency in a set of observations, or the level of confidence that a certain event will occur.

the purpose of eliminating (or reducing) the uncertainty factors between the "required" entity structure and the "randomness" of the environmental factors. The degree of such redundancy defines the allowable relation between the specified dependability and the possible undependability [8]. A good example is the strength calculation. The redundancy of structural strength of the selected structural materials and specified dimensions of structures that bear the external loads defines the required safety factor and thus conditions the choice of design solutions (the materials, dimensions, mass, action principles, manufacturing processes and other structural features). Any designer who knows that his/her structure has an insufficient safety factor (e.g. 0.9) has the required knowledge of the strength of materials that allow, through the use of design methods, bringing the strength to the required level. With dependability, the situation is completely different. No designer, knowing that the operational reliability of his/her structure is, e.g. 0.998, is able to substantiate its increase to, for instance, 0.999. Moreover, based on the external features, it is practically impossible to distinguish same-purpose entities with the reliability of, let us assume, 0.9 and 0.(9) (i.e. zero and nine in period). At the same time, an expert opinion regarding the strength can be provided by any qualified engineer even without calculations (at least in terms of "strong – flimsy").

Such uncertainty with dependability is explained by the fact that its purpose is to provide an integral characteristic of literally all properties of an entity able to affect its reliable operation, whose list alone is difficult to identify. If we take, for instance, strength, it characterizes the ability of the structural material to resist destruction under the stress caused by external forces and simultaneously is a property that constitutes dependability. Whereby, along with other component properties of dependability, when evaluating dependability, strength is to be considered in terms of retention over time (formally, dependability is a property that characterizes the manifestation of properties over time). As complex technical systems are endowed with a sum of multidisciplinary properties (material, dimensional, temporal, thermal, electrical, mechanical, etc.), each of which is examined using various engineering disciplines, there are two possible approaches to the research of dependability:

• identifying and taking into consideration in the course of dependability evaluation each of the component properties of an entity;

• not individualize each of the properties of an entity, but characterize its operation with certain generalized indicators.

In the Russian school of dependability (at least since 1989, at most since 1983), out of such approaches followed the unity and opposition of the two definitions of the term "dependability", i.e. the functional and the parametric [9], whose priority in the terminological dependability standard GOST 27.002 changes over time.

In practice, both approaches to dependability with not limitation are employed in strength calculation using the "load – strength (resistance)" failure model. In this case it is deemed that the probability of no failure (generalized strength indicator) is the same as the probability that within the given time interval the value of the stress parameter will not once exceed the value assumed by the strength parameter (specific parameters affecting strength) ([1], Annex (informative). Notes to the terms given in the standard). Whereby the degree of excess strength corresponding to the specified probability of no failure, in practice, is normally standardized through specified reliability coefficients and margins of safety [10]. However, such failure model is only valid for those cases when dependability is defined only by the strength or mainly strength, if the required dependability is not too high.

If dependability, besides strength, is equally affected by another factor, e.g. excess driving torque in case of moving mechanical assemblies, dependability, subject to both factors, is defined using the method of dummy items [11]. Nevertheless, that approach has its limitations as well. It is applicable for design dependability when substantiating fundamental design solutions as regards the selection of design parameters of structures. In the present case, it is the structural strength and power sufficiency of the opening drives installed in the structure, provided that it has required strength [12]. In the course of development of working design documentation, besides ensuring the strength and power sufficiency of drives, it is always required to carefully design all the aspects of the structure in view of the manufacturing capabilities, therefore it is required to additionally consider a large number of design and manufacturing factors that have an effect on dependability [12]. Statistical methods of dependability calculations in this case are not applicable, as they do not allow identifying sufficient factors for characterizing dependability subject to specific design features of an entity and substantiating them quantitatively in order to verify the required dependability indicators.

The primary contradiction between designing and researching dependability consists in the fact that, according to the modern dependability theory, the dependability indicators of an entity characterize the consequences as the result of the design activities with no consideration for the underlying causes, while a designer has to "design" (take into consideration all) the causes in order to obtain the required consequence, i.e. the specified dependability [13]. In other words, a designer must evaluate and prevent practically all possible causes of failure, while a researcher (estimator) of dependability only needs to represent dependability with a probabilistic indicator that provides an integral characteristic of all properties of an entity enabling the performance of the required functions (without elaborating on the causes of non-performance of each individual function). In practice, a dependability expert looks at the results of a designer's work from the point of view of the accidental nature of events and processes, whose causes not necessarily can (or must) be known, while for a designer any structure obeys the causality principle: each decision and action causes potential events able to entail failures. Thus, a designer always examines an entity as a deterministic set of causal relationships, while a dependability estimator sees it as a certain technical item with no regard for the genesis, whose behaviour is postulated in the form of statistical hypotheses. This difference between the perspectives of a designer and estimator of dependability is so, that in the aerospace industry there is a common saying that goes: "*dependability is calculated by those who don't know how to make it"* and *"nines don't fly"*, which once again confirm the absence of correlation between the results of design activities on a specific entity and dependability calculation based on statistical data regarding similar items.

**The terminological aspect of the designers' perspective of dependability.** In order to substantiate the relevance and viability of the designer vision of dependability, let us address the dependability terminology. Without engaging into a terminological dispute [9], let us accept the definition of the term "dependability" in accordance with GOST 27.002: *"Dependability is the property of an object to maintain in time the ability to perform the required functions in the specified modes and conditions of operation, maintenance, storage and transportation."* As it can be clearly observed, the term "dependability" is based on term elements, whose meanings in the above standard are defined only for one term, i.e. "(*technical*) *item"*. The other term elements that are significant for an unambiguous understanding by a designer of the meaning of dependability are not defined in the dependability terminology standard. Most importantly, those are the "*property"*, "*ability"* and "(*required*) *function*". Probably, the standard's developers thus intentionally provided anyone interested (based on the specificity) with the opportunity to decide upon the meaning of the concepts that make up the primary term of dependability. Let us use this right, taking into consideration a designer's vision of the matters of dependability.

The term "*property"* was many times defined in Russian standards GOST R 8.614, GOST R ISO 22745-2, GOST R 54136 and GOST R 15531-31, but, in the context of fail-safe entities (that operate without failures), the author prefers the concise and aphoristic concept of property set forth in [14] as the *relation of things*. Terminologically, that concept is defined as follows: *"Property is a philosophical category that expresses such aspect of an object that conditions its difference or similarity with other objects and is manifested in its relation to them"* [15].

The term "*ability*" is defined in the Russian standards GOST 33707 and GOST R ISO 15531-1, but, again, in the context of fail-safe entities (for lack of a better option) the author deems it to be appropriate to use the dictionary definition [16]: *"Ability is a quality, property, state that enables the performance of certain actions, work"*.

The situation with the definition of "(*required*) *function" per* GOST 27.002 is more complicated. First, it is not very clear what is the difference between the "(*required*) *function"* and the concepts used in other dependability standards, i.e. "(*specified*) *function"* per DSTU 2860 and "(*target*) *function"* from the Space Systems and Stations group of standards. Given that the "(*required*) *function"* and "(*specified*) *function"* are indiscriminately used in GOST 27.002, those are probably equivalent. Second, taking into consideration the homonymic and synonymic specificity of the concept of "*function*", let us address the definitions of that terms' synonymic chain that best match the characteristic of technical items (assuming that such function can indiscriminately indicate required, specified or target):

- *description (normally, verbal) of the service purpose of an entity, i.e. what the entity (component) is to do when used* [GOST R 53394, article 3.2.4];
- *implementation of output effect by the item*[1];
- *execution within the item of a process corresponding to its purpose, manifestation of a specified condition or property of the item according to the requirements of the regulatory technical and/or design (project) documentation* [DSTU 2860, article 3.1.8];
- *external manifestation of the properties of a certain item in the given relational system* [17].

Given that the required function is a function that was initially conceived by man (designer) and is to be executed in the course of an item's operation in order to achieve its service purpose, let us agree – when talking about fail-safe items – to understand the ***required function*** as the *external manifestation of the expected properties of the item in specified modes and conditions of operation (when the item performs the specified output effect) that have been identified and correspond to the provisions of the design documentation*.

Let us note that the above concepts of "*property*", "*ability*", and "(*required*) *function*" clearly show an orderly evolution of the states of matter that changes in time in the form of ***properties*** as certain relations between objects within a material system, ***ability*** as the state that enables the manifestation of certain properties and ***required functions*** as the realization by the object of the specified abilities. Thus, the required function is the result of the manifestation of an object's inherent properties that, in turn, are the realized ability (potential capability) of an object to manifest such required functions. The above hierarchy of concepts allows, from the very beginning, conceiving (designing and developing) the ability of an object to perform the required functions, describing (analyzing and calculating) the ability quantitatively as a property and realizing (manufacturing and using the item) this property in the form of the required function. If the non-performance of any of the required functions is considered as failure, then early prevention of possible failures becomes just a result of the methodological approach to the design (adoption of design solutions, their

[1] The definition of the term is in accordance with the upcoming Russian standard "Space systems and complexes. Analysis of the types, consequences and criticality of failures of entities and processes. Availability analysis. General requirements".

substantiation, execution and supervision). Consequently, all problems of technical object dependability as part of design and development can be solved on the basis of the engineering disciplines and design methods of product dependability starting from the early stages of the life cycle. In this case, preventing failures only requires the application of the principles of physicality (causal connections) and physical necessity (consistency with the laws of nature) of their causes.

**Models required by the designer in order to understand dependability.** Let us use the principles of construction of simple mathematical models that enable the creation of functional models of complex technical systems [18]:

- the simpler the model, the lower is the probability of improper conclusions;
- the model must be simple, but not simpler than possible;
- anything can be neglected; we only need to make sure we know how it will affect the decision;
- the model must be crude: small corrections are not to radically modify its behaviour;
- the model and calculation must not be more accurate than the input data;
- while analyzing the results of model study, what matters is not only the specific numerical results, but the understanding why and how everything happens and how it depends on the parameters.

In practice, in order to achieve the design objectives, a designer uses two models that reflect his/her idea of the actual object and its operating environment:

- an information model of temporal factors and external effects on the item through the interfaces in the form of operating modes and conditions as per the design specifications;
- a digital model that corresponds with the stationary probabilistic model of the item in the form of design documentation that he/she is ultimately developing.

The information model of temporal factors and external effects defines the allowable set and range of values of the factors of the environment, in which a structure is to resist possible failures. The distinctive feature of this model is that it normally remains unchanged throughout development iterations. If failures in operation are due to the fact that some model parameters do not correspond to reality, that has nothing to do with dependability (the latter, according to its definition, is the property that manifests itself only in predefined modes and conditions of operation). For instance, the first descent vehicles of the Venera automatic interplanetary stations were designed for pressures of up to 20 ATM and were simply crushed in the planets' atmosphere without achieving the specified goals, as the actual pressure on the surface of Venus, as it turned out later, was about 90 ATM (probably, at 20 ATM the descent vehicles were sufficiently dependable; the problem is that the design objectives were defined incorrectly). A designer initially regards any external effects as deterministic regardless of the reasons they were designated as such (this difference in the standpoints of the designer, dependability specialist and final user is a potential source of conflicts).

The stationary probabilistic model of an object is an abstract description of actual or hypothetical (not yet manufactured) entities that can be obtained as the result of repeated manufacture under condition of strict observance of all requirements of the design documentation. This model is subject to iterative improvement (modification) up to the moment the entity is put into operation, therefore, the probabilistic model of an item at each iteration step of modification of documentation is considered to be stationary "as is". Tolerances of structure parameters within each iteration step are unchanged (stationary), but the values of such parameters may change randomly (stochastically) within the set tolerances in each actual or hypothetical implementation, and, subsequently, can be realized and expanded in time. Thus, the number of hypothetical reproductions of same-type entities $\tau$ (manufactured using the same documentation, same equipment, same specialists), whereas they are able to ensure reliability is a random value that, in its meaning, cannot be anything else but the failure-free time of entity $t$ expressed in the number of actual reproductions. The above property of the stationary probabilistic model of an item corresponds to the condition of dependability $R(t)=P(\tau>t)$ at each iteration step of modification of the technical documentation "as is". Among the examples of practical application of stationary probabilistic models are the dimension chain calculations per GOST 16320 using the probabilistic method based on a model, according to which closing dimensions are allowed to overrun the tolerance limits with substantiated economic risk, and using the maximum-minimum method based on a model, according to which closing dimensions are not allowed to overrun the tolerance limits in order to ensure complete interchangeability.

An item's operation subject to a temporal factor model and external effects can be represented as two mathematical models that describe the performance of the required functions in the specified modes and conditions of operation:

- the stochastic, whereas the stationary probabilistic model of the item is regarded as the information model in the form of a black box that implements the output effects depending on the specified modes and conditions of operation (based on mathematical processing of the statistical information on the behaviour of the actual item or its physical model with no regard for the laws of nature) (similar to the dimension chain calculation by the probabilistic method);
- the physical (or, most probably, quasi-physical, as no actual item exists yet), when a stationary probabilistic model of the item in the specified modes and conditions of operation is represented as a system of corresponding mathematical equations that reflect the sum of the knowledge, notions and hypotheses associated with the realization of output effects based on the physical laws of nature (equivalent of dimension calculation by the maximum-minimum method).

The above mathematical functional models correspond to the dependability models that are based on the functional and parametric definition of dependability [9]:

• functional, whereas the required functions are characterized by the probability measures of failures (statistical, logical, Bayesian, subjective);

• parametric, whereas the required functions are represented as a set of parameters that characterize the ability to perform them and the allowed range of variation of such parameters (the parameters are measurable or calculated physical values).

If required, the parameters and probabilistic functional indicators of the item can be reduced to a consistent dimensionless form (if the parameters can be represented as the probability of value variation within the allowed range similarly to the explanation given in GOST 27.002 [1]). That allows considering the functional dependability model as a special case of the single parametric model of dependability that simultaneously takes into consideration the physical and statistical (mathematical) nature of things based on the physical (quasiphysical) and stochastic models [19, 20].

The above models allow regarding an entity as a set of properties of structural components and elements that are to become manifest in the course of required operation. Such properties may be conceived in drawings separately from the entity as abilities and implemented in its physical form provided that required functions are fulfilled at the stage of manufacture and operation. The abilities and properties can be described indiscriminately by both parameters, and probability measures depending on the adopted dependability models (functional or parametric). The dependability of the required functions is defined using a dependability structure diagram after reducing the quasi-physical functional model to the dimensionless form consistent with the probabilistic model. As the result, the known model of dependability calculation of unique and small-batch entities based on known dependability indicators of components and elements [1] is replaced – with no loss of meaning – with a dependability calculation model based on the probabilities of performance by the components and elements of the required functions. In this case the designer is able to choose the dependability calculation model based on the objective knowledge of the nature (mathematical or physical) of the entities' operation, while the probability of performance by the entity of any of its functions can be conceived, implemented and supervised by the designer at any life cycle stage.

**Generalized parametric model of product operation.** If an entity is regarded as a structure that, in the course of operation, is able to resist the environmental effects [7], it can be represented with a set of output parameters (or probability measures), whose values are defined and limited by the modes and conditions of such exposure under the specified operation time. Thus, any entity can be reduced to a parametric representation in the form of:

• a set of output parameters that characterize the required functions for the performance of the service purpose,

• the allowed values of output parameter variation defined by the modes and conditions of application;

• the operation time, during which the values of the output parameters will not exceed the allowed limits.

The sum of an entity's output parameters (or probability measures) that characterize the presence and specific set of abilities to perform the required functions is its ***functionality*** that can be expressed as

$$X = \{X_1, X_2, \ldots, X_i\}, \tag{1}$$

where $X$ is the set of output parameters $X_i$ that define the performance of the required functions.

Output parameters can be any parameters of an entity that can be associated with the environmental effects based on the "more-less" criteria, e.g. for instance:

• strength as a generalized characteristic of the geometrical dimensions of the cross-sections of structural units and mechanical properties of structural materials resisting environmental loads (the load-carrying ability of the structure is to exceed the actual loads);

• the drive moment as the characteristic of the power sufficiency of the mechanism actuator for the purpose of overcoming the obstructing stress (drive moment is to be higher than the moment of the resisting forces);

• gaps in kinematic pairs as the parameters that resist the possible temporal variation of the dimensions of the mating parts, e.g. due to thermal deformations (the allowances within the couplings are to be positive);

• other parameters that characterize an entity in terms of resistance to the specified environmental loads and effects (that can be calculated and measured).

In the course of operation of a structure, the output parameters $X_i$ can change their values with time within the allowable ranges defined by the modes and conditions of application. The values of output parameters (or probability measures), under which an entity is able to perform the required functions, characterizes its ***operability*** (up state):

$$D_x = \{X_i(t) | \alpha_i \le X_i(t) \le \beta_i\}, \tag{2}$$

where $D_x$ is the range of acceptable values of variation of output parameters $X_i(t)$; $\alpha_i$ and $\beta_i$ are the lower and upper limits of the variation range of output parameters.

Identifying operability (2) involves all necessary calculations of entity parameters based on the physical models of natural phenomena and man-made processes with regard to the limitations imposed by the modes and conditions of operation.

The probability of output parameter (or probability measure) values of a structure being within the allowable area over time is characterized by the ***dependability***, the property of retaining in time the ability to perform the required functions in the specified modes and conditions of operation:

$$R = P\{X_i(t) \in D_x, 0 < t < t_k\}, \tag{3}$$

where $R$ is the dependability of the item as the probability $P$ of the values of output parameters $X_i(t)$ being within the allowable range $D_x$ within the time to failure $t_k$.

Identifying the probabilities (3) by estimating if parameter values are within the allowable limits within the time to failure can be done with the use of two interchangeable methods [1, 19, 20]:

• deterministic (by designing reserves per each of the parameters in such a way as to, with a certain degree of confidence, guarantee the presence of the values of the considered parameters within the allowable limits);

• stochastic (e.g. by estimating the design individual dependability, which essentially consists in calculating the probabilities of parameters being within the allowable limits based on the individual characteristics of the materials, loading/exposure processes and entity manufacture processes).

The set of formulas (1) – (3) is a generalized parametric model of an entity's operation [20], in which the criteria of the required functions (output parameters and allowable value variation limits) are interrelated, mutually conditioned and serve the aim of achieving the specified operability and dependability of the item in the process of completion of the service purpose.

As the presented model is based on the functional approach [21], such model allows disregarding the specifics of the design of entities and can be used for describing the operation of technical systems of various purposes, e.g. structures, single or multiple operation mechanisms, electromechanical devices, electronic assemblies, load-bearing and precision-built structures, etc. Researching the generalized parametric model of operation allows the designer to get rid of the cognitive distortion of the meaning of dependability, as it associates the feasibility of all calculations required for the selection of structural parameters with the consideration of compliance with the criteria of required functions to ensure the specified operability and dependability. The dependability in this case acts as operability expanded in time (3).

The above models can be solved using design engineering analysis of dependability (DEAD) described in detail in [19, 20] that, without getting into specifics, can be broadly reduced to the performance of three analysis procedures:

• initialization in the form of parametrization (transformation of the entity into a set of parameters or probability measures and allowable ranges of variation), that is done for establishing conditions (1) – (2);

• calculation of theoretical dependability based on design parameters according to (3);

• providing the evidence that the analysis (estimation) corresponds to the reality (requirements of the design and process engineering documentation, conditions of production, quality assurance measures) [19].

Thus, DEAD is in reality a roadmap for the design and development of entities with required dependability that allows – based on parametric modeling – selecting the structural parameters that ensure unconditional performance of the required functions that at the stage of manufacture must be executed and confirmed.

**Conclusion**. Applying the above concepts, approaches, models and methods, dependability – in the eyes of a designer – becomes operability expanded in time. Such dependability is always specific and takes into consideration all the distinctive features of an entity.

The process of design and assurance of dependability is becoming an integral part of entity creation activities regardless of their uniqueness, series production, presence or absence of dependability indicators of components and elements. But most importantly, such approach to dependability, on the one hand, does not contradict the foundations of the modern dependability theory, and, on the other hand, relieves the designer of the impression that dependability is something foreign, not associated with the real design.

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## The author's contribution

The paper examines the mathematical models of dependability that can be solved using the method of design and process dependability analysis developed by the author for the purpose of analyzing and assessing design solutions as part of high-dependability item design. The paper builds upon the author's ideas set forth in the paper *Dependability in digital technology* (see. Dependability Journal no. 2, 2020).

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# Development of the technology dependability automaton (substantiation of standardization regulation)

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**Abstract. Aim.** *This paper presents the development of the dependability automaton. The development is a conceptual description of the automaton as the term structure of a fixed complexity that shows non-contradictory interrelations and clear dependability state transitions of an item. The description of the state structure of the automaton implies subsequent development of a computing device for monitoring the dependability of items of any nature. Unlike in the standard, dependability is defined as a set of states, the measure of concordance with the purpose of an item. The purpose is defined as the property of an object attributed to the natural origin or designed application. In accordance with such definitions, alternative definitions of dependability states have been developed. An observation of the dependability states of an item can be described with a common algorithm. The problem is defined with the help of the automata theory.* **Methods.** *We will call a dependability automaton (DA) a deterministic, fully specified finite-state automaton. In the automata theory, the properties of items are examined in terms of being in states and transitioning between them. Dependability states change in terms of disruption and restoration of item purpose. Such changes can be represented as a directed graph, whose nodes correspond to states, while the edges correspond to transitions between states. As the dependability restoration states are deterministic, they can be represented as processes, i.e. planned, consisting of activities, measures, procedures, operations. The states of disrupted dependability are random, therefore they can be considered as events. Thus, the property of an entity's purpose is observed when the states of dependability are observed that change in events and processes. The automation is described using terms and symbols from standards, as well as alternative definitions of states developed by the author. A review of the appropriate standards is to involve a new terminology. The operation of the dependability automaton reflects transitions and alternative transitions. Restoration is designed as a complete and partially incomplete processes: a) transition from the down state into the up state; b) transition from the down state into the faulty state; c) transition from the down state into the good state. The findings contributed to the development of theoretical and practical dependability of organization, social groups and individuals. The dependability automaton concept includes the development of the engineering design of an expert decision support system for flight operation of an airline.* **Conclusion**. *Technical standards require prior preliminarily philosophical, philological, logical review. Such research is to produce logical proof and substantiation of a set of coordinated, non-contradictory ontological terms: property, state, event, etc. The results will be used in technical standards for the purpose of construction and substantiation of special terms. The paper provides a theoretical and practical substantiation of applying individual provisions of the dependability theory of technology for the purpose of developing the dependability theory of non-digital entities.*

**Keywords:** *dependability, terminology, standardization, regulation, dependability automaton.*

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## 1. Introduction

In this paper, unlike in the standard [1], dependability is defined as a set of states, the measure of concordance with the purpose of an item. The purpose is defined as the property of an item attributed to the natural origin or designed application. In accordance with such definitions, alternative definitions of dependability states have been developed.

An observation of the dependability states of an item can be described with a common algorithm. The problem is defined with the help of the automata theory [2]. In order to solve the problem, it is suggested to develop a dependability automaton (DA). The development is a conceptual description of the automaton as the term structure of a fixed complexity that shows non-contradictory interrelations and clear dependability state transitions of an item. The description of the state structure of a DA implies subsequent development of a computing device for monitoring the dependability of items of any nature.

## 2. Development of dependability automaton

**Problem definition.** We will further call a dependability automaton designated as D (dependability) a deterministic, fully specified finite-state automaton. DA is defined by a set consisting of the following elements:

$D = \{X, S, Y, \delta, \lambda, s_0\}$,

where $D$ is the DA;

$X$ is the input alphabet of the automaton (set of input symbols): $X=\{x_1, \ldots, x_m\}$;

$S$ is the automaton states: $S = \{s_0, \ldots, s_n\}$, $s_0$ is the initial automaton state;

$Y$ is the output alphabet of the automaton (set of output symbols): ;

δ is the specified indication of states at a set of input signals, the function of automaton transition from one state into another: $s_j = \delta_i(s_i, x_k)$, where $s_j$ is the subsequent state of the automaton, $s_i$ is the current state of the automaton; $x_k$ is the current input symbol;

λ is the specified indication of states at a set of output signals, the output function: $y_l = \lambda_i(s_i, x_k)$, where $y_l$ is the subsequent output symbol of the automaton, $s_i$ is the current state of the automaton; $x_k$ is the current input symbol.

The conditions are: sets $X, S, Y$ are finite; the output symbol ($y_l \in Y$) depends on the input symbol $x_k \in X$) and the current state of the automaton ($s_i \in S$); description entries of the automaton are defined at discrete instants in time.

The deterministic automaton: a) from state $s_i$ under the influence of signal $x_k$ transitions into state $s_i$; at the output, $y_h$ changes to $y_1$; b) for $(x_i, y_i) \in (X, Y)$ δ and λ are defined.

## 3. Structure of automaton states

In the automata theory, the properties of items are examined in terms of being in states and transitioning between them. Dependability states change in terms of disruption and restoration of item purpose. Figure 1.

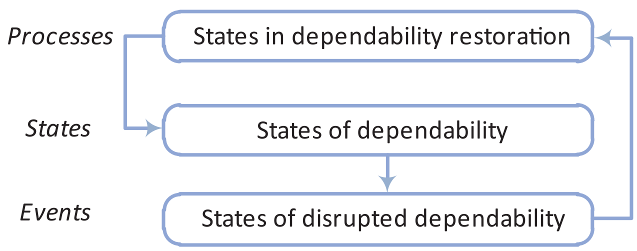


Fig. 1. Observation of dependability

Such changes can be represented as a directed graph, whose nodes correspond to states, while the edges correspond to transitions between states. As the dependability *restoration* states are *deterministic*, they can be represented as processes, i.e. planned, consisting of activities, measures, procedures, operations. The states of disrupted dependability are *random*, therefore they can be considered as events. Thus, the property of an entity's purpose is observed when the *states* of dependability are observed that change in *events* and *processes*.

