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DEVELOPMENT OF A MATHEMATICAL MODEL OF RELIABLE STRUCTURES OF INFORMATION-CONTROL SYSTEMS

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A mathematical model of the information system (IS) for monitoring the state of objects that may be exposed to extreme influences has been built. The system consists of n devices that work independently of each other. To construct the specified information system, which has the minimum permissible reliability of event recognition, a class of structures of the type «k with n» is considered.

Formulas for determining the probabilistic characteristics of n parallel reserved sensors for structures of the «k with n» type were derived; the probability of these events was calculated; and plots of their distribution were constructed. The peculiarity of the derived formulas is that they can be implemented on logical elements with which one can build a physical decision support device. The number of sensors and their corresponding probabilities of correct detection of fire at the given majority values of fire probability were also determined; the cost indicators of the information system were defined.

A method for improving the reliability of IS has been developed, based on the use of the optimal number of information sensor. The ratio of finding probabilistic states of IS for structures of the «k with n» type was obtained. Algorithms for calculating the probabilities of IS states, as well as an algorithm for determining the number of information sensors and the corresponding probabilities of fire detection, have been developed. The feature of these algorithms is that they make it possible to determine the optimal number of information sensors. An estimate of the effectiveness of IS indicators of the considered types of structures was found: the probability of correct detection, the probability of non-detection, and false alarm.

The reported results can be used to select the optimal structure for recognizing dangerous flight situations: choosing the number of sensors corresponding to the high probability of correct detection and the minimum probabilities of non-detection and false alarms, taking into consideration the cost of sensors

Keywords: information redundancy, information security, reliability of event recognition, possibility of correct detection

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1. Introduction

Information systems of aviation equipment perform important functions of collecting, processing, storing information about the technical condition of functional systems and complexes and significantly affect flight safety. These systems can be implemented as autonomous channels or are organizationally an integral part of energy channels. Information systems include:

– display of flight information in the cockpit;

– warnings about aircraft or functional systems (FS) approaching critical parameters;

– signaling of the occurrence of dangerous flight situations (DFS) (the occurrence of a fire on aircraft engines, in compartments, icing, and others);

– control of the operation of flight and navigation, energy complexes, and fuel aircraft systems;

– organization of various kinds of «tips» to the crew;

– control of the operation of on-board integrated control systems, etc.

Quorum elements perform such tasks.

Information systems for the recognition of hazardous modes are the weakest link in solving the issues of automation of firefighting. Thus, at present, when addressing this issue, designers do not sufficiently use the methods of statistical physics in the interpretation of many states of such systems.

Of course, the quality of functioning of such information and control systems (ICS) directly affects the level of flight safety, the quality of polyergic systems «crew – aircraft», and the occurrence and prevention of electronic disasters. Thus, the issue of building models of the reliability of aircraft ICS is relevant for improving flight safety and preventing electronic, software, and software-electronic aviation accidents.

2. Literature review and problem statement

Analysis of aircraft FSs reveals that their effectiveness largely depends on the reliability of the information that is the basis for making appropriate decisions. Therefore, there is a need to improve the reliability of information in aircraft FSs.

The solution to the problems of verifying the reliability of data during their transmission and processing in process control systems is given in work [1], where the principles and methods of using statistical redundancy data are considered. At the same time, the work did not consider the possibility and ways of obtaining reliable information by the operator when making a decision. In [2], for active fault-tolerant control systems, a scheme for monitoring reliability using the stochastic modeling method is reported. However, the reliability of the systems is considered only from the point of view of monitoring and does not take into consideration the need to make a decision and the transfer of reliable information to the operator and all crew members.

The issues of determining the components of failures that lead to the degradation of the system are addressed in [3]. The probabilistic model is built on the basis of the Erlang distribution, and the failure rate of the elements is subject to exponential law. At the same time, the task of assessing the reliability in the processing and transmission of information is not solved.

Work [4] assesses the safe time of fire detection, determining which is necessary to start fire extinguishing procedures. The method of estimating the time of fire detection by temperature sensors, the rate of temperature increase, and light-scattering smoke detectors is adopted as a basis. At the same time, the problem of reliability of information of the fire alarm system (FAS) has not been solved.

The use of serial and parallel information redundancy to improve the efficiency of IS is investigated in [5, 6]. These works show that the use of sequential redundancy makes it possible to reduce the probability of false alarm, and parallel redundancy – to reduce the probability of non-detection. The study builds on previous work, taking into consideration economic costs.

A physical-probabilistic model of reliability, which takes into consideration both the physical laws of the aging process, which reduce the performance of the machine, and the probabilistic nature of all phenomena, is considered in work [7]. However, the processes of formation of failures are not considered at the same time as an information component of the system as a whole. The failure model of electromechanical systems is given in [8], where the emphasis is on the processes of degradation of system elements using diffusion processes, which are described by the Fokker-Planck-Kolmogorov equation. With the help of this distribution, failure is formed as a process with a monotonous or non-monotonic character, and its suitability for functioning is also determined.

Paper [9] considers the option of building a mathematical model of the reliability of an information system operating in a residual class system. The proposed mathematical model of reliability in terms of the probability of trouble-free operation takes into consideration the impact of the reliability of switching devices on the process of functioning of the computational information system. The results of studies of the mathematical model of the reliability of the computer system and the results of the comparative analysis of the reliability indicators show that the use of these methods provide a higher fault tolerance of IS at lower hardware costs than the majority method. However, there is no research on the effect of probabilistic characteristics such as the probability of correct detection, the probability of non-detection, and the probability of false alarm.

Paper [10] considers the criteria for the reliability of information and gives a definition of its evaluation. The following signs for monitoring the reliability of information are considered: doubtfulness of the facts stated, emotional coloring of the content, tonality of the content in relation to the event, sensationality of the content, hidden content. However, the problem of quantifying the probabilistic characteristics for determining priorities when adopting solutions is not tackled.

Work [11] discusses statistical methods of data analysis to ensure reliability, in particular methods of maximum plausibility and Bayesian methods for solving practical tasks. This area covers a wide range of reliability issues but does not solve the issues of decision-making on the basis of reliability and priority of the information provided.

Despite numerous studies in the field of structural reliability, the issues of reliability and information parallel and sequential redundancy are not fully disclosed. In addition, existing studies on the reliability of information systems do not solve the issues of choosing the optimal structure of the system taking into consideration economic costs.

The issues of choosing the optimal structure in the ICS of signaling and recognition of DFS are multifaceted and unstructured and require the construction and development of new methods of analysis. It is necessary to take into consideration the degree of danger of the situation and their technical and economic efficiency in such a way that these solutions are applicable both for production and operation.

Works [12–19] detail the issues of improving the efficiency of using operational information to control the reliability of ICS.

