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ENHANCING THE RELIABILITY OF INFORMATION IN POSITIONING SYSTEMS ON ROAD TRANSPORT BY USING PARALLEL INFORMATION REDUNDANCY

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The object of research is the reliability of information in information-control systems. The work considers a solution to an important scientific and practical problem – increasing the reliability of information in real-time control systems, in particular in positioning systems on road transport. To solve this task, the use of information redundancy, in particular, parallel information redundancy, is proposed. The paper studies the influence of the probability of occurrence of a controlled event, the majority coefficient, as well as the number and quality of information sensors on the reliability of information in an information control system with parallel information redundancy. For these dependences, the corresponding plots were constructed. The paper shows that a change in the quality of information sensors by 20 % can lead to an increase in the reliability of information by more than 0.5. Also, the paper shows that an increase in the majority index by 1 can lead to a change in the reliability of information by more than 0.3. The paper investigates parallel information redundancy systems with different structures and defines formulas for calculating the probabilistic characteristics of their operation. The mathematical modeling was carried out taking into account the probability of occurrence of the controlled event, which made it possible to determine the tendencies to build information-control systems with parallel information redundancy to control events with variable probability of occurrence. The results obtained are based on the theory of probability. The results reported in this work can be used in the construction of an information and control system with a programmatically variable structure to control the occurrence of an event with a variable probability of occurrence, in particular in positioning systems on road transport

Keywords: information security, information sensors, information reliability, information redundancy, positioning system

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1. Introduction

One of the main trends in the automotive industry at present is the improvement of information support for drivers and the automation of the process of driving a motor vehicle. At the same time, one of the most important aspects of informatization and automation of motor vehicles is the warning and prevention of traffic accidents. To improve road safety, first of all, it is necessary to enable the process of positioning the motor vehicle, that is, to determine the parameters of its position and movement relative to other elements of the road and transport system. Informatization and automation of motor vehicles is achieved through the development and implementation of information systems, signaling systems, decision support systems, and subsystems of automatic control of the motor vehicle or its subsystems. In general, the work of all these systems is as follows. A sensor or a system of sensors provides for the formation of information about the value of the controlled parameter. After analyzing this information, a decision is made regarding the possibility of the occurrence of a controlled event (CE) and the implementation of the necessary control effects under automatic, semi-automatic, or manual mode. Thus, the safety of motor vehicle movement directly depends on the quality of information sensors (IS) since management decisions are made on the basis of information from them.

One of the main characteristics of information that determine its quality is the reliability of information. The reliability of information characterizes the ability of information to objectively describe the actual state of affairs.

At the same time, the assessment of the reliability of the information consists in determining the degree of correspondence of the obtained data about the researched object to its real state. In positioning systems on road transport, the researched object is a motor vehicle, in particular, and the main researched parameters are the distance and time interval of movement to the point of potential collision. At the same time, the main controlled event is the achievement of the minimum permissible or recommended distance or time interval of movement to the point of potential collision. Separately, it should be noted that modern positioning systems provide for the availability of information exchange channels between motor vehicles for the purpose of early forecasting the possibility of the occurrence of controlled events. Therefore, to ensure high reliability of information, it is necessary to ensure a high level of information security.

Thus, improving the security and reliability of information in information-control systems (ICS), which includes the positioning system on road transport, is an important scientific and practical task that requires research and solution. Increasing the reliability of information in ICSs could improve the quality of their work, in particular, reduce the probability of erroneous detection and omission of CE. This, in turn, will improve the efficiency, safety and quality of road traffic. Therefore, research on increasing the reliability of information in positioning systems on road transport is relevant.

2. Literature review and problem statement

The main directions of increasing the reliability of information in ICS are improving the quality of IS, the application of IS with different physical principles of action, complex information processing, information redundancy (IR), increasing technical reliability, and others.

In [1], an algorithm for identifying the states of a technical system was developed on the basis of identification theorems. In the work, based on the analysis of the received states of the technical system, it is shown that increasing the reliability of determining the state in which the technical system is possible only through the use of structural, procedural, and informational redundancy. The work also offers approaches to increase the reliability of data on the basis of which a decision is made. At the same time, the proposed algorithm is sensitive to external influences and is focused on accurate input information.

Work [2] focuses on solving the issue of optimizing system performance through the optimal distribution of spare elements in an n-component system with serially connected elements. In the work, the main focus is on solving the problem of optimal distribution of one reserve element. The solution of this problem in the work is carried out from the point of view of the stochastic approach. In the work, based on numerical examples, it is shown that it is necessary to reserve the element with the lowest probability of failure-free operation, and optimal allocation policies for cases of hot and cold redundancy are proposed. The main advantage of this work over most others is that it considers an n-component system. At the same time, the work does not define the maximum number of elements n for which the proposed policies of optimal distribution of reserve elements can be applied, as well as the influence of the system structure on the distribution policy.

Paper [3] considers the problem of optimal distribution of reserve elements in systems with serial and parallel connection of interdependent elements, as well as in systems of the "k of n" type. The paper proposes a solution to this problem thanks to the multidimensional expansion of joint two-dimensional stochastic indicators. The approach proposed in the work can be applied both for hot and cold backup. The main advantage of the work is that it considers the problem of distribution of reserve elements in systems with dependent components. At the same time, the work does not define the limitations and scope of the proposed approach.

Work [4] raises the question of the need to provide the ICS operator with reliable information from sensors of controlled parameters under normal and special operating conditions. An aircraft fire alarm system is considered as an ICS. The paper proposes a probabilistic-physical model of the processes of formation of information flows and gives the probabilistic characteristics of the operation of ICS. In the work, mathematical dependences of the probability of omission and false detection of CE on the number and quality of the primary sensors of the controlled parameters were obtained. At the same time, the work lacks a study on the dependence of the probability of correctly determining the absence of a fire on the number and quality of primary ISs. Although it is the event of no fire that is the event with the predominant probability of occurrence during the operation of the fire alarm system.

Work [5] reports the results of studying the driver's reaction to visual and auditory information in the road traffic advisory system. The results of the study show that audio information helps increase the driver's reaction, and visual information helps drivers to drive more accurately and efficiently. The results demonstrate that the simultaneous use of sound and visual information in the traffic advisory system increases the efficiency and safety of driving. The work shows that the combination of different channels of providing information to the driver improves the quality of information perception and positively affects traffic safety. At the same time, the work does not consider the priority in providing information under the condition of the occurrence of a factor overlay situation. Also, the work does not raise the question of the reliability of information in the traffic advisory system.

Heavy machine tools with numerical software control are considered as ICS in [6]. The paper proposes the use of a multi-product, multi-sequence hidden Markov model to assess their reliability by building a model of relationships between the states of the machines and several key performance parameters of their work. The proposed approach makes it possible to improve the accuracy of machine condition assessment and provides better support for their maintenance. At the same time, the work does not assess the reliability of information about the machine's operating condition. Also, the work does not evaluate the influence of the reliability of information about the values of key performance parameters on the quality of the system for evaluating the reliability of numerically controlled machines.

In work [7], a mathematical model of reliable IC structures was built. The paper proposes the use of parallel IR to increase the reliability of information about the appearance of CE. One of the main scientific results of the work is the development of an algorithm for choosing the optimal design of the CE recognition system. In particular, the proposed algorithm allows determining the optimal number of ISs and the majority index of the parallel IR system. At the same time, the paper considers a three-parameter state graph of the information system. That is, the event of correctly determining the presence of a CE and the event of correctly determining the absence of a CE are combined into one event – the event of the correct operation of the system. Thus, when choosing the optimal structure of ICS, the probability of the appearance of CE is not taken into account.

Work [8] considers the analysis of the reliability of information about the speed of the vehicle obtained at the scene of the accident between the vehicle and the pedestrian, taking into account the uncertainty of the information. The paper examines the influence of methods of positioning and determination of the collision speed, as well as the influence of approaches to the determination of reference points on the reliability of information. In addition, the work considers ways to increase the reliability of information about the collision speed. At the same time, the paper does not determine the contribution of the reliability of each type of input information to the reliability of the received information about the collision speed.

In work [9], the aircraft fire alarm system is considered as an IC. It is proposed to increase the reliability of information about the occurrence of a fire on board an aircraft in the work by using parallel IR using nested modules. One of the main scientific results of the work is the construction of a mathematical model of parallel IR based on the principle of nested modules and their implementation on logical elements. In addition, the work provides mathematical formulas for evaluating the effectiveness of hierarchies, which can be used to evaluate and select the optimal structure of IC, built on the basis of nested modules. At the same time, the probability of occurrence of CE is not taken into account when evaluating and choosing the optimal structure of ICS.

Work [10] reports the study of methods for modeling and reliability analysis of an automated controlled vehicle based on synchronized machines. The work shows that the existing experimental methods of determining the reliability of an automated controlled car at the stages of design and manufacture have a significant drawback – they have significant limitations regarding the detection of unreliable events, that is, events with a low probability of occurrence. To eliminate this shortcoming in the design process, a method for determining the reliability of an automated controlled vehicle based on time machines is proposed in the paper. The proposed method in combination with the reliability calculation formula makes it possible to model and calculate the factors that affect the correct operation of the system. Determination of related components that affect the correct operation of the system provide the formation of theoretical foundations for optimal system design. At the same time, the limitations and scope of the proposed method are not sufficiently disclosed in the work.