The automaton is described using terms and symbols of standards [1], [3] and alternative definitions of states developed by the author. A review of the appropriate standards is to involve a new terminology. For instance, the definition of the term "defect" clearly does not correspond to the technical sense. In standard [1], "defect" is defined as the non-compliance on an item with the requirements specified in the documentation. In standard [4], "defect" is defined as non-fulfillment of the requirement associated with the presumed or specified use. The basic states in this paper are set forth as follows (Table 1).

**Table 1. States of the dependability automaton**

| Terms | States | Ω |
|---|---|---|
| | maintenance | $(s_{mtn})$ |
| Processes | repair | $(s_{rep})$ |
| | restoration | $(s_{rest})$ |
| | up state | $(s_{up})$ |
| | perfect state | $(s_{per})$ |
| States | imperfect state | $(s_{imp})$ |
| | down state | $(s_{dw})$ |
| | failure | $(s_{fail})$ |
| Events | defect | $(s_{def})$ |
| | degraded state | $(s_{deg})$ |

## 4. Development of DA algorithms

The description of the DA operation consists in the translation of the standard terms into symbolic algorithms suitable for subsequent software development. Let us introduce the following symbols and construct the algorithm of DA operation:

$\overline{D}$ is dependability;

↓D are dependability disruptions;

↑D are dependability restorations;

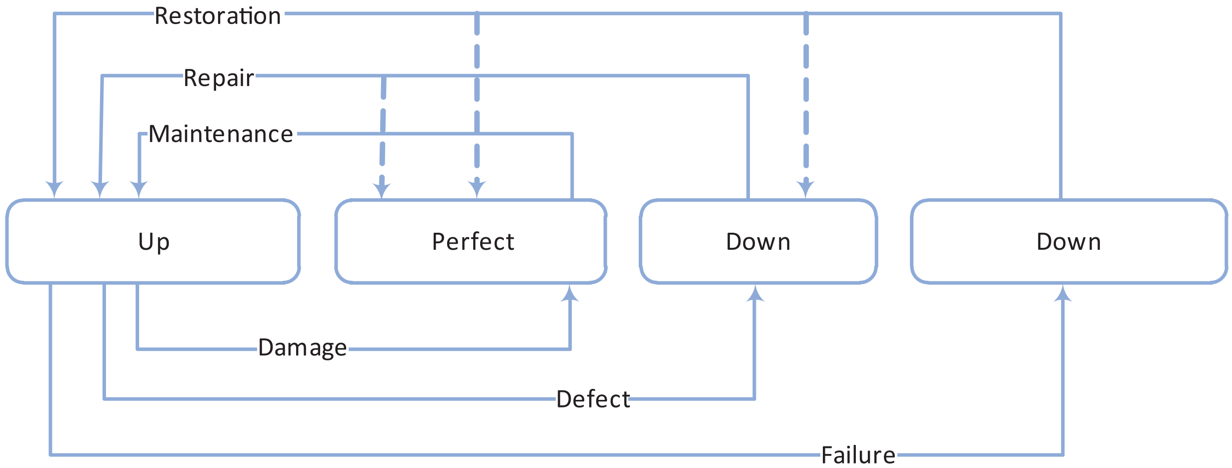


Fig. 2. Conceptual diagram of the dependability automaton

$(s_j \rightarrow s_i)$ are the transitions from the current state into the subsequent state in dependability disruption events;

$(s_j \leftarrow s_i)$ are the transitions from the current state into the subsequent state in dependability restoration processes;

$\overleftarrow{S}$: $(s_{rest} \subseteq s_{rep} \subseteq s_{eng})$ are subsets of dependability restoration states (processes);

$\vec{S}$: $(s_{fail} \subseteq s_{def} \subseteq s_{deg})$ are subsets of dependability disruption states (events);

$(s_j \rightarrow s_i)| \vec{S}$ are transitions amidst dependability disruption events;

$(s_j \leftarrow s_i)| \overleftarrow{S}$ are state transitions amidst dependability restoration events;

DA states are shown in the diagram (Fig. 2).

Dependability states:

$\overline{D}: s_{up} \mid \left(s_{up} \leftarrow s_{eng}\left(s_{per} \leftarrow s_{rep}(\leftarrow s_{rest})\right)\right)$ is the up state by maintenance, repairs, recovery condition;

$\overline{D}: s_{per} \mid \left(s_{per} \leftarrow s_{rep}(\leftarrow s_{rest})\right)$ is the good state by repairs, recovery condition;

$\overline{D}: s_{imp} \mid \left(s_{imp} \leftarrow s_{rest}\right)$ is the faulty state by recovery condition;

$\overline{D}: s_{up} \mid s_0$ is the down state.

States in dependability disruption events:

$\downarrow \mathrm{D}: s_{deg} \mid s_{eng}$ is the damage by maintenance condition;

$\downarrow \mathrm{D}: s_{def} \mid s_{rep}$ is the defect by no-repairs condition;

$\downarrow \mathrm{D}: s_{fail} \mid s_{rest}$ is the failure by no-restoration condition.

States in dependability restoration processes:

$\uparrow \mathrm{D}: s_{eng} \mid \left(s_{up} \leftarrow s_{per}\right)$ is the maintenance for transition from the good state into the up state;

$\uparrow \mathrm{D}: s_{rep} \mid \left(s_{up} \leftarrow s_{per}(\leftarrow s_{imp})\right)$ are the repairs for transition from the faulty state into the up (good) state;

$\uparrow \mathrm{D}: s_{rest} \mid \left(s_{up} \leftarrow (s_{per} \leftarrow \left(s_{imp} \leftarrow s_{dw})\right)\right)$ is the restoration for transition from the down state into the up (faulty, good) state.

**Discussion**. The operation of a DA reflects transitions and alternative transitions. Restoration is designed as a complete and partially incomplete processes: a) transition from the down state into the up state; b) transition from the down state into the faulty state; c) transition from the down state into the good state. The states of DA summarize the resource hierarchy in terms of "restoration" $\subseteq$ "repairs" $\subseteq$ "maintenance". However, all technology dependability standards lack a substantiation of the term hierarchy.

## 5. Theoretical and practical implementation of DA

The findings contributed to the development of theoretical and practical dependability of organization, social groups and individuals (Fig. 3) [5].

The DA concept includes the development of the engineering design of an expert decision support system (ES) for flight operation of an airline. The ES has functional modules, includes a knowledge base or ES shell, as well as named functional units: information assets transformation system (IATS); module for indicator data analysis and prediction of the states of pilot resources; solver or pilot resources management decision-making module. The DA is represented as the sum of pilot resources (SPR) consisting of three groups of properties of dependability: individual dependability resources (IDR), professional dependability resources (PDR), operational dependability resources (ODR). Such grouping is based upon the structural approach to defining standard terms consisting in the partition of abstract concepts using the example of the category of "dependability".

Using that approach, a base of observation in time has been developed: IDR, the time of human evolution, PDR, the time of employment between ages 20 and 60, ODR, the time from the duration of one flight up to a year. The new SPR structure allows defining various norms and limits, which improves the flight efficiency and safety supervision [6].

## 6. Conclusion

Technical standards require prior philosophical, philological, logical review. Such research is to produce logical proof and substantiation of a set of coordinated, non-contradictory ontological terms: property, state, event, etc. The results will be used in technical standards for the purpose of construction and substantiation of special terms. For instance, why the term "failure" is larger than the term "damage" in terms of

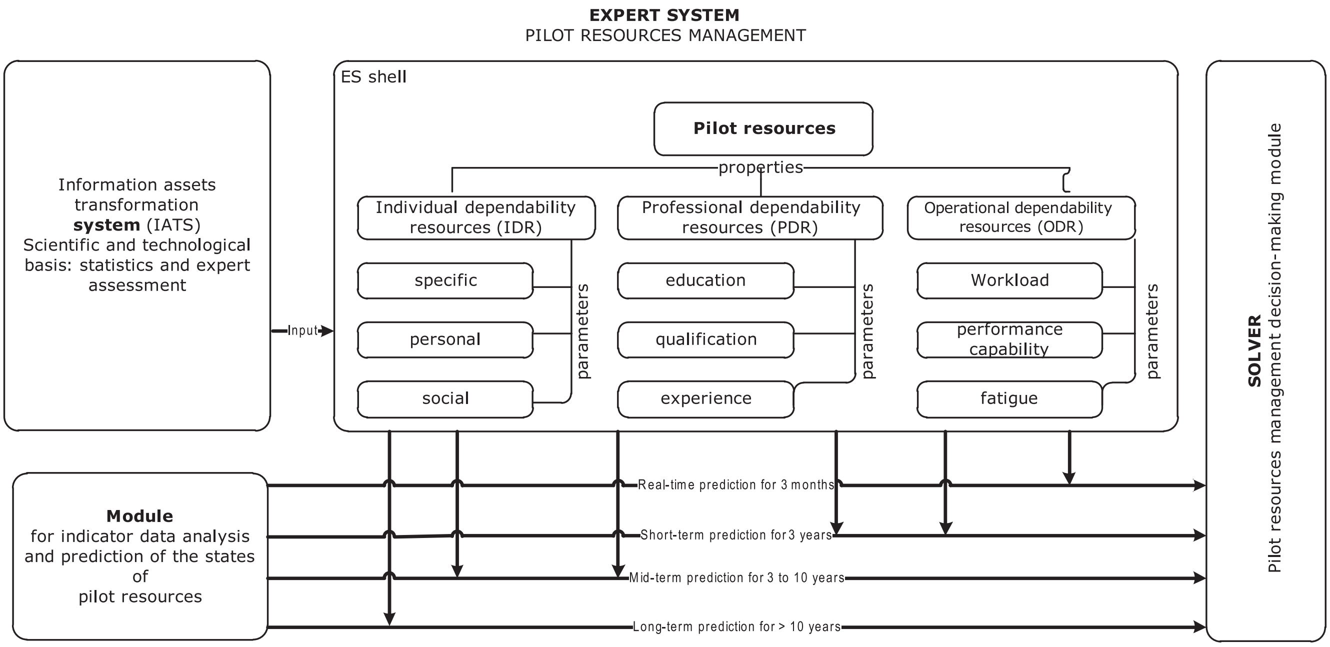


Fig. 3. Dependability automaton of an individual (commercial aviation pilot)

scope and content in the physical and technical senses. The paper provides a theoretical and practical substantiation of applying individual provisions of the dependability theory of technology for the purpose of developing the dependability theory of non-digital entities.

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## The author's contribution

The author analyzed dependability standards. Logical analysis of the concept of dependability was performed. The author suggests solving the dependability terminology problem in the automata theory by describing the general algorithm of state transition in the restoration processes and dependability disruption events.

## Conflict of interests

The author declares the absence of a conflict of interests.

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# On safety assessment of artificial intelligence

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**Abstract**. **Aim.** *In this paper we discuss how systems with Artificial Intelligence (AI) can undergo safety assessment. This is relevant, if AI is used in safety related applications. This holds also for railway systems, where AI is expected to take a role in railway automation.* **Methods.** *The focus of this paper is on safety assessment of AI rather than on AI itself. Taking a deeper look into AI models, we show that many models of artificial intelligence, in particular machine learning, are statistical models. Safety assessment would then have to concentrate on the model that is used in AI, besides the normal assessment procedure.* **Results.** *Part of the budget of dangerous random failures for the relevant safety integrity level needs to be used for the probabilistic faulty behavior of the AI system. We demonstrate our thoughts with a simple example and propose a research challenge that may be decisive for the use of AI in safety-related systems.*

**Conclusion.** *The method of safety assessment of systems with AI is presented in this article.*

**Keywords:** *artificial intelligent, safety assessment, functional safety.*

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## Introduction

In the last years, artificial intelligence (AI) has become more and more popular and an increasing number of applications has been reported. These include for example

- Data processing
- Assistance systems
- Speech recognition
- Face recognition
- Nursing robots
- Autonomous driving systems
- Art etc.

Some of the applications of artificial intelligence may be safety relevant. Then, functional safety standards [8, 9. 10] should be applied and as a consequence, safety assessment is required.

In this paper, we consider safety assessment of systems with AI. In the second section we describe, what AI means. In the third section we show, how a safety integrity level for AI systems can be obtained. In section four we will take a deeper view into AI systems – this is necessary to understand AI systems and to have an approach to them in terms of functional safety. In the fifth section, we describe the requirements of the functional safety standards for AI systems and a possible assessment procedure. In section six, we provide an example, of how safety assessment could be carried out on a very simple system. In the last section, we present our conclusions.

## What is artificial intelligence?

There exist many publications and many systems are named as being artificially intelligent. An overview can be found e.g. in Brunette et al [3]. The starting point of AI development was the Turing test in the 50s, which is intended to check whether a computer exhibits intelligent behavior, comparable to that of a human being. Later on, the concept of evolutionary programs has been established. The term "Artificial Intelligence" has first been used at Dartmouth College in 1956. In the meanwhile, different concepts have been proposed by many researchers.

Artificial Intelligence can be defined as intelligence demonstrated by machines. Artificial intelligence mimics cognitive functions, learning, problem solving etc.

A question is, whether the following are criteria of intelligence points would be criteria for artificial intelligence or not:

- use of speech,
- consciousness,
- self-awareness.

But while there are truly astounding results, there are many articles and presentations about the „deep learning hype", see e.g. Hättasch&Geisler [7], and as far as we know there is so far no published complete safety argument for any AI application, but there are many research projects on safety justifications for AI.

However some approaches have been recently made from a safety point of view, most notably the draft UL 4600 standard [15], which demands a safety case approach for autonomous vehicles, that may utilize AI algorithms. However also UL 4600 elaborates only on What to argue, but not the How. This is clearly described in the preface: "Conformance with this standard is not a guarantee of a safe automated vehicle." Its emphasis is rather on "repeatable assessment of the thoroughness of a safety case". UL 4600 is intended be used as an extension of IEC 61508 [10].

Other standardization committees, e. g. the German DKE, focus on a process and lifecycle oriented approach. Putzer [13] propagates a $\lambda$AI, a measure similar to a hazard rate in functional safety, but gives no concise definition.

## Does AI need a SIL?

In this section we will discuss, whether we would need a safety integrity level for artificial intelligence and if yes, how it should be determined.

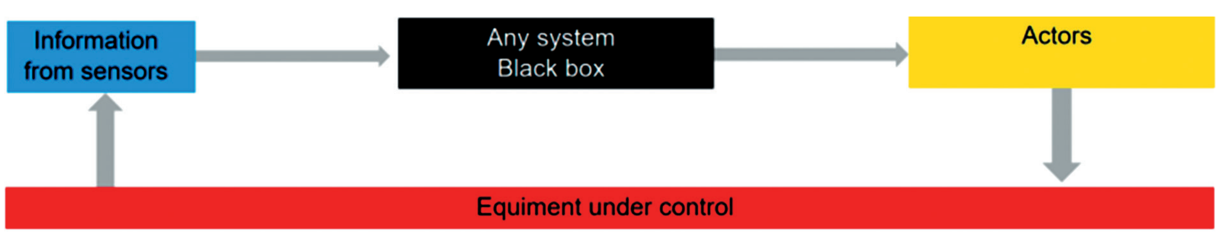


Figure 1 – E/E/PE Control system

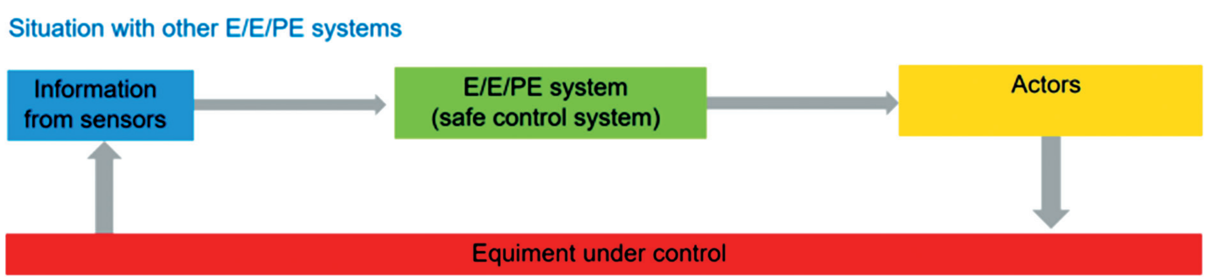


Figure 2 – Arbitrary control system (black box)

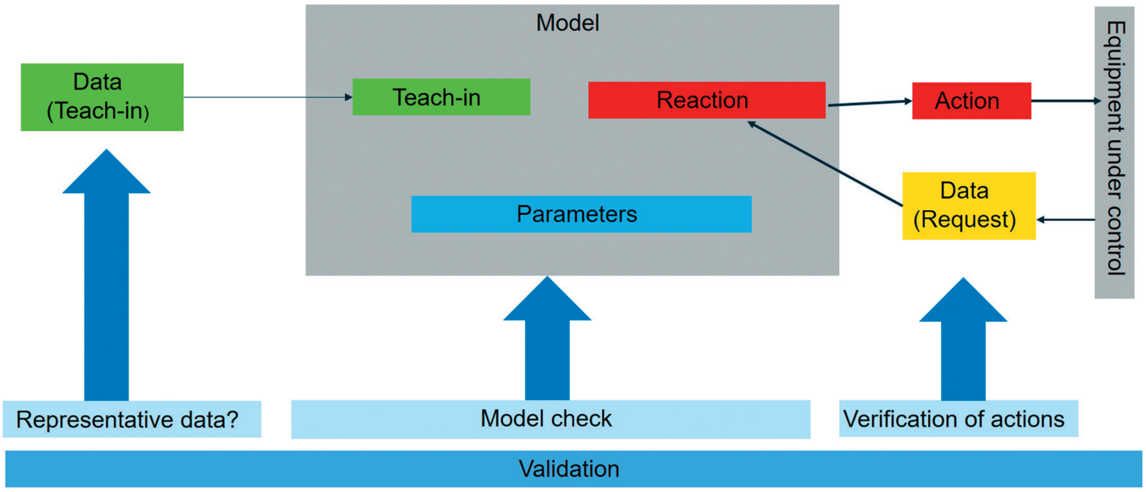


Figure 3 – Architecture of an AI system

The concept of Safety Integrity Level (SIL) is used in many standards for functional safety. The mother standard is the well-known IEC 61508. The reader may be referred to Schäbe [14] for the determination of SILs.

The following figure 1 shows the situation with a conventional electric, electronic, programmable electronic system (E/E/PE system). Here, we have an equipment under control, information form sensors that enter the control system and actors operated by the control system. Depending on the consequences of faulty behavior of the control system, the latter gets a safety integrity level (SIL).

Now, it does not matter what type of control system we have. For the hazard analysis and the determination of the SIL it is considered as a black box anyway. This is depicted in figure 2.

Now, the black box can also be an AI system. Therefore, also a safety integrity level can be necessary if the AI system fulfills safety relevant tasks and the SIL can be determined by the same methods as for an E/E/PE system. Only the rules for the assessment of the SIL may be different depending on the type of system that implements the black box.

What SIL would we have to expect for different AI applications? This would mainly depend on the failure consequence and if other risk mitigations are possible:

• Data processing – depends on the results and what is done with it

• Assistance systems – normally no SIL if a human can always override the system

• Speech recognition – depends on what is done with the result and whether there are safe backups

• Face recognition – depends on what is done with the result, i.e. which functions are activated

• Nursing robots – giving medicine, carrying patients, so surely a SIL would be required

• Autonomous driving systems – can lead to accidents, so a SIL would be required

In any case, a hazard and risk analysis needs to be carried out to determine the SIL – or the fact that it is not necessary to determine one. The relevant functional safety standard has to be applied.

## Looking inside AI

### AI architecture

Figure 3 shows a very simple architecture of an AI system. The architecture has been inspired by Wang [16] but does not resemble it.

Inside the AI system is the model, the most important feature. This model is flexible and needs to undergo a teach-in. This is done on the basis of some data. These data must be representative, i.e. they must be adequate to resemble future situations. It is necessary to avoid situations as mentioned e.g. reported by Corni [5], where an AI system shows racism, which was imported via a non-representative set of data for learning.

After teach-in, parameters are set in the model. This is later used to generate reactions to request data and activate actors in order to control the equipment under control. Possibly, teach-in can continue even after the system has been put into exploitation.

Then it is important to

• Check the model,

• Check the representativeness of the data,

• Verify the data – model reaction – action chain, and to

• Carry out an overall validation.

Verification of the model includes the use of test data – they must also be representative and cannot be the same as the data used for teach-in. In the following subsections, we will take a deeper look into several types of AI systems. This will refine the model part of the architecture described in figure 3.

### Looking at AI by Similarity Analysis

As explained by figure 3 most AI algorithms rely on or are at least similar to statistics. So as a first approach to explore the requirements for use of AI in safety applications we could what a statistical procedure would have to fulfill if we wanted to use it for safety applications. This can also be interpreted as a kind of similarity analysis. What can we learn from statistical procedures? What would be the consequences if AI algorithms e. g. machine learning could just be interpreted as statistical data fitting – but with very complex algorithms and big data? Note that this consideration is a simplified one in order to support a basic understanding of AI that would allow applying methods of safety assessment.

To explain the situation intuitively, let's use one of the simplest statistical models, which every engineer knows from school: linear regression i. e. fitting of a (straight) line to data. What can we learn in general from it? Note that this observation is not new, Pearl and Mackenzie [12] already stated that neural networks "…are driven by a stream of observations to which they attempt to fit a function, in much the same way that a statistician tries to fit a line to a collection of points." But to the knowledge of the authors this similarity has not been fully exploited yet.

Let us assume that some safety-critical decision would depend on the goodness of the fitted curve. A very good example what can go wrong has been constructed by Anscombe [1]. In his data sets, see figure 4, all relevant statistical measures are equal to at least two decimal places, although obviously the sets appear very different.

Figure 4 gives some examples of a correct fit (data set 1); a data set (2), where obviously the wrong model was used; a data set (3), which is influenced by an outlier; and data set (4) with a leverage point, which results from a completely inadequate experimental design. Even from this simple example we can draw some important conclusions:

1. The model must be correct – otherwise we will never fit the data well (see data set 2), no matter how long we learn or how good the data might be.

2. The training data must be representative of the real data; particular we must make sure that the sampling is adequate (see data set 4)

3. We must have means to detect outliers (and even to remove them, see data set 3) or even Black Swans

4. We need a measure of goodness of fit (like R2 in normal regression). But such a measure and the calculated fit depends on the loss function (see data set 1, where the usual least squares loss function is assumed like in all other fits in figure 4)

## Machine Learning as a classification problem

Machine learning (ML) is a particularly successful variant of AI. Statistically it can also be interpreted as a classification problem, which provides another look on the problem. So, all our findings in the preceding section directly hold for ML. Basically, many ML algorithms solve classification problems, similar to cluster or discrimination analysis in statistics. We have (at least) two classes of (big) data in a high dimensional space., see figure 5 for an illustrative two-dimensional example. In other cases, ML algorithms solve regression problems or reduce dimensionality, later a statistical approach could be applied to understand those models. In the remainder of this section, we restrict ourselves to classification problems.

An optimal discrimination function would separate the classes completely for the training set. We may assume that a true ("correct") discrimination function exists (the red curve in figure 5), but in practice ML algorithms calculate

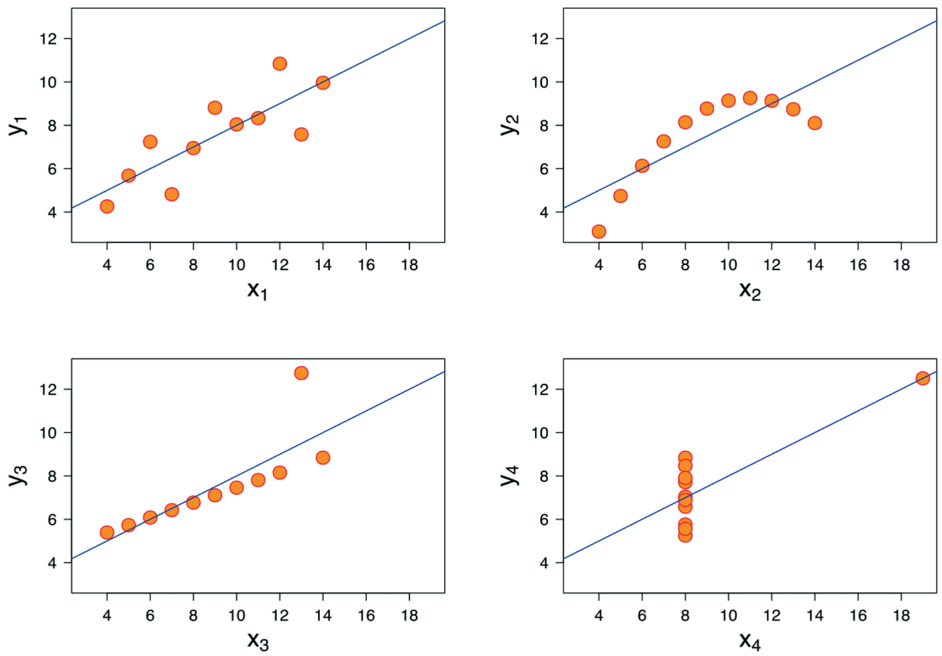


Figure 4 – Examples of what can be learned from linear regression

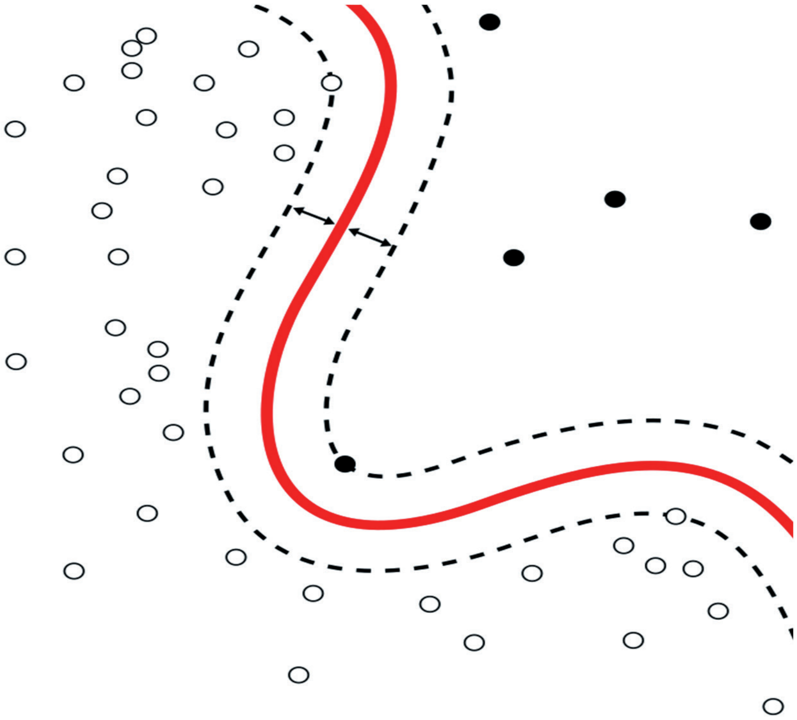

Figure 5 – Discrimination of two data sets in classification


an approximation of the true function. However, there remains some space between the two classes and there exists no unique solution for the problem.