However, most methods are limited to the use of statistical procedures of information processing. Issues of information redundancy in most cases are considered only as issues of information protection or programs in the computational part of ICS, and the choice of method depends on a large number of factors.

To make the right decision under the conditions of DFS, the reliability of information received from sensors and sources of information (SI) about flight modes is of great importance. Therefore, it is proposed to solve this problem using sequential information redundancy, which is an effective method of combating false alarms and non-detection of fire.

The quality and efficiency of ICS functioning largely depend on the reliability of the information that comes to the input of ICS calculators from various kinds of meters that control the state of the technological process.

Real sensors have a certain accuracy in processing and representing information. The reliability of information is influenced by both design features and technical reliability of sensors, which, as a rule, do not satisfy, or poorly satisfy existing requirements [12, 13].

As a rule, the reliability of information can be increased by its statistical processing. If the information is supplied to ICS calculators simultaneously from parallel connected sensors, then we are talking about parallel information redundancy as a way to enter information [18, 19].

If information is fed to ICS calculators simultaneously from the same sensor in series at a given pace, then we are talking about sequential information backup as a way of entering information. Both techniques make it possible to increase both the accuracy and reliability of the controlled information coming from low-quality and technically unreliable sensors.

As a result of our review of literary sources tackling the problem of building reliable structures of information and control systems, it was found that the issue of ensuring the necessary level of event recognition in the information and control systems of aircraft remains unresolved.

3. The aim and objectives of the study

The purpose of this work is to determine the minimum number of additional redundancy elements in order for the information system to function reliably with a given accuracy. This will make it possible to ensure the effectiveness of the functioning of fire alarm ICS by increasing the reliability of the recognition of the controlled DFS.

To accomplish the aim, the following tasks have been set:

– to determine the main ways to build an information system for recognizing dangerous situations based on the analysis of the conditions of the object;

– to build a mathematical model of parallel information redundancy;

– to develop algorithms for solving the problem of choosing a structure using majoritarian logic according to the «*k* out of *n*» principle.

4. The study materials and methods

The object of this study is the process of fire recognition in the information and control systems of aircraft.

The hypothesis of the study is as follows. If we apply the method of parallel information redundancy, taking into consideration the majority principle, then it is possible to increase the efficiency of information management systems for recognizing dangerous situations.

The study assumes that the information sensor is ideal, so the probabilistic characteristics of the sensor represent the full group of events.

The study does not accept any simplifications.

Analysis of the information system (IS) can be carried out by studying the reliability function $P(a)$ – the probability that the event in question will be detected, which depends on the probability a – the probability that the event will be detected by at least one device. At large values $P(a)$, and it is desirable to reach the value of $P(a)\geq a$, the IS becomes highly reliable. Thus, the information redundancy system is a device with increased reliability.

Under certain conditions, it is possible to achieve reliable functioning of the system by introducing a sufficiently large number of unreliable elements. Research methods are based on probabilistic-statistical methods of analysis of ICS structures.

These methods are based on such concepts as information reliability and information redundancy, taking into consideration economic costs, thereby proving that reliable structures can be built from unreliable elements.

Parallel information redundancy of sensors is associated with the cost of both technical and economic resources. Therefore, this paper solves the issues of choosing parallel information reserve structures in combination with economic costs. At the same time, structures are selected provided that the accuracy and reliability of the information obtained for making management decisions in normal and emergency modes are preserved.

Formally, a model for solving the problem of constructing an IS for tracking the state of an object that may be subjected to extreme influences can be described as follows. Suppose that some idealized information system consists of n technical devices. At the same time, each of the devices can be in one of three states: 1 – determining a controlled event; 2 – determining the absence of a controlled event; 3 – the state of an uncertain situation (circuit break). The readings of the devices are independent of each other. The probabilities of determining each situation are, respectively, *a, b, c*. Usually, the probability a is quite large, the probabilities b and c are small, and $b\geq c$. These probabilities do not change over time. The task is to achieve the required probability Pa that the system will correctly show state 1, that is, the state of detection of the event in question. To ensure such probability (reliability of event detection), a sufficient number of initial devices may be used.

5. Results of investigating the mechanism that forms probabilistic characteristics

5. 1. The main ways to build an information system for recognizing dangerous situations

A model of the task of determining the structure of the information system designed to track a fire hazard situation was considered in the following statement.

There are n parallelly reserved sensors. According to the physical representation of the display system, the real sensor can be in one of three incompatible random states: correct fire detection, fire non-detection, and undefined state.

The readings of each of the sensors are determined by the random variable X, the values of which correspond to the reading of the sensor. The probabilities of these values are, respectively, a, b, and c, and $a+b+c=1$.

The diagram of the alarm system in question can be depicted in such a way as shown in Fig. 1 [9].

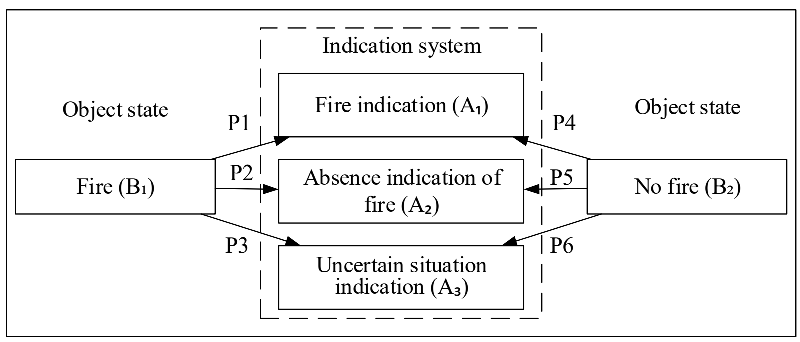

Fig. 1. Graph of states of the information system of alarm about fire

B1, B2 designate hypotheses of the appearance or absence of a controlled phenomenon at the input of the sensor. A1, A2, A3 designate an indication of its appearance or absence at the output. In each test, events A_1, A_2, A_3 occur according with the probabilities P_n.

Information systems can be built in various ways:

1. If system 1 having a reliability function $P_1(a)$ is connected in series to system 2 having a reliability function $P_2(a)$, the resulting system will have a reliability function:

$$\Pr(a)=P_1(a)P_2(a). \quad (1)$$

2. If the two systems are connected in parallel, the resulting system will have a reliability function:

$$\Pr(a)=1-\left[1-P_1(a)\right]\left[1-P_2(a)\right]. \quad (2)$$

3. If system 1 is constructed of elements, each of which itself represents system 2, then the resulting system has a reliability function:

$$\Pr(a)=P_1(P_2(a)). \quad (3)$$

4. If $P_1(a)=P_2(a)=P(a)$ and a similar process of «composition» is successively used to build a system, then the reliability of such a system is determined by the function:

$$\Pr(a)=P(P(P...P(a)...)). \quad (4)$$

Here's a numerical example.