Work [11] reports the results of studying the impact of multi-level modular redundancy on the reliability of coherent systems. At the same time, the work examines systems with active and passive redundancy, as well as systems with component redundancy and module redundancy. One of the main scientific results of the work is the construction of a mathematical model for the study of modular redundancy, which allows obtaining several general results under various assumptions. The model proposed in the work takes into account the dependence between the components and modules of the system in the form of copulas and represents various backup mechanisms and reliability of different systems in the form of distortions. At the same time, the work does not include the results of evaluating the efficiency of work and the cost of building different families of copulas.

In general, various approaches are used to solve the issue of increasing the reliability of information in ICS operating in real time. The main ones are IR and increasing the reliability of elements of the measurement and information processing system. At the same time, the question of the influence of the value of the probability of occurrence of CE and the quality of IS on the reliability of information in ICS remains unresolved. Also, the procedure for choosing the optimal structure of the IR system, depending on the probability of occurrence of CE and the quality of IS, also needs research.

3. The aim and objectives of the study

The purpose of our study is to determine the influence of the probability of occurrence of CE, as well as the quality and quantity of IS on the reliability of information in ICS with parallel IR. This will make it possible to devise a procedure for choosing the optimal structure of the IR system to increase the reliability of information in ICS. In the future, the results of the work can be used in the construction of parallel IR systems with a programmatically variable structure, to control the occurrence of an event with a variable probability of occurrence, in particular, in positioning systems on road transport.

To achieve the goal, the following tasks were set:

– to determine the probabilistic characteristics of the parallel IR system;

– to investigate the dependence of the probabilistic characteristics of the parallel IR system on the quality of information sensors;

– to investigate the dependence of the probabilistic characteristics of the parallel IR system on the majority index;

– to investigate the dependence of the probabilistic characteristics of the parallel IR system on the probability of the occurrence of a controlled event.

4. The study materials and methods

The object of our study is the process of increasing the reliability of information in ICS, in particular, in positioning systems in road transport. The subject of the study is models for improving the reliability of information in ICS with the use of parallel IR.

The paper puts forward the following hypothesis – increasing the reliability of information in ICS that work in real time, in particular in positioning systems on road transport, could make it possible to increase the efficiency of their work. And the determination of the dependence of the probabilistic characteristics of the ICS operation on the quality of IS and the probability of the occurrence of CE will allow the construction of an ICS with a programmatically variable structure. ICS with a program variable structure could be applied to control the occurrence of an event with a variable probability of occurrence.

The paper reports the results of a computer (numerical) experiment. The numerical experiment was carried out in the form of mathematical modeling of the process of increasing the reliability of information in positioning systems on road transport under the condition of using parallel IR. In the course of the numerical experiment, the dependence of the information reliability of the parallel IR system on the quality of IS, the probability of occurrence of CE and the majority index of the parallel IR system was investigated. The processing of the results of the numerical experiment was carried out using the method of graphic processing of the results of the experimental research. The application of the specified method has made it possible to build a family of plots of the dependence of probabilistic characteristics and the quality of the parallel IR system's operation on the quality of IS. Families of plots are built for different values of the probability of occurrence of CE and different values of the majority index of the parallel IR system.

The following hardware was used for mathematical modeling: a personal computer based on an Intel(R) Core(TM) i5-10400F processor with a 64-bit Windows 11 Pro operating system. Mathematical modeling was carried out using the following software – a specialized mathematically oriented software tool for scientific and engineering calculations Mathcad, version 14.0.0.163.

The following can be attributed to the assumptions that are the basis of the simplification of the real process of increasing the reliability of information in positioning systems on road transport used in the work. The probabilistic characteristics of the operation of IS, the parallel IR system and the ICS do not change during their development and do not affect the reliability of the information in the positioning systems on road transport.

The work adopts the following assumptions. A sensor characterized by a constant value of the probability of correct measurement of the controlled parameter is considered an IS. As a controlled parameter, such a parameter is considered, which unambiguously determines the moment of onset of CE. An event characterized by a constant value of the probability of its occurrence is considered a CE.

The following simplifications are accepted in the work. ISs have the same probabilistic characteristics, which do not change during their development, and do not depend on the probability of occurrence of CE. The moment of CE onset is characterized by a specific value of the controlled parameter, which does not depend on the characteristics of the studied system. The reliability of the information depends on the probability of occurrence of CE and the quality of IS and does not depend on the quality of the IR system. The value of the probability of occurrence of CE does not depend on the characteristics of the studied system. The value of the probability of correct measurement of the controlled parameter does not depend on the characteristics of the measurement system and the probability of occurrence of CE.

The initial data for our modeling are the following ranges of values of the quality of IS, the probability of occurrence of the controlled event and the majority coefficient of the parallel IR system. In the simulation, the range of change in the quality value of CI P_{cd} was taken from 0 to 1 with a step of 0.01, and the probability of occurrence of the controlled event P_{pe} – from 0.1 to 0.9 with a step of 0.2. The simulation was carried out for parallel IR systems with four ISs with a majority ratio from 1 to 4.

Information in positioning systems on road transport, like other ICS, is formed on the basis of data from certain ISs. In particular, such sensors include distance, speed and acceleration measurement system sensors and other sensors. Any IS, due to its design and technical features, has a finite accuracy of measurement of the parameter controlled by it. And accordingly, the information about the onset of the CE, received by the control system based on the data on the value of the controlled parameter determined by the IS, has finite reliability. At the same time, depending on the absence or presence of CE, the following four situations can be distinguished in the process of CE detection: determination of the presence of CE, determination of the absence of CE, omission of CE, false detection of the presence of CE. The specified events are characterized by the probability of their occurrence, which is determined by the design and technical characteristics of the IS and the measurement system. At the same time, the occurrence of undesirable situations of false detection and passing of checkpoints can lead to a decrease in the safety and efficiency of road traffic.

In order to build a model of the dependence of the reliability of information about the appearance of CE in positioning systems on the probability of its appearance and the quality of IS, the process of its detection was considered. The process of detection of CE is considered on the example of the scheme for determining the distance between motor vehicles Δd, which is shown in Fig. 1. The process of detection of CE is as follows. There is a critical value of the controlled parameter $\Delta d_{critical}$, when it is reached, a signal is generated in the control system about the onset of CE. The critical value of the controlled parameter, depending on its type and physical content, can be a constant value or depend on certain factors and be determined at each moment of movement. In particular, the critical value of the distance between motor vehicles depends on the state of the road surface, the relative speed of the motor vehicles, the state of their braking system, and other parameters. At the same time, it is possible to highlight the time functions of the actual $\Delta d_{actual}(t)$ and the measured $\Delta d_{measured}(t)$ value of the controlled parameter. Under the condition of the occurrence of CE, that is, when $\Delta d_{actual.} \leq \Delta d_{critical}$ (Fig. 1, *a*), the following two events can occur, which make up a complete group of events: determination of the presence of CE with the probability of occurrence P_d, when $\boldsymbol{\Delta d_{measured.} \leq \Delta d_{critical}}$ and the omission of CE with the probability of occurrence P_p, in the case when $\Delta d_{measured.} > \Delta d_{critical}$. Under the condition of the absence of CE, that is, when $\Delta d_{actual.} > \Delta d_{critical}$ (Fig. 1, *b*), the following two events may occur, which make up a complete group of events: false detection of the presence of CE with the probability of P_f when $\Delta d_{measured.} \leq \Delta d_{critical}$ and determination of the absence of CE with the probability P_a appearing when $\Delta d_{measured.} > \Delta d_{critical}$.

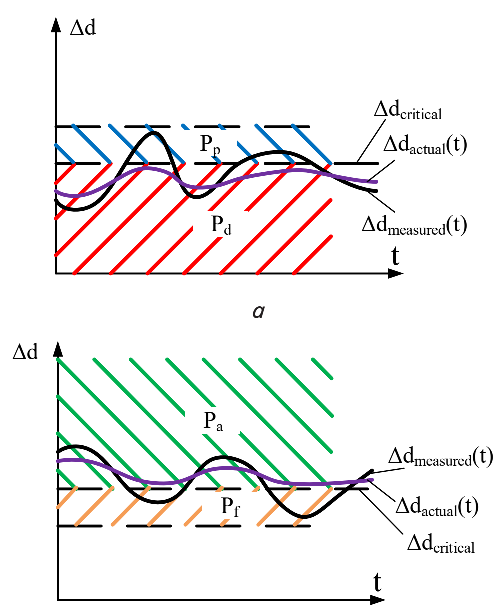

Fig. 1. Scheme for determining the controlled parameter: *a* — under the condition of the presence of a controlled event; *b* — provided there is no controlled event

To derive the formulas for determining the probability of occurrence of the specified events, the graph of the states of the CE onset signaling system was considered, which is shown in Fig. 2. To begin with, two events that make up a complete group of events are considered: the presence and absence of CE with the probability P_{pe} and P_{ae} occurrence, respectively. The specific values of the probabilities of the occurrence of these two events will depend on the characteristics of the studied system, in particular on the characteristics of the road and transport system: the density of the traffic flow, the state of the road surface, the speed of motor vehicles, and others.