## Artificial Neuronal Networks and the General approximation Theorem

The most polular and recently most successful variant of ML algorithms are Artificial Neural Networks (ANN) [4, 11]. Each ANN has at least two layers that are connected by weights. A simple example is shown in figure 6.

A mathematical model of this simple ANN can be described as follows: the input data vector x is transformed by weights v and w, offsets b and an output function φ (non-constant, bounded and continuous) to two output classes

$$F(x) = \sum_{i=1}^{N} v_i \phi\left(w_i^{\mathrm{T}} x + b_i\right) \tag{1}$$

The optimal weights for a particular cost function C, which is defined in addition to (1), are found iteratively based on the training data and a numerical algorithm.

More complex ANN add additional hidden layers (often called deep networks), but the mathematical description and solution is similar.

From our general discussion above immediately the following questions arise:

1. Is F the correct function to discriminate the data well?
2. Does it approximate the true function well?
3. Or do we need more layers or more complex functions?
4. How can we make sure that the training data are representative?

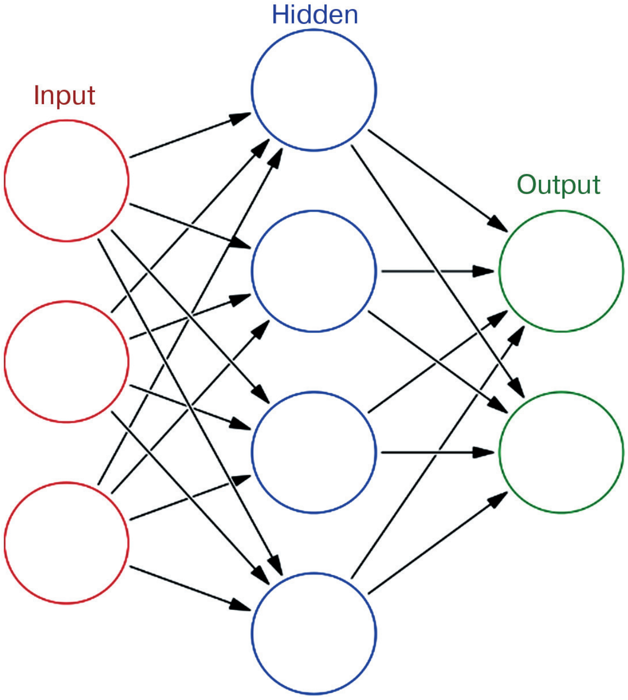


Figure 6 – artificial neural network with two layers


5. How can we detect outliers?
6. How can we justify the cost function C?

If we cannot answer the questions sufficiently, we might have systematic flaws in the model!

Fortunately, for question 1 there exist a variety of so called “universal approximation theorems”, that show convergence of F to f, the true function, provided φ is a bounded and continuous function and if f is continuous, see Cybenko [6]. Note that this is convergence as in the calculus definition, not some stochastic convergence.

This is quite a strong result, but it has implications related to the other questions. The most limiting assumption is the continuity of the true function f, which means that our problem space must be separable by a continuous function. And also φ must be continuous, so we can't use jump functions for the decision making.

At first glance this result is surprising because it already holds for ANN with a single hidden layer but on second thought the results are quite obvious and a have a simple explanation:

1) F is a kind of general linear approximation to f. But it is obvious that such linear approximation for a continuous function f should be possible if the number of nodes N is sufficiently large. Also, in the classification example in figure 5 f could be approximated by stepwise linear functions.

2) Also, deep ANN with several hidden layers could be represented by single layer (with large N). Just think that the true function f would be the function represented by the multi-layer network, which by the approximation theorem again could be approximated by a single layer function F.

For dependable applications, the requirements to answer question 1 could be:

1) Choose a single-layer ANN with sufficiently large N. N could be determined by a convergence criterion as known from calculus.

2) The more difficult assumption that needs to be justified would be that the data sets can be separated by a continuous function. This argument would depend on the type of application data and can hardly be general.

3) Choose an appropriate cost function C (with justification).

## Data and Goodness of fit

The second question deals with the adequacy of the training data and also with the associated stopping rule: when is training finished?

Representative data means that teach-in must occur in a typical environment for this type of system and the environment must be such that the influences are typical for this type of use, including all the changes in the environment. So, all replications of the system (after teach-in) must be operated at least in similar environments and all replications of the system must be similar, compare Braband et al. [2]. Here we must in particular also take care of the Black Swan problem (related to question 3). Possibly we have to introduce safety-related application rules for the environment in which the system will operate.

Another question is goodness of fit. How do we measure goodness-of-fit for the training data? Can we accept failure in training data? Generally, any misclassification in training data could lead to a high proportion of classification failure in practice. Take as an example the black point on the boundary line in figure 5. Assume now that both data sets are separated by the true (red) function f in figure 5. If this particular point is mis-classified, a whole set of points close to the black point would be misclassified, too, resulting in a high failure rate. On the other hand this point might also be an outlier.

This means

1. Either we have 100% correct classification in the training data, or

2. We can calculate the error probability well

The problem is that we cannot simply count classification errors. We have to weight them according to their importance, which may be difficult in high-dimensional spaces and big data.

Furthermore, teach-in has clearly statistical aspects. This means:

- Confidence bounds need to be taken into account.
- Derived parameters are random values containing some spread
- The subsequent decisions of the AI will also be random, with some errors:

- First kind error: wrong decision, although the input data are in the „right" domain

- Second kind error: input data are in the „wrong domain", but decision is „right".

As a consequence, the AI will have a failure probability. This must be taken into account, assigning part of the budget of the rate of dangerous failures to the AI (here: the algorithm).

## The position of functional safety standards on AI and a possible assessment procedure

If AI is used for safety relevant applications, the standards on functional safety would come into play. We consult the basic standard, IEC 61508 [10]. Requirements of the functional safety standards – example: IEC 61508. The main information is contained in IEC 61508-3, table A.2:

no. 5 – Artificial intelligence / fault correction SIL 2 – SIL 4: NR (see C.3.12)

no. 6 – Dynamic reconfiguration SIL 2 – SIL 4: NR (see C3.13)

In part IEC 61508-7 an explanation can be found, what ai means in the terms of the standard

C.3.9 Artificial intelligence

Fault forecasting (calculating trends), fault correction, maintenance and supervisory actions may be supported by artificial intelligence (AI) based systems in a very efficient way in diverse channels of a system, since the rules might be derived directly from the specifications and checked against these. Certain common faults which are introduced into specifications, by implicitly already having some design and implementation rules in mind, may be avoided effectively by this approach, especially when applying a combination of models and methods in a functional or descriptive manner. The methods are selected in such a way that faults may be corrected, and the effects of failures be minimised, in order to meet the desired safety integrity.

In fact, the IEC 61508 sees AI as a means for fault correction and dynamic reconfiguration as a reaction of a fault in the control system. Such an application would make the control system unpredictable.

How to cope with the IEC 61508 rules against artificial intelligence? The statement in the standard is combined with a statement about dynamic reconfiguration, which is undesired for SIL 2 …SIL 4. If AI is implemented in the control system itself, this would not be a reaction on faults of the control system, it would be a feature.

The functional safety standard requires a predictable system. Predictable means that measures against systematic failures are sufficiently implemented, so that they can be neglected. Random failures‘ occurrence is brought to a sufficiently low level.

Therefore, AI system‘s behavior must be predictable in a statistical sense. Note that this predictive behavior here is not a deterministic behavior, but a statistically predictable behavior. This means that the AI system will contribute to random dangerous failures that would be caused by a random behavior of the software itself. This is a key difference to normal E/E/PE systems, where software is considered deterministic with systematic errors only requirements and following the software requirements of the functional safety standards would reduce them to an acceptable level.

An assessment approach can then be based on the following steps:

- Analyzing the model,
- Taking part of the budget for random failures for the AI system since it shows probabilistic behavior,
- Treat the AI system as a normal mathematical model, but only with probabilistic behavior.

Then assessment is carried out in the same manner as a normal safety assessment with a complicated mathematical model. It is not the intention of the author to repeat the procedures of safety assessment. For details of an assessment process see e.g. Wigger [17].

The main part of the assessment is the model check.

The mathematical model needs to be checked regarding the following aspects:

- correctness of the model according to physical / chemical / mathematical and other scientific proven theories,
- equivalence to other mathematical models as e.g. of brake curves, thermal models etc.

That means, the theory / model must be disclosed to the assessor. The models might be of one of the following types, see e.g. Wang [16]:

- Neural network,
- Long short-term memory,
- Auto encoder,
- Deep Boltzman machine,
- Generative adversarial network,
- Attention-based LSTM.

The more flexible the model, the more complicated its analysis will be. In the next section we provide an example on how such a model analysis could be carried out for a very simple model.

The great effort for model checking leads to the question, whether proven in use approaches could be applied. According to Braband et al [2] this would mean to accumulated a minimum number of failure free hours (here: no dangerous failures) according to the following scheme:

- $3 \cdot 10^6$ failure free hours for SIL 1;
- $3 \cdot 10^8$ failure free hours for SIL 4.

Practical experience shows that it is hard to accumulate such a quantity of failure free hours. As a result, model analysis as one of the main parts of safety assessment needs to be done.

## Academic Example

The following example is provided in order to give a general impression, how safety assessment could be carried out rather than to provide a model of an AI system. Assume a classification system that classifies objects in two categories: „left“ and „right“ based on one real-valued parameter. The parameter is assumed to be normally distributed. Note that statistically the model is completely defined by this assumption, which would have to be justified in practical applications. It can’t be taken for granted, and for this reason we label it as an academic example as we assume to know the true model.

There are two sub-populations characterized by the following distributions:

- „left“ is characterized by a normal distribution with mean $m_L$ and spread $\sigma_L$,
- „right“ is characterized by a normal distribution with mean $m_R$ and spread $\sigma_R$.

First, assume the parameters to be known.

Then the following classification rule is established:

„left“ if $X \leq z$ and „right“ if $X > z$,

where is a „properly“ chosen constant. Now the first kind error and the second kind error can be computed

$$\alpha = 1 - \Phi(z - m_L/\sigma_L) \text{ first kind error,} \tag{2}$$

$$\beta = \Phi(z - m_R/\sigma_R) \text{ second kind error,} \tag{3}$$

$$\Phi(z - m_L/\sigma_L) \text{probability of correct „left“ classification,} \tag{4}$$

$$1 - \Phi(z - m_R/\sigma_R) \text{ probability of correct „right“ classification,} \tag{5}$$

$\Phi$ – standard normal integral.

The first kind error is the probability that an object is classified in the sub-population "right" although it belongs to "left". The second kind error is the probability that that an object is classified in the sub-population "left" although it belongs to "right". The parameters $\sigma_R$ and $\sigma_L$ should be as small as possible to have small errors.

Now there is one missing point. Parameters $m_L$, $m_R$, $\sigma_L$ and $\sigma_R$ are not known but must be obtained by a statistical procedure that means that they must be learned from a sample of data.

How does the system learn? The system learns from two samples for the both sub-populations:

A „left" sample $XL_i$, i = 1, $n_L$ and a „right" sample $XR_i$, i = 1, …, $n_R$ are used for teaching.

From the samples, the unknown parameters can be estimated:

$$m_R = \frac{1}{n_R}\sum_i XR_i; \tag{6}$$

$$m_L = \frac{1}{n_L}\sum_i XL_i; \tag{7}$$

$$\sigma_R^2 = \frac{1}{(n_R-1)}\sum_i (XR_i - m_R)^2; \tag{8}$$

$$\sigma_L^2 = \frac{1}{(n_L-1)}\sum_i (XL_i - m_L)^2. \tag{9}$$

The point estimators of statistical characteristics are given in italics. The sum runs over the index i for 1 to $n_L$ or $n_R$, respectively.

In a next step the confidence limits for the parameters have to be used instead of the point estimators given by (6) – (9). Confidence limits will be chosen as such that the misclassification error becomes small, i.e. upper bounds for the sigmas and $m_L$ and a lower bound for $m_R$. We use single parameter bounds – not combined ones – to simplify the computation.

The point estimators (6) – (9) have the following distributions:

$(n_L-1)\sigma_L^2/\hat{\sigma}_L^2$, where $\hat{\sigma}_L^2$ is the dispersion of the "left" entire assembly that is chi-squared distributed with $n_L$-1 degrees of freedom;

$(n_R-1)\sigma_R^2/\hat{\sigma}_R^2$, where $\hat{\sigma}_R^2$ is the dispersion of the "right" entire assembly that is chi-squared distributed with $n_R$-1 degrees of freedom;

$\sqrt{n_L}\,(m_L-\hat{m}_L)/\hat{\sigma}_L$, where $\hat{m}_L$, $\hat{\sigma}_L$ are respectively the mean and standard deviations of the "left" entire assembly that has a *t* distribution with $n_L$-1 degrees of freedom;

$\sqrt{n_R}\,(m_R-\hat{m}_R)/\hat{\sigma}_R$, where $\hat{m}_R$, $\hat{\sigma}_R$ are respectively the mean and standard deviations of the "right" entire assembly that has a *t* distribution with $n_R$-1 degrees of freedom.

The least favorable values are:

upper confidence bounds for the standard deviation, i.e.

$$\sqrt{(n_R-1)/\mathrm{Chi2}(n_R-1;1-\gamma)}\cdot\sigma_R, \tag{10}$$

$$\sqrt{(n_L-1)/\mathrm{Chi2}(n_L-1;1-\gamma)}\cdot\sigma_L, \tag{11}$$

where Chi2(n;1-γ) is the quantile of the Chi-squared distribution with 1-γ coverage and

the lower confidence bound for $m_L$

$$m_L - \frac{t(n_L-1,\gamma)\cdot\sigma_L}{\sqrt{n_L}} \tag{12}$$

and the upper confidence bound for $m_R$

$$m_R + \frac{t(n_R-1,\gamma)\cdot\sigma_R}{\sqrt{n_R}}, \tag{13}$$

where t(n; γ) is the quantile of the t distribution with n degrees of freedom and coverage 1-γ.

Inserting the confidence bounds (10) – (13) into the formulae (2) – (5) gives the probabilities of errors.

If misclassification with a type one error is dangerous, (1) with (6) and (8) gives the probability of a dangerous failure. However, to account for errors coming from the confidence intervals, value

$$\alpha+2\gamma$$

should be used. The interpretation of γ as a probability that the true value lies outside the confidence interval is not a frequentist one, but a Bayesian using an appropriate prior.

For a SIL 1 system, a probability of failure on demand of 0.1 must not be exceeded. This value can be seen as a budget:

One might give 0.05 as a maximal value for hardware failures and 0.05 for the AI algorithm. The latter can be split according to

$0.05 = \alpha+2\gamma$

e.g. in the form

$\alpha = 0.025$, $\gamma = 0.0125$.

For a SIL 4, IEC 61508 provides a threshold value of 0.0001 for the probability of failure on demand.

The reader might repeat the calculation. As a further exercise, she might consider conditions on m and the Sigma values to fulfil the requirements. This simple example shows that complicated computations are to be expected. Even with this very simple example, we were confronted with complex mathematics.

What is now the way out of this complicated situation?

There exist mainly two options:

1. The AI system does not need a SIL since its behavior does not have critical consequences (no injuries to persons etc.)

2. The AI system is supported by a sufficiently simple E/E/PE system, having the necessary SIL, that checks all dangerous decisions according to simpler algorithms and inhibits dangerous reactions

The options need to be supported by a risk analysis (see IEC 61508).

## Research Challenge

We admit that the example is quite simple and academic, but we believe that we need to understand and solve small problems first before we can approach high-dimensional problems.

In order to take a little bit more practical example, consider the following problem: You are given a set of n two-dimensional points which are classified into two sets (like figure 5, but only the points). The model is unknown, but you can control the number of points to a certain extent. You do not know anything else but that the decision problem is safety-related with SIL x. You may choose your favorite classification method, e.g. ANN.

Under which assumptions can you provide a safety argument according to an acknowledged safety standard e. g. IEC 61508? Can you also provide reasonable guidance how the validity of your assumptions may be checked in practice?

This may seem a simple problem, but it has high leverage: If we can't provide a safety argument (under assumptions that can reasonably be checked in practice) then (at least some classes of) AI algorithms can't be used for safety-related applications. But if we can solve the problems under certain conditions, we might be able to generalize the approach to higher dimensions.

## Conclusions

In this paper we have described a possible approach to safety assessment of AI systems although several questions remain open and may only be solved in the context of a particular application.

A Safety Integrity Level can be determined as for a normal E/E/PE system. This has to be substantiated by a hazard and risk analysis. This is also necessary, if the system does not require a SIL.

AI can be easily used in situations, where no critical consequences occur, which has to be supported by a risk analysis. Then, no safety integrity level requirements need to be implemented in the system and safety assessment is not necessary.

We have proposed an approach to analyze the model. The analysis to be carried out depends very much on the type of model. An assessment requires always an in-depth model analysis of the model of AI that means AI as such cannot be analyzed since it covers a lot of different approaches. The more flexible the model, the more complicated the analysis has to be. For use in critical systems it seems a useful approach is to restrict the type of models in order to simplify the design and the assessment of the AI system.

Pearl and Mackenzie [12] have approached the problem from a similar angle and have concluded that causality needs to be introduced into AI, before we can rely on its conclusions. One of their conclusions is that it is necessary to "formulate a model of the process that generates the data, or at least some aspects of that process".

We have provided an academic example in order to show how one would have to proceed for this specific type of model.

Finally, we have introduced a research challenge whose solution might be decisive for the use of AI algorithms for safety-related applications. The challenge is to formulate a model of the data generation process that allows a safety analysis and that can be justified to hold in practical applications.

In order to use AI systems without the burden of an extensive safety assessment there are only two possibilities: either have an AI system that is not safety relevant or have another safety relevant E/E/PE system that take over full responsibility for safety.

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## Contribution of the authors

The contribution of the authors consists of an analysis of AI systems as statistical models, analysis of safety assessment procedures and consideration of an example. The contribution of the authors is equal.

## Conflict of interest

The authors declare that there is no conflict of interest.

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# Method of instrumental estimation of critical information infrastructure under information technology interference

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**Abstract.** *The* **Aim** *of the paper is to develop a method enabling quantitative estimation of stability indicators of critical information infrastructure (CII) facilities under information technology interference (ITI) using testbed experimental research data. CII facilities include information and telecommunication networks (ITCN), information systems (IS), automated systems (AS) and telecommunication systems that are used as part of computer-based systems in transportation, energy, communications, navigation, manufacturing and other domains. For the purpose of this paper, the stability of CII operation shall be understood as the ability of CII facility elements to maintain operating parameter values within the specified limits within the specified time period when affected by intruders' ITI. Intruders' ITI is understood as intentional hardware and software interference that cause disruptions (blocking, distortion) of information computation processes in CII facilities within a specified period of time. The developed method is based on experimental research, accelerated testing methods and computational methods of estimation of CII facilities operational stability that were applied subject to the specificity of system analysis of the process of ITCN, IS and ACS operation under simulated intruder ITI. The method uses two primary types of indicators, i.e. the probability of faults and additional (artificial) faults in the course of data communication between CII facility elements caused by ITI, and the probability of faults and additional faults as the result of ITI in the course of information processing in CII facilities. The inclusion in the method of indicators for estimating additional faults due to ITI enables a priori analysis of rare and sudden events of CII facility operational stability disruptions. Subject to the obtained estimates, technical and organizational measures are substantiated for the purpose of neutralizing ITI against CII facilities. Applying the method requires the availability of trial sites for the purpose of estimating the stability and actual security of CII facilities that host the functional equivalents of CII facilities, ITI simulators, information security tools (IST) and computer incident recovery tools. The developed method enables estimating the values of stability indicators, i.e. probability of successful transmission of data between CII facility elements and probability of successful processing of information in CII facility elements affected by faults based on instrumental estimation of system elements' operation processes assessment under simulated ITI.*

**Keywords:** *information technology interference, critical information infrastructure facilities, faults, stability.*

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## Introduction

The development of critical information infrastructure (CII) facilities is characterized by fast deployment of new information technology of distributed collection, processing, storage and communication of significant amounts of heterogeneous data for the purpose of efficient management of industrial and manufacturing processes in various domains of human activities [13, 14].

A significant share of network protocols and data in CII facilities, standard settings of information security tools (IST) objectively cause a lot of vulnerabilities. The potential vulnerabilities in CII facility elements include the parameters of software vulnerability, dataware, telecommunication equipment, as well as the parameters of functional and network vulnerabilities.

The vulnerabilities in CII facility elements enable potential internal and external information technology interference (ITI) that reduces the operational stability of CII facilities [1, 2, 6, 12].

The paper examines ITI threats that are intentional hardware and software interferences that cause the disruption of the operational stability of CII facilities. An ITI is implemented by an intruder in the form of interrelated and multi-stage actions by means of fuzzing, Denial-of-Service attacks (DDoS attacks) and traffic load [7].

The consequences of a successful ITI against CII facilities are characterized by the following:

- unauthorized access to protected information in CII facilities;
- disruption of operational stability;
- faults and failures in the performance of information processing tasks;
- reduced rate of transfer of process-related information on the status of CII facility elements;
- blocking (disruption) of CII facilities networking;
- possible distortion of information critical for CII facilities application;
- initiation of undocumented features for the purpose of launching mass ITI against SMF CII facilities that are comparable to technological catastrophes in terms of their consequences.

In accordance with the existing requirements for information security, the protection of information in CII facilities is to involve operational stability under an intruder's ITI [10, 11, 13, 14].

Improving the operational stability of CII facilities under ITI requires prior experimental assessment of their actual security and stability using testbeds or trial sites [3, 4, 9].

Bed testing and actual security and stability assessment of CII facilities under ITI will ensure the preparation, selection of substantiated organizational and technical information security measures aimed at eliminating any vulnerabilities reducing the probability of ITI, which will allow improving the operational stability of CII facilities through the implementation of such measures.

Thus, the development of the method enabling improved operational stability of CII facilities under ITI by means of a priori assessment and multiple selection of organizational and technical information security measures, vulnerability elimination is relevant and of practical interest.

## Problem definition

For the purpose of substantiating the instrumental estimation of CII stability under ITI and when affected by faults, the following assumptions were made:

- increased structural complexity, list, number of active tasks, simultaneous operation of subsystems of various generations, organization of information interaction between remote elements of CII facilities under ITI en able possible faults and require estimation for the purpose of maintaining the required level of stability of CII facilities;
- the random nature of detection of vulnerabilities by an intruder and ITI penetration of CII facilities causes the requirement for multivariate simulation of ITI threats;
- assessing CII facilities resilience against faults caused by ITI through analytical means only is complicated; a full-scale simulation of significant CII elements is required under conditions similar to actual processes of operation;
- instrumental estimation of CII facilities stability under simulated ITI is, in its nature, a verification, subject to the results of which it is established that the values of the probabilistic stability indicators in the presence of faults are not below the targets;
- in the course of instrumental estimation, accelerated testing of CII facilities is conducted at the trial site with the simulation of information loading modes that precipitate faults;
- given the CII facility information security measures taken, the values of the probability indicators of stable operation in the presence of low-intensity faults may be so low as to require significant system testing time, which underlines the importance of calculated prediction based on the instrumental estimation [8, 11, 13];
- the duration of instrumental prediction equals to the time required for an accurate estimation of the probabilistic indicators of CII facility stability under allowable values of time to fault [14];
- the use of an ITI simulator enables accelerated testing of CII facilities as part of instrumental estimation, as the testbed imitates factors of increased intensity of artificial faults (their increased probability) under CII facility overloading.

In a general way, the problem of CII facility stability estimation under ITI is defined as follows:

It is given:

$w_{ac}$, the number of actual faults in data transfer between CII facilities;

$h_{ac}$, the number of actual faults in information processing systems in CII facilities;

$\Delta t_{DCM}$, is the mean time of data transfer between CII facilities;

$\Delta t_{\text{HSS}}$, the mean time of information processing in CII facilities.