Suppose there are two systems consisting of n_1 and n_2 parallel connected devices for tracking the state of some object with a probability of detecting a special state equal to a. Algorithms for constructing various resulting systems based on given systems with reliability functions $P_1(a)$, $P_2(a)$ may be represented as follows:

$$n_1:=2,\ \ n_2:=1,\ \ a:=0.8.$$

1. Reliability of source systems:

$$P_1(a):=1-(1-a)^{n_1},\ \ P_1(a)=0.96.$$

$$P_2(a):=1-(1-a)^{n_2},\ \ P_2(a)=0.8.$$

2. Reliability of the resulting serial system:

$$P_r(a):=P_1(a)P_2(a),\ \ P_r(a)=0.768.$$

3. Reliability of a system consisting of $n=n_1+n_2$ (n=3) elements:

$$P_n(a):=1-(1-a)^n,\ \ P_n(a)=0.992.$$

4. System reliability in parallel connection of the source systems:

$$P_r(a):=1-(1-P_1(a))(1-P_2(a))=P_1(a)+P_2(a)-P_1(a)P_2(a),$$

$$P_r(a)=0.992.$$

5. Reliability of system 1 comprising system 1:

$$P_r(a):=P_1(P_1(a)),\ \ P_r(a)=0.9984.$$

6. Reliability of a system that includes the original system twice:

$$P_r(a):=P_1(P_1(P_1(a))),\ \ P_r(a)=0.999997.$$

To construct an information system that has the minimum allowable reliability of event recognition, a class of structures with majoritarian logic is considered, the condition for the operability of which is the operability of k elements out of the total number of n elements of the system. Structures of the «k out of n» type are in a certain sense optimal monotonous structures. The structure of the «k out of n» type is such a structure of the k-th order, which functions normally if and only if at least k elements are operational, where $1 \le k \le n$. Such structures are characterized by the most sensitive function of the reliability of structures of the k-th order.

It should be noted that the special case $k=n$ corresponds to the series connection of elements, and the special case $k=1$ – parallel. An interesting and important case for practice is the case when $k=n-m$, i.e., a system in which the failure of m elements does not violate the operability of the system, and the failure of $m+1$ elements leads to a failure of the system. Our paper explores cases when elements have the same probabilistic characteristics of operation while failures of elements are independent events. In this paper we also investigate cases when elements have different probabilistic characteristics.

In this case, the probability distribution of some event of a structure of the «k out of n» type with probability p is determined by the formula:

$$P(p,k,n)=\sum_{m=k}^{n} C_n^m\, p^m (1-p)^{n-m}. \quad (5)$$

5. 2. Construction of a mathematical model of parallel information redundancy

To build a model of the problem, the following notations are introduced:

– N is the total number of sensors;

– a, b, c – probabilistic characteristics of sensors – probabilities of detection of a controlled event, probability of false alarm, and probability of reading an uncertain situation (circuit break);

– A_1 – an event indicating the presence of a controlled event;

– A_2 – an event demonstrating the indication of a false alarm;

– A_3 – an event demonstrating the indication of an uncertain event;

– Pa_n, Pb_n, Pc_n – unconditional probabilities of detection of events A_1, A_2, A_3 by at least n sensors from N;

– B_1 – an event involving the presence of a fire;

– B_2 – an event demonstrating a false indication of a fire;

– p, q – probabilities of the presence and false indication of fire (probabilities of events B_1, B_2);

– p_0 is the majority value of the probability of fire detection.

The probabilistic characteristics of the states of the sensor system can be described using a trinomial probability distribution describing the test scheme, which is as follows. The sequence of independent trials with $k=3$ mutually exclusive outcomes A_1, A_2, A_3 is considered. At the same time, in each trial, events A_1, A_2, A_3 occur respectively with probabilities p_1, p_2, p_3. Then the probability $P_n(n_1, n_2, n_3)$ that in n independent tests event A_1 will occur n_1 times, A_2 will happen n_2 times, A_3 will happen n_3 times ($n_1+n_2+n_3=n$), is determined by the formula:

$$P_n(n_1,n_2,n_3)=\frac{n!}{n_1!\,n_2!\,n_3!}\,p_1^{n_1}\,p_2^{n_2}\,p_3^{n_3}. \quad (6)$$

$P_n(n_1, n_2, n_3)$, calculated from formula (6), is determined taking into consideration the fact that the event in question can be represented as a sum of incompatible variants. At the same time, the probability of each of the incompatible variants according to the probability multiplication theorem of incompatible events is equal $p_1^{n_1}\,p_2^{n_2}\,p_3^{n_3}$, and the number of variants is determined by the number of permutations with repetitions of n elements.

Equation (6) can be represented in a more convenient form by adopting:

$$n_1=k,\ \ n_2=m,\ \ n_3=n-k-m,$$

$$p_1=a,\ \ p_2=b,\ \ p_3=c=1-a-b.$$

The result is:

$$P_n(k,m)=\frac{n!}{k!\,m!\,(n-k-m)!}\,a^k\,b^m\,c^{(n-k-m)}. \quad (7)$$

For the convenience of further use of formula (7) in the calculation algorithm in Mathcad, it is converted to the form:

$$P_n(k,m)=C_n^k\,C_{n-k}^m\,a^k\,b^m\,c^{(n-k-m)}, \quad (8)$$

where n is the total number of sensors in the system, C_n^k – the number of ways in which subsets of k sensors can be selected so that these sensors show the presence of event A, and the remaining $n–k$ – its absence. Here C_N^n is the number of combinations of N elements of n, for which Mathcad (USA) has the function combin (N, n).

Let's introduce the majoritarian principle, according to which information becomes reliable if at least k sensors out of n (structure of the «k out of n» type) show the presence of controllable features. In this case, using expression (8), it is possible to derive dependences that determine the probability $a_{n,k}$ of correct detection, as well as the probabilities $b_{n,k}$ and $c_{n,k}$ of the non-detection of controlled information and the probability of an uncertain situation. These probabilities are determined provided that the detectable features are recorded simultaneously and independently by at least k sensors out of n.