At the next stage, two events that occur during the operation of the measurement system and that make up a complete group of events are considered: correct and incorrect measurement of the controlled parameter with the occurrence probabilities P_{cd} and P_{id}, respectively. The specific values of the probabilities of the occurrence of these two events can be both the same and different under the condition of occurrence and absence of CE and will depend on the characteristics of the measurement system. The main such characteristics include measurement inertia, sensitivity threshold, resolution, and others.

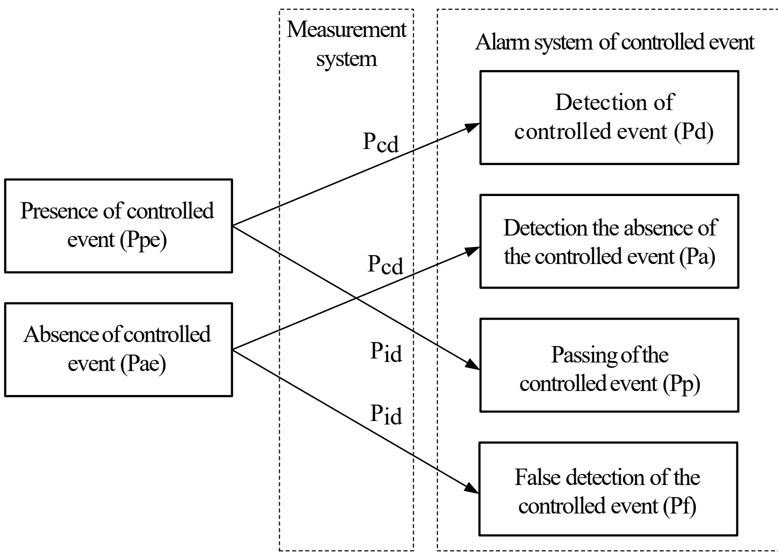

Fig. 2. State graph of the controlled event signaling system

Thus, different combinations of the situation of occurrence or non-occurrence of CE and the situation of correct or incorrect measurement of the controlled parameter will form the above four situations.

In general, the following four situations may occur during the operation of the CE alarm system, which make up a complete group of events:

– determination of the presence of CE, which occurs as a result of the correct measurement of the controlled parameter under the condition of the occurrence of CE with the probability P_d;

– determination of the absence of CE, which occurs as a result of the correct measurement of the controlled parameter under the condition of non-occurrence of CE with probability P_a;

– the omission of CE, which occurs as a result of an incorrect measurement of the controlled parameter under the condition of the occurrence of CE with the probability P_p;

– false detection of the presence of CE, which occurs as a result of incorrect measurement of the controlled parameter, provided that the CE does not occur with the probability P_f.

Since the events of correct measurement of the controlled parameter and the onset of CE are independent events, the formulas for determining the probabilities P_d, P_a, P_p, P_f take the following form:

$$\left.\begin{aligned} P_d &= P_{cd1}\cdot P_{pe}, \\ P_a &= P_{cd2}\cdot P_{ae}, \\ P_p &= P_{id1}\cdot P_{pe}, \\ P_f &= P_{id2}\cdot P_{ae}, \end{aligned}\right\} \qquad (1)$$

where P_{cd1} and P_{cd2} are the probability of correct measurement of the controlled parameter under the condition of occurrence and non-occurrence of the controlled event, respectively; P_{id1} and P_{id2} are the probability of incorrect measurement of the controlled parameter under the condition of occurrence and non-occurrence of CE, respectively.

In our mathematical model of the probability of the presence P_{pe} and the absence P_{ae} of CE, the influence of the probability of the appearance of CE on the probabilistic characteristics of the CE signaling system is determined. And the probabilities of the correct P_{cd} and incorrect P_{id} measurement of the controlled parameter determine the influence of the quality of the IS on the probabilistic characteristics of the CE signaling system.

The use of IR is one of the ways to increase the reliability of information in ICS. The essence of IR is the statistical processing of information coming from several sources of information. At the same time, serial, parallel, modular, and combined IR are distinguished.

The essence of sequential IR consists in the statistical processing of information received at a given time interval v from one source of information n times. At the same time, the decision on the presence of CE is made according to the "*m* out of *n*" majority principle. The main advantage of sequential IR is to reduce the probability of false detection of CE, and the disadvantage is to reduce the reliability of information with a decrease in the technical reliability of IS and as a result of information aging.

The essence of parallel IR consists in the statistical processing of information simultaneously coming from *n* ISs. At the same time, the decision on the presence of CE is made according to the "*m* out of *n*" majority principle. The main advantages of parallel IR are the ability to increase the reliability of information in real time and reduce the probability of missing a CE. And the main disadvantage of the parallel IR is the increase in the cost, size, and weight of the system as a result of installing additional ISs.

The essence of the modular IR consists in the step-by-step statistical processing of information simultaneously coming from *n* IR modules. The module of the first hierarchy implements parallel IR with the majority principle "*m* out of *n*". ISs for each subsequent hierarchy are modules of the previous hierarchy. At the same time, the decision on the presence of CE at each of the stages is made according to the "*m* out of *n*" majority principle. The main advantage of the modular IR is the simultaneous reduction of the probability of omission and false detection of CE. And the main disadvantages of the modular IR are the slight aging of the information and the increase in the cost, dimensions, and weight of the system as a result of the installation of additional ISs.

The essence of the combined IR consists in the statistical processing of information that comes from *n* parallel-connected elements of the serial IR. The element of sequential IR provides statistical processing of information according to the majority principle "*k* out of *l*", which is sequentially received at a given time interval v from one source of information *l* times. At the same time, the decision about the presence of CE is made on the basis of information from the parallel-connected elements of a serial IR according to the "*m* out of *n*" majority principle. The main advantage of the combined IR is the simultaneous reduction of the probability of omission and false detection of CE. And the main disadvantages of the combined IR are the aging of information, the need to develop the optimal structure of the combined redundancy system, increasing the cost, dimensions, and mass of the system due to the installation of additional ISs.

In general, the most appropriate for increasing the reliability of information in real-time control systems, which includes the positioning system, is parallel IR. Combined, modular or sequential IR can also be used, but only on the condition that their structure of the IR system provides an acceptable aging time of information.

5. Results of research on the use of parallel IR to increase the reliability of information

5. 1. Determination of the probabilistic characteristics of the parallel IR system.

The real CI at a given moment in time can be in one of two random, incompatible states: incorrect and correct determination of the value of the controlled parameter with the probabilities of their occurrence P_{id}, and P_{cd}, respectively, as shown in Fig. 1. The measurement system that implements parallel IR can be in one of the random incompatible states with the following probabilities of their occurrence: $P_{1,n}, P_{2,n}, \dots, P_{n-1,n}, P_{n,n}$. At the same time, $P_{i,n}$ determines the probability of the occurrence of an event when *i* of *n* CIs correctly, and *n*-th CIs – incorrectly determine the value of the controlled parameter. In general, the probability of the measurement system being in each of the specified states can be determined based on the expression that describes the binomial distribution and is defined as follows:

$$P_{i,\mathrm{n}} = C_n^i P_{cd}^i \cdot P_{id}^{n-i}. \tag{2}$$

In accordance with this, the measurement system that implements parallel IR with the "*m* out of *n*" majority principle, provided there is CE, is characterized by the following probabilistic characteristics. The probability of a correct measurement of P_{cd} is determined by the sum of the event probabilities $P_{m,n}, \dots, P_{n,n}$. The probability of an incorrect measurement P_{id}, which is determined by the sum of the probabilities of occurrence of events $P_{0,n}, \dots, P_{m-1,n}$. This is explained by the fact that in the presence of CE, the measurement system will detect its presence if *m* and more CIs correctly measure the value of the controlled parameter. And in the absence of CE, the measurement system is characterized by the following probabilistic characteristics. The probability of correct measurement P_{cd} is determined by the sum of the probabilities of occurrence of events $P_{n-m+1,n}, \dots, P_{n,n}$. The probability of incorrect measurement P_{id}, which is determined by the sum of the probabilities of occurrence of events $P_{0,n}, \dots, P_{n-m,n}$. This is explained by the fact that in the absence of CE, the measurement system will falsely detect its presence, if *m* and more CIs incorrectly measure the value of the controlled parameter. Thus, for a measurement system that implements a parallel IR with the "*m* out of *n*" majority principle, formulas (1) taking into account formula (2) can be written as follows:

$$\left.\begin{aligned} P_d &= P_{pe} \cdot \sum_{q=m}^{n} \left(C_n^q \cdot P_{cd1}^q \cdot P_{id1}^{n-q} \right); \\ P_a &= P_{ae} \cdot \sum_{q=n-m+1}^{n} \left(C_n^q \cdot P_{cd2}^q \cdot P_{id2}^{n-q} \right); \\ P_p &= P_{pe} \cdot \sum_{q=0}^{m-1} \left(C_n^q \cdot P_{cd1}^q \cdot P_{id1}^{n-q} \right); \\ P_f &= P_{ae} \cdot \sum_{q=0}^{n-m} \left(C_n^q \cdot P_{cd2}^q \cdot P_{id2}^{n-q} \right). \end{aligned}\right\} \tag{3}$$

Further research into the probabilistic characteristics of the parallel IR system is considered using the example of the system for measuring the distance between ATCs Δd, which implements the majority decision-making principle "*m* out of 4". When considering this system, it was considered that it consists of 4 ISs of the same type. The following four parallel IR systems with different majority decision-making principles are considered: "1 of 4", "2 of 4", "3 of 4", and "4 of 4", respectively. For each of the proposed systems, the probabilistic characteristics of its operation are defined. To simplify the type of calculation formulas, it was considered that the probabilities of correct and incorrect measurement of the controlled parameter under the condition of presence and absence of CE are equal to each other, i. e., $P_{cd1}=P_{cd2}=\mathrm{P}_{cd}$ and $P_{id1}=P_{id2}=P_{id}$.