It is required:

to find such values of actual fault parameters in CII facilities: number $w^*_{ad}$ of additional faults in the data communication network (DCN) , number $h^*_{ad}$ of additional faults in the data processing system (DPS), time $t^{\text{FT*}}_{\text{DCN}}$ of fault in the DCN and time $t^{\text{FT*}}_{\text{HSS}}$ of fault in the DPS whereas the required values of the probability of stable operation are preserved

$$P^*_{\text{SHSS}} \ge P^{\text{REQ}}_{\text{UHSS}} \left[\left(w^*_{ac}, w^*_{ad}, t^{\text{FT*}}_{\text{DCN}}\right), \left(h^*_{ac}, h^*_{ad}, t^{\text{FT*}}_{\text{HSS}}\right), \left(\Delta t^*_{\text{DCN}}, \Delta t^*_{\text{HSS}}\right)\right]$$

subject to limited characteristic of data transmission and processing features in CII facilities:

$$\Delta t_{\text{DCN}} \in T_{\text{DCN}},\ \Delta t_{\text{HSS}} \in T_{\text{HSS}}.$$

The problem was defined on the assumption that the CII operation is represented by Markovian processes, while the ITI processes that cause additional faults are described by a Poisson distribution.

Figure 1 shows the diagram of the instrumental estimation of CII facility stability under ITI. A fault in CII facilities will be understood as a short (from several seconds to 60 minutes accounting for the restoration time) disruption of the parameters of operation [1, 8, 14]. Due to the fact that the categorized CII facilities are of hazard to life and their disruption causes significant damage, the research assumes that in CII facilities failure is unacceptable. In other words, in case of ITI, events of disrupted CII facility operability of more than 60 minutes are neutralized by means of organizational and technical information security measures, operability restoration facilities and redundant elements.

Essentially, the presented method ensures confirmation of the compliance of the stability indicators of planned or upgraded CII facilities affected by faults caused by ITI with the customer's technical requirements.

For the purpose of collecting evidence of the compliance of the actual indicators of CII facility stability when

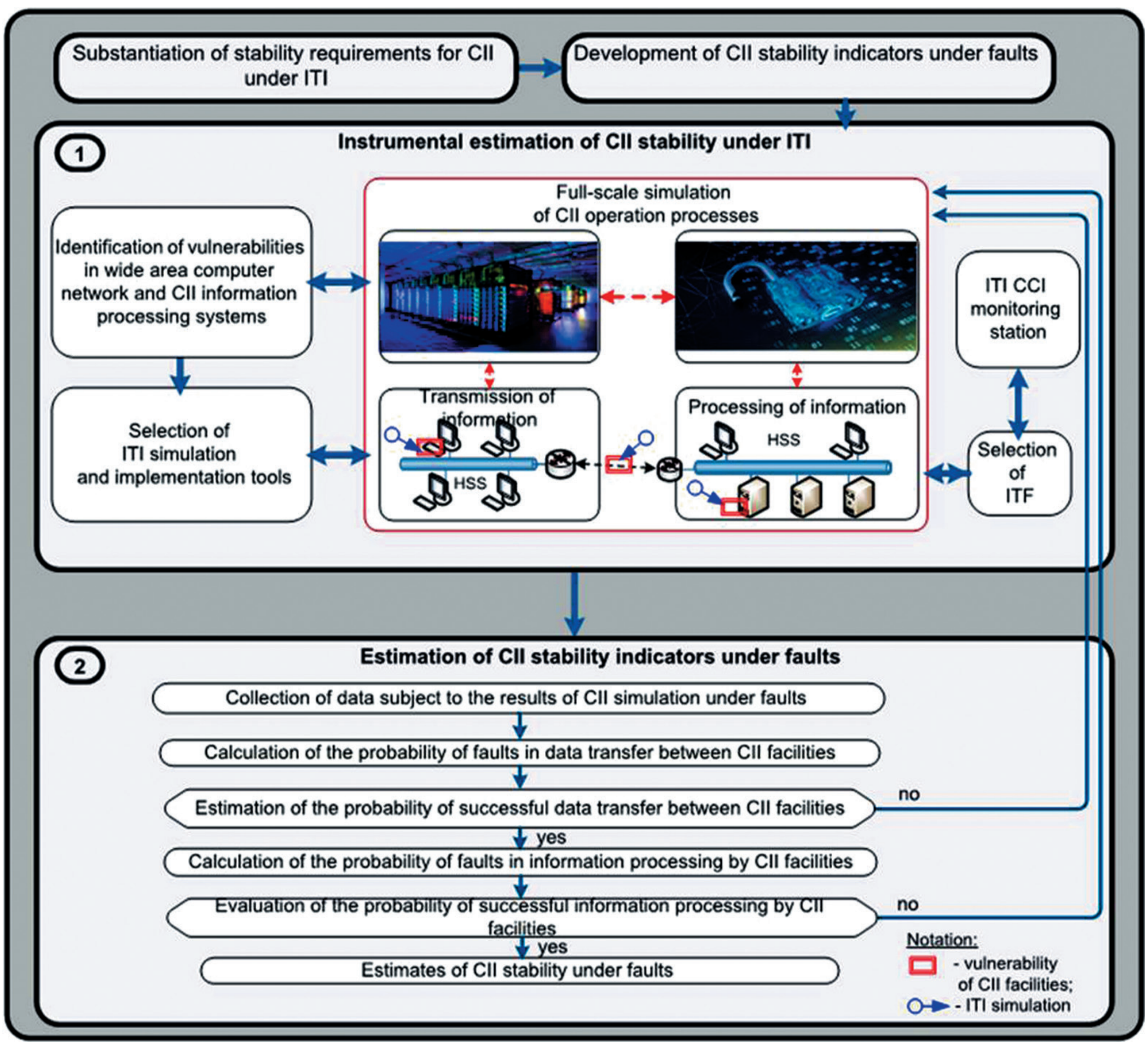


Fig. 1. Diagram of instrumental estimation of CII stability under simulated ITI

**Table 1. Initial data for the estimation of the probability of successful transmission of data between elements of standard TCP/IP data communication features of CII facilities**

| Name of the characteristic of the processes of data transfer between elements of standard CII facility data communication assets affected by faults | Value of characteristic |
|---|---|
| Mean time of data transfer between elements of standard CII facility data communication assets | $\Delta t_{\mathrm{DCN}} = 2, \ldots, 16$ sec |
| Number of additional faults in CII facility data communication assets under within 24 hours | $w_{ad} = 1, \ldots, 10$ |
| Mean fault time in standard CII facility data communication assets | $t^{\mathrm{FT}}_{\mathrm{DCN}} = 2, 4, \ldots, 24$ hours |

affected by faults with the obtained estimates, the method verifies the concordance between the results of full-scale modeling and trial site simulation and the estimates of the selected indicators.

The method involves a step-by-step sequence of indicator identification as part of instrumental estimation of the operational stability of CII facilities affected by faults that includes two primary stages:

I. Instrumental estimation of CII stability under simulated ITI.

II. Estimation of CII stability indicators under faults.

First, the requirements for stable operation of CII facilities affected by ITI are to be substantiated. Such requirements are to be included in the performance specifications for research and development activities regarding the CII facility (prototype, trial site of the CII facility) or taken into consideration while upgrading the CII facility's elements.

Then, in accordance with the method, the indicators are calculated for the instrumental estimation of CII facilities stability when affected by ITI.

Due to the fact that the operation of a CII facility is characterized by two primary processes: data communication between elements of a CII facility and information processing, it is proposed to use two indicators as part of the method:

1. Probability of successful data transfer between CII facilities.

2. Probability of successful information processing by a CII facility.

The instrumental estimation of the operational stability of a CII facility under simulated ITI is conducted using a test bed and consists in the following:

1. Full-scale simulation of the CII facility elements' operation processes on the test bed or at the trial site, including data communication between elements, as well as data processing in local area networks with hardware and software systems (HSS) in CII facilities.

2. Selection of information security tools in accordance with the requirements for the security class of automated systems (AS), computer technology, data security tools, intrusion detection tools, virus protection tools, firewalls, cryptographic tools, as well as the trust level of AS software [5].

3. Identification of vulnerabilities in a wide area computer network and HSS for model-based CII facility information processing [8].

4. Selection of ITI simulation and implementation tools using the method [9].

Output statistical data of the stage of instrumental estimation of CII facilities' stability under simulated ITI are the input parameters for the estimation of their stability in the presence of faults.

At the stage of estimation of the operation process stability of CII facilities under simulated ITI using the method of accelerated testing [14] the following assumptions were made:

a) CII facilities include two primary types of elements:

1) $j$-th data communication features of a CII facility, in which over time $t_{\mathrm{DCF}j}$ with the probability $P^{\mathrm{FTAC}}_{\mathrm{DCN}}$ actual faults $w_{acj}$ occur, and with the probability $P^{\mathrm{FTAD}}_{\mathrm{DCN}}$ additional (artificially created) faults $w_{adj}$ occur in case of ITI;

2) $i$-th data processing features of a CII facility, in which over time $t_{\mathrm{HSS}i}$ with the probability $P^{\mathrm{FTAC}}_{\mathrm{HSS}}$ actual faults $h_{aci}$ occur, and with the probability $P^{\mathrm{FTAD}}_{\mathrm{HSS}}$ additional (artificially created) faults $h_{adi}$ occur in case of ITI;

b) in the course of data communication and processing in a CII facility, each element performs a process-related operation in the course of which a fault may occur;

c) the probability of a fault in elements of a CII facility in the course of process-related operations is normally geometrically distributed that is approximated by the exponential distribution law [14];

d) the flow of fault events in data communication and processing elements of a CII facility is interpreted as a continuous Poisson flow.

The estimation of a CII facility's stability when affected by faults caused by ITI using the method of acceleration testing consists of the following steps:

Step 1. Collection of data subject to the results of CII facility ITI simulation, required and sufficient parameters for the estimation of CII facility stability when affected by faults.

Step 2. Calculation of the probability of faults in data transfer between CII facilities:

a) calculation of the probability $w_{acj}$ of actual faults in the course of data transmission between CII facilities during time $t_{\mathrm{DCN}j}$ in the $j$-th data transmission facility:

$$P_{\mathrm{DCN}}^{\mathrm{FTAC}}\left(w_{acj}\right)=\prod_{j=1}^{k} e^{-t_{\mathrm{DCN}j}^{\mathrm{FT}} P_{\mathrm{DCN}j}^{\mathrm{FT}} / \Delta_{\mathrm{DCN}}}\left(P_{\mathrm{DCN}j}^{\mathrm{FT}}\right)^{w_{acj}}, \quad (1)$$

where $w_{acj}$ is the number of actual faults in the $j$-th data transmission facilities;

$t_{\mathrm{DCN}j}^{\mathrm{FT}}$ is the duration of a fault in the $j$-th data transmission facility;

$P_{\mathrm{DCN}j}^{\mathrm{FT}}$ is the probability of actual fault in the $j$-th data transmission facility;

$\Delta t_{\mathrm{DCN}}$ is the mean time of data transfer between CII facilities;

$k$ is the number data transmission facilities.

b) calculation of the probability of $w_{adj}$ additional (artificially created) faults in the course of data transmission between CII facilities during time $t_{\mathrm{DCN}j}$ in the $j$-th data transmission facility:

$$P_{\mathrm{DCN}}^{\mathrm{FTAD}}\left(w_{adj}\right)=\prod_{j=1}^{k} e^{-t_{\mathrm{DCN}j}^{\mathrm{FT}} P_{\mathrm{DCN}j}^{\mathrm{FTAD}} / \Delta t_{\mathrm{DCN}}}\left(P_{\mathrm{DCN}j}^{\mathrm{FTAD}}\right)^{w_{adj}}, \quad (2)$$

where $w_{adj}$ is the number of additional faults in the $j$-th data transmission facility;

$P_{\mathrm{DCN}j}^{\mathrm{FTAD}}$ is the probability of additional fault in the $j$-th data transmission facility.

Step 3. Estimation of the probability of successful data transfer between CII facilities.

$$P_{\mathrm{SDCN}}=\frac{1}{N_w}\sum_{j=1}^{N_w} U_{P_{\mathrm{UDCN}}}\left(w_{acj}, w_{adj}\right)\frac{\prod_{j=1}^{k} e^{-t_{\mathrm{DCN}j}^{\mathrm{FT}} P_{\mathrm{DCN}j}^{\mathrm{FT}} / \Delta t_{\mathrm{DCN}}}\left(P_{\mathrm{DCN}j}^{\mathrm{FT}}\right)^{w_{acj}}}{\prod_{j=1}^{k} e^{-t_{\mathrm{DCN}j}^{\mathrm{FT}} P_{\mathrm{DCN}j}^{\mathrm{FTAS}} / \Delta t_{\mathrm{DCN}}}\left(P_{DCNj}^{FT}\right)^{w_{adj}}}, \quad (3)$$

where $N_w$ is the number of instrumental assessments done at the trial site with realization of fault vectors $w_{acj}$ and $w_{adj}$;

$U_{P_{\mathrm{SDCN}}}\left(w_{acj}, w_{adj}\right)$ is the indicator function that takes on the value of 1 if the event corresponds to indicator $P_{\mathrm{SDCN}}$, and 0 if otherwise.

Step 4. Calculation of the probability of faults in information processing in a CII facility:

a) calculation of the probability of $h_{aci}$ actual faults in the course of information processing in a CII facility over time $t_{\mathrm{HSS}i}$ in the $i$-th HSS:

$$P_{\mathrm{HSS}}^{\mathrm{FTAC}}\left(h_{pi}\right)=\prod_{i=1}^{l} e^{-t_{\mathrm{HSS}i}^{\mathrm{FT}} P_{\mathrm{HSS}}^{\mathrm{FT}} / \Delta t_{\mathrm{HSS}}}\left(P_{\mathrm{HSS}i}^{\mathrm{FT}}\right)^{h_{aci}}, \quad (4)$$

where $h_{aci}$ is the number of actual faults in the information processing facilities;

$t_{\mathrm{HSS}i}^{\mathrm{FT}}$ is the duration of a fault in the $i$-th data processing facility;

$P_{\mathrm{HSS}i}^{\mathrm{FT}}$ is the probability of actual fault in the $i$-th data processing facility;

$\Delta t_{\mathrm{HSS}}$ is the mean time of information processing in CII facilities;

$l$ is the number of the information processing facilities.

b) calculation of the probability of $h_{adi}$ additional (artificially created) faults in the course of information processing in a CII facility over time $t_{\mathrm{HSS}i}$ in the $i$-th HSS:

$$P_{\mathrm{HSS}}^{\mathrm{FTAD}}\left(h_{adi}\right)=\prod_{i=1}^{l} e^{-t_{\mathrm{HSS}i}^{\mathrm{FT}} P_{\mathrm{HSS}i}^{\mathrm{FTAD}} / \Delta t_{\mathrm{HSS}}}\left(P_{\mathrm{HSS}i}^{\mathrm{FTAD}}\right)^{h_{adi}}, \quad (5)$$

where $h_{adi}$ is the number of additional faults in the information processing facilities;

$P_{\mathrm{HSS}i}^{\mathrm{FTAD}}$ is the probability of additional fault in the $i$-th data processing facility;

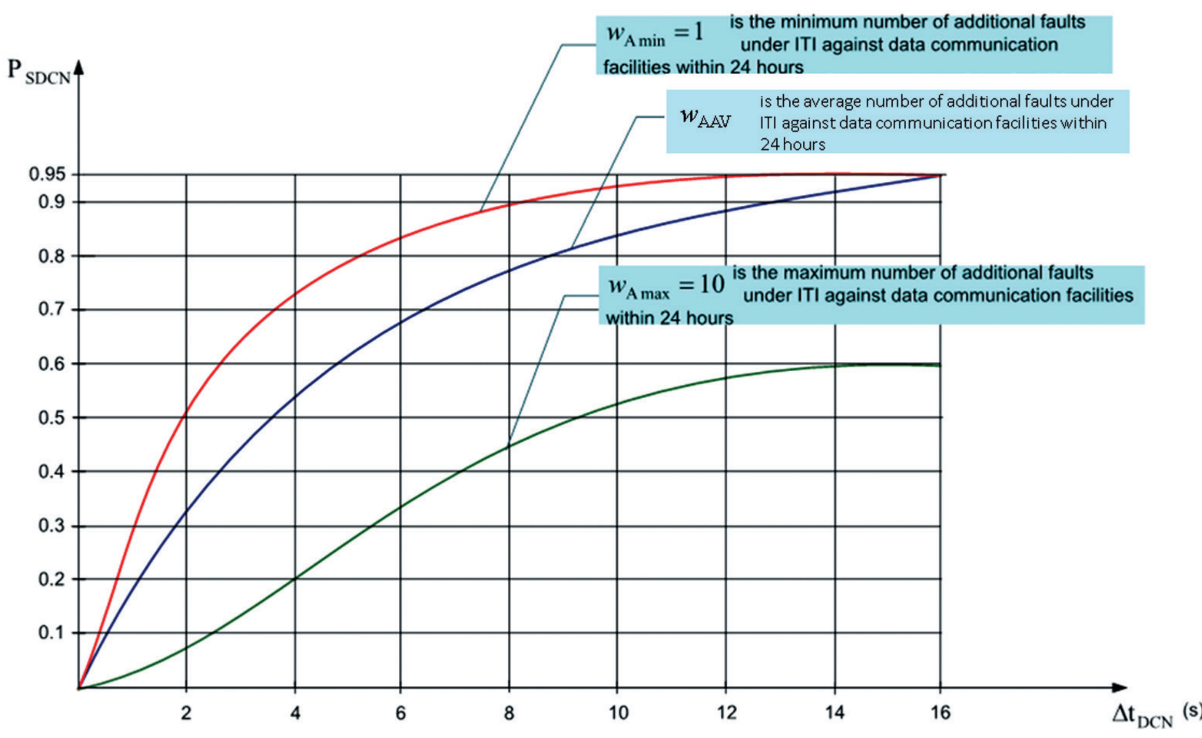


Fig. 2. Values of the probability of successful data communication between elements of data communication features of CII facilities under varying mean time of data communication and number of additional faults

Step 5. Evaluation of the probability of successful information processing by a CII facility:

$$P_{\mathrm{SHSS}}=\frac{1}{N_h}\sum_{i=1}^{N_h}U_{P_{\mathrm{SHSS}}}\left(h_{aci},h_{adi}\right)\frac{\prod_{i=1}^{l}e^{-t_{\mathrm{HSS}i}^{\mathrm{FT}}P_{\mathrm{HSS}i}^{\mathrm{FT}}/\Delta t_{\mathrm{HSS}}}\left(P_{\mathrm{HSS}i}^{\mathrm{FT}}\right)^{h_{aci}}}{\prod_{i=1}^{l}e^{-t_{\mathrm{HSS}i}^{\mathrm{FT}}P_{\mathrm{HSS}i}^{\mathrm{FTAD}}/\Delta t_{\mathrm{HSS}}}\left(P_{\mathrm{HSS}i}^{\mathrm{FTAD}}\right)^{h_{adi}}}, \quad (6)$$

where $N_h$ is the number of instrumental assessments done at the trial site with realization of fault vectors $h_{aci}$ and $h_{adi}$;

$U_{P_{\mathrm{SHSS}}}\left(h_{aci},h_{adi}\right)$ is the indicator function that takes on the value of 1 if the event corresponds to indicator $P_{\mathrm{SHSS}}$, and 0 if otherwise.

Upon completion of steps 1 to 5 of the method, the set of estimates is prepared of indicators of CII facility stability when affected by faults.

As part of the research, a preliminary estimation was conducted of the probability of successful transmission of data between elements of standard TCP/IP data communication features of CII facilities (initial data shown in Table 1). The estimates of the effect of faults caused by ITI on the stability of elements of standard TCP/IP data communication features of CII facilities are shown in Figure 2.

The analysis of the values of the probability of successful data communication between elements of standard TCP/IP data communication features of CII facilities affected by faults under varying mean time of data communication and number of additional faults shows the following:

- the probability of successful data communication between elements of standard data communication features of CII facilities reaches 0.9 within 8 seconds under the minimal number of additional faults when affected by an intruder’s ITI (1 fault per a 24-hour work period);
- the probability of successful data communication between elements of standard data communication features of CII facilities becomes 0.8 within 10 seconds under the average number of additional faults when affected by an intruder’s ITI through the use of redundancy and recovery (5 faults per a 24-hour work period);
- the probability of successful data communication between elements of standard data communication features of CII facilities reaches only 0.6 within 16 seconds under the maximum number of additional faults when affected by an intruder’s ITI even if computer incident recovery facilities are used (10 faults per a 24-hour work period).

In cases when an intruder’s ITI are identified in a timely manner and neutralized by ISS at a CII facility, the functional stability of data communication facilities affected by additional faults is ensured.

## Conclusion

The suggested method of instrumental estimation of CII facilities stability under an intruder’s ITI allows estimating the values of stability indicators, i.e. probability of successful transmission of data between CII facilities and probability of successful processing of information in CII facilities affected by faults based on instrumental estimation of system elements’ operation processes assessment under simulated ITI.

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## The authors' contribution

**Antonov S.G.** Development of the diagram and description of the method of instrumental estimation of CII facilities stability under simulated ITI. Performance and analysis of the results of experimental estimation of the probability of successful transmission of data between elements of standard data communication features of CII facilities.

**Antsiferov I.I.** Mathematical problem description for the development of the method of instrumental estimation of CII facilities stability under ITI.

**Klimov S.M.** System analysis of the basic assumptions and development of mathematical expressions for calculating the probabilities of faults in the course of data communication between CII facilities and successful processing of information in the CII facility.

## Conflict of interests

The authors declare the absence of a conflict of interests.

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# Solving the problem of risk synthesis as part of infrastructure facility management

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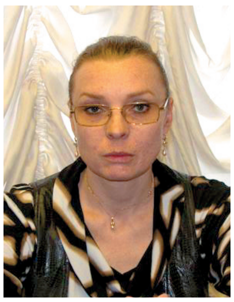

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**Abstract. Aim.** *Infrastructure facility management involves many decision-making problems that require estimating alternatives in the absence of clear criteria. Sufficiently common are problems that require the consideration of various numbers of factors. Those factors normally belong to different fields of knowledge and require the involvement of subject-area experts. Thus, for instance, the estimation of infrastructure facilities may involve economists, experts in land law, environment, logistics, design engineers and other specialists. The problem is often complicated by the existence of many alternatives. In such cases, it is difficult to organize even the initial expert evaluation in order to reduce the number of options for subsequent consideration. The paper primarily aims to develop a model of evaluation of the criteria that have an effect on the advisability of modernization of an infrastructure facility allowing to take into account factors from various fields of knowledge, as well as to elaborate a method of simplifying the process of evaluation of large numbers of alternative options. Therewith, such estimates can be expressed in various formats: both quantitatively and qualitatively. Such approaches have found application as part of the problem of ranking of airports as part of selection of candidates for inclusion into the Moscow air cluster (MAC). The specificity of this problem consists in the large set of various factors to be taken into account, as well as the great number of options, over 30 airports within 300 kilometers of Moscow.* **Methods.** *The risk synthesis model was used that relies on expert data that characterize the criteria that have an effect on the sought risk, as well as the values of damage for each facility by the given criteria. The criteria were estimated using a method based on pairwise comparisons allowing experts to define fuzzy and incomplete estimates of the preferability of the compared options. Damage estimation was done using the method of conversion of qualitative estimates into quantitative ones, as well as scaling of quantitative data into quantitative estimates of damage.* **Results.** *Implementing the ideas set forth in this paper allowed defining the contribution of eleven criteria that have an effect on the goals associated with relieving the MAC workload. Based on those criteria, specific risks for airports within 300 kilometers of Moscow were evaluated, and integral risks of modernization of each airport were obtained. The airports were then rated in terms of the integral risk of modernization.* **Conclusion.** *The suggested method is universal and can be used for decision-making under uncertainty in those domains where it is required to involve experts of various qualification and level of subject-matter knowledge, as well as accounting for many factors along with a great diversity of options.*

**Keywords:** *risk synthesis, method of incomplete pairwise comparison, estimation of damage, quantitative risk assessment.*

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## Introduction

Managing infrastructure facilities is quite often associated with complex multi-aspect problems, whose solution requires the involvement of various subject-matter experts for the purpose of evaluating great numbers of factors, from economic to those related to land law or the environment. For many years, the problem of optimal decision-making in system management under the condition of poor mathematical formulation has remained of great relevance. It is characterized by, first, the uncertainty in the choice of the target function and definition of limitations associated with a large number of heteronymous and contradictory indicators of the possible system development scenarios, and second, the non-standard decision-making situation that consists in the capability to only calculate for each option only the values of individual indicators, lack of knowledge on and difficulty to implement a number of important properties of the objective function, properties of the search domain, etc. Overcoming uncertainties in the requirements for the quality of the options in non-standard situations is normally based on a more complete and correct formalization of a multi-objective decision-making problem that allows the construction of a set of regular algorithms (that is the reason such problems are normally regarded as poorly formalized). For that purpose, at the semantical level of the simulation, the concepts of goal hierarchy, resource, difficulty in achieving the objective, compensation, value equivalence function, etc. They are the foundation of the axiomatic construction of integrated indices that describe the properties of a system and its operational environment.