Probabilities $P_1(a)$, $P_2(a)$, $P_1(b)$, $P_2(b)$, $P_1(c)$, $P_2(c)$ for the co-occurrence of events B_1, B_2 and events A_1, A_2, A_3 are introduced as follows. Based on the conditions, we have:

$$P(B_1)=p,\;\; P(B_2)=1-p=q. \quad (9)$$

$$\left.\begin{aligned}
&P(B_1A_1)=P(B_1)P(A_1/B_1)=p\,Pa,\\
&P(B_2A_1)=P(B_2)P(A_1/B_2)=q\,Pa,\\
&P(B_1A_2)=P(B_1)P(A_2/B_1)=p\,Pb,\\
&P(B_2A_2)=P(B_2)P(A_2/B_2)=q\,Pb,\\
&P(B_1A_3)=P(B_1)P(A_3/B_1)=p\,Pc,\\
&P(B_2A_3)=P(B_2)P(A_3/B_2)=q\,Pc.
\end{aligned}\right\} \quad (10)$$

An information gathering system consisting of N sensors can be arranged so that the output signal will be only when 1 or more sensors are triggered (n=1, ..., N). Formulas for calculating the probabilities of the states of the system $a_{n,k}$, $b_{n,k}$, $c_{n,k}$ for a structure of the «k out of n» type (n=1, ..., N) and (k=1, ..., N) are defined by the following expressions [10–12]:

$$\left.\begin{aligned}
&Pa_{n,k}=1-\sum_{i=0}^{k-1}C_n^i a^i(b+c)^{n-i},\\
&Pb_{n,k}=(b+c)^n-c^n=\\
&=\sum_{i=0}^{k-1}C_n^i a^i(b+c)^{n-i}-c^n,\\
&Pc_{n,k}=c^n.
\end{aligned}\right\} \quad (11)$$

It can be shown that at k=1 the probabilities $a_{n,k}$ will have a maximum value at a given n, and the probabilities $b_{n,k}$, $c_{n,k}$ will be minimal. With an increase in k, the probabilities $a_{n,k}$ decrease, and the probabilities $b_{n,k}$ increase accordingly. Probabilities $c_{n,k}$ remain unchanged.

The probabilities of events A_1, A_2, A_3 for one type of sensor and structure of the «1 out of n» type can be determined by the following formulas:

$$\left.\begin{aligned}
&Pa_n=\sum_{i=1}^{n}C_n^i a^i(b+c)^{n-i}=1-(b+c)^n,\\
&Pb_n=\sum_{k=1}^{n}C_n^k b^k c^{n-k}=(b+c)^n-c^n,\\
&Pc_n=1-Pa_n-Pb_n=c^n.
\end{aligned}\right\} \quad (12)$$

The meaning of formulas (11) can be clarified by writing them down in an expanded form.

$$1)\; Pa_n=1-(b+c)^n=\sum_{k=1}^{n}C_n^k a^k(b+c)^{n-k}=$$
$$=C_n^1a^1(b+c)^{n-1}+C_n^2a^2(b+c)^{n-2}+\ldots+C_n^n a^n(b+c)^0. \quad (13)$$

It can be seen that the probability of detecting the event in question is equal to the sum of the terms of this expression, in which there is a probability of detecting it by one of n sensors. That is, the probability of detecting the event in question is equal to the probability of detecting it by at least one of n sensors (n=1, ..., N):

$$2)\; Pb_n=(b+c)^n-c^n=\sum_{k=1}^{n}C_n^k b^k c^{n-k}=$$
$$=C_n^1b^1c^{n-1}+C_n^2b^2c^{n-2}+\ldots+C_n^n b^n c^0. \quad (14)$$

Similar to the previous one, the probability of not detecting the event in question is equal to the sum of the terms of this expression, in which there is a probability b of not detecting it by one of n sensors. That is, the probability of not detecting the event in question is equal to the probability of not detecting it by at least one of n sensors.

3) $Pc_n=c^n$, i.e., the probability of demonstrating an uncertain situation is equal to the probability of its joint demonstration by each of n sensors.

Systems of equations (11), (12) determine the probabilistic states of the system of N sensors when they all have identical probabilistic characteristics a, b, c. Probabilistic characteristics Pa, Pb, Pc of the system, which is a set of N sensors with different probabilistic characteristics a_i, b_i, c_i, are determined depending on the number of types of sensors and the ratio of their number.

For example, for two kinds of probability sensors, Pa, Pb, Pc take the following form:

$$\left.\begin{aligned}
&Pa_n=1-\prod_{S_k=(n_1,n_2,\ldots,n_k)}(b_k+c_k)^{n_k},\\
&n_1+n_2+\ldots+n_k=N,\\
&Pb_n=\prod_{S_k=(n_1,n_2,\ldots,n_k)}\left[(b_k+c_k)^{n_k}-c_k^{n_k}\right],\\
&n_1+n_2+\ldots+n_k=N,\\
&Pc_n=\prod_{S_k=(n_1,n_2,\ldots,n_k)}c_k^{n_k},\\
&n_1+n_2+\ldots+n_k=N.
\end{aligned}\right\} \quad (15)$$

It can be assumed that the reliability of information determined by parameters a, b, c increases under at least two conditions:

1. As the number of monitored sensors increases, the probability of detecting a controlled Pa event will increase, and the probabilities of not detecting the event and the probabilities of an uncertain situation Pb and Pc will decrease.

2. If the same sensor is called k times for a certain time interval, then the probability Pa of correctly detecting the

monitored event will also increase, and the probabilities of *Pb* and *Pc* will decrease accordingly. That is, this condition is equivalent in efficiency to an increase in the number of sensors.

Obviously, both of these conditions contribute to increasing the reliability of information but there are limitations.

For the first condition, the constraints are determined by the material costs associated with the increase in the number of sensors *n*. For the second condition, the limit on the number of requests of the sensor *k* is determined by the dependence $k=t_c/t_0$, where t_0 is the reaction time of the random function $Y(t)$ of the change in the controlled feature, t_c is the time of «aging of information» determined by the speed of the controlled process.

For each specific situation, there are reserves for both *n* (parallel redundancy) and *k* (sequential redundancy). These reserves can significantly increase the reliability of controlled information, provided by increasing the probability of correctly determining the presence of a controlled feature and reducing the probability of its absence or non-detection of the signal.

If we assume that the main characteristic of IS is the probability of correctly determining fire *Pa*, then the rational number of sensors *m*, which provides a given accuracy of the probability of correctly determining the presence of fire according to some given probability p_0 (majoritarian) and the corresponding probability *pm*, is determined from the condition $Pa_{n-1}<p_0\le Pa_n$.

5. 3. Algorithms and results of solving the problem of choosing structures using majoritarian logic according to the «*k* out of *n*» principle

Algorithm for solving the problem for a structure of the «1 out of n» type with the same sensors.