The system of parallel IR with the majority principle "1 out of 4" forms a signal about the presence of CE $S_{1,4}$, in the event that it was detected by at least one IS. The formulas for determining the probabilistic characteristics of the operation of this parallel IR system take the following form:

$$\left.\begin{aligned} P_d &= P_{pe} \cdot \begin{pmatrix} P_{cd}^4 + 4 \cdot P_{cd}^3 \cdot P_{id} + \\ +6 \cdot P_{cd}^2 \cdot P_{id}^2 + 4 \cdot P_{cd} \cdot P_{id}^3 \end{pmatrix}; \\ P_{ad} &= P_{ae} \cdot P^4; \\ P_p &= P_{pe} \cdot P_{id}^4; \\ P_f &= P_{ae} \cdot \begin{pmatrix} 4 \cdot P_{cd}^3 \cdot P_{id} + 6 \cdot P_{cd}^2 \cdot P_{id}^2 + \\ +4 \cdot P_{cd} \cdot P_{id}^3 + P_{id}^4 \end{pmatrix}. \end{aligned}\right\} \tag{4}$$

The system of parallel IR with the "2 out of 4" majority principle generates a signal about the presence of CE $S_{2,4}$, in the event that it is detected by at least two ISs. The formulas for determining the probabilistic characteristics of the operation of this parallel IR system take the following form:

$$\left.\begin{aligned} P_d &= P_{pe} \cdot \left(P_{cd}^4 + 4 \cdot P_{cd}^3 \cdot P_{id} + 6 \cdot P_{cd}^2 \cdot P_{id}^2 \right); \\ P_{ad} &= P_{ae} \cdot \left(P_{cd}^4 + 4 \cdot P^3 \cdot P_{id} \right); \\ P_p &= P_{pe} \cdot \left(4 \cdot P_{cd} \cdot P_{id}^3 + P_{id}^4 \right); \\ P_f &= P_{ae} \cdot \left(6 \cdot P_{cd}^2 \cdot P_{id}^2 + 4 \cdot P_{cd} \cdot P_{id}^3 + P_{id}^4 \right). \end{aligned}\right\} \tag{5}$$

The system of parallel IR with the majority principle "3 out of 4" generates a signal about the presence of CE $S_{3,4}$, in the event that it is detected by at least three ISs. The formulas for determining the probabilistic characteristics of the operation of this parallel IR system take the following form:

$$\left.\begin{aligned}
&P_d = P_{pe} \cdot \left(P_{cd}^4 + 4 \cdot P_{cd}^3 \cdot P_{id}\right);\\
&P_a = P_{ae} \cdot \left(P_{cd}^4 + 4 \cdot P_{cd}^3 \cdot P_{id} + 6 \cdot P_{cd}^2 \cdot P_{id}^2\right);\\
&P_p = P_{pe} \cdot \left(6 \cdot P_{cd}^2 \cdot P_{id}^2 + 4 \cdot P_{cd} \cdot P_{id}^3 + P_{id}^4\right);\\
&P_f = P_{ae} \cdot \left(4 \cdot P_{cd} \cdot P_{id}^3 + P_{id}^4\right).
\end{aligned}\right\} \qquad (6)$$

The system of parallel IR with the “4 out of 4” majority principle generates a signal about the presence of CE $S_{4,4}$, in the event that it is detected by all four ISs. The formulas for determining the probabilistic characteristics of the operation of this parallel IR system take the following form:

$$\left.\begin{aligned}
&P_d = P_{pe} \cdot P_{cd}^4;\\
&P_a = P_{ae} \cdot \begin{pmatrix} P_{cd}^4 + 4 \cdot P_{cd}^3 \cdot P_{id} + \\ +6 \cdot P_{cd}^2 \cdot P_{id}^2 + 4 \cdot P_{cd} \cdot P_{id}^3 \end{pmatrix};\\
&P_p = P_{pe} \cdot \begin{pmatrix} 4 \cdot P_{cd}^3 \cdot P_{id} + 6 \cdot P_{cd}^2 \cdot P_{id}^2 + \\ +4 \cdot P_{cd} \cdot P_{id}^3 + P_{id}^4 \end{pmatrix};\\
&P_f = P_{ae} \cdot P_{id}^4.
\end{aligned}\right\} \qquad (7)$$

For the considered parallel IR systems, their block diagrams of signal formation about the presence of CE were built based on the logic elements shown in Fig. 3.

In general, the probabilistic performance characteristics of the parallel IR system with any required number of ISs and the required majority index can be determined using formulas (3).

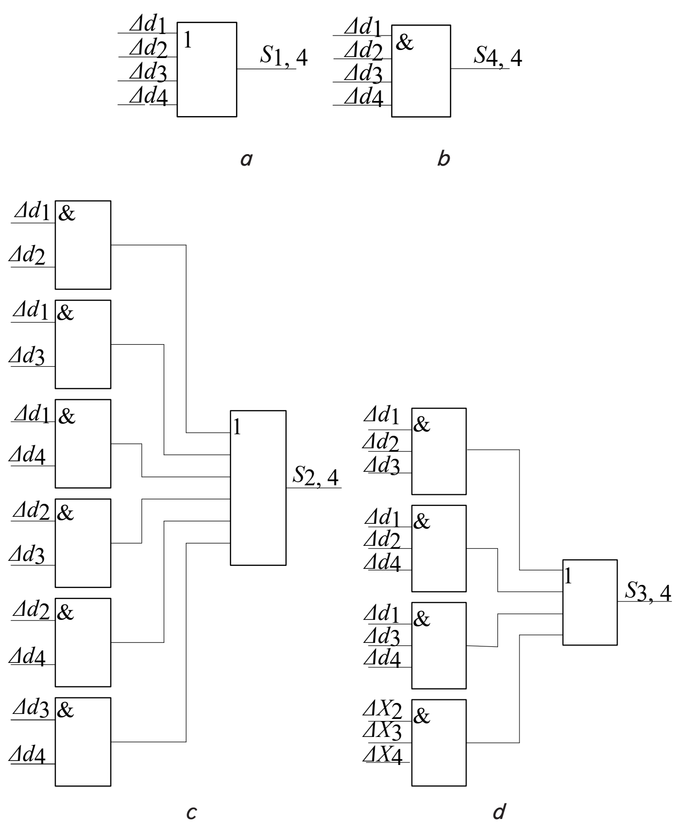

Fig. 3. Block diagrams of parallel IR systems: *a* – with the majority principle “1 out of 4”; *b* – with the majority principle “4 out of 4”; *c* – with the majority principle “2 out of 4”; *d* – with the majority principle “3 out of 4„

5. 2. Studying the dependence of probabilistic characteristics of the parallel IR system on the quality of information sensors

The quality of CI considered its probability of correct measurement of the controlled parameter P_{cd}. At the same time, it was considered that with $P_{cd} \le 0.5$, ISs are characterized by low quality, and with $P_{cd} > 0.5$ – high quality. To study the dependence of the probabilistic characteristics of the parallel IR system on the quality of IS, mathematical modeling of their operation was carried out based on formulas (4) to (7). The results of mathematical modeling are represented in the form of appropriate plots. Plots of the dependence of the probabilities P_d, P_a, P_p, P_f on the quality of the IS are shown in Fig. 4. In order to take into account the probability of occurrence of CE, the specified plots are constructed for different probabilities of occurrence of CE. Three situations were considered: with a high probability of CE, when P_{pe}=0.9 and P_{ae}=0.1; with equal probability of presence and absence of CE, when P_{pe}=P_{ae}=0.5; with a high probability of no CE, i.e., when P_{pe}=0.1 and P_{ae}=0.9. For each situation in the plots of Fig. 4, a separate family of plots is constructed in a separate color. In order to take into account the majority index of the parallel IR system, the specified plots are constructed for the values of the majority index from 1 to 4. In Fig. 4, plots for systems with different majority indicators are constructed with different types of lines and the type of parallel IR system is indicated next to the parameter name: “m, n”.