The decision-making in this case is generally defined as the process of selection of the best alternative out of those available, but, in practice, achieving optimal results may be difficult, as decision-makers (DMs) and experts often have difficulties making decisions. One of the most important sections of the decision theory used for the purpose of identifying the best decision out of those available is the multi-criterial decision-making (MCDM). There are several methods that enable improved MCDM, including: T. Saaty's [1] analytic hierarchy process (AHP); superiority and inferiority ranking method [2]; Simos ranking method [3]; multiple attribute utility theory (MAUT) [4]; ELimination Et Choix Traduisant la REalité (ELECTRE) [5-7]; preference ranking and choosing by advantages (CBA) [8]. Those methods, some of which the authors examined in the Abstract above, are often used for the purpose of simplifying decision-making as part of practical activity.

Saaty's AHP is the most popular MCDM that attracted a lot of attention and gained well-earned popularity over the last two decades. AHP provides the DM with powerful tools for making substantiated strategic decisions, which allows the DM using several quantitative criteria for estimating potential alternatives and selecting the optimal one. Such widespread use is certainly due to the simplicity of its application and the structure of AHP that reflects the intuitive method of problem-solving by the DM. The hierarchical modeling of a problem, capability to use verbal assertions and conformance verification are the primary advantages of the method. Along with the conventional applications, new ones develop, e.g. those that consist in using AHP in combination with other methods: mathematical programming methods, such as linear programming, data envelopment analysis (DEA), fuzzy sets, genetic algorithms, neural networks, SWOT analysis, etc. One of the significant shortcomings of AHP is the growing computational complexity of finding proper values as the dimension of the MCDM matrix grows, however, there is no doubt that the application of AHP will be becoming more and more widespread.

As an example of its practical use, let us examine the problem of reducing the workload of the Moscow air cluster (MAC) that is the airport system of Moscow and Moscow Oblast. The airports of MAC perform 800 ths airfield operations a year as part of passenger, cargo and business flights. An overwhelming majority is passenger operations that, according to statistical data[1], ensure a passenger flow of over 100 mil a year. According to projections, by 2030, the passenger flow will be as high as 180 mil people per year [9], which will require an increased system capacity. Modernizing MAC airports is currently insufficient due to the high load on Moscow's overland transportation systems, which brings about the discussion of increasing the number of the airports.

Building a new airport is costlier that upgrading an existing one. For instance, according to preliminary estimates, constructing a passenger terminal would cost 30 bln rubles, while upgrading and existing one is about 5-7 bln rubles. As there are many airports in and around Moscow and Moscow Oblast, it is primarily required to evaluate the practicality of investment in each particular airport. Investment into the modernization of each of them bears a number of risks associated with their efficiency in terms of reducing the load on the MAC.

The difficulty to estimate the alternatives is due to the large number of factors affecting the decision-making process and non-availability of appropriate statistics. That inevitably requires the involvement of experts in various fields of knowledge. Such experts can provide a qualified assessment in their area of competence, but struggle when it comes to related fields. Due to the mutual relation and effect of decision-making factors, the problem of processing expert judgements arises, in which the estimates of some factors for the compared alternatives are missing or fuzzy. Such untrivial problem can be solved using the so-called method of risk synthesis [10].

Let us examine the problem of MAC workload in this setting.

## 1. Problem definition

Let $K_1$, $K_2$, …, $K_n$ be the list of $n$ criteria, upon which

[1] Source: https://bit.ly/MOW_stat19, statistics of the Federal Air Transport Agency of Russia (https://favt.ru/)

it is required to estimate and rank the list $A_1$, $A_2$, …, $A_m$ of $m$ airports in terms of the magnitude of the risk associated with their modernization for the purpose of relieving the load on the MAC.

The risk in this case is defined by the magnitude of possible damage caused by the realization of the alternative selected as the result of the analysis as compared to the ideal situation that is characterized by the absence (or acceptable minimum for the DM) of such damage. In this setting, the risk is understood in terms of the effect of uncertainty on the achievement of the specified objectives[1]. The uncertainty in the context of the problem under consideration is due to the uncertainty of the selected criteria and the degree of their effect, while the aim is to relieve the load on the MAC at the minimal possible cost. In this context, it is pointless talking about the frequency or probability of risk realization, as the aim of the analysis consists in selecting the MAC modernization project that is acceptable in terms of damage in case of inefficient operation.

The risk of an item (process) is the value proportional to the deviation from the item (process) quality reference [11, p. 15]. The quality of items and the risk can be measured in comparable scales. The measure of risk is the "threat of changes in the composition or properties of the item or its environment, or emergence of changes associated with possible undesirable processes that are due to anthropogenic or natural effects". At the same time, it is emphasized that the sense of the definition is probabilistic.

At the bottom level of the hierarchical structure, the compared items are described by certain sets of indicators, the particular indicators of risk (PIR). As the analysis of the states of complex items and systems used in systems research of integral estimates [12, 13, 14] has shown, generalized criteria (indices) of risk are widely used, i.e. the additive (weighted arithmetical) and multiplicative (weighted geometrical) forms.

Given the above, let us define the risk in the problem under consideration as the function of two vectors $U = (u_1, u_2, \ldots, u_{n-1}, u_n)$, i.e. the vector of damage and $W = (w_1, w_2, \ldots, w_{n-1}, w_n)$, i.e. the vector of weighted coefficient of damage (essentially, that is the expert estimate of their possibility). It may be written as follows [15]:

$$R(U,W) = 1 - \prod_{i=1}^{n} (1 - u_i)^{w_i}, \tag{1}$$

where $w_i > 0$ is the non-zero probabilities of contributions (weight) such as

$$\sum_{i=1}^{n} w_n = 1. \tag{2}$$

In [15], it is shown that in both cases the integrated criterion can be constructed through repetitive use of a binary associative and communicative operation and is an integer analytical function of local criteria. Also in [15], it is shown that the class of such operations is sufficiently narrow and there are only three (accurate to constant parameters) binary operations that meet the condition of commutativity, associativity and integral analyticity. They are defined by the following functions[2]: a) $c$; b) $\Phi_1+\Phi_2+c$; c) $a(\Phi_1 + \Phi_2) + b\Phi_1\Phi_2 + \frac{a(a-1)}{b}; a,b,c - const, b \neq 0$. Importantly, the third of the provided estimates (under certain values of the coefficients that are part of it) is to be used for the purpose of obtaining the integrated criterion of quality, provided there is interaction between subsystems and criterial limitations of the ranges of variation of local estimates.

Based on the above, the integral risk associated with the adoption of a modification option of the $m$-th airport for the purpose of inclusion in the air cluster is:

$$R^m = 1 - \prod_{i=1}^{n} \left(1 - u_i^m\right)^{w_i}. \tag{3}$$

For small values of $U^m$, the integral risk of decision-making for option $m$ matches the adopted definition of risk:

$$R^m \approx 1 - \prod_{i=1}^{n} \left(1 - w_i \times u_i^m\right) \approx \sum_{i=1}^{n} w_i \times u_i^m, \tag{4}$$

where $u_i^m$ is the value of damage for option $m$ under criterion $i$, $w_i$ is the probability of the criteria's effects.

The introduced risk (1) that is sometimes called the geometrical antirisk [16] meets the primary a priori requirements underlying the risk-based approach to the construction of the non-linear integral estimate $R_\varnothing$.

1) smoothness, continuous correlation between the integral estimate $R$ and its derivatives and the partial estimates: $R(r_1, \ldots, r_M)$;

2) boundedness, the boundaries of the variation interval of the partial $r_i$ and integral $R$ estimates: $0 < R(r_1, \ldots, r_M) < 1$ if $0 < r_1, r_2, \ldots, r_M < 1$;

3) equality, the equal importance of partial estimates $r_i$ and $r_j$;

4) hierarchical single-levelness, meaning that only those partial estimates $r_i$ are aggregated that belong to a single level of the hierarchical structure;

5) neutrality, i.e. the integral estimate matches the partial estimate when the other assumes the minimal value: $R(r_1,0)=r_1$; $R(0,r_2)=r_2$; $R(0,0)=0$; $R(1,1)=1$.

6) uniformity $R(r_1=r, \ldots, r_M=r)=r$.

The geometrical antirisk is the upper-bound estimate for the weighted arithmetical and weighted geometrical. Let us also emphasize that the geometrical antirisk meets the theorem on the "fragility of good things" in the catastrophe theory, according to which "… in case of small variation of the parameters, a system belonging to a special part of the stability limit is more likely to fall within the instability zone rather than the stability zone. That is a manifestation of the general principle, according to which all good things (e.g. stability) are more fragile that bad things" [17, p. 31-32]. Risk analysis uses a similar principle of the limiting factor

[1] GOST R ISO 31000-2019. Risk management. Principles and guidelines

[2] Ibidem

of risk.

Thus, any system can be considered to be "good", if it meets a certain set of requirements, but must be recognized as "bad", if does not fulfill at least one of them. At the same time, all the "good things", e.g. the environmental safety of a territory, is more fragile. It can be easily lost, but difficult to recover.

In [18], it is suggested to perform substantial interpretation using the Harrington verbal and numerical scale that is sufficiently universal in its nature.

For the purpose of solving the problem at hand, it is required to successively solve the following sub-problems:

1. Selecting the criteria that affect the risk magnitude.
2. Identifying the contribution of the criteria into the risk magnitude.
3. Making the list of the considered alternatives.
4. Identifying the magnitude of the particular risks of each alternative per each criterion.
5. Evaluating the integral risk in accordance with the selected model for each alternative and rank them.

## 2. Expert data and processing results

### 2.1. Criteria and estimation of their contribution to the integral risk

In order to identify the list of criteria that have an effect on the risk caused by an airport's modernization, experts were questioned according to the method that was generally described in [10] and that includes two stages:

Stage 1. Based on their personal experience and preference, the experts use a certain numerical scale to rate the value of damage that may be caused by a certain parameter value. At the same time, if the parameters are discrete, an expert rates each one of them. For continuous values, ranges of adopted values are selected, for which the experts give an estimate. The higher is the estimated damage, the higher is, in the experts' opinion, the probability of a negative outcome.

Stage 2. The weights are identified, which can be done both by means of direct calculation (experts' opinions regarding other experts' estimates are collected, rating coefficients are specified and the weights are calculated), and by calculating weights through coefficients. In the latter case the weights are defined in accordance with a procedure of the hierarchy analysis method through the normalized vector under the maximum own value of the matrix of pairwise comparisons [1]. For each pair of compared items, a coefficient is defined based on all obtained expert estimates. In case of a significant range of opinions regarding such coefficient, it would be reasonable to choose not to make any estimate, i.e. leave the cell undefined.

As the result, the following list of criteria was made:

1. Optimal distance from downtown Moscow (COD).
2. Airport capacity (CAC).
3. Quality and number of runways (CRW).
4. Airfield infrastructure (CAFI).
5. Airport infrastructure (CAPI).
6. Other transportation infrastructure (COTI).
7. Land resources (CLR).
8. Availability of cargo terminal (CCT).
9. International status (CIS).
10. Joint deployment (CJD).
11. Form of ownership (CFO).

As it was noted above, as such criteria deal with various domains, their comparison requires the involvement of experts with different professional experience that might have difficulties comparing criteria outside the scope of their expertise. In this context, the method of incomplete pairwise comparisons was used [19] with interval-based preference judgement on the Saaty scale [1]. Thanks to its flexibility, this method allows experts to provide accurate estimates in domains of their respective most solid expertise, and, additionally, to specify a wide range of preference judgement regarding those pairs of alternatives that the expert cannot provide an unambiguous opinion for due to the above reasons. This approach, among other things, allows improving the concordance of the matrix of pairwise comparisons by removing such preference judgements that disrupts the concordance due to the insufficiency of the grading scale [20].

The data obtained using the weight method are shown in Table 1.

**Table 1. Probability of criteria effect**

| № | Criterion | Abbreviation | Criterion's effect |
|---|---|---|---|
| 1 | Optimal distance from Moscow | COD | 0.1624 |
| 2 | Airport capacity | CAPC | 0.0673 |
| 3 | Quality and number of runways | CRW | 0.1301 |
| 4 | Airfield infrastructure | CAFI | 0.1390 |
| 5 | Airport infrastructure | CAPI | 0.1330 |
| 6 | Land resources | CLR | 0.1282 |
| 7 | Other transportation infrastructure | COTI | 0.1570 |
| 8 | Availability of cargo terminal | CCT | 0.0233 |
| 9 | International status | CIS | 0.0201 |
| 10 | Joint deployment | CJD | 0.0219 |
| 11 | Form of ownership | CFO | 0.0178 |

### 2.2. Estimation of the magnitude of damage by criteria

So, 11 criteria were selected for the purpose of assessing the options. Given that the group of the significant criteria includes the criterion of optimal distance from Moscow (see Table 1), as well as that airports outside the 300-km zone of Moscow will not appeal to passengers [21], only airports within this range were considered. Besides Vnukovo, Domodedovo and Sheremetyevo, 31 airports are within 300 km of Moscow (Table 2). Thus, if we attempt to estimate each airport per each criterion directly (i.e. asking an expert to specify the value of risk), due to the dimension of the problem, a great number of errors might occur. Additionally, it was observed that many criteria could be characterized by

**Table 2. The list of options under consideration**

| № | List of airports | № | List of airports |
|---|---|---|---|
| 1 | Klin-5 – Klin, Moscow Oblast (MO) | 17 | Turlatovo – Ryazan |
| 2 | Semyazino – Vladimir | 18 | Krutyshki – Stupinio, MO |
| 3 | Dobrynskoye – Vladimir | 19 | Zmeyovo – Tver |
| 4 | Miachkovo – Ramenskoye District, MO | 20 | Tretiakovo – Lukhovitsy, MO |
| 5 | Tunoshna – Yaroslavl | 21 | Mozhaysky – Mozhaysk, MO |
| 6 | Klokovo – Tula | 22 | Alferievo – Volokolamsk, MO |
| 7 | Migalovo – Tver | 23 | Volosovo – Chekhov, MO |
| 8 | Ramenskoye – Zhukovsky, MO | 24 | Monino – Monino, MO |
| 9 | Ivanovo South – Ivanovo | 25 | Chiornoye – Balashikha, MO |
| 10 | Yefremov East – Tula Oblast | 26 | Vikhrevo – Sergiyev-Posad District, MO |
| 11 | Chkalovsky – Shchyolkovo, MO | 27 | Vatulino – Ruza, MO |
| 12 | Grabtsevo – Kaluga | 28 | Severka – Kolomna, MO |
| 13 | Bykovo – Moscow | 29 | Korobcheyevo – Kolomna, MO |
| 14 | Ostafyevo – Moscow | 30 | Borki – Kimry, Tver Oblast |
| 15 | Protasovo – Ryazan | 31 | Yermolino – Balabanovo, Kaluga Oblast |
| 16 | Dyagilevo – Ryazan | | |

additional unambiguously objective parameters that can be found in technical documentation: distance, length, number. In this context, a simplified expert evaluation process was implemented, according to which experts were to estimate not the value of risk for each specific airport, but its characteristics. Where such characteristics were not defined in official sources (e.g. the quality of the infrastructure), expert evaluation was conducted for each specific airport.

Jointly with the experts, for each criterion, airport evaluation scales were made. For instance, it was suggested evaluating runways (RW) using a two-dimensional scale proceeding from the number of strips and the length of the longest of them. Additionally, it was established that in terms of the number there is a difference for airports with 1 RW, 2 RWs, while if an airport has 3 and more RWs they fall into a single category. In terms of length, for instance, intervals were defined such that, within a group, the difference between RWs is insignificant (on each such interval there is no significant diversity of aircraft able to safety take off/land).

According to those scales, the following parameters were calculated: $C_i$, the risk coefficient for the $i$-th value of the scale expressed in any nonnegative number, and $\gamma$, the maximum value of damage (on the scale from 0 to 1) by the selected criterion. Based on those parameters, the value of risk $R_i$ is calculated based on the respective parameter value on the scale, as well as the amount of damage $U_i$ according to the following formulas:

$$R_i = \frac{C_i}{\max\limits_i C_i}, \tag{5}$$

$$U_i = \gamma \times R_i. \tag{6}$$

The formulas and value characteristics show that $0 \le U_i \le R_i \le 1$. Thus, for instance, let us examine the estimates assessment by criterion of CCT (see Table 1) shown in Table 3. Those estimates provide a qualitative characteristic of the airport's cargo terminal (CT).

As the concepts used in this scale are evaluative (except the latter one, for which information can be found), the

**Table 3. Assessment of airport evaluation scale in terms of the CCT criterion**

| Parameter | Perfect CT condition | Good CT condition | Limited CT activities | No cargo activities |
|---|---|---|---|---|
| Assessment, $C_i$ | 1 | 2 | 4 | 8 |
| Max damage, $\gamma$ | 0.4 | | | |
| Risks, $R_i$ | 0.125 | 0.25 | 0.5 | 1 |
| Damage, $U_i$ | 0.05 | 0.1 | 0.2 | 0.4 |

**Table 4. Values of damage per airport evaluation scale in terms of the CCT criterion**

| Capacity, ths pass./year as of 2019 | 10000 and more | 2000 | 1000 | 200 | 100 | 40 | 10 and less |
|---|---|---|---|---|---|---|---|
| Damage, $U_i$ | 0.01 | 0.02 | 0.04 | 0.1 | 0.2 | 0.4 | 1 |

**Table 5. Processing of expert assessments of the suggested options for the MAC modernization**

| № | Expert assessments | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | COD | CAPC | CRW | CAFI | CAPI | CLR | COTI | CCT | CIS | CJD | CFO |
| 1 | 0.04 | 0.99 | 0.16 | 0.8 | 0.8 | 0.2 | 0.1 | 0.4 | 0.2 | 0.1 | 0.05 |
| 2 | 0.08 | 0.8 | 0.28 | 0.8 | 0.8 | 0.99 | 0.8 | 0.4 | 0.2 | 0 | 0.05 |
| 3 | 0.05 | 0.35 | 0.13 | 0.4 | 0.8 | 0.01 | 0.4 | 0.4 | 0.2 | 0.1 | 0.05 |
| 4 | 0.01 | 0.99 | 0.62 | 0.8 | 0.8 | 0.99 | 0.1 | 0.4 | 0.2 | 0.1 | 0.05 |
| 5 | 0.38 | 0.3 | 0.07 | 0.1 | 0.1 | 0.2 | 0.4 | 0.05 | 0 | 0 | 0.02 |
| 6 | 0.1 | 0.99 | 0.3 | 0.8 | 0.8 | 0.99 | 0.4 | 0.4 | 0.2 | 0.1 | 0.05 |
| 7 | 0.95 | 0.99 | 0.13 | 0.8 | 0.4 | 0.5 | 0.2 | 0.4 | 0 | 0 | 0.03 |
| 8 | 0.01 | 0.01 | 0 | 0.1 | 0.1 | 0.2 | 0.1 | 0.05 | 0 | 0 | 0.02 |
| 9 | 0.37 | 0.38 | 0.13 | 0.1 | 0.1 | 0.2 | 0.4 | 0.2 | 0 | 0 | 0.03 |
| 10 | 0.38 | 0.8 | 0.13 | 0.4 | 0.8 | 0.5 | 0.8 | 0.01 | 0 | 0 | 0.02 |
| 11 | 0.01 | 0.8 | 0.02 | 0.8 | 0.4 | 0.2 | 0.1 | 0.01 | 0 | 0 | 0.05 |
| 12 | 0.055 | 0.4 | 0.2 | 0.4 | 0.4 | 0.5 | 0.4 | 0.4 | 0 | 0 | 0.02 |
| 13 | 0.01 | 0.5 | 0.23 | 0.2 | 0.8 | 0.99 | 0.1 | 0.1 | 0.2 | 0.1 | 0.05 |
| 14 | 0.01 | 0.8 | 0.23 | 0.2 | 0.4 | 0.8 | 0.1 | 0.4 | 0 | 0 | 0.01 |
| 15 | 0.09 | 0.4 | 0.23 | 0.2 | 0.4 | 0.99 | 0.4 | 0.4 | 0.2 | 0.1 | 0.05 |
| 16 | 0.09 | 0.8 | 0.07 | 0.2 | 0.8 | 0.8 | 0.2 | 0.4 | 0 | 0 | 0.03 |
| 17 | 0.09 | 0.99 | 0.76 | 0.8 | 0.8 | 0.8 | 0.8 | 0.4 | 0.2 | 0.1 | 0.05 |
| 18 | 0.05 | 0.8 | 0.2 | 0.4 | 0.8 | 0.2 | 0.2 | 0.01 | 0 | 0 | 0.05 |
| 19 | 0.08 | 0.99 | 0.93 | 0.4 | 0.8 | 0.99 | 0.8 | 0.4 | 0.2 | 0.1 | 0.05 |
| 20 | 0.065 | 0.99 | 0.07 | 0.2 | 0.8 | 0.5 | 0.4 | 0.4 | 0.2 | 0.1 | 0.05 |
| 21 | 0.05 | 0.99 | 0.54 | 0.8 | 0.8 | 0.99 | 0.8 | 0.4 | 0.2 | 0.1 | 0.05 |
| 22 | 0.75 | 0.99 | 0.92 | 0.8 | 0.8 | 0.99 | 0.8 | 0.4 | 0.2 | 0.1 | 0.05 |
| 23 | 0.03 | 0.99 | 0.98 | 0.4 | 0.4 | 0.99 | 0.1 | 0.4 | 0.2 | 0.1 | 0.05 |
| 24 | 0.01 | 0.99 | 0.7 | 0.8 | 0.8 | 0.99 | 0.1 | 0.4 | 0.2 | 0.1 | 0.05 |
| 25 | 0.01 | 0.99 | 0.92 | 0.4 | 0.4 | 0.99 | 0.1 | 0.4 | 0.2 | 0.1 | 0.05 |
| 26 | 0.03 | 0.99 | 0.62 | 0.4 | 0.8 | 0.99 | 0.1 | 0.4 | 0.2 | 0.1 | 0.05 |
| 27 | 0.04 | 0.99 | 0.95 | 0.4 | 0.4 | 0.99 | 0.2 | 0.4 | 0.2 | 0.1 | 0.05 |
| 28 | 0.05 | 0.99 | 0.99 | 0.4 | 0.4 | 0.8 | 0.2 | 0.4 | 0.2 | 0.1 | 0.05 |
| 29 | 0.05 | 0.99 | 0.76 | 0.8 | 0.4 | 0.99 | 0.2 | 0.4 | 0.2 | 0.1 | 0.05 |
| 30 | 0.06 | 0.99 | 0.62 | 0.8 | 0.4 | 0.99 | 0.8 | 0.4 | 0.2 | 0.1 | 0.05 |
| 31 | 0.05 | 0.02 | 0.07 | 0.1 | 0.15 | 0.2 | 0.2 | 0.2 | 0 | 0 | 0.03 |

| № | Calculated utility components | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | COD | CAPC | CRW | CAFI | CAPI | CLR | COTI | CCT | CIS | CJD | CFO |
| 1 | 0.99272 | 0.77543 | 0.97412 | 0.81421 | 0.83564 | 0.96997 | 0.98319 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 2 | 0.98520 | 0.91495 | 0.95180 | 0.81421 | 0.83564 | 0.53299 | 0.77185 | 0.98746 | 0.99544 | 1.00000 | 0.99917 |
| 3 | 0.99087 | 0.97649 | 0.97927 | 0.93684 | 0.83564 | 0.99863 | 0.92109 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 4 | 0.99820 | 0.77543 | 0.86458 | 0.81421 | 0.83564 | 0.53299 | 0.98319 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 5 | 0.91805 | 0.98049 | 0.98915 | 0.98663 | 0.98831 | 0.96997 | 0.92109 | 0.99873 | 1.00000 | 1.00000 | 0.99967 |
| 6 | 0.98133 | 0.77543 | 0.94777 | 0.81421 | 0.83564 | 0.53299 | 0.92109 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 7 | 0.58517 | 0.77543 | 0.97927 | 0.81421 | 0.94460 | 0.90964 | 0.96473 | 0.98746 | 1.00000 | 1.00000 | 0.99950 |
| 8 | 0.99820 | 0.99945 | 1.00000 | 0.98663 | 0.98831 | 0.96997 | 0.98319 | 0.99873 | 1.00000 | 1.00000 | 0.99967 |
| 9 | 0.92068 | 0.97394 | 0.97927 | 0.98663 | 0.98831 | 0.96997 | 0.92109 | 0.99450 | 1.00000 | 1.00000 | 0.99950 |
| 10 | 0.91805 | 0.91495 | 0.97927 | 0.93684 | 0.83564 | 0.90964 | 0.77185 | 0.99975 | 1.00000 | 1.00000 | 0.99967 |
| 11 | 0.99820 | 0.91495 | 0.99697 | 0.81421 | 0.94460 | 0.96997 | 0.98319 | 0.99975 | 1.00000 | 1.00000 | 0.99917 |
| 12 | 0.98993 | 0.97218 | 0.96700 | 0.93684 | 0.94460 | 0.90964 | 0.92109 | 0.98746 | 1.00000 | 1.00000 | 0.99967 |
| 13 | 0.99820 | 0.96244 | 0.96146 | 0.97190 | 0.83564 | 0.53299 | 0.98319 | 0.99740 | 0.99544 | 0.99819 | 0.99917 |
| 14 | 0.99820 | 0.91495 | 0.96146 | 0.97190 | 0.94460 | 0.80259 | 0.98319 | 0.98746 | 1.00000 | 1.00000 | 0.99984 |
| 15 | 0.98327 | 0.97218 | 0.96146 | 0.97190 | 0.94460 | 0.53299 | 0.92109 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 16 | 0.98327 | 0.91495 | 0.98915 | 0.97190 | 0.83564 | 0.80259 | 0.96473 | 0.98746 | 1.00000 | 1.00000 | 0.99950 |
| 17 | 0.98327 | 0.77543 | 0.80684 | 0.81421 | 0.83564 | 0.80259 | 0.77185 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 18 | 0.99087 | 0.91495 | 0.96700 | 0.93684 | 0.83564 | 0.96997 | 0.96473 | 0.99975 | 1.00000 | 1.00000 | 0.99917 |
| 19 | 0.98520 | 0.77543 | 0.67037 | 0.93684 | 0.83564 | 0.53299 | 0.77185 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 20 | 0.98805 | 0.77543 | 0.98915 | 0.97190 | 0.83564 | 0.90964 | 0.92109 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 21 | 0.99087 | 0.77543 | 0.88978 | 0.81421 | 0.83564 | 0.53299 | 0.77185 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 22 | 0.78038 | 0.77543 | 0.68397 | 0.81421 | 0.83564 | 0.53299 | 0.77185 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 23 | 0.99457 | 0.77543 | 0.55525 | 0.93684 | 0.94460 | 0.53299 | 0.98319 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 24 | 0.99820 | 0.77543 | 0.83438 | 0.81421 | 0.83564 | 0.53299 | 0.98319 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 25 | 0.99820 | 0.77543 | 0.68397 | 0.93684 | 0.94460 | 0.53299 | 0.98319 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 26 | 0.99457 | 0.77543 | 0.86458 | 0.93684 | 0.83564 | 0.53299 | 0.98319 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 27 | 0.99272 | 0.77543 | 0.63729 | 0.93684 | 0.94460 | 0.53299 | 0.96473 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 28 | 0.99087 | 0.77543 | 0.50029 | 0.93684 | 0.94460 | 0.80259 | 0.96473 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 29 | 0.99087 | 0.77543 | 0.80684 | 0.81421 | 0.94460 | 0.53299 | 0.96473 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 30 | 0.98899 | 0.77543 | 0.86458 | 0.81421 | 0.94460 | 0.53299 | 0.77185 | 0.98746 | 0.99544 | 0.99819 | 0.99917 |
| 31 | 0.99087 | 0.99888 | 0.98915 | 0.98663 | 0.98203 | 0.96997 | 0.96473 | 0.99450 | 1.00000 | 1.00000 | 0.99950 |

airports were assessed by experts, and the most popular assessment was taken into account. However, for instance, there is the CAPC criterion (see Table 1) that characterizes an airport's capacity (number of passengers per year). For this criterion, the damage values were evaluated per the scale shown in Table 4.