Initial data: number of sensors, probability of fire and false alarm of fire in zone B, probability of detection of fire signal by one sensor in zone A:

$$ORIGIN \equiv 1,\ N:=8,\ n:=1\ldots N,\ i:=1\ldots 3.$$

$$p:=0.9,\ q:=1-p,\ q=0.1.$$

$$a:=\begin{pmatrix}0.99\\0.9\\0.85\end{pmatrix},\ b:=\begin{pmatrix}0.007\\0.07\\0.1\end{pmatrix},\ c:=\begin{pmatrix}0.003\\0.03\\0.05\end{pmatrix}.$$

Computation:

1. Probabilities of events A_1, A_2, A_3 for one kind of the «1 out of *n*» type structure sensors:

$$Pa_i,n:=1-\left(b_i+c_i\right)^n,$$

$$Pb_i,n:=\left(b_i+c_i\right)^n-\left(c_i\right)^n,$$

$$Pc_i,n:=\left(c_i\right)^n.$$

$$Pa=\begin{pmatrix}0.99 & 0.9999 & 0.999999 & 1 & 1 & 1 & 1\\ 0.9 & 0.99 & 0.999 & 0.9999 & 0.99999 & 0.999999 & 0.9999999\\ 0.85 & 0.9775 & 0.996625 & 0.9994937 & 0.9999241 & 0.9999886 & 0.9999983\end{pmatrix},$$

$$Pb=\begin{pmatrix}0.007 & 0.000091 & 0.000001 & 0 & 0 & 0 & 0\\ 0.07 & 0.0091 & 0.000973 & 0.0000992 & 0.00001 & 0.000001 & 0.0000001\\ 0.1 & 0.02 & 0.00325 & 0.0005 & 0.0000756 & 0.0000114 & 0.0000017\end{pmatrix},$$

$$Pc=\begin{pmatrix}0.003 & 0.000009 & 0 & 0 & 0 & 0 & 0\\ 0.03 & 0.0009 & 0.000027 & 0.0000008 & 0 & 0 & 0\\ 0.05 & 0.0025 & 0.000125 & 0.0000063 & 0.0000003 & 0 & 0\end{pmatrix},$$

2. Plotting the distribution of probabilities *Pa*, *Pb*, *Pc* (Fig. 2).

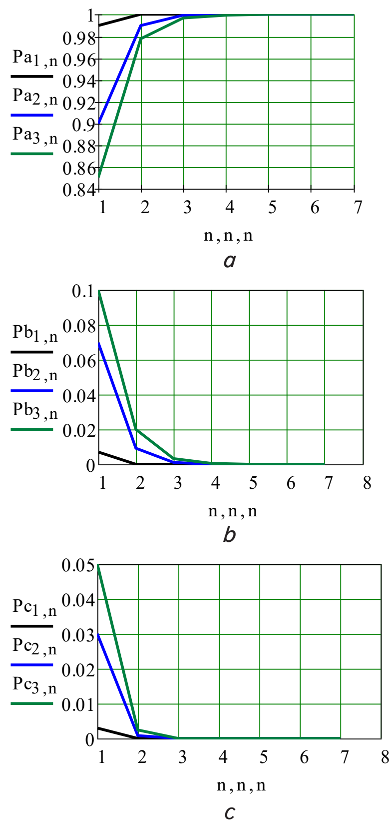

Fig. 2. Plots of probability distributions: *a* – correct detection *Pa*; *b* – false alarm *Pb*; *c* – non-detection *Pc*

3. Determining the probabilities of sensor readings in the presence of fire and its absence:

$$Pap:=p\cdot Pa,\ Paq:=q\cdot Pa,$$

$$Pbp:=p\cdot Pb,\ Pbq:=q\cdot Pb,$$

$$Pcp:=p\cdot Pc,\ Pcq:=q\cdot Pc.$$

4. Determining the number of sensors and their corresponding probabilities of correct fire detection according to the specified majoritarian values of the probabilities of fire detection.

$$p0:=\left(0.999999\ \ 0.9997\ \ 0.9995\right),$$

$$m_i:=\sum_{n=2}^{N}\text{if}\left\lfloor\left(Pa_{i,n-1}<p0_{1,i}\le Pa_{i,n}\right),n,0\right\rfloor,$$

$$m^T=\left(3\ \ 4\ \ 5\right).$$

$$pm_i:=\sum_{n=2}^{N}if\left(Pa_{i,n-1}<p0_{1,i}\le Pa_{i,n},Pa_{i,n},0\right).$$

$$pm^T:=\left(0.999999\ \ 0.9999\ \ 0.999924\right).$$

5. Cost indicators of IS (profits and losses due to the non-detection of fire in its presence and in an uncertain situation).

To calculate IS profit indicators, the following cost indicators were introduced, which are measured in conditional units: G – profit from the flight, Cnp – additional costs associated with the occurrence of a situation of false alarm of the fire alarm, Cns – additional costs associated with the occurrence of the situation of undetected fire, S – the cost of an additional set of devices to determine the presence of a fire aboard the aircraft.

For the calculation of IS profit indicators, the following values of the cost IS indicators were taken, derived empirically.

$$G := 6000,\ Cnp := 3000,\ Cns := 1000,\ S := 100.$$

6. Values of IS profit indicators.

The formula for determining the IS profit margin is as follows:

$$D_{i,n} := G\cdot Pap_{i,n} - Cnp\cdot Pbp_{i,n} - Cns\cdot Pcp_{i,n} - S\cdot n,$$

where $Pap_{i,n}$ is the probability of a situation of correct detection of the presence or absence of a fire on board the aircraft, $Pbp_{i,n}$ is the probability of occurrence of a situation of false alarm of a fire alarm, $Pcp_{i,n}$ is the probability of occurrence of a situation of undetected fire, n is the number of parallel connected devices (instruments) for determining the presence of fire on board the aircraft.

The results of the calculation are as follows:

$$D = \begin{pmatrix} 5224.4 & 5199.2 & 5100 & 5000 & 4900 & 4800 & 4700 \\ 4544 & 5120.6 & 5091.9 & 4999.2 & 4899.9 & 4800 & 4700 \\ 4175 & 5022.3 & 5072.9 & 4995.9 & 4899.4 & 4799.9 & 4700 \end{pmatrix}.$$

7. Plotting IS profits (Fig. 3).

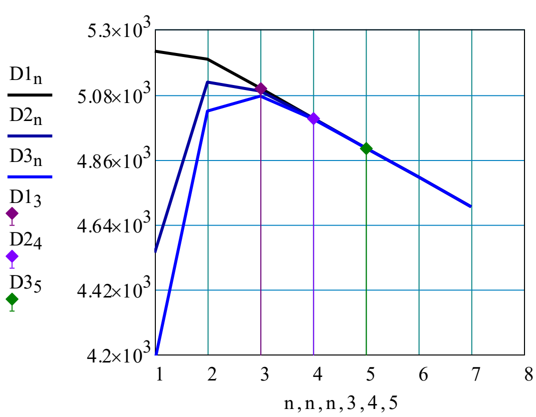

Fig. 3. Plots of information system profit indicators for the «1 out of n» type structure with identical sensors

8. Determining maximum values of IS cost indicators.

To determine the maximum values of IS cost indicators, we use the max() function built into Mathcad.