Plots of the dependence of the probability of correct $P_{cd.s}$ and incorrect $P_{wd.s}$ operation of the parallel IR system depending on the quality of IS P_{cd}, which are shown in Fig. 5, were also considered. The probability of the correct operation of the parallel IR system was understood as the sum of the probabilities of correctly determining the presence P_d and the absence P_a of CE. And the probability of incorrect operation of the system meant the sum of the probabilities of missing P_p and false detection P_f of the presence of CE. In order to take into account the probability of occurrence of CE, these plots are built for different probabilities of occurrence of CE. The following 4 situations were considered:

– with a high probability of CE, with P_{pe}=0.9 and P_{ae}=0.1;

– with moderate probability of presence of CE, with P_{pe}=0.7 and P_{ae}=0.3;

– with moderate probability of absence of CE, with P_{pe}=0.3 and P_{ae}=0.7;

– with a high probability of the absence of CE, with P_{pe}=0.1 and P_{ae}=0.9.

For each situation in the plots of Fig. 5, a separate family of plots is constructed on a separate coordinate plane. In order to take into account the majority index of the parallel IR system, the specified plots are constructed for the values of the majority index from 1 to 4. In Fig. 5, the plots for systems with different majority indicators are constructed with different types of lines and next to the name of the parameter the type of parallel IR system is indicated: “m, n”. Also, on each coordinate axis of the plots in Fig. 5, there is a plot of the dependence of the probabilistic characteristics of a single source of information on its quality.

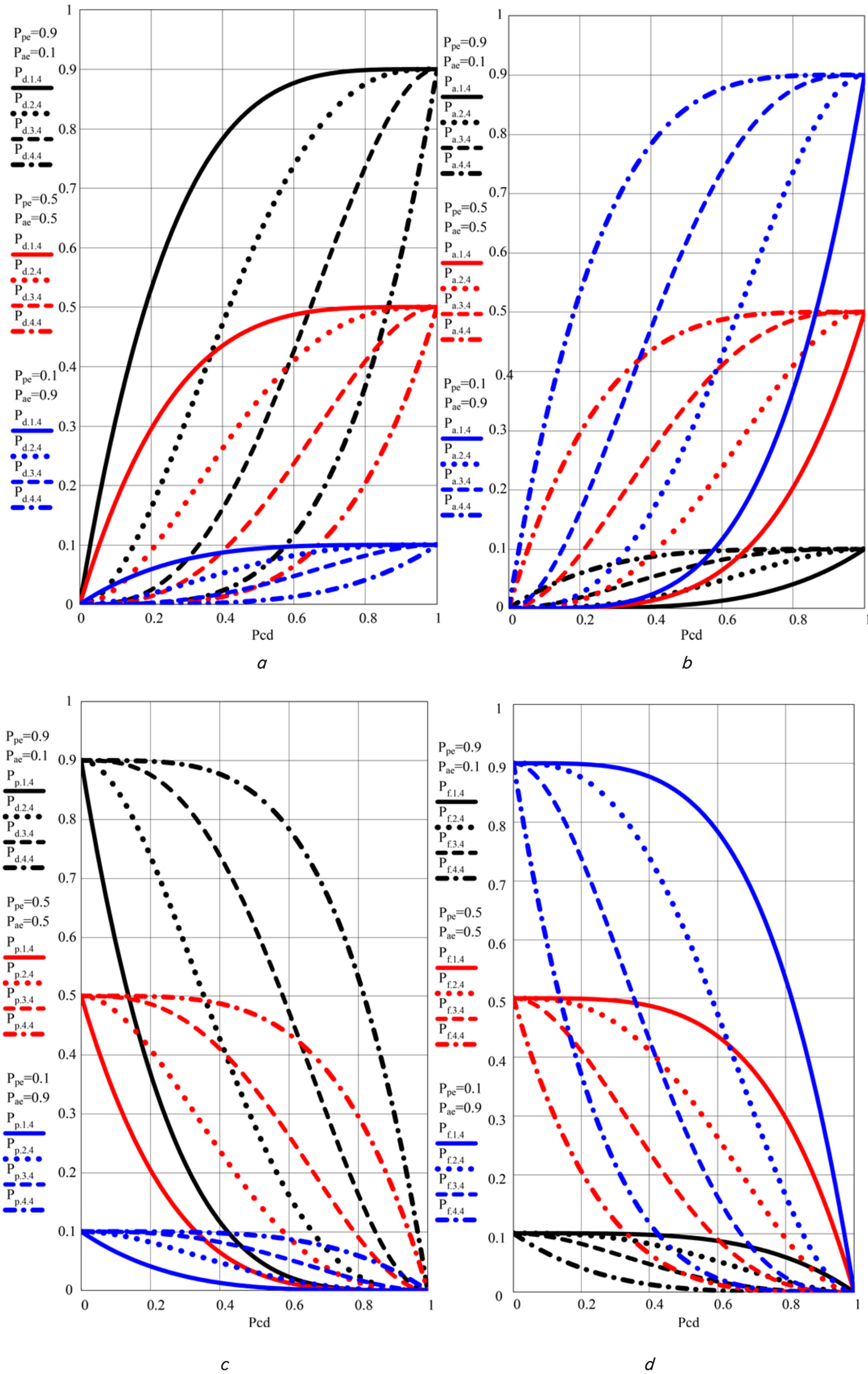

Fig. 4. Plots of the dependence of probabilities: *a* — correct determination of the presence of a controlled event P_d; *b* — correctly determining the absence of a controlled event P_a; c — omission of the controlled event P_p; *d* — false detection of the presence of a controlled event P_f depending on the quality of information sensors for different probabilities of the presence of a controlled event

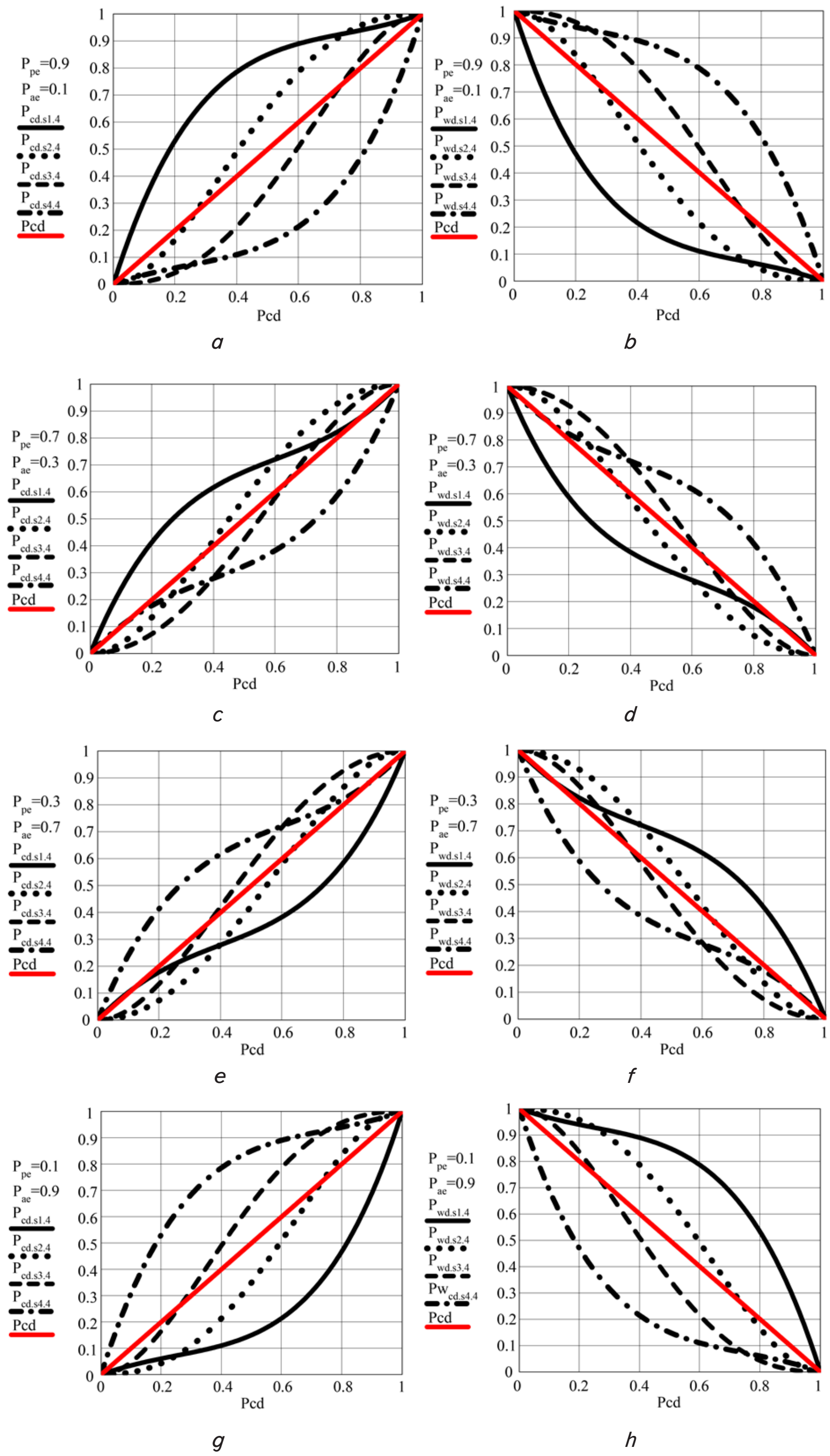

Fig. 5. Plots of the dependence of $P_{cd.s}$ and $P_{wd.s}$ on P_{cd}: *a* – plot of the dependence of $P_{cd.s}$ on P_{cd} at P_{pe}=0.9; *b* – plot of the dependence of $P_{wd.s}$ on P_{cd} at P_{pe}=0.9; *c* – plot of the dependence of $P_{cd.s}$ on P_{cd} at P_{pe}=0.7; *d* – plot of the dependence of $P_{wd.s}$ on P_{cd} at P_{pe}=0.7; *e* – plot of the dependence of $P_{cd.s}$ on P_{cd} at P_{pe}=0.3; *f* – plot of the dependence of $P_{wd.s}$ on P_{cd} at P_{pe}=0.3; *g* – plot of the dependence of $P_{cd.s}$ on P_{cd} at P_{pe}=0.1; *h* – plot of the dependence of $P_{wd.s}$ on P_{cd} at P_{pe}=0.1