It is obvious that, such airport parameters are predominantly between scale values. For such airports, piecewise line approximation was used. For value $c$ from the value range of criterion $[a, b]$ and corresponding risk range $[U_a, U_b]$ the formula for calculating the risk is written as:

$$U_c = U_a + (c-a)\frac{U_b - U_a}{b-a}. \qquad (7)$$

The experts' estimates for each considered option and calculated components of usefulness for all previously selected criteria are shown in Table 5.

## 3. Ranking of airports by value of integral risk

The integral risk was calculated according to formula (1) using the data obtained per the above principles (see Table 5). As the result, a list of alternative airports was made, the first ten of which are shown in Table 6. The following airports in the rating have the risk value above 0.5 and are not considered due to unacceptable risk associated with modernization.

**Table 6. Rating of airports in terms of the integral risk of modernization**

| № | Airport | City/Town | Region | Integral risk |
|---|---|---|---|---|
| 1 | Ramenskoye | Zhukovsky | Moscow Oblast | 0.0747 |
| 2 | Yermolino | Balabanovo | Kaluga Oblast | 0.1173 |
| 3 | Tunoshna | Yaroslavl | Yaroslavl Oblast | 0.2293 |
| 4 | Yuzhny | Ivanovo | Ivanovo Oblast | 0.2380 |
| 5 | Grabtsevo | Kaluga | Kaluga Oblast | 0.3105 |
| 6 | Chkalovsky | Shchelkovo | Moscow Oblast | 0.3627 |
| 7 | Dobrynskoye | Vladimir | Vladimir Oblast | 0.3777 |
| 8 | Ostafievo | Moscow | Moscow | 0.3799 |
| 9 | Krutyshki | Stupino | Moscow Oblast | 0.3907 |
| 10 | Dyagilevo | Ryazan | Ryazan Oblast | 0.4684 |

As it can be seen from Table 6, the projects numbered 1, 2, 3 and 4 have the minimal risk. Those options should be considered as preferable when taking the final decision regarding the funding of the MAC modernization.

## Conclusion

Obviously, the presented algorithm of risk synthesis for ranking infrastructure facilities cannot be recommended as the one and only in situations of decision-making regarding investment in certain projects. However, such algorithms allow significantly reducing the number of compared options and enable DMs to carefully examine the remaining options for the purpose of finding the best one.

The above approach to risk synthesis may find application in many domains, both by major companies, for instance, for the purpose of investment project estimation, infrastructure facilities construction, and small business, e.g. for estimating the risk associated with warehouse or new client office leasing. The latter problems are interesting due to the fact that there are many property units, whose descriptions are available at various online aggregators. Manual analytical data processing as regards such units is impossible, as it often limits the selection of options that (in the experts' opinion) best comply with the DM's preferences, and eliminates a great number of equally valid options. The suggested algorithm of risk synthesis simplifies the problem faced by a DM and allows easily automating the process of multicriteria selection out of a large number of options.

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## The authors' contribution

**Kuzmina N.M.** supported the collection of expert data, selection and verification of statistical data and characteristics of airports, provided the information and selected sources associated with commercial operation.

**Ridley A.N.** used the above model of risk synthesis for the purpose of solving the problem at hand, presented ideas regarding the management of obtained data, set forward the results of the research and possible applications of the involved ideas, models and methods for solving complex problems.

## Conflict of interests

The authors declare the absence of a conflict of interests.

# A methodological approach to identifying the priority of scout/attack and attack unmanned aerial vehicles

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**Abstract.** *The* **Aim** *of this paper is to develop an evaluation scheme of priority indicators for scout/attack and attack unmanned aerial vehicles (UAVs).* **Methods.** *The evaluation scheme of UAV priority indicators was developed using the mathematics of metrical analysis and known expert estimates of indicators for some UAVs.* **Results.** *Development of UAV priority indicators evaluation scheme.* **Conclusions.** *The suggested UAV priority evaluation scheme can be used for rational decision-making when creating (acquiring) UAVs.*

**Keywords:** *selection of the model of unmanned aerial vehicle, priority estimation, unmanned aerial vehicle system, scout/strike unmanned aerial vehicle, strike unmanned aerial vehicle, estimates, metrical analysis, expert estimate*

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## Introduction

The selection problem is of great importance both while acquiring certain products, and while developing them, especially complex technical systems (CTS), primarily military ones.

Nowadays, aircraft and weapons systems are designed based on the systems approach with wide use of mathematical and semirealistic simulation with subsequent ground and field tests [1]. That, for instance, was demonstrated in the presentations of the Anniversary National Science and Technology Conference Aviation Systems in the XXI Century on May 26 and 27, 2016, organized by GosNIIAS. The conference hosted a number of presentations dedicated, for instance, to the design of unmanned aerial vehicles (UAVs) and missile equipment. According to one of them, a model system for design characteristics synthesis had been developed for the purpose of researching the effect of the design parameters on the conceptual design of UAVs. The system includes the basic calculations of flight and economic characteristics, which enables comparative analysis of various types of UAVs ensuring visualization of the obtained characteristics and estimates. Thus, it was attempted to analyze the effect of new and emerging technologies on the conceptual design of UAVs [2]. Another presentation dealt with an approach to the system concept definition and general design of unmanned aircraft systems enabling reconnaissance and attack missions. A research method was suggested, a structure diagram of a system of models was developed, and a system of operational efficiency criteria was developed and substantiated [3].

There is a wide range of scientific and technical literature dedicated to both the design and the selection of optimal technical solutions when creating complex systems based, among other things, on the assessment of the quality and engineering level (EL). The bibliographical description of the sources is given in monographs [4, 5]. The relevance of scientifically substantiated selection as part of new technology development is currently supported by the publication of a number of monographs dealing with the methodology of aircraft engineering [6 – 9]. In practice, the selection of aircraft and weapons systems heavily relies on benchmarking, whereas the comparison of same-purpose items involves criteria for comparing the merits of items in terms of functional, technical and economic indicators [8, 10]. Thus, in [10], there is an example of selection of the best naval missile system based on the comparison of characteristics rendered in a single data format taking into consideration the cost of each element of the system and its life cycle as a whole. In the authors' opinion, under time constraints, implementing such approach allows optimizing the selection of a missile system and saving significant funds. Materials cited in [11] provide an insight into the complexity of the process of selection between the Rafale and the Typhoon aircraft by India. Such indicators were taken into consideration as the operational effectiveness against ground targets and in air-to-air combat, operating properties, sophistication of avionics, price, and time of project delivery. As the result, India chose the Rafale 4-th generation multirole fighter ([Delivery of the first Rafale fighter to India]. Ekspress-informatsia 2020;13:2). Field testing is an efficient tool of selecting CTS.

It must also be noted that the current stage of development of airborne armament is characterized by a significant growth of the scope of missions assigned to a strike aircraft system, and stricter requirements for the performance of upgraded and newly developed high-precision weapons amidst significant budgetary restraints. Under such conditions, the requirement of reduced time of development and selection of optimal solution as regards weapons systems actualizes the development of automated decision support systems. It is suggested to understand the solution as a man-machine

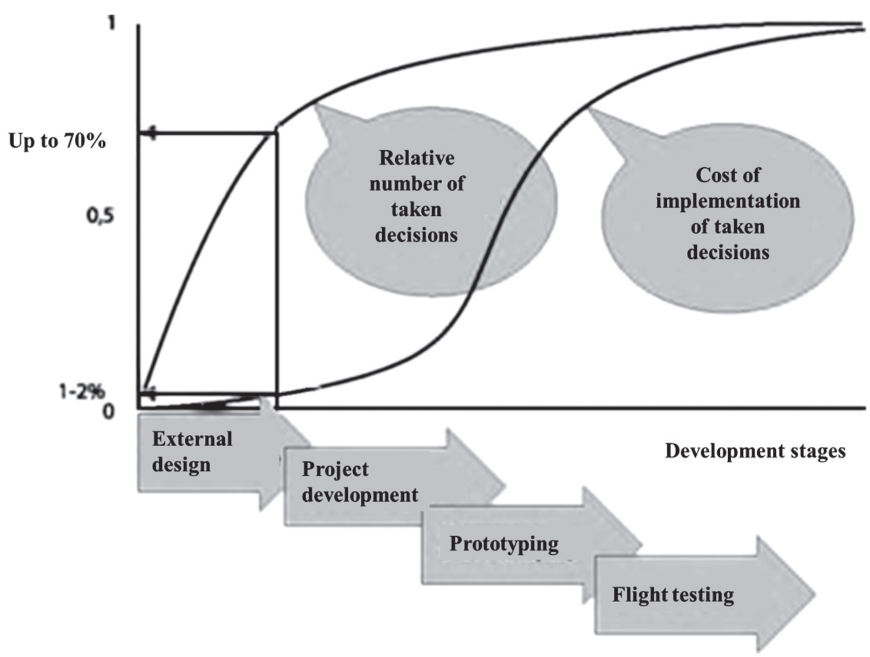


Figure 1. Significance of made decisions as part of aircraft design

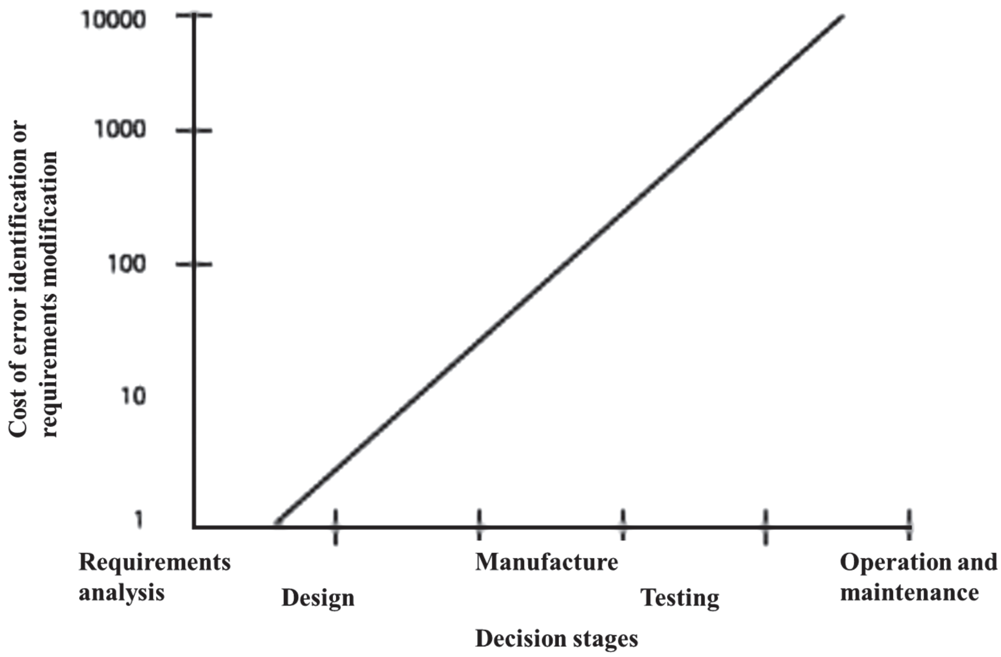


Fig. 2. Relative cost of fault correction

system that allows using both objective, and subjective data for the purpose of analyzing and solving problems, including those poorly formalized. For instance, methods were suggested for selecting the rational concepts of combat aircraft systems and rational airborne armament options based on simulation and assessment of combat effectiveness, decision theory [12-15]. In [16], a method is proposed for selecting the rational types of primary elements of developed weapons and military equipment based on expert estimations and comparison of multicriterial alternatives under uncertainty provided by the hierarchy analysis methods and decision theory. We should also name [5, 6, 17] among the works dedicated to the problem of selection of the best technical solutions, quality evaluation and EL of weapons and military equipment, which includes with the involvement of experts.

The initial stages of design are crucial in terms of defining the conceptual features of newly created products and have a large effect on the quality of the technological groundwork. The conducted systems research aimed at identifying the nature of CTS development and evaluation of their quality and EL has revealed a general trend in the correlation between the estimated effect of decision-making and the amount of incurred costs at various life cycle stages of CTS regardless of the area of scientific and technological activities. In case of aircraft systems [18], the significance of conceptual decisions is as high as 70% of the total number, while the costs are at 2% of the total cost of system development (Fig. 1). In Fig. 1, the relative significance of decision-making is defined as the percentage of made decisions.

The cost of correction of the identified errors rises exponentially in the course of entity development and at the final stage of the project life cycle as compared with the cost of such modifications at the very early stages of its development [19] (Fig. 2).

That is why the initial design stages of CTS, which includes UAV, should be the focus of attention in terms of concept definition, while the process of selection of the rational technical solution is to be regarded as conceptual.

This paper suggests an evaluation scheme of UAV priority indicators based on methods of metrical analysis as applied to scout/attack and attack UAVs with the take-off mass between 300 and 25000 kg or more as one of the most promising types of unmanned craft. The application of methods of metrical analysis with regards to applied multidimensional and multicriterial problems has shown its high efficiency [20 – 22]. As the primary criterion of UAV classification (airframe, engine, navigation and control systems, etc.) this paper considers the takeoff mass (examined in [23 – 26]) that reflects the quality of the adopted design solutions. The mass of a UAV defines its power characteristics, loadlifting capacity and cost of development. An example of such classification for UAV heavier than 100 kg is shown in Table 1 [23].

**Table 1. US armed forces UAV classification**

| Category | Maximum takeoff mass, kg | Maximum altitude (ceiling), m | Flight duration, h |
|---|---|---|---|
| Medium | 100 – 1500 | 3000 – 8000 | 2 – 24 |
| Medium-altitude long-endurance (MALE) | 1500 – 2500 | 3000 – 8000 | 12 – 24 |
| High-altitude long-endurance (HALE) | 2500 – 5000 | 5000 – 20 000 | 12 – 24 |
| Strike/Combat | – | 8000 – 12 000 | – |

The general view of certain scout/attack and attack UAVs is shown in Fig. 3 – 6. The engineering quality of a UAV manifests itself in the novelty and improved performance supported by technological innovation. The level of engineering quality is the property of an item that reflects the degree of incorporation of world's best engineering achievements. In [27], based on the analysis of the primary functions and states inherent to aircraft at various life cycle stages it is suggested to identify the level of engineering quality according to four composite indicators that characterize the design, operational, manufacturing and functional quality. The EL (as the criterion of technical quality) will be understood as a set of properties of an entity that reflect its engineering quality as compared with the reference. Assessing a UAV's EL is especially important both at the stage of concept definition, and the early design stages. In order for a new generation of UAV to be more advanced in comparison with the current one, it is required to ensure a higher EL.


Fig. 3. Heron TP unmanned aerial vehicle (Israel)


Fig. 4. Cloud Shadow unmanned aerial vehicle (China)

Fig. 5. Mantis European unmanned aerial vehicle aircraft (UK)

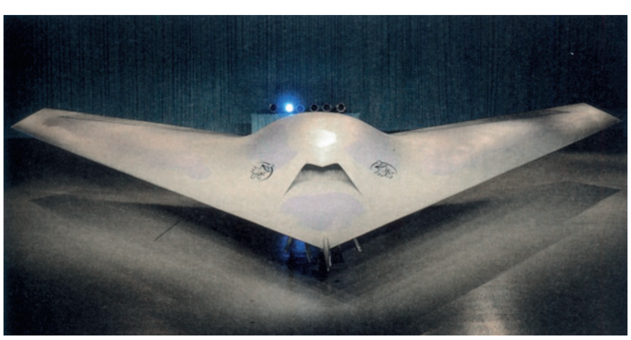
Figure 6. Phantom Ray multi-mission unmanned aerial vehicle (US)

In this paper, for the purpose of identifying the significance of the analyzed UAV in relation to other UAVs (which is equivalent to EL evaluation), whose estimated level is already known, the concept of a UAV's "priority" is introduced.

The suggested UAV priority evaluation method can be used for rational decision-making when creating (acquiring) UAVs.

In this paper, the priority of UAVs is evaluated using the following estimates: takeoff mass, mass of the payload, flight duration, flight distance, cruising speed, flight altitude.

## 1. Some provisions of metrical analysis used in the evaluation of unmanned aerial vehicle priority

In this paper, the UAVs with no expert estimates are evaluated with the use of an interpolation scheme based on metrical analysis. With the development of computer technology, the problem of data analysis and processing became especially relevant. Metrical analysis enables efficient solution of various problems in respect to functions of many variables without prior definition of the type of functional dependence from the variables, but using only the information from the actual values of function $Y_1$, …, $Y_n$, in points $X_1$, …, $X_n$ [20-22].

**1.1. Interpolation of functions of one and several variables using metrical analysis**

Interpolation in numerical mathematics is a method of finding the intermediate values of a function based on the available set of known function values in a finite number of points, i.e. the values of function arguments.

We examine a problem associated with functional dependence

$$Y = F(X_1,...,X_m) = F(X) \tag{1}$$

where function $F(X)$ is unknown and is to be recovered either in one point $X^*$, or in a set of specified points based on the known function values $Y_k$, $k = 1, ..., n$, in fixed points $X_k = (X_{k1},...,X_{km})^T$. Point **X** belongs to a unit $m$-dimensional cube $K \in E^m$ of space $E^m$.

In space $E^m$ a normed metric is selected:

$$\|X\|^2 = \sum_{j=1}^{m} w_j * X_j^2, \tag{2}$$

where metric weights $w_j \geq 0, \sum_{j=1}^{m} w_j = m.$

Metric weights $w_1$, …, $w_m$ are values that take into consideration the variation pattern of the examined function following changes in its arguments. They are calculated taking into consideration the mutual arrangement of the interpolation nodes and function values in them. An important part of the suggested metrical analysis is not the a priori definition of the weights that set the norm, but the selection of weights $w_j$, $j = 1, \ldots, m$, based on the set of known data $Y_k$, $X_k$, $k = 1, \ldots, n$.

In order to identify the metric weights, a number of schemes have been developed [20 – 22].

It is required to recover the function value in point $X^*$.

For that purpose, a matrix of metric uncertainty **W** is compiled for point $X^*$ relative to the assembly of points $X_1, \ldots, X_n$. A matrix of metric uncertainty is a matrix of the dimension of $(n \times n)$ defined by the arrangement of the interpolation nodes $X_1, \ldots, X_n$, the value $X^*$ and metric weights $w_1, \ldots, w_m$:

$$W = \begin{pmatrix} p^2\left(X_1, X^*\right)_w & \left(X_1, X_2\right)_w & \ldots & \left(X_1, X_n\right)_w \\ \left(X_2, X_1\right)_w & p^2\left(X_2, X^*\right)_w & \ldots & \left(X_2, X_n\right)_w \\ \ldots & \ldots & \ldots & \ldots \\ \left(X_n, X_1\right)_w & \left(X_n, X_2\right)_w & \ldots & p^2\left(X_n, X^*\right)_w \end{pmatrix} \quad (3)$$

where

$$p^2\left(X_i, X^*\right)_w = \sum_{k=1}^{m} w_k \left(X_{ik} - X_k^*\right)^2, \quad (4)$$

$$\left(X_i, X_j\right)_w = \sum_{k=1}^{m} w_k \left(X_{ik} - X_k^*\right)\left(X_{jk} - X_k^*\right), \; i, j = 1, \ldots, n. \quad (5)$$

The sought value $Y(X^*)=Y^*$ is defined by the formula:

$$Y^* = \frac{\left(w^{-1}\,\mathbf{Y}, \mathbf{1}\right)}{\left(w^{-1}\,\mathbf{1}, \mathbf{1}\right)} \quad (6)$$

where $\mathbf{1} = (1,\ldots,1)^{\mathrm{T}}$, $\mathbf{Y} = (Y_1, \ldots, Y_n)^{\mathrm{T}}$.

**1.2. Identification of metrical weights definition through successive exclusion of arguments**

If the metric weights $w_1, \ldots, w_m$ are equal to one, i.e. $w_i=1$, $i = \overline{1, m}$, the matrix of metric uncertainty will only take into consideration the geometrical arrangement of the interpolation nodes in the initial geometrical space. However, by matching the values of metric weight we can take into consideration the unequal level of variation of function

**Table 2. Expert estimates of category one UAV priority.**

| UAV take-off mass in ascending order $M_{TOM}$, kg | Correlation of $M_{PL}/M_{TOM}$ | Flight duration $T_F$, h | Flying range $D_F$, km | Cruising speed $V_{CR}$, km/h | Flight altitude (service ceiling) $H_F$, m | Expert estimate per a 100-point scale |
|---|---|---|---|---|---|---|
| 1100 | 0.32 | 36 | 4000 | 120 | 9100 | 100 |
| 1200 | 0.17 | 20 | 350 | 120 | 7000 | 65 |
| 1250 | 0.12 | 40 | 2500 | 800 | 6900 | 70 |
| 1300 | 0.46 | 25 | 1200 | 220 | 7000 | 80 |

**Table 3. Expert estimates of category two UAV priority.**

| UAV take-off mass in ascending order $M_{TOM}$, kg | Correlation of $M_{PL}/M_{TOM}$ | Flight duration $T_F$, h | Flying range $D_F$, km | Cruising speed $V_{CR}$, km/h | Flight altitude (service ceiling) $H_F$, m | Expert estimate per a 100-point scale |
|---|---|---|---|---|---|---|
| 3300 | 0.36 | 40 | 2000 | 220 | 7000 | 50 |
| 4000 | 0.10 | 12 | 1300 | 700 | 2000 | 20 |
| 4760 | 0.5 | 28 | 5900 | 425 | 15240 | 100 |

**Table 4. Expert estimates of category three UAV priority.**

| UAV take-off mass in ascending order $M_{TOM}$, kg | Correlation of $M_{PL}/M_{TOM}$ | Flight duration $T_F$, h | Flying range $D_F$, km | Cruising speed $V_{CR}$, km/h | Flight altitude (service ceiling) $H_F$, m | Expert estimate per a 100-point scale |
|---|---|---|---|---|---|---|
| 5300 | 0.40 | 40 | 3700 | 300 | 13700 | 100 |
| 5600 | 0.13 | 30 | 7000 | 330 | 9000 | 50 |

**Table 5. Expert estimates of category four UAV priority.**

| UAV take-off mass in ascending order $M_{TOM}$, kg | Correlation of $M_{PL}/M_{TOM}$ | Flight duration $T_F$, h | Flying range $D_F$, km | Cruising speed $V_{CR}$, km/h | Flight altitude (service ceiling) $H_F$, m | Expert estimate per a 100-point scale |
|---|---|---|---|---|---|---|
| 16556 | 0.12 | 2 | 2400 | 988 | 12200 | 20 |
| 65000 | 0.37 | 30 | 7500 | 800 | 13000 | 100 |