$$D := D^T,$$

$$D1 := D^{\langle 1\rangle},\ D2 := D^{\langle 2\rangle},\ D3 := D^{\langle 3\rangle}.$$

$$D1_{\max} := \max(D1),\ D1_{\max} := 5224.4,$$

$$m_1 := \text{match}(D1_{\max}, D1),\ m_1 = (1).$$

$$D2_{\max} := \max(D2),\ D2_{\max} := 5120.6,$$

$$m_2 := \text{match}(D2_{\max}, D2),\ m_2 = (2).$$

$$D3_{\max} := \max(D3),\ D3_{\max} := 5072.9,$$

$$m_3 := \text{match}(D3_{\max}, D3),\ m_3 = (3).$$

Analysis of the probabilistic characteristics $P1a$, $P1b$, $P1c$, determined from (11), makes it possible to draw the following conclusions:

1. To improve the quality of information systems consisting of N SI, in terms of increasing the reliability of information, is possible in three ways:

– an increase in the number n of SI;

– improvement of the characteristics a_i, b_i, d_i of the given SI;

– the choice of the optimal information structure, namely, the choice of the correct index of the majority Q.

2. For ISs made of N sensors with probabilistic characteristics $a=0.99$, $b=0.007$, $c=0.003$, the most acceptable structure is one with a majority index $m_1=3$, which ensures the reliability of fire detection $pm_1=0.999999$. For IS with probabilistic characteristics $a=0.9$, $b=0.007$, $c=0.003$ – a structure with a majority index $m_2=4$, and fire detection reliability $pm_2=0.9999$. For IS with probabilistic characteristics $a=0.85$, $b=0.1$, $c=0.05$, a structure with a majority index of $m_3=5$, and reliability of fire detection $mp_3=0.999924$.

Similar conclusions can be drawn for ISs with other probabilistic characteristics and structures of other types, as shown below.

Algorithm for solving the problem for a structure of the «2 out of n» type with the same sensors.

Initial data: number of sensors, probabilities of fire and false alarm of fire in zone B, probability of detection of fire signal by one sensor in zone A:

$$N := 8,\ n := 2\ldots N,\ i := 1\ldots 3.$$

$$p := 0.9,\ q := 1-p,\ q = 0.1.$$

$$a := \begin{pmatrix} 0.99 \\ 0.9 \\ 0.85 \end{pmatrix},\ b := \begin{pmatrix} 0.007 \\ 0.07 \\ 0.1 \end{pmatrix},\ c := \begin{pmatrix} 0.003 \\ 0.03 \\ 0.05 \end{pmatrix}.$$

Computation:

1. Probabilities of events A_1, A_2, A_3 for one kind sensors of the «2 out of n» type structure:

$$Pa_{i,n} := 1 - (b_i + c_i)^n - n\cdot a_i\cdot (b_i + c_i)^{n-1},$$

$$Pb_{i,n} := (b_i + c_i)^n + n\cdot a_i\cdot (b_i + c_i)^{n-1} - (c_i)^n,$$

$$Pc_{i,n} := (c_i)^n.$$

$$Pa = \begin{pmatrix} 0 & 0.9801 & 0.999702 & 0.999996 & 1 & 1 & 1 & 1 \\ 0 & 0.81 & 0.972 & 0.9963 & 0.99954 & 0.999945 & 0.9999936 & 0.9999993 \\ 0 & 0.7225 & 0.93925 & 0.9880187 & 0.9977725 & 0.9996013 & 0.9999305 & 0.9999881 \end{pmatrix},$$

$$Pb = \begin{pmatrix} 0 & 0.019891 & 0.000298 & 0.000004 & 0 & 0 & 0 & 0 \\ 0 & 0.1891 & 0.027973 & 0.0036992 & 0.00046 & 0.000055 & 0.0000064 & 0.0000007 \\ 0 & 0.275 & 0.060625 & 0.011975 & 0.0022272 & 0.0003987 & 0.0000695 & 0.0000119 \end{pmatrix},$$

$$Pc = \begin{pmatrix} 0 & 0.000009 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.0009 & 0.000027 & 0.0000008 & 0 & 0 & 0 & 0 \\ 0 & 0.0025 & 0.000125 & 0.0000063 & 0.0000003 & 0 & 0 & 0 \end{pmatrix}.$$

2. Plotting the distribution of probabilities *Pa*, *Pb*, *Pc* (Fig. 4).

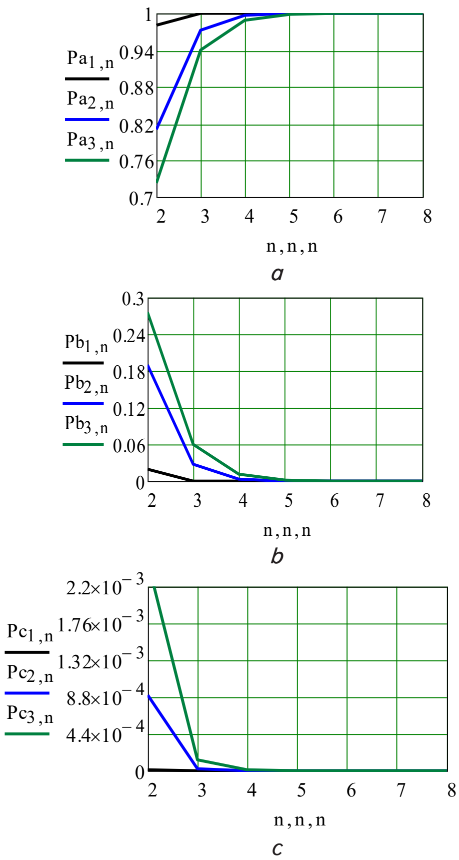

Fig. 4. Plots of probability distributions: *a* — correct detection *Pa*; *b* — false alarm *Pb*; *c* — non-detection *Pc*

3. Determining the probabilities of sensor readings in the presence of fire and its absence.

$$P1a := p \cdot Pa,\ \ P2a := q \cdot Pa,$$

$$P1b := p \cdot Pb,\ \ P2b := q \cdot Pb,$$

$$P1c := p \cdot Pc,\ \ P2c := q \cdot Pc.$$

4. Determining the number of sensors and their corresponding probabilities of correct fire detection according to the specified majority values of the probabilities of fire detection.

$$p0 := \begin{pmatrix} 0.89999 & 0.899 & 0.8988 \end{pmatrix},$$

$$m_i := \sum_{n=2}^{N} \text{if}\left[\left(P1a_{i,n-1} < p0_{1,i} \le P1a_{i,n}\right), n, 0\right],$$

$$m^T = \begin{pmatrix} 4 & 5 & 6 \end{pmatrix},$$

$$pm_i := \sum_{n=2}^{N} \text{if}\left[\left(P1a_{i,n-1} < p0_{1,i} \le P1a_{i,n}\right), P1a_{i,n}, 0\right],$$

$$pm^T = \begin{pmatrix} 0.9 & 0.89959 & 0.89964 \end{pmatrix}.$$

5. Value indicators of IS (profits and losses due to non-detection of fire in its presence and in an uncertain situation).