5. 3. Studying the dependence of probabilistic characteristics of the parallel IR system on the majority index

To study the impact of the majority index and the number of ISs on the probability of correct and incorrect operation of the parallel IR system, mathematical modeling of their operation was carried out based on formulas (4) to (7). The results of mathematical modeling are represented in the form of corresponding plots of the dependence of the probability of correct $P_{cd.s}$ and incorrect $P_{\mathbf{ud.s}}$ operation of the parallel IR system depending on the quality of IS P_{cd}, which are shown in Fig. 6. Fig. 6 displays the corresponding dependence plots for the following systems of parallel

IR with two, three, and four identical ISs: "1 of 2", "2 of 2", "1 of 3", "2 of 3", "3 of 3", " 1 of 4", "2 of 4", "3 of 4", "4 of 4". Also, a plot of the dependence of the probability of correct and incorrect operation of a separate IS is plotted on each coordinate axis.

In order to take into account the probability of occurrence of CE, these plots are built for different probabilities of occurrence of CE. 2 situations were considered: with a high probability of CE, with P_{pe}=0.9 and P_{ae}=0.1; with a high probability of no CE, with P_{pe}=0.1 and P_{ae}=0.9.

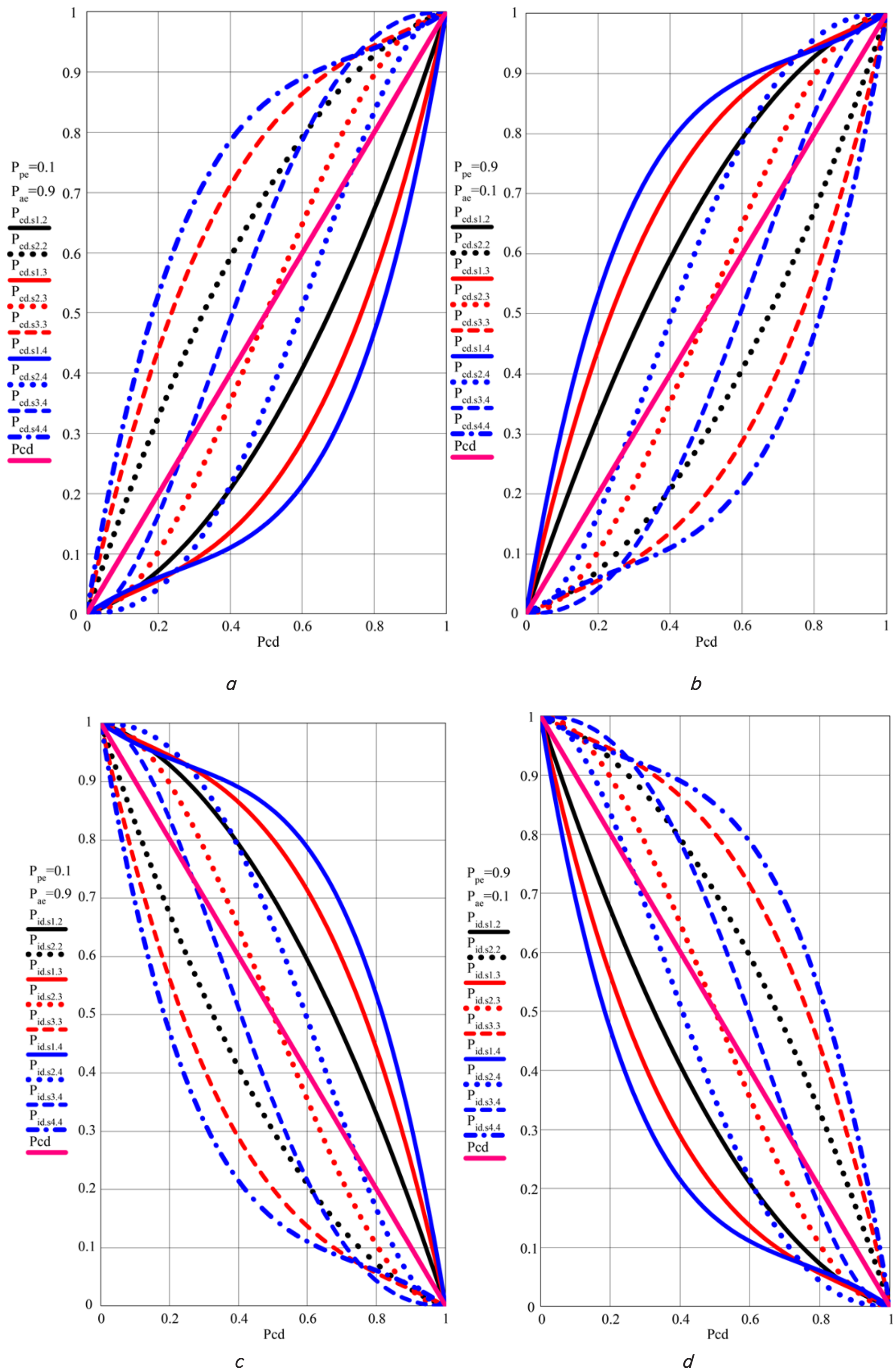

Fig. 6. Plot of the dependence of $P_{cd.s}$ and $P_{id.s}$ on P_{cd} for different values of the majority index m: *a* – plot of the dependence of $P_{cd.s}$ on P_{cd} at P_{pe}=0.1; *b* – plot of $P_{cd.s}$ dependence on P_{cd} at P_{pe}=0.9; *c* – plot of the dependence of $P_{id.s}$ on P_{cd} at P_{pe}=0.1; *d* – plot of the dependence of $P_{id.s}$ on P_{cd} at P_{pe}=0.9

5. 4. Studying the dependence of probabilistic characteristics of the parallel IR system on the probability of CE appearance

To study the impact of the value of the probability of the appearance of CE on the probabilistic characteristics of the parallel IR system, mathematical modeling of their operation was carried out based on formulas (4) to (7). The results of mathematical modeling are represented in the form of corresponding dependence plots. Fig. 4 shows plots of the dependence of the probabilistic characteristics of the parallel IR system on the quality of IS. Fig. 5 shows plots of the dependence of the probability of correct and incorrect operation of the parallel IR system on the quality of IS. Fig. 6 shows plots of the dependence of the probability of correct and incorrect operation of the parallel IR system on the quality of IS for various values of the majority index.

Thus, the study of the dependence of probabilistic characteristics of the parallel IR system on the probability of CE appearance was carried out taking into account the quality of IS and taking into account the majority index.

6. Discussion of results of the research on the use of parallel IR to increase the reliability of information

Our results of mathematical modeling of the operation of the parallel IR system made it possible to determine the probabilistic characteristics of the parallel IR system and their dependence on the quality of IS, the probability of the appearance of CE, and the majority index.

The features of the proposed four-parameter approach to determining the probabilistic characteristics of the parallel IR system and the obtained results in comparison with the existing ones are as follows. Unlike [1], in which the proposed algorithm for identifying system states is focused on accurate input information, the proposed approach allows building a system for increasing the reliability of information under the condition of low accuracy of input information. This becomes possible due to taking into account the quality of information sensors, that is, the reliability and accuracy of the information received from them when determining the probabilistic characteristics of the parallel IR system. In contrast to [4], in which the proposed probabilistic-physical model allows determining the overall probability of correct operation of the system, our approach allows separately determining the probability of correctly determining the presence and absence of CE. This becomes possible due to the consideration of a four-parameter approach to determining the probabilistic characteristics of the signaling system, in contrast to the three-parameter approach considered in [4], and due to the consideration of the probability of the occurrence of CE. In contrast to [5], in which the issue of the reliability of input information in the traffic advisory system is not raised, the proposed approach takes into account the reliability of the information received from the traffic control system. This becomes possible thanks to taking into account the quality of IS, that is, the reliability and accuracy of the information they provide, when determining the probabilistic characteristics of the signaling system of the occurrence of CE. In contrast to [7], in which the proposed algorithm for choosing the optimal design of the CE recognition system does not take into account the probability of its appearance, our approach takes into account the probability of the CE appearance when choosing the structure of the IR system. This becomes possible due to the consideration of a four-parameter graph of states of the system of signaling the appearance of CE, in contrast to the three-parameter one considered in paper [7]. In contrast to [9], in which the probability of the appearance of CE is not taken into account when evaluating and choosing the optimal structure of ICS, the proposed four-parameter approach to determining the probabilistic characteristics of the ICS operation takes into account the probability of the appearance of CE. This becomes possible due to the consideration of a four-parameter graph of states of the CE appearance signaling system, in contrast to the three-parameter one considered in paper [9].