**Table 6. Primary UAV performance data related to take-off mass.**

| UAV take-off mass in ascending order $M_{TOM}$, kg | Mass of the payload / Correlation of $M_{PL}/M_{TOM}$ | Flight duration $T_F$, h | Flying range $D_F$, km | Cruising speed $V_{CR}$, km/h | Flight altitude (service ceiling) $H_F$, m | Priority indicators assessment |
|---|---|---|---|---|---|---|
| *1* | *2* | *3* | *4* | *5* | *6* | *7* |
| 300 | 70/0.23 | 8 | 290 | 150 | 5000 | 43.31 |
| 450 | 150/0.33 | 20 | 200 | 130 | 6000 | 68.24 |
| 450 | 140/0.31 | 24 | 250 | 170 | 5500 | 69.47 |
| 640 | 489/0.34 | 30 | 3700 | 210 | 7500 | 86.21 |
| 650 | 55/0.08 | 24 | 150 | 220 | 7000 | 49.64 |
| 727 | 90/0.12 | 12 | 260 | 148 | 4500 | 35.84 |
| 1000 | 200/0.20 | 24 | 750 | 250 | 8000 | 63.97 |
| 1020 | 345/0.34 | 24 | 1100 | 148 | 7620 | 77.88 |
| 1040 | 204/0.2 | 20 | 740 | 130 | 7600 | 59.93 |
| 1100 | 350/0.32 | 36 | 4000 | 120 | 9100 | **100.00** |
| 1100 | 350/0.32 | 36 | 600 | 110 | 9000 | 91.88 |
| 1200 | 200 /0.17 | 20 | 350 | 120 | 7000 | **65.00** |
| 1200 | 300/0.25 | 24 | 300 | 200 | 7500 | 67.79 |
| 1250 | 150/0.12 | 40 | 2500 | 800 | 6900 | **70.00** |
| 1260 | 345/0.27 | 30 | 2000 | 180 | 7200 | 77.29 |
| 1300 | 400/0.30 | 30 | 6000 | 240 | 9000 | 87.47 |
| 1300 | 600 /0.46 | 25 | 1200 | 220 | 7000 | **80.00** |
| 1450 | 350/0.24 | 10 | 1300 | 480 | 7000 | 48.99 |
| 1450 | 300 /0.20 | 22 | 260 | 287 | 7900 | 60.82 |
| 1451 | 489/0.34 | 30 | 800 | 250 | 9000 | 86.52 |
| 1500 | 400/0.27 | 35 | 2000 | 280 | 7500 | 82.47 |
| 1500 | 370/0.25 | 40 | 800 | 200 | 7500 | 85.81 |
| 1600 | 200/0.12 | 24 | 180 | 200 | 9000 | 58.17 |
| 1633 | 478/0.29 | 36 | 400 | 280 | 8840 | 86.96 |
| 1650 | 450/0.27 | 24 | 260 | 268 | 7800 | 69.77 |
| 2400 | 350/0.14 | 24 | 250 | 280 | 10600 | 63.05 |
| 2678 | 454/0.16 | 12 | 2800 | 720 | 12200 | 54.24 |
| 2800 | 400/0.14 | 35 | 6000 | 850 | 8000 | 69.73 |
| 2800 | 340/0.12 | 24 | 1000 | 600 | 8200 | 53.87 |
| 3000 | 400/0.13 | 6 | 2000 | 550 | 14000 | 49.74 |
| 3000 | 300/0.10 | 22 | 260 | 287 | 7900 | 50.96 |
| 3000 | 100/0.03 | 32 | 800 | 2200 | 6500 | 36.36 |
| 3200 | 1000/0.31 | 45 | 250 | 240 | 7000 | 94.93 |
| 3250 | 300/0.09 | 35 | 200 | 600 | 6000 | 57.12 |
| 3300 | 1200/0.36 | 40 | 2000 | 220 | 7000 | **50.00** |
| 3500 | 600/0.14 | 20 | 250 | 400 | 600 | 35.78 |
| 4000 | 400/0.10 | 12 | 1300 | 700 | 2000 | **20.00** |
| 4200 | 480/0.11 | 32 | 2000 | 370 | 9000 | 66.13 |
| 4500 | 1360/0.30 | 24 | 400 | 390 | 14000 | 85.46 |
| 4760 | 1700/0.5 | 28 | 5900 | 425 | 15240 | **100.00** |
| 4760 | 1800/0.38 | 32 | 1852 | 313 | 15240 | 94.98 |
| 4763 | 1746/0.36 | 30 | 5900 | 425 | 152409 | 93.33 |
| 4800 | 1589/0.33 | 20 | 6000 | 647 | 18000 | 96.04 |
| 5000 | 480/0.09 | 12 | 2500 | 400 | 7400 | 39.32 |
| 5000 | 480/0.09 | 15 | 260 | 253 | 5100 | 36.52 |
| 5000 | 480/0.09 | 50 | 260 | 213 | 9100 | 83.10 |
| 5300 | 1800/0.40 | 40 | 3700 | 300 | 13700 | **100.00** |
| 5450 | 1000/0.18 | 3 | 1200 | 920 | 10700 | 40.25 |
| 5600 | 700/0.13 | 30 | 7000 | 330 | 9000 | **50.00** |

| UAV take-off mass in ascending order $M_{TOM}$, kg | Mass of the payload / Correlation of $M_{PL}/M_{TOM}$ | Flight duration $T_F$, h | Flying range $D_F$, km | Cruising speed $V_{CR}$, km/h | Flight altitude (service ceiling) $H_F$, m | Priority indicators assessment |
|---|---|---|---|---|---|---|
| *1* | *2* | *3* | *4* | *5* | *6* | *7* |
| 6000 | 600/0.10 | 25 | 3000 | 400 | 12200 | 65.44 |
| 6000 | 800/0.13 | 14 | 500 | 850 | 12000 | 49.87 |
| 6146 | 500/0.08 | 16 | 8149 | 592 | 13700 | 60.08 |
| 7000 | 800/0.11 | 20 | 2500 | 555 | 15240 | 65.84 |
| 7500 | 2000/0.26 | 48 | 1000 | 250 | 12000 | 95.02 |
| 8000 | 950/0.12 | 26 | 1000 | 950 | 12000 | 61.47 |
| 8255 | 2948/0.35 | 18 | 1600 | 650 | 15240 | 85.71 |
| 9000 | 1000/0.11 | 30 | 1600 | 370 | 16700 | 80.50 |
| 10000 | 2000/0.20 | 28 | 4000 | 960 | 15000 | 80.89 |
| 13000 | 2000/0.15 | 34 | 3000 | 730 | 13000 | 79.09 |
| 16556 | 907/0.05 | 12 | 2800 | 850 | 12200 | 42.55 |
| 16556 | 2040/0.12 | 7 | 2200 | 850 | 12200 | 43.41 |
| 16556 | 2000/0.12 | 2 | 2400 | 988 | 12200 | 37.14 |
| 20190 | 2040/0.12 | 12 | 2960 | 850 | 12200 | 49.38 |
| 22000 | 6010/0.27 | 16 | 7000 | 900 | 1200 | 47.85 |
| 25000 | 4000/0.16 | 15 | 6000 | 1500 | 15000 | 60.22 |
| 65000 | 24000/0.37 | 30 | 7500 | 800 | 13000 | **100.00** |

under varying function arguments. In this paper, the metric weights were found using a scheme based on the comparison of the recovered function values in the points, in which function values are defined with sequential exclusion of each argument individually [20].

## 2. Estimating the priority of scout/attack and attack unmanned aerial vehicles through metrical analysis

There are data available regarding primary UAV indicators (takeoff mass, mass of the payload, flight duration, flight distance, cruising speed, flight altitude (practical ceiling)).

The experts divided the vehicles into a number of categories (depending on the takeoff mass): first, up to 1650 kg; second, from 1650 kg to 5000 kg; third, from 5000 to 10000 kg; fourth, over 10000 kg. In each category, the experts could rate the priority indicator of a certain number of UAVs on a 100-point scale (see. Tables 2 – 5) with respect to the remaining five indicators: mass of the payload, flight duration, flight distance, cruising speed, flight altitude.

It is required to, using the priority indicator values for certain UAVs provided by experts, identify the unknown values of such indicator for other UAVs.

This problem is solved using the scheme shown above in sections 1.1 and 1.2, where the priority indicator serves as the function, while the above five UAV indicators serve as the arguments.

The solution algorithm calculates the priority indicator according to formula (6), where $Y^*$ is the priority indicator of the UAV under consideration, , $k$ = 1, …, 5 are the five above indicators for such UAV.

The results of the priority indicator evaluation for all UAVs are shown in the last column of Table 6.

## 3. Integration of several expert estimates

In practice, it is not uncommon for different experts to provide a different estimate of a value. The problem of UAV estimation is no exception. In this section, the authors suggest four schemes for integrating estimates by different experts. Below, those four priority estimate integration schemes are set forth with the example of the first category of UAVs, i.e. from 1000 to 1650 kg.

**Scheme no. 1.** In scheme no. 1, based on each expert's estimate, the remaining UAVs are individually estimated, then the obtained estimates are averaged (Table 7). Shown in bold are the UAVs estimated by experts; shown in normal font are the estimates obtained through metrical analysis.

The initial UAV indicators shown in Table 6 were normalized relative to the mathematical expectation and dispersion:

$$\hat{X}_i = \frac{X_i - \mu}{\sqrt{\sigma^2}}.$$

**Scheme no. 2.** According to the second integration scheme, initially, for each estimated UAV, the expert estimates are averaged (arithmetic mean of the estimates) for a UAV (Table 8):

– No. 10: average estimate $= \dfrac{100+95+90}{3} = 95;$

– No. 12: average estimate $= \dfrac{65+63+60}{3} = 62,67;$

– No. 14: average estimate $= \dfrac{70+72+75}{3} = 72,33;$

– No. 17: average estimate $= \dfrac{80+84+85}{3} = 83;$

Then, the metrical analysis scheme is used.

**Table 7. UAV priority assessment per scheme no. 1 (averaged estimate).**

| UAV number | UAV take-off mass in ascending order $M_{TOM}$, kg | Correlation of $M_{PL}/M_{TOM}$ | Flight duration $T_F$, h | Flying range $D_F$, km | Cruising speed $V_{CR}$, km/h | Flight altitude (service ceiling) $H_F$, m | Priority indicators assessment (expert estimates given in bold) | | | Priority indicators assessment |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 1 | 2 | 3 | 4 |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 1 | 1000 | 0.20 | 24 | 750 | 250 | 8000 | 43.31 | 39.51 | 39.04 | 40.62 |
| 2 | 1020 | 0.34 | 24 | 1100 | 148 | 7620 | 68.24 | 68.73 | 69.99 | 68.99 |
| 3 | 1040 | 0.2 | 20 | 740 | 130 | 7600 | 69.47 | 70.47 | 68.09 | 69.34 |
| 4 | 1100 | 0.32 | 36 | 4000 | 120 | 9100 | 86.21 | 84.59 | 85.29 | 85.36 |
| 5 | 1100 | 0.32 | 36 | 600 | 110 | 9000 | 49.64 | 48.24 | 45.83 | 47.90 |
| 6 | 1200 | 0.17 | 20 | 350 | 120 | 7000 | 35.84 | 33.77 | 34.66 | 34.76 |
| 7 | 1200 | 0.25 | 24 | 300 | 200 | 7500 | 63.97 | 62.65 | 63.54 | 63.39 |
| 8 | 1250 | 0.12 | 40 | 2500 | 800 | 6900 | 77.88 | 76.57 | 76.31 | 76.92 |
| 9 | 1260 | 0.27 | 30 | 2000 | 180 | 7200 | 59.93 | 57.71 | 59.94 | 59.19 |
| **10** | **1300** | **0.30** | **30** | **6000** | **240** | **9000** | **100.00** | **95.00** | **90.00** | 95.00 |
| 11 | 1300 | 0.46 | 25 | 1200 | 220 | 7000 | 91.88 | 97.91 | 95.44 | 95.08 |
| **12** | **1450** | **0.24** | **10** | **1300** | **480** | **7000** | **65.00** | **63.00** | **60.00** | 62.67 |
| 13 | 1450 | 0.20 | 22 | 260 | 287 | 7900 | 67.79 | 69.54 | 67.21 | 68.18 |
| **14** | **1451** | **0.34** | **30** | **800** | **250** | **9000** | **70.00** | **72.00** | **75.00** | 72.33 |
| 15 | 1500 | 0.27 | 35 | 2000 | 280 | 7500 | 77.29 | 78.58 | 75.31 | 77.06 |
| 16 | 1500 | 0.25 | 40 | 800 | 200 | 7500 | 87.47 | 85.10 | 86.36 | 86.31 |
| **17** | **1600** | **0.12** | **24** | **180** | **200** | **9000** | **80.00** | **84.00** | **85.00** | 83.00 |
| 18 | 1633 | 0.29 | 36 | 400 | 280 | 8840 | 48.99 | 46.01 | 45.17 | 46.72 |
| 19 | 1650 | 0.27 | 24 | 260 | 268 | 7800 | 60.82 | 62.93 | 60.86 | 61.54 |

**Table 8. UAV priority assessment per scheme no. 2 (averaged expert assessment)**

| UAV number | UAV take-off mass in ascending order $M_{TOM}$, kg | Payload $M_{PL}$, kg / Correlation of $M_{PL}/M_{TOM}$ | Flight duration $T_F$, h | Flying range $D_F$, km | Cruising speed $V_{CR}$, km/h | Flight altitude (service ceiling) $H_F$, m | Priority assessment |
|---|---|---|---|---|---|---|---|
| 1 | 1000 | 200/0.20 | 24 | 750 | 250 | 8000 | 42.36 |
| 2 | 1020 | 345/0.34 | 24 | 1100 | 148 | 7620 | 68.58 |
| 3 | 1040 | 204/0.2 | 20 | 740 | 130 | 7600 | 69.97 |
| 4 | 1100 | 350/0.32 | 36 | 4000 | 120 | 9100 | 86.49 |
| 5 | 1100 | 350/0.32 | 36 | 600 | 110 | 9000 | 47.86 |
| 6 | 1200 | 200 /0.17 | 20 | 350 | 120 | 7000 | 34.1 |
| 7 | 1200 | 300/0.25 | 24 | 300 | 200 | 7500 | 63.22 |
| 8 | 1250 | 150/0.12 | 40 | 2500 | 800 | 6900 | 78.07 |
| 9 | 1260 | 345/0.27 | 30 | 2000 | 180 | 7200 | 58.58 |
| **10** | **1300** | **400/0.30** | **30** | **6000** | **240** | **9000** | 95.00 |
| 11 | 1300 | 600 /0.46 | 25 | 1200 | 220 | 7000 | 92.01 |
| **12** | **1450** | **350/0.24** | **10** | **1300** | **480** | **7000** | 62.67 |
| 13 | 1450 | 300 /0.20 | 22 | 260 | 287 | 7900 | 67.49 |
| **14** | **1451** | **489/0.34** | **30** | **800** | **250** | **9000** | 72.33 |
| 15 | 1500 | 400/0.27 | 35 | 2000 | 280 | 7500 | 77.07 |
| 16 | 1500 | 370/0.25 | 40 | 800 | 200 | 7500 | 86.75 |
| **17** | **1600** | **200/0.12** | **24** | **180** | **200** | **9000** | 83.00 |
| 18 | 1633 | 478/0.29 | 36 | 400 | 280 | 8840 | 49.21 |
| 19 | 1650 | 450/0.27 | 24 | 260 | 268 | 7800 | 60.25 |

**Table 9. UAV priority assessment per scheme no. 3.**

| UAV number | UAV take-off mass in ascending order $M_{TOM}$, kg | Payload $M_{PL}$, kg / Correlation of $M_{PL}/M_{TOM}$ | Flight duration $T_F$, h | Flying range $D_F$, km | Cruising speed $V_{CR}$, km/h | Flight altitude (service ceiling) $H_F$, m | Priority indicators assessment |
|---|---|---|---|---|---|---|---|
| *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* |
| 1 | 1000 | 200/0.20 | 24 | 750 | 250 | 8000 | 42.72 |
| 2 | 1020 | 345/0.34 | 24 | 1100 | 148 | 7620 | 68.53 |
| 3 | 1040 | 204/0.2 | 20 | 740 | 130 | 7600 | 69.87 |
| 4 | 1100 | 350/0.32 | 36 | 4000 | 120 | 9100 | 86.45 |
| 5 | 1100 | 350/0.32 | 36 | 600 | 110 | 9000 | 48.39 |
| 6 | 1200 | 200 /0.17 | 20 | 350 | 120 | 7000 | 34.66 |
| 7 | 1200 | 300/0.25 | 24 | 300 | 200 | 7500 | 63.46 |
| 8 | 1250 | 150/0.12 | 40 | 2500 | 800 | 6900 | 78.05 |
| 9 | 1260 | 345/0.27 | 30 | 2000 | 180 | 7200 | 59.01 |
| **10** | **1300** | **400/0.30** | **30** | **6000** | **240** | **9000** | 96.5 |
| 11 | 1300 | 600 /0.46 | 25 | 1200 | 220 | 7000 | 91.99 |
| **12** | **1450** | **350/0.24** | **10** | **1300** | **480** | **7000** | 63.40 |
| **14** | **1451** | **489/0.34** | **30** | **800** | **250** | **9000** | 71.60 |
| 15 | 1500 | 400/0.27 | 35 | 2000 | 280 | 7500 | 77.16 |
| 16 | 1500 | 370/0.25 | 40 | 800 | 200 | 7500 | 87.0 |
| **17** | **1600** | **200/0.12** | **24** | **180** | **200** | **9000** | 82.20 |
| 18 | 1633 | 478/0.29 | 36 | 400 | 280 | 8840 | 42.09 |
| 19 | 1650 | 450/0.27 | 24 | 260 | 268 | 7800 | 60.44 |

**Table 10. UAV priority assessment per scheme no. 4 (subject to the weight of each expert per sample)**

| UAV number | UAV take-off mass in ascending order $M_{TOM}$, kg | Payload $M_{PL}$, kg / Correlation of $M_{PL}/M_{TOM}$ | Flight duration $T_F$, h | Flying range $D_F$, km | Cruising speed $V_{CR}$, km/h | Flight altitude (service ceiling) $H_F$, m | Priority assessment |
|---|---|---|---|---|---|---|---|
| 1 | 1000 | 200/0.20 | 24 | 750 | 250 | 8000 | 42.03 |
| 2 | 1020 | 345/0.34 | 24 | 1100 | 148 | 7620 | 68.26 |
| 3 | 1040 | 204/0.2 | 20 | 740 | 130 | 7600 | 69.69 |
| 4 | 1100 | 350/0.32 | 36 | 4000 | 120 | 9100 | 86.3 |
| 5 | 1100 | 350/0.32 | 36 | 600 | 110 | 9000 | 47.87 |
| 6 | 1200 | 200 /0.17 | 20 | 350 | 120 | 7000 | 33.92 |
| 7 | 1200 | 300/0.25 | 24 | 300 | 200 | 7500 | 63.12 |
| 8 | 1250 | 150/0.12 | 40 | 2500 | 800 | 6900 | 77.8 |
| 9 | 1260 | 345/0.27 | 30 | 2000 | 180 | 7200 | 58.44 |
| **10** | **1300** | **400/0.30** | **30** | **6000** | **240** | **9000** | 95.10 |
| 11 | 1300 | 600 /0.46 | 25 | 1200 | 220 | 7000 | 91.88 |
| **12** | **1450** | **350/0.24** | **10** | **1300** | **480** | **7000** | 62.56 |
| 13 | 1450 | 300 /0.20 | 22 | 260 | 287 | 7900 | 67.32 |
| **14** | **1451** | **489/0.34** | **30** | **800** | **250** | **9000** | 72.44 |
| 15 | 1500 | 400/0.27 | 35 | 2000 | 280 | 7500 | 76.94 |
| 16 | 1500 | 370/0.25 | 40 | 800 | 200 | 7500 | 86.66 |
| **17** | **1600** | **200/0.12** | **24** | **180** | **200** | **9000** | 82.48 |
| 18 | 1633 | 478/0.29 | 36 | 400 | 280 | 8840 | 48.96 |
| 19 | 1650 | 450/0.27 | 24 | 260 | 268 | 7800 | 60.14 |

**Scheme no. 3.** Normally, estimates by different experts have different weights depending on such expert's experience [4]. Subsequently, that must be taken into consideration in order to obtain a more accurate final estimate using metrical analysis

$$K = \sum_{i=1}^{n} W_i * K_i,\ i = 1, \ldots, n,$$

where $\sum_{i=1}^{n} W_i = 1$, $K_i$ is the estimate of the priority indicator of the $i$-th expert.

Let the weight of expert 1 be 0.5; weight of expert 2 be 0.3; weight of expert 3 be 0.2, then the priority estimate for UAV (Table 8):

– No. 10: $K_{10} = 0,5 \cdot 100 + 0,3 \cdot 95 + 0,2 \cdot 90 = 96,5;$

– No. 12: $K_{12} = 0,5 \cdot 65 + 0,3 \cdot 63 + 0,2 \cdot 60 = 63,4;$

– No. 14: $K_{14} = 0,5 \cdot 70 + 0,3 \cdot 72 + 0,2 \cdot 75 = 71,6;$

– No. 17: $K_{17} = 0,5 \cdot 80 + 0,3 \cdot 84 + 0,2 \cdot 85 = 82,2.$

The results of UAV estimation per scheme no. 3 are shown in Table 9.

**Scheme no. 4.** In case if the weights $W_i$ of experts are unknown, we can find them using the initial expert estimates [20]:

$$W_i = \frac{1/\Delta_i^2}{\sum_{k=1}^{n} 1/\Delta_k^2},$$

$$\bar{K}_j = \frac{1}{n} \sum_{i=1}^{n} K_{ij},\ j = 1, \ldots, m,$$

$$\Delta_i^2 = \frac{1}{m} \sum_{j=1}^{m} \left(K_{ij} - \bar{K}_j\right)^2,$$

where $m$ is the number of the estimated UAVs, $n$ is the number of experts, $K_{ij}$ is the estimated priority indicator of the $j$-th UAV based on the $i$-th expert's estimate.

The calculations provided the following values of the weight of each of the three experts: $w_1 = 0.50$; $w_2 = 0.02$; $w_3 = 0.48$.

Then, we obtain the priority estimate for four UAVs examined by the experts:

– No. 10: $K_{10} = 0,5 \cdot 100 + 0,02 \cdot 95 + 0,48 \cdot 90 = 95,1;$

– No. 12: $K_{12} = 0,5 \cdot 65 + 0,02 \cdot 63 + 0,48 \cdot 60 = 62,56;$

– No. 14: $K_{14} = 0,5 \cdot 70 + 0,02 \cdot 72 + 0,48 \cdot 75 = 72,44;$

– No. 17: $K_{17} = 0,5 \cdot 80 + 0,02 \cdot 84 + 0,48 \cdot 85 = 82,48.$

The results of UAV estimation per scheme no. 4 are shown in Table 10.

## Conclusions

1. The paper shows the relevance of the selection and definition of the priority indicators of various aviation equipment and weapons, including UAVs at the initial stages of creation out of a list of existing ones or design of a new technical item.

2. The UAV priority indicators are defined using metrical analysis schemes that allow – based on experts estimates of the priority of certain UAVs – defining the priority indicators of all other UAVs knowing the initial indicators for each evaluated UAV.

3. The initial indicators for UAV priority are the mass of the payload, flight duration, flight distance, cruising speed, flight altitude.

4. The priority indicator evaluation schemes presented in the paper can be used to decide upon further development of UAVs of various purpose, as well as acquisition of ready-made UAVs.

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## The authors' contribution

**Kryanev A.V.** Suggested a method of estimation of priority indicators for scout/attack and attack UAVs with the use of metrical analysis based on known expert estimates of the priority of some UAVs and primary UAV estimates.

**Semenov S.S.** Examined various methods of rational engineering solution selection in aircraft design, presented a classification and data on scout/attack and attack UAVs, suggested a method of CTS priority indicators estimation based on metrical analysis in the context of UAV under various schemes of expert estimation.

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## Conflict of interests

The authors declare the absence of a conflict of interests.

# Increasing the reliability of stress tolerance prediction as part of aptitude screening of flight specialists

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**Abstract. Aim.** *The paper describes a research aimed at improving the reliability of stress tolerance prediction as part of aptitude screening (AS) of flight school applicants using a proprietary objectifying method of Stress Tolerance Assessment. Stress tolerance (ST) is an important psychophysiological professional quality and serves as one of the factors ensuring both successful flight training, and further professional flight work. However, the methods recommended in regulatory documents for the purpose of ST identification as part of AS are not efficient enough and are affected by subjective factors. Therefore, an objective and thus more efficient method is still required.* **Methods.** *The method was developed based on the analysis of subject-matter literature and own experience. Stress stimuli and methods of indicator recording were selected based on their empirical verification. The stress-inducing property of the stimuli was confirmed by the pulse rate increase by 40 – 100% and higher, associated behavioural manifestations and significant dynamics of mental productivity in the course of tests. Out of the methods of mathematical statistics, the authors used correlation analysis.* **Results.** *The method of ST assessment is based on the Reakor multifunctional psychophysiological system by the Medicom MTD research and development company from Taganrog, Russia, with a proprietary procedure built in the system's software. As stress stimulus material and for performance assessment, arithmetically complicated problems were selected, whose solutions involve a larger portion (areas) of the brain than verbal tests. In order to eliminate the effect of habituation and learning, the arithmetic tests were displayed one by one on a computer screen in a random order. The 3-4-second time interval between individual problems was selected based on premises of aviation psychology and tests conducted on a group of students. The sample consisted of 1135 male applicants to the higher flight school in 2016. Correlation analysis shows that the correlations between the external criterion indicators (successful simulator training and flying practice) and the integrated ST indicator are statistically significant: the higher is the ST indicator measured in the course of AS using the respective method, the higher are the expert estimates of the simulator training and flying practice.* **Conclusion.** *Thus, the conducted research showed that the application of the developed method of ST assessment in the course of higher flight school AS ensures higher predicted stress tolerance in the selected candidates as the psychophysiological factor of professional efficiency and reliability of flight personnel.*

**Keywords:** *aptitude screening, professionally important qualities, flight personnel, stress tolerance, dependability.*

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## Introduction

Despite the immense technological progress, the matter of in-flight reliability and safety holds relevant and attracts the attention of researchers in various fields of knowledge [1 – 8]. One of the most important features of the flight personnel professional activity is the situations of stress. Despite the ongoing improvement of the aptitude screening (AS) of flight school applicants, about 50% of flight student expulsions in the recent past, and 20% in the last few years [9, 10] were due to poor air training results. Stress tolerance (ST) is one of the most important psychophysiological professional qualities of a pilot that contribute to the flight safety. ST is understood as a complex, multilevel and comprehensive professional quality, a system of individual psychological, psychophysiological and socio-psychological properties that allows successfully resisting extreme negative environmental factors while maintaining an optimal mental and emotional state and the ability to carry out a certain activity at an adequate physiological "cost" and maintained high level of efficiency. The systemic nature of the ST properties is expressed in the fact that the individual human characteristics are manifested only in unity and interaction with each other. Currently, in accordance with the regulatory requirements, the ST assessment as part of aptitude screening of flight school applicants primarily involves questionnaire survey [11, 12]. The experience of such methods' application for the purpose of flight school applicants ST assessment has shown their insufficient informative value, sometimes data inconsistency, inferior objectivity and susceptibility to subjective factors. The flight school applicants' ST assessment is also very important due to the fact that it defines the quality of not only their flight training, but subsequent flight activity as well, thus being, among other factors, a contributor to the professional dependability [9, 13].