For the calculation of IS profit indicators, the following values of IS cost indicators were adopted, derived empirically.

$$G := 6000,\ \ Cnp := 3000,\ \ Cns := 1000,\ \ S := 100.$$

6. Values of IS profit indicators.

The formula for determining the IS profit indicator is as follows:

$$D_{i,n} := G \cdot Pap_{i,n} - Cnp \cdot Pbp_{i,n} - Cns \cdot Pcp_{i,n} - S \cdot n,$$

where $Pap_{i,n}$ is the probability of a situation of correct detection of the presence or absence of a fire on board the aircraft, $Pbp_{i,n}$ is the probability of occurrence of a situation of false alarm of a fire alarm, $Pcp_{i,n}$ is the probability of occurrence of a situation of undetected fire, *n* is the number of parallel connected devices (instruments) for determining the presence of fire on board the aircraft.

The results of the calculation are as follows:

$$D = \begin{pmatrix} 0 & 5038.8 & 5097.6 & 5000 & 4900 & 4800 & 4700 & 4600 \\ 0 & 3662.6 & 4873.2 & 4970 & 4896.3 & 4799.6 & 4699.9 & 4600 \\ 0 & 2956.8 & 4608.1 & 4903 & 4882 & 4796.8 & 4699.4 & 4599.9 \end{pmatrix}.$$

7. IS profit values corresponding to majority probabilities:

$$Dm_1 := G \cdot P1a_{1,4} - Cnp \cdot P1b_{1,4} - Cns \cdot P1c_{1,4} - S \cdot m_1,$$

$$Dm_1 = 5000,$$

$$Dm_2 := G \cdot P1a_{1,5} - Cnp \cdot P1b_{1,5} - Cns \cdot P1c_{1,5} - S \cdot m_2,$$

$$Dm_2 = 4900,$$

$$Dm_3 := G \cdot P1a_{1,6} - Cnp \cdot P1b_{1,6} - Cns \cdot P1c_{1,6} - S \cdot m_3,$$

$$Dm_3 = 4800.$$

8. Plotting IS profits (Fig. 5).

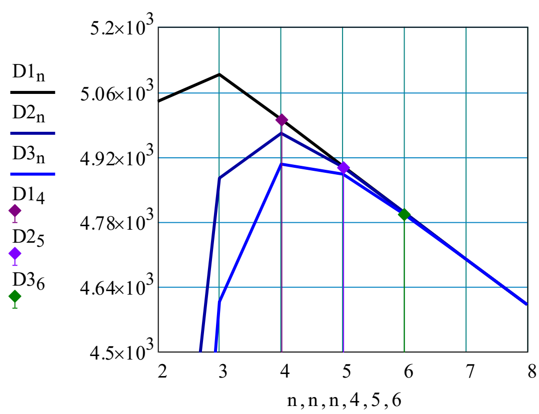

Fig. 5. Plots of information system profit indicators for the «2 out of *n*» type structure with identical sensors

9. Determining maximum values of IS profit indicators.

To determine the maximum values of IS cost indicators, we use the max() function built into Mathcad.

$$D := D^T,\ \ D1 := D^{\langle 1 \rangle},\ \ D2 := D^{\langle 2 \rangle},\ \ D3 := D^{\langle 3 \rangle}.$$

$$D1_{\max} := \max(D1),\ \ D1_{\max} := 5097.6,$$

$$m_1 := \text{match}(D1_{\max}, D1),\ \ m_1 = (3).$$

$$D2_{max} := \max(D2),\ D2_{max} := 4970,$$

$$m_2 := \text{match}(D2_{max}, D2),\ m_2 = (4).$$

$$D3_{max} := \max(D3),\ D3_{max} := 4903,$$

$$m_3 := \text{match}(D3_{max}, D3),\ m_3 = (4).$$

Algorithm for solving the problem for a structure of the «2 out of n» type with sensors of two kinds.

Initial data: number of sensors, probability of fire and false alarm of fire in zone B, probability of detection of fire signal by one sensor in zone A:

$$n := 2 \ldots N,\ n := 2 \ldots N,\ i := 1 \ldots 3.$$

$$p := 0.9,\ q := 1 - p,\ q = 0.1.$$

$$a := \begin{pmatrix} 0.99 \\ 0.9 \end{pmatrix},\ b := \begin{pmatrix} 0.008 \\ 0.08 \end{pmatrix},\ c := \begin{pmatrix} 0.002 \\ 0.02 \end{pmatrix}.$$

Computation:

1. Probabilities of events A_1, A_2, A_3 for IS of the «2 out of n» type structure with sensors of two kinds:

$$Pa_n := 1 - (b_1 + c_1) \cdot (b_2 + c_2)^{n-1},$$

$$Pb_n := (b_1 + c_1) \cdot (b_2 + c_2)^{n-1} - c_1 \cdot (c_2)^{n-1},$$

$$Pc_n := c_1 \cdot (c_2)^{n-1}.$$

$$Pa^T = (0\ 0.999\ 0.9999\ 0.99999\ 0.999999\ 0.9999999\ 1\ 1).$$

$$Pb^T = \\ = (0\ 0.00096\ 0.0000992\ 0.00001\ 0.000001\ 0.0000001\ 0\ 0).$$

$$Pa^T = (0\ 0.00004\ 0.0000008\ 0\ 0\ 0\ 0\ 0).$$

2. Determining the probabilities of sensor readings in the presence of fire and its absence.

$$P1a := p \cdot Pa,\ P2a := q \cdot Pa,$$

$$P1b := p \cdot Pb,\ P2b := q \cdot Pb,$$

$$P1c := p \cdot Pc,\ P2c := q \cdot Pc.$$

3. Determining the number of sensors and their corresponding probabilities of correct fire detection according to the specified majority values of the probabilities of fire detection.

$$p0 := 0.89999,\ N := N - 1,\ n := 1 \ldots N.$$

$$m := \sum_{n=2}^{N} if\left(P1a_{n-1} < p0 \le P1a_n, n, 0\right),\ m = 4.$$

$$pm := \sum_{n=2}^{N} if\left[\left(P1a_{n-1} < p0 \le P1a_n\right), P1a_n, 0\right],$$

$$pm = 0.899991.$$

4. Value indicators of IS (profits and losses due to non-detection of fire in its presence and in an uncertain situation).