In the work, based on the scheme for determining the controlled parameter, which is shown in Fig. 1 and the state graph of the CE signaling system, which is shown in Fig. 2, we defined states in which the signaling system of the onset of a certain CE can be. Formulas are also obtained in the work for determining the probability of the system being in each of the possible states: correct determination of the presence of CE, correct determination of the absence of CE, omission of CE, false detection of the presence of CE. In the current work, general formulas (2) were obtained for determining the probability of the system being in each of the specified states. And also, for the parallel IR system with 4 ISs, the probabilities of the system being in each specified state for systems with different majority indices were determined – (4) to (7).

Our results are based on probability theory. The advantage of the approach proposed in the work to determine the probabilistic characteristics of the parallel IR system is the consideration of 4 states of the system. An alternative approach is to consider 3 states of the system. At the same time, the states of correct determination of the presence and absence of CE are combined into one state. Consideration of 4 states of the system made it possible to take into account the probability of the occurrence of CE and determine the optimal characteristics of the parallel IR system for detecting events with a high and low probability of occurrence. The obtained formulas for determining the probabilistic characteristics of the parallel IR system allow taking into account the influence of the probability of occurrence of CE and the quality of IS on the reliability of information in IC. When applying the proposed approach in practice, one may encounter the following limitations: the lack of an exact value of the probability of the occurrence of CE and the lack of accurate information about the quality of the work of IS. At the same time, alternative approaches to determining the probabilistic characteristics of the parallel IR system face the same limitations. Removing these restrictions requires additional research. Among the shortcomings of this study, the following can be highlighted – a failure to take into account the decrease in the quality of the work of IS and their failure over time. The paper considers parallel IR systems with identical ISs. The next step in the development of the approach proposed in the work to determine the probabilistic characteristics of the parallel IR system is the consideration of the parallel IR system with IS, which are characterized by different quality. This will allow simulating the operation of real parallel IR systems in order to determine the optimal parameters of their operation.

The results of mathematical modeling, which reflect the dependence of the probabilistic characteristics of the parallel IR system on the quality of IS, are shown in Fig. 4, 5. After analyzing the plots shown in Fig. 4, the following conclusions were drawn. When the quality of CI P_{cd} is increased, there is a decrease in the probability of missing P_p and false detection P_f of the presence of CE and an increase in the probability of determining the presence P_d and the absence of CE P_a. At the same time, increasing the quality of CI by 20 % can lead to an increase in the probability of correctly determining the presence and absence of CE by more than 0.5. At the same time, increasing the quality of CI by 20 % can lead to a decrease in the probability of omission and false determination of the presence of CE by more than 0.5.

After analyzing the plots shown in Fig. 5, the following conclusions were drawn. With the increase in the quality of IS P_{cd}, there is an increase in the probability of correct $P_{cd.s}$ work and a decrease in the probability of incorrect $P_{wd.s}$ operation of the parallel IR system. That is, when the quality of IS increases, the quality of the CE signaling system is improved. At the same time, increasing the quality of IS by 20 % can lead to an increase in the probability of correct $P_{cd.s}$ operation and a decrease in the probability of incorrect $P_{wd.s}$ operation of the parallel IR system by more than 0.5. The resulting direct relationship between the quality of the IS and the quality of the CE signaling system is explained as follows. In formulas (1), there is a direct relationship between the probability of correct measurement of the controlled parameter and the probability of correctly determining the presence and absence of the controlled parameter. The advantage of the proposed four-parameter approach to determining the probabilistic characteristics of the parallel IR system is that it makes it possible to separately determine the probability of situations of correctly determining the presence and absence of CE. Thus, with an increase in the quality of IS, i.e., an increase in the probability of correct determination of the controlled parameter, there is a simultaneous decrease in the probability of its incorrect determination. This, in turn, leads to an increase in the probability of correct operation of the system and a decrease in the probability of its incorrect operation. In general, our results made it possible to determine the influence of the quality of IS on the reliability of information in ICS. When applying the proposed approach in practice, you may encounter the following limitation – the lack of accurate information about the quality of work of IS.

The limitations of this study, which determine the scope and nature of the use of our results, include the following. The work considered a system of parallel IR with equally probable ISs, i.e., ISs that have the same probabilistic characteristics. At the same time, the results obtained in the work cannot be applied to ICS with different probability ISs without additional studies. It should also be noted that the paper considered the simulation of the operation of a parallel IR system with 4 sensors. At the same time, the results obtained in the work cannot be applied to a parallel IR system with a different number of sensors without additional research.

Among the shortcomings of this study, the following can be highlighted – over time, the quality of the work of IS decreases, which is not taken into account in the proposed approach. The paper examines the probabilistic characteristics of IS, the operation of which does not change with the time of operation. The next step in the development of the approach proposed in the work to determine the dependence of the probabilistic characteristics of the parallel IR system on the quality of IS is to take into account the decrease in the reliability and quality of the work of IS with the time of operation. This will make it possible to determine the service time of IS with a given level of reliability in order to replace it in a timely manner in order to maintain the required level of reliability of information in ICS.

The results of mathematical modeling, which reflect the dependence of the probabilistic characteristics of the parallel IR system on the majority index, are shown in Fig. 4–6.

After analyzing the plots shown in Fig. 4, the following conclusions were drawn. As the majority index of the parallel IR system increases, there is a decrease in the probability of correct P_d and false P_f determining the presence of CE. There is also an increase in the probability of missing P_p presence and correctly determining the absence of CE P_a. At the same time, an increase in the majority index by one unit can lead to a decrease in the probability of correct P_d and false P_f determining the presence of CE by more than 0.3. Also, an increase in the majority indicator by one unit can lead to an increase in the probability of missing P_p presence and correctly determining the absence of CE P_a by more than 0.3. That is, for situations with a high probability of the presence of CE, that is, when P_{pe}>0.5, it is advisable to use parallel IR systems with a low majority index. This is explained by the fact that they are characterized by a high probability of correctly determining the presence P_d and a low probability of missing CE P_p. And for situations with a high probability of the absence of CE, that is, when P_{ae}>0.5, it is advisable to use parallel IR systems with a high majority index. This is explained by the fact that they are characterized by a high probability of correctly determining the absence $P_{\mathbf{a}}$ and a low probability of false detection of the presence of CE P_f. After analyzing the plots shown in Fig. 5, the following conclusions were drawn. For parallel IR systems with a low majority index, there is an increase in the probability of correct operation $P_{cd.s}$ and a decrease in the probability of incorrect $P_{id.s}$ operation of the system with increasing probability of occurrence of CE P_{pe}. And for systems with a high majority index, on the contrary, the probability of correct operation $P_{cd.s}$ decreases and the probability of incorrect $P_{id.s}$ increases. system operation. At the same time, with an increase in the majority index for systems with a high probability of occurrence of CE (P_{pe}>0.5), there is a decrease in the probability of the correct operation $P_{cd.s}$ of the system and an increase in the probability of incorrect $P_{id.s}$ system operation. And for systems with a high probability of the absence of CE (P_{pe}>0.5), on the contrary, there is an increase in the probability of correct operation P_{pe} and a decrease in the probability of incorrect operation of systems $P_{id.s}$. At the same time, an increase in the majority index by one unit can lead to a change in the probabilities of correct $P_{cd.s}$ and incorrect $P_{id.s}$ system operation by more than 0.3.

When comparing the probability of correct operation $P_{cd.s}$ of the parallel IR system and the probability of correct operation of IS P_{cd}, the following conclusions were made. Under the condition of a high probability of the presence of CE (P_{pe}>0.5), the probability of correct operation of the system $P_{cd.s}$ is greater than the probability of correct operation of IS P_{cd} mainly for parallel IR systems with a low majority index. And under the condition of a high probability of the absence of CE (P_{ae}>0.5), on the contrary – mainly for systems with a high majority index. When comparing the probability of incorrect operation of the parallel IR system $P_{id.s}$ and the probability of incorrect operation of PI P_{id}, the following conclusions were made. Under the condition of a high probability of the presence of CE (P_{pe}>0.5), the probability of incorrect operation of the system $P_{id.s}$ is greater than the probability of incorrect operation of the PI P_{id}, mainly for parallel IR systems with a high majority index. And under the condition of a high probability of the absence of CE (P_{ae}>0.5), on the contrary, it is mainly for systems with a low majority index.