## Problem definition

It is not uncommon for those who performed well under normal conditions to underperform in a stressful situation. The primary indicators of stress tolerance include the capability to retain the ability for adaptive activity (keeping or improving the working capacity) in a critical situation [3, 10, 14]. According to literature, informational overload is one of the main sources of a pilot's professional stress [4, 15, 16]. Therefore, it is logical to assume that the mental performance indicators registered under experimental stress will be informative criteria for predicting ST in an actual professional emergency situation [14, 15, 16]. The limiting factors in the development of the method of predictive evaluation of ST as part of AS are the absence of sophisticated equipment for simulating stress situations and the 14-16-minute time limit for one survey with the potential number of applicants of 1200 or more. The basic premises of the method under development are based on the works of B.V. Lomov, V.A. Bodrov, L.A. Kitaev-Smyk, V.A. Ponomarenko, V.L. Marishchuk [14, 15, 17, 18, 19]. The following problems were solved in the course of the method's development: 1) conditioning of the stress stimulus (stimulus complex) that causes the experimental stress; 2) selection of the ST indicators in the experimental stress (dynamics of the mental productivity in the course of testing, its physiological cost, behavioral reactions).

## Material and methods

The developed method is intended for AS of flight school applicants. As stress stimulus material and for performance assessment, arithmetically complicated problems were selected, whose solutions, according to literature, involves a larger portion (areas) of the brain than verbal tests [20, 21]. This corresponds to literary sources [15, 16, 22] that confirm that the primary cause of stress in flight personnel is information overload [15, 16, 22], which is also associated with the fact that in today's airplanes the instruments are digital rather than analogue. Additionally, in order to increase the stressfulness of the test situations, the process of problem-solving was complicated by information interference (sound of a metronome, a tense radio exchange between an air traffic controller and a pilot over a failed engine, etc.) delivered through headphones. In order to eliminate the effect of habituation and learning [23], the arithmetic tests were displayed one by one on a computer screen in a random order. The 3-4-second time interval between individual problems was selected based on premises of aviation psychology and tests conducted on a group of students. The test problems and methods of indicator recording were selected on the basis of their empirical verification as part of the AS of flight school applicants of the years 2013 to 2016. The stressfulness of the developed test was confirmed by the 40-100% or higher heart rate, as well as associated behavioural manifestations and significant dynamics of mental productivity in the course of the tests [24, 25]. For the present study, the latest version of the method was chosen, that was used in 2016 to survey 1135 male applicants. In 2020, upon receiving the results of flying practice of 562 students of that admission year, the method's criterion validity was verified per that external criterion. Out of the methods of mathematical statistics, the authors used correlation analysis.

## Results and discussion

The method of ST assessment is based on the Reakor multifunctional psychophysiological system by the Medicom MTD research and development company from Taganrog, Russia, with a proprietary procedure built in the system's software.

The ST assessment procedure consists in the mental productivity survey in the course of three cognitive tests in parallel with physiological parameters registration (heart rate) at all stages of the survey, as well as observation of the behavioral manifestations in a stressful situation. The cognitive tests include two modified versions of "Arithmetical calculations", the "Arithmetical calculations 1" (AC-1) and

**Table 1: The integral estimation of the ST based on multidimensional scaling**

| ST indicator (integral estimate) | 154.58 and more | 132.48 – 154.57 | 120.63 – 132.47 | 120.62 and less |
|---|---|---|---|---|
| Description | Predicted practical reliability in emergency situations: low. Low stress tolerance. Not recommended for flight training | Predicted practical reliability in emergency situations: satisfactory. Satisfactory stress tolerance. Conditionally recommended for flight training | Predicted practical reliability in emergency situations: high. High stress tolerance. Recommended for flight training. | Predicted practical reliability in emergency situations: very high. Very high stress tolerance. Highly recommended for flight training |

"Arithmetical calculations 2" (AC-2), as well the specially developed method of "Addition of numbers". Each of the tests, the AS-1 and AS-2, consists of 20 problems. Essentially, the method consists in the verbal solution of the arithmetical problems with integers from 1 to 25. The modification of the method consists in the fact that each individual problem includes two actions, is displayed to the tested student with a time intervals from 4 to 3 seconds, i.e. the problem is to be solved within a specified time limit: the first 10 problem are displayed with the time interval of 4 seconds, the last 10 problems are displayed every 3 seconds. In the process of test performance, additional (psychological) stress is introduced: besides the artificially created time pressure, the problems are accompanied by sound interference in the form of metronome sound delivered through headphones.

There are 5 possible answers for each problem. It is required to choose the correct one and name the letter of the corresponding line. The tested person is to perform arithmetical operations in the order as they are written, from left to right, disregarding the rules of arithmetical calculations. After finding the answer, the tested person is to say the number of the problem and the letter of the corresponding answer line, e.g. "one – C", "two – B", etc.

The "Addition of numbers" (AD) test consists of 60 arithmetical problems, in each of which it is required to summarize 5 one-figure numbers displayed on the monitor every 3.5 seconds. The tested person is to find the sum of 5 numbers and say the answer corresponding to the number of the problem, e.g. "one – 19", "two – 25", etc.). Additional stress is created in the process of the test performance, i.e. through time shortage (only 3.5 seconds are allocated for each problem) and sound interference delivered through headphones (radio exchange between an air traffic controller and a pilot regarding an engine failure).

The answers are given orally, as the hands of the tested person carry special sensors that register physiological signals (heart rate), which makes giving written answers impossible. The oral form of the answers also has a heuristic dimension, as it allows observing the tested person's verbal behavior and monitoring his/her emotional tension during the test.

The physiological "cost" of the activity is assessed by the shifts in the physiological indicators (heart rate) at all stages of testing and their persistence after the removal of stress at the stage of "rest". The registered behavioral reactions include the varied emotional stress response: tremor, stuttering, motor and verbal retardation, freezing, hyperactivity (unnecessary fidgeting), mimic, skin vegetative and postural behavioral reactions. The qualitative behavioral characteristics were converted into quantitative indicators according to the qualimetric approach [26].

A comprehensive ST conclusion is made by integrating the parameters of all indicators. The integral ST estimation is based on expert analytics involving multidimensional scaling that was demonstrated by leading aviation psychology experts to be the optimal method of practical assessment of the professionally important qualities of a military pilot [15, 27]. The integral estimation allows – on the basis of indicators standardized as part of pilot research [4, 28, 29] – ranking each tested person into one of the four professional aptitude groups in terms of the degree of ST: most fit, fit, conditionally fit and unfit, as it is shown in Table 1.

Upon the completion of the ST assessment procedure, for each applicant, a test report is made that includes the results with a description of individual psychological and psychophysiological features and generated comprehensive conclusion regarding the professional aptitude in terms of ST.

The method's validity was confirmed by the research of the correlation between the integral ST estimate and the indicators of the external criterion, i.e. indicators of successful practical simulator training and successful flight practice.

The study of the correlation between the ST indicators and successful simulator training was conducted as part of a preliminary verification of the method's criteria validity [30]. At the end of the simulator training, instructors assess

**Table 2. Correlation coefficients between the integral ST estimate and the external criterion indicators of simulator training ($n$ = 562)**

| External criterion indicator name | Integral ST estimate |
|---|---|
| tension during simulated flight | -0.316 |
| actions in special cases | 0.276 |

**Table 3. Quantitative distribution of the students (admission year 2016) among flight training performance groups in 2020.**

| Sample of students (number, percentage) | Number of individuals: | | | |
|---|---|---|---|---|
| | 1-st group (“strong”) | 2-nd group (“above average”) | 3-rd group (“average”) | 4-th group (“below average”, “weak”) |
| $n$ = 562 | 41 | 136 | 272 | 113 |
| 100 % | 7.3 | 24.2 | 48.4 | 20.1 |

the students in terms of the rate of development and stability of skills, coordination of movements, distribution of attention, actions in special cases (failure, engine fire, etc.) and other abilities they have shown during their “flights” in the simulators, which was chosen as the external criterion. The comparison of the ST indicators with the stress indicators and students’ actions in the special cases of simulator “flights” brought out significant correlations ($p < 0.05$) between the integral ST estimate and the external criterion that are shown in Table 2.

The analysis of the data presented in Table 2 establishes that the correlations between the integral ST estimate and the instructors’ assessments are statistically significant (if $p < 0.05$). That means that the higher is the ST measured as part of AS using the ST assessment method, the lower is the students’ stress indicator and better are the students’ actions in the simulated special cases.

The initial flight training (flying practice) is the more accurate external criterion for confirming the method’s predictive valuation. In 2020, the students of the 2016 year of admission demonstrated similar results during the flying practice at the training bases of the Krasnodar Higher Aviation School of Pilots.

The flying practice performance was assessed by the flight instructors in the form of the following ratings that characterize students in terms of the flying aptitude and quality of flight training:

- a strong student with very good flying aptitude;
- an above-average student with good or above-average flying aptitude;
- an average student with an average flying aptitude;
- a below-average student with a below-average flying aptitude;
- weak student with a very poor flying aptitude.

The flying practice rating was distributed in accordance with the regulatory document [12] as follows:

- expert assessment “strong” corresponds to the 1-st performance group, the occupational aptitude class I;
- expert assessment “above average” corresponds to the 2-nd performance group, the occupational aptitude class II;
- expert assessment “average” corresponds to the 3-rd performance group, the occupational aptitude class III;
- expert assessment “below average” corresponds to the 4-th performance group, the occupational aptitude class IV.

The quantitative distribution of the students among flight training performance groups is shown in Table 3.

Examining the students’ distribution among flight training performance groups in accordance with the normal distribution law will reveal a sample bias in the direction of “average” and “below average and weak”. In order to mitigate the statistical bias, the 1-st and 2-nd groups of students were merged. After that, the sample of students ($n$ = 562) was split into 3 groups as follows: the 1-st and 2-nd groups are 273 students; the 3rd group is 207 students; the 4th group is 82 students.

According to this approach, the distribution of students by their integral ST estimate was also done into three groups: the 1-st group includes those “recommended and highly recommended” for the flight training; the 2-nd group includes those “conditionally recommended”; the 3-rd group includes those “not recommended”. It should be noted that in the third year of study students undergo initial flight training that is concluded with a solo flight on a trainer aircraft. In the course of further training involving basic and advanced flight training, students develop flying aptitudes. The proportion of students with high flying aptitudes grows, while the proportion of “weak” students significantly decreases.

The research of the correlation between the obtained external criterion indicator (results of the flying practice) and the integrated ST indicator has shown its statistical significance (if $p < 0.05$). The distribution of the flying practice performance indicators depending on the ST indicator values is shown in Table 4.

The data shown in Table 4 demonstrate that the students with high ST have higher ratings in simulator training and expert assessments of flying practice by flight instructors.

**Table 4. Average values and confidence intervals of flying practice assessments in terms of ST (if $p < 0.05$, the denominator shows the sizes of the groups).**

| Test sample | The flying practice rating based on the ST assessment method | | |
|---|---|---|---|
| | 1-st ST group | 2-nd ST group | 3-rd ST group |
| students of the 2016 admission year; $n$ = 562 | $\frac{3.32\pm0.09}{273}$ | $\frac{3.09\pm0.12}{207}$ | $\frac{3.02\pm0.17}{82}$ |

However, the statistical validity ($p < 0.05$) of such differences is manifested when we compare opposing groups: students with high ST indicators, the 1-st group, have the expert assessment of flying practice "strong", while students rated as "weak" and "below average" by the experts have low ST indicators, the 3-rd group.

**Conclusion.** Thus, the above correlation analysis showed that the correlations between the integrated ST indicator and external criterion indicators are statistically significant (if $p < 0.05$): the higher is the ST indicator identified using the respective method, the higher are the expert estimates of the flying practice by the flight instructors (reliably if $p < 0.05$). Currently, the method of Stress Tolerance Assessment is undergoing expert verification for the purpose of possible inclusions into AS regulatory documents. Therefore, the application of the developed method of ST assessment in the course of higher flight school AS ensures higher predicted ST in the selected candidates as the psychophysiological factor of professional efficiency and reliability of flight personnel.

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## The authors' contribution

**Krachko E.A.** Review and analysis of the state of the art of the problem under consideration. The theoretical aspect of the paper, development of the method of Stress Tolerance Assessment, pilot trial of the method of Stress Tolerance Assessment and statistical processing of the obtained results.

**Krasilnikov G.T.** Review and analysis of the state of the art of the problem under consideration.

The theoretical aspect of the paper, development of the method of Stress Tolerance Assessment, pilot trial of the method of Stress Tolerance Assessment.

**Malchinsky F.V.** Review and analysis of the state of the art of the problem under consideration, development of the method of Stress Tolerance Assessment, organization of the pilot trial of the method of Stress Tolerance Assessment.

**Medvedev V.I.** Review and analysis of the state of the art of the problem under consideration, development of the method of Stress Tolerance Assessment, organization of the pilot trial of the method of Stress Tolerance Assessment.

## Conflict of interests

The authors declare the absence of a conflict of interests.

# GNEDENKO FORUM

INTERNATIONAL GROUP ON RELIABILITY


The Gnedenko Forum was founded in 2004 by an unofficial international group of experts in the dependability theory for the purpose of professional support of researches from all over the world who are interested in studying and developing the scientific, technical and other aspects of the dependability theory, risk analysis and safety in the theoretical and practical domains.

The Forum exists on the Internet as a non-for-profit organization. It aims to involve into joint discussion and communication technical experts interested in developing the dependability theory, safety and risk analysis regardless of their home country and membership in whichever organization.

The Forum acts as an impartial and neutral entity that delivers scientific information to the press and public as regards the matters of safety, risk analysis and dependability of complex technical systems. It publishes reviews, technical documents, technical reports and research essays for the purpose of dissemination of knowledge and information.

The Forum is named after Boris V. Gnedenko, an outstanding Soviet mathematician, expert in the probability theory and its applications, member of the Ukrainian Academy of Sciences. The Forum is the platform for distribution of information on educational grants, academic and professional positions related to dependability, safety and risk analysis all over the world.

Currently, the Forum has 500 members from 47 countries.

Since January 2006, the Forum has been publishing its quarterly journal, Reliability: Theory & Applications (www.gnedenko.net/RTA). The Journal is registered in the Library of Congress (ISSN 1932-2321) and publishes articles, reviews, memories, information and literature references regarding the theory and application of dependability, survivability, maintenance, risk analysis and management methods.

Since 2000, the Journal is indexed in Scopus.

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# DEPENDABILITY JOURNAL ARTICLE SUBMISSION GUIDELINES

***Article formatting requirements***

Articles must be submitted to the editorial office in electronic form as a Microsoft Office Word file (*.doc or *.docx extension). The text must be in black, on a A4 sheet with the following margins: 2 cm for the left, top and bottom margins; 1.5 or 2 cm for the right margin. An article cannot be shorter than 5 pages and longer than 12 pages (can be extended upon agreement with the editorial office). The article is to include the structural elements described below.

***Structure of the article***

The following structural elements must be separated with an *empty line*. Examples of how they must look in the text are shown *in blue*.

## 1) Title of the article

The title of the article is given in the English language.

*Presentation:* The title must be in 12-point Times New Roman, with 1.5 line spacing, fully justified, with no indentation on the left. The font face must be bold. The title is not followed by a full stop.

An example:

**Improving the dependability of electronic components**

## 2) Author(s)' name.

This structural element for each author includes:

In English: second name and first name as "First name, Second name" (John Johnson).

*Presentation:* The authors' names must be in 12-point Times New Roman, with a 1.5-line spacing, fully justified, with no indentation on the left. The font face must be bold. The authors' names are separated with a comma. The line is not followed by a full stop.

*An example:*

**John Johnson[1], Karen Smith[2*]**

## 3) The author(s)' place of employment

The authors' place of employment is given in English. Before the place of employment, the superscripted number of the respective reference to the author's name is written.

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*An example:*

[1] Moscow State University, Russian Federation, Moscow

[2] Saint Petersburg Institute of Heat Power Engineering, Russian Federation, Saint Petersburg

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*An example:*

*johnson_j@aaa.net

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This structural element includes a structured summary of the article with the minimal size of 350 words and maximum size of 400 words. The abstract is given in the English language. The abstract must include (preferably explicitly) the following sections: Aim; Methods; Results/Findings; Conclusions. The abstract of the article should not include newly introduced terms, abbreviations (unless universally accepted), references to literature.

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*An example:*

**Abstract.** Aim.Proposing an approach … taking into consideration the current methods. **Methods.** The paper uses methods of mathematical analysis,…, probability theory. **Results.** The following findings were obtained using the proposed method … **Conclusion**. The approach proposed in the paper allows…

## 6) Keywords

5 to 7 words associated with the paper's subject matter must be listed. It is advisable that the keywords complimented the abstract and title of the article. The keywords are written in English.

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*An example:*

**Keywords:** dependability, functional safety, technical systems, risk management, operational efficiency.

## 7) Text of the article

It is recommended to structure the text of the article in the following sections: Introduction, Overview of the sources, Methods, Results, Discussion, Conclusions. Figures and tables are included in the text of the article (the figures must be "In line with text", not "behind text" or "in front of text"; not "With Text Wrapping").

*Presentation:*

The titles of the sections must be in 12-point Times New Roman, with a 1.5-line spacing, fully justified, with no indentation on the left. The font face must be bold. The titles of the sections (except the Introduction and Conclusions) may be numbered in Arabic figures with a full stop after the number of a section. The number with a full stop must be separated from the title with a no-break space (Ctrl+Shift+Spacebar).

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where $n$ is the number of products.

*An example:*

**1. State of the art of improving the dependability of electronic components**

An analysis of Russian and foreign literature on the topic of this study has shown that …

Figures (photographs, screenshots) must be of good quality, suitable for printing. The resolution must be at least 300 dpi. If a figure is a diagram, drawing, etc. it should be inserted into the text in editable form (Microsoft Visio). All figures must be captioned. Figures are numbered in Arabic figures in the order of their appearance in the text. If a text has one figure, it is not numbered. References to figures must be written as follows: "Fig. 3. shows that …" or "It is shown that … (see. Fig. 3.)." The abbreviation "Fig." and number of the figure (if any) are always separated with a no-break space (Ctrl+Shift+Spacebar). The caption must include the counting number of the figure and its title. It must be placed a line below the figure and center justified:

Fig. 2. Description of vital process

Captions are not followed by a full stop. *With center justification there must be no indent!* All designations shown in figures must be explained in the main text or the captions. The designations in the text and the figure must be identical (including the differences between the upright and oblique fonts). *In case of difficulties with in-text figure formatting, the authors must – at the editorial office's request – provide such figures in a graphics format (files with the* *.tiff, *.png, *.gif, *.jpg, *.eps extensions).

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Table 2. Description of vital process

The title of a table is not followed by a full stop. *With center justification there must be no indent!* All designations featured in tables must be explained in the main text. The designations in the text and tables must be identical (including the differences between the upright and oblique fonts).

Mathematical notations in the text must be written in capital and lower-case letters of the Latin and Greek alphabets. Latin symbols must always be oblique, except function designators, such as sin, cos, max, min, etc., that must be written in an upright font. Greek symbols must always be written in an upright font. The font size of the main text and mathematical notations (including formulas) must be identical; in Microsoft Word upper and lower indices are scaled automatically.

Formulas may de added directly into the text, for instance:

Let $y = a{\cdot}x + b$, then…,

or written in a separate line with center justification, e.g.:

$$y = a{\cdot}x + b.$$

In formulas both in the text, and in separate lines, the punctuation must be according to the normal rules, i.e. if a formula concludes a sentence, it is followed by a full stop; if the sentence continues after a formula, it is followed by a comma (or no punctuation mark). In order to separate formulas from the text, it is recommended to set the spacing for the formula line 6 points before and 6 points after). If a formula is referenced in the text of an article, such formula must be written in a separate line with the number of the formula written by the right edge in round brackets, for instance:

$$y = a{\cdot}x + b. \qquad (1)$$

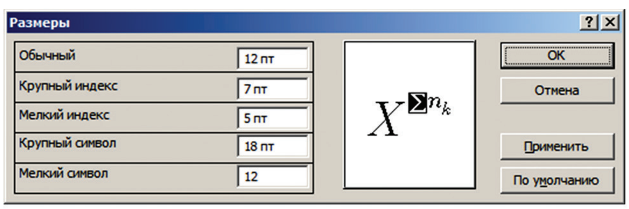
If a formula is written in a separate line and has a number, such line must be right justified, and the formula and its number must be tab-separated; tab position (in cm) is to be chosen in such a way as to place the formula roughly at the center. Formulas that are referenced in the text must be numbered in Arabic figures in the order of their appearance in the text.

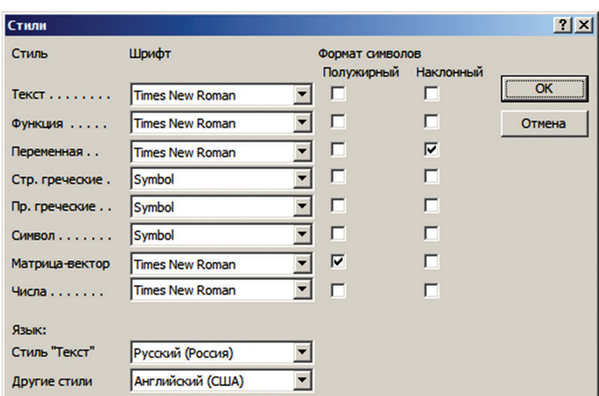
Simple formulas should be written without using formula editors (in MS Word, Latin should be used, as well as the "Insert" menu + "Special Characters", if Greek letters and mathematical operators are required), while observing the required slope for Latin symbols, for example:

$$\Omega = a + b{\cdot}\theta.$$

If a formula is written without using a formula editor, letters and +, –, = signs must be separated with no-break spaces (Ctrl+Shift+Spacebar).

Complex formulas must be written using a formula editor. In order to avoid problems when editing and formatting formulas it is highly recommended to use Microsoft Equation 3.0 or MathType 6.x. In order to ensure correct formula input (symbol size, slope, etc.), below are given the recommended editor settings.




When writing formulas in an editor, if brackets are required, those from the formula editor should be used and not typed on the keyboard (to ensure correct bracket height depending on the formula contents), for example (Equation 3.0):

$$Z = \frac{a \cdot \left( \sum_{i=1}^{n} x_i + \sum_{j=1}^{m} y_i \right)}{n+m}. \qquad (2)$$

Footnotes in the text are numbered with Arabic figures, placed page by page. Footnotes may include: references to anonymous sources on the Internet, textbooks, study guides, standards, information from websites, statistic reports, publications in newspapers, magazines, autoabstracts, dissertations (if the articles published as the result of thesis research cannot be quoted), the author's comments.

References to bibliographic sources are written in the text in square brackets, and the sources are listed in the order of citation (end references). The page number is given within the brackets, separated with a comma and a space, after the source number: [6, p. 8].

## 8) Acknowledgements

This section contains the mentions of all sources of funds for the study, as well as acknowledgements to people who took part in the article preparation, but are not among the authors. Participation in the article preparation implies: recommendations regarding improvements to the study, provision of premises for research, institutional supervision, financial support, individual analytical operations, provision of reagents/patients/animals/other materials for the study.

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The References must include only peer-reviewed sources (articles from academic journals and monographs) mentioned in the text of the article. It is not advised to references autoabstracts, dissertations, textbooks, study guides, standards, information from websites, statistic reports, publications in newspapers, websites and social media. If such information must be referred to, the source should be quoted in a footnote.

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References to journal articles must contain the year of publication, volume and issue, page numbers.

The description of each source must mention all of its authors.

The references, imprint must be verified according to the journals' or publishers' official websites.

*Presentation:*

References must be written in accordance with the Vancouver system.

The references must be in 12-point Times New Roman, with a 1.5-line spacing, fully justified, with a 1.25-cm indent on the left. The font face must be normal. Each entry must be numbered in Arabic figures with a full stop after the number. The number with a full stop must be separated from the entry with a no-break space (Ctrl+Shift+Spacebar).

## 10) About the authors

Full second name, first name (in English); complete mailing address (including the postal code, city and country); complete name of the place of employment, position; academic degree, academic title, honorary degrees; membership in public associations, organizations, unions, etc.; official name of the organization in English; e-mail address; list and numbers of journals with the author's previous publications; the authors' photographs for publication in the journal.

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Detailed information as to each author's contribution to the article. For example: Author A analyzed literature on the topic of the paper, author B has developed a model of real-life facility operation, performed example calculation, etc. Even if the article has only one author, his/her contribution must be specified.

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