For the calculation of IS profit indicators, the following values of IS cost indicators were taken, derived empirically.

$$G := 6000,\ Cnp := 3000,\ Cns := 1000,\ S := 100.$$

5. Values of IS profit indicators.

The formula for determining the IS profit indicator is as follows:

$$D_{i,n} := G \cdot Pap_{i,n} - Cnp \cdot Pbp_{i,n} - Cns \cdot Pcp_{i,n} - S \cdot n,$$

where $Pap_{i,n}$ is the probability of a situation of correct detection of the presence or absence of a fire on board the aircraft, $Pbp_{i,n}$ is the probability of occurrence of a situation of false alarm of a fire alarm, $Pcp_{i,n}$ is the probability of occurrence of a situation of undetected fire, n is the number of parallel connected devices (instruments) for determining the presence of fire on board the aircraft.

The results of the calculation are as follows:

$$D^T = (0\ 5192\ 5099.2\ 4999.9\ 4900\ 4800\ 4700).$$

6. Determining maximum values of IS profit indicators.

To determine the maximum values of IS cost indicators, we use the max() function built into Mathcad.

$$D_{max} := \max(D),\ D_{max} = 5192,$$

$$m := \text{match}(D_{max}, D),\ m = (2).$$

7. Plotting IS profits (Fig. 6).

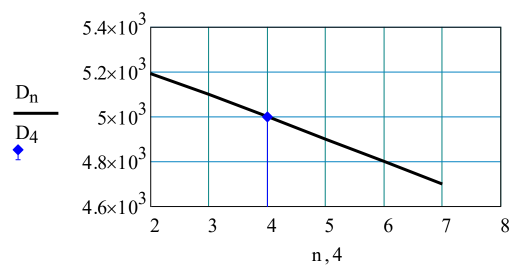

Fig. 6. Profit of information systems for the «2 out of n» type structure with two types of sensors

Fig. 6 shows that with the number of sensors equal to «4», it is possible to obtain optimal indicators, both in terms of the probability of correct detection and in terms of cost.

6. Discussion of results of investigating the reliable characteristics of information systems

From the analysis and disclosure of the mechanism of event formation, the definition of failure was introduced. Failures of information management systems are not just random situations but are characterized as a complex phenomenon that poses a significant degree of risk and extreme uncertainty for the management process.

Our studies of probabilistic characteristics a, b, c, structures built according to the «k out of n» principle have shown that parallel redundancy of information makes it possible to construct reliable information systems with low information capabilities of individual SIs.

The parallel redundancy method reduces the likelihood of non-detection but has little effect on reducing the likelihood of a false alarm.

The probability of a false alarm can be reduced by «coarsening» (reducing sensitivity by increasing the threshold of triggering) of individual SIs while increasing their number compensates for the shortcomings of this method.

Analysis of probabilistic characteristics *Pa, Pb, Pc,* determined from (12) and (13), allows us to draw the following conclusions:

1. It is possible to improve the quality of information systems consisting of *n* SI in terms of increasing the reliability of information in at least three ways, namely:

– an increase in the number of *n* SI;

– improving the characteristics a_i, b_i, d_i of SIs;

– the choice of the optimal information structure, in particular, the choice of the correct majority index *Q*.

2. For information systems made of *n* SIs with identical probabilistic characteristics, the most acceptable structure will be one in which the majority index $Q=n/2$.

The disadvantage of parallel redundancy is:

1. Relatively high probability of false alarms and an increase in the cost of their technical implementation.

2. The modular principle, based on majority logic, makes it possible to reduce the likelihood of false alarms. However, this increases the economic costs due to the increase in the number of parallel-redundant sensors.

The above methods of selection and optimization of parallel redundancy structures can be used to recognize dangerous situations in control systems in different areas. It is especially important for the fire recognition and localization system, navigation systems on aircraft and nuclear power plants, and others.

Increasing the reliability of information in ICS makes it possible to increase profits and reduce losses due to reduced costs associated with the occurrence of false alarm situations and the failure to detect a controlled situation. Such costs include the following types of costs:

– stopping the operation of the monitored system, inspecting, and diagnosing the equipment of the controlled system and ICS, restarting the controlled system and others in the event of a false alarm situation;

– emergency shutdown of the controlled system, elimination of the consequences of a dangerous situation, inspection, diagnostics, and repair of the equipment of the controlled system and ICS, and others in the event of a situation of undetected dangerous situation.

To advance the method of parallel information redundancy of SIs, it is expedient and cost-effective to apply the modular principle of their construction [19].

7. Conclusions

1. The states of the object of study, as an indication system and the state of the object system, were determined by three characteristics: the probability of correct detection, non-detection, and false alarm. For example, for the «*k* of *n*» system, with the probabilistic characteristics of the sensors $a=0.9$, $b=0.00096$, $c=0.02$, the following probabilities were determined. The probability of correct detection $Pa=0.999$, false alarm probability $Pb=0.0009$, and the probability of non-detection $pc=0.02$. In this paper, we identified the main ways of building an information system for recognizing dangerous situations: with a serial, parallel, and mixed connection of system elements. The essence of the proposed methods of building an information system is to reduce the likelihood of false alarm and non-detection situations. The peculiarity of the proposed methods of building an information system is as follows. Systems with a series connection of elements can reduce the likelihood of a false alarm situation and increase the likelihood of a situation of undefined of the controlled situation. Systems with parallel connection of elements reduce the likelihood of a situation of the non-detection of a controlled situation and increase the likelihood of a false alarm situation. Systems with a mixed connection of system elements, with the correct selection of parameters, can reduce the likelihood of situations of both false alarm and non-detection. The current paper proposes a majority principle for building a system with a parallel connection of elements, which simultaneously reduces the probability of occurrence of situations of both false alarm and non-detection.

2. The developed model of parallel information redundancy is based on the use of the optimal number of information sensors, which ensures the selection of optimal structures based on a polynomial probabilistic model. The relations for finding the probabilities of IS states for structures of type «*k* of *n*» are obtained, taking into consideration the priority for identifying hazardous situations. The features of the obtained ratios are that they can be used both at the stage of designing systems and at the stages of improving and operating systems to improve the technical and economic performance of the system.

3. Algorithms have been developed in Mathcad for calculating the probabilities of the states of IS at parallel connection of sensors of initial information for structures of type «1 of *n*» and «2 of *n*» with sensors of the same type. Algorithms for calculating the probabilities of the states of IS at parallel connection of sensors of initial information for the structure «2 of *n*» with sensors of two types were found. Estimates of the effectiveness of IS indicators of the considered types of structures were found. Algorithms for determining the number of information sensors and the corresponding probabilities of fire detection have been developed, taking into consideration economic efficiency. For «2 out of *n*» structures, as the number of sensors increases, there is a decrease in profit. This is due to an increase in the cost of purchasing additional sensors. At the same time, for «2 out of *n*» structures, optimal indicators in terms of the probability of correct detection and cost indicators are observed at $n=4$.

Conflict of interests

The authors declare that they have no conflict of interests in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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