After analyzing the plots shown in Fig. 6, the following conclusions were drawn. As the majority index increases, there is a decrease in the probability of correct operation of the parallel IR system $P_{cd.s}$ and an increase in the probability of its incorrect operation $P_{id.s}$ under the condition of a high probability of presence (P_{pe}>0.5) of CE. And under the condition of a high probability of absence (P_{ae}>0.5) of CE, on the contrary, there is an increase in the probability of the correct operation of the parallel IR system $P_{cd.s}$ and a decrease in the probability of its incorrect operation $P_{id.s}$ with an increase in the majority index. At the same time, an increase in the majority index by one unit can lead to a change in the probabilities of correct $P_{cd.s}$ and incorrect $P_{id.s}$ system operation by more than 0.3. With an increase in the number of IS n, under the condition of a high probability of the presence of CE (P_{pe}>0.5) and an unchanged value of the majority indicator m, there is an increase in the probability of the correct operation of the system of parallel IR $P_{cd.s}$. At the same time, there is also a decrease in the probability of its improper operation $P_{id.s}$. And under the condition of a high probability of the absence of CE (P_{ae}>0.5) with an increase in the number of IS n, under the condition of an unchanged value of the majority indicator m, there is a decrease in the probability of the correct operation of the system of parallel IR $P_{cd.s}$. At the same time, there is also an increase in the probability of its improper operation $P_{id.s}$.

Thus, under the condition of a high probability of the appearance of CE (P_{pe}>0.5), it is advisable to use parallel IR systems with a low majority index m and a large number of ISs n. The use of parallel IR systems with a high majority index m and a large number of CIs n under the condition of a high probability of occurrence of CE (P_{pe}>0.5) is undesirable. And if there is a high probability of the absence of CE (P_{ae}>0.5), on the contrary, it is advisable to use systems of parallel IR with a high majority index m and a large number of ISs n. The use of parallel IR systems with a low majority index m and a large number of CIs n under the condition of a high probability of the absence of CE (P_{ae}>0.5) is undesirable.

Our results of mathematical modeling are explained by the fact that with the growth of the majority index, the number of terms increases when determining the value of the probabilities of correctly detecting the absence and omission of CE. Also, as the majority index increases, the number of terms in determining the value of the probability of correct and false detection of the presence of CE decreases, as can be seen from formulas (4) to (7). The advantage of the proposed four-parameter approach to determining the probabilistic characteristics of the parallel IR system, in contrast to the alternative three-parameter approach, is that the proposed approach allowed determining the following. The use of parallel IR systems with a high majority index is desirable only if there is a high probability of the absence of CE, and if there is a high probability of the presence of CE, the use of systems with a high majority index is undesirable. Also, the proposed approach made it possible to determine that with the increase in the number of ISs in the parallel IR system, the probability of correct operation of the system increases. In general, our results make it possible to determine the influence of the majority index of the parallel IR system on the reliability of information in ICS. When applying the proposed approach in practice, you may encounter the following limitation – the inertia of the work of the majority elements and the lack of accurate information about the quality of the work of t–IS. Among the shortcomings of this study, the following can be highlighted – over time, the quality of work decreases, and the majority of elements fail, which is not taken into account in the proposed approach. In this study, a system of parallel IR with identical ISs is considered, the quality of which does not decrease with the time of operation. The application of the proposed approach in practice requires additional research for parallel IR systems with different ISs, the quality of which decreases over time. The next step in the development of this research is the determination of the influence of the majority index on the probabilistic characteristics of the parallel IR system under the condition of using IS of different quality. This will make it possible to build systems of parallel IR using different ISs, including ISs with different physical principles of action.

The results of mathematical modeling, which reflect the dependence of the probabilistic characteristics of the parallel IR system on the probability of the appearance of CE, are shown in Fig. 4, 5.

After analyzing the plots shown in Fig. 4, the following conclusions were drawn. Under the condition of high probability of the appearance of CE (P_{pe}>0.5), there is a predominance of P_d over P_a, and P_p over P_f, and under the condition of a high probability of the absence of CE (P_{ae}>0.5), on the contrary, there is a predominance of P_a over P_d and P_f over P_p. It should also be noted that when the probability of occurrence of CE P_{pe} decreases, the probabilities of P_d and P_p decrease and the probabilities of P_a and P_f increase. At the same time, the magnitude of the change in the specified probabilities, for real ISs, is smaller than the magnitude of the change in the probability of the occurrence of CE. Thus, for situations with a high probability of the presence of CE (P_{pe}>0.5), the main problem is the omission of the presence of CE, and for situations with a high probability of the absence of CE (P_{ae}>0.5), the main problem is the false detection of the presence of CE. For a situation where P_{ae}=P_{pe}=0.5, situations of omission and false detection of the presence of CE are equally likely events.

After analyzing the plots shown in Fig. 5, the following conclusions were drawn. With an increase in the probability of the appearance of CE P_{pe}, there is an increase in the probability of the correct operation of the parallel IR system $P_{cd.s}$ with a low majority index and its decrease for parallel IR systems with a high majority index. At the same time, the magnitude of change in the specified probabilities, for real ISs, is smaller than the magnitude of the change in the probability of the occurrence of CE.

The resulting direct relationship between the probability of occurrence of CE and the quality of the CE signaling system is explained as follows. As can be seen from (1), there is a direct relationship between the probability of occurrence of CE and the probability of correctly determining the presence and absence of the controlled parameter. In addition, our results of mathematical modeling are explained by the fact that as the majority index increases, the number of terms decreases when determining the probability of correct and false detection of the presence of CE, as can be seen from formulas (4) to (7). The advantage of the proposed four-parameter approach to determining the probabilistic characteristics of the parallel IR system is as follows. It makes it possible to separately determine the probabilistic characteristics of the parallel IR system under conditions of high and low probability of occurrence of CE. In general, our results make it possible to determine the influence of the probability of the occurrence of CE on the reliability of information in ICS.

When applying the proposed approach in practice, one may encounter the following limitation – the absence of a controlled parameter that uniquely determines the moment of onset of CE. Among the shortcomings of this study, the following can be highlighted – over time, there is a change in the probability of the appearance of CE, which is not taken into account in the proposed approach. Since in this study the probability of occurrence of CE is a constant value, the application of the proposed approach in practice requires taking into account the fact that the value of the probability of occurrence of CE changes over time. The next step in the development of this research is the development of a procedure for choosing the optimal structure of the parallel IR system depending on the value of the probability of the occurrence of CE. This will make it possible to develop systems of parallel IR with a program variable structure. This, in turn, will make it possible to programmatically adjust the structure of the parallel IR system in accordance with the state of the investigated system in order to ensure high reliability of information regarding the appearance of CE.

7. Conclusions

1. In our work, based on the four-parameter state graph of the CE signaling system, the formulas for the dependence of the probabilistic characteristics of the parallel IR system operation on the quality of the IS, the majority indicator, and the probability of the CE appearance were derived. The peculiarity of the resulting formulas, in contrast to existing ones, is that they take into account the probability of the appearance of CE. This, in turn, makes it possible to take into account the probability of the appearance of CE when choosing the optimal structure of the parallel IR system. The formulas are based on the theory of probability.

2. On the basis of mathematical modeling, it was shown that there is a direct relationship between the probabilistic characteristics of the parallel IR system and the quality of IS. As the quality of IS increases, the quality of the parallel IR system increases and the probability of omission and false detection of CE decreases. At the same time, a 20 % improvement in the quality of CI can lead to a change in the specified probabilities by more than 0.5. The peculiarity of our results is that the results of the study of the probabilities of correctly determining the presence and absence of CE were obtained separately. This, in turn, makes it possible to take into account the quality of IS when choosing the optimal structure of the parallel IR system. Taking into account the quality of IS work when determining the probabilistic characteristics of the parallel IR system will make it possible in the future to determine the time of replacing IS in order to ensure the necessary level of reliability of information in ICS.

3. Based on mathematical modeling, it was shown that the value of the majority index of the parallel IR system affects its probabilistic characteristics as follows. As the majority index increases, there is a decrease in the probability of correctly and incorrectly determining the presence of CE and an increase in the probability of missing and correctly identifying the absence of CE. At the same time, an increase in the majority indicator by unity can lead to a change in the specified probabilities by more than 0.3. The peculiarity of our results is that they made it possible to determine the following. Under the condition of high probability of the appearance of CE, it is advisable to use systems of parallel IR with a low majority index, and under the condition of high probability of the absence of CE – systems of parallel IR with a high index of majority. This allows taking into account the majority index when choosing the optimal structure of the parallel IR system, depending on the state of the investigated situation and the quality of IS. Taking into account the majority index when determining the probabilistic characteristics of the parallel IR system will make it possible in the future to build parallel IR systems with a program variable structure in order to ensure the necessary level of information reliability in ICS.

4. On the basis of mathematical modeling, it was shown that the following relationship exists between the probabilistic characteristics of the parallel IR system and the probability of occurrence of CE. With an increase in the probability of occurrence of CE, there is an increase in the probability of missing and correctly determining the presence of CE and a decrease in the probability of false detection and correct detection of the absence of CE. At the same time, the magnitude of change in the specified probabilities, for real ISs, is smaller than the magnitude of change in the probability of the occurrence of CE. The peculiarity of our results is that they made it possible to determine the following. Under conditions of high and low probability of the appearance of CE, parallel IR systems with different majority indicators should be used. Given the high probability of the absence of CE, it is advisable to use systems of parallel IR with a high majority index. Given the high probability of the appearance of CE, it is advisable to use systems of parallel IR with a low majority indicator. This will make it possible to take into account the probability of the appearance of CE when choosing the optimal structure of the parallel IR system and using parallel IR systems with a software-variable structure to ensure the necessary level of information reliability in the ICS.

Conflicts of interest

The authors declare that they have no conflicts of interest 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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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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