UDC 004.81
DOI: 10.15587/1729-4061.2025.335688

DEVELOPMENT OF A POLYMODEL COMPLEX OF INFORMATION SYSTEMS RESOURCE MANAGEMENT

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The object of the study is information systems. The research addresses the problem of increasing the accuracy of modeling the functioning processes of information systems. A polymodel complex for resource management in information systems has been developed.

The originality of the research is ensured by:

– a comprehensive description of the functioning processes of various types of information systems through the development of corresponding mathematical expressions, which enhances the accuracy of modeling for subsequent managerial decision-making;

– the inclusion of both static and dynamic processes occurring within information systems, using a hierarchical system of interconnected mathematical models;

– the ability to model either an individual process within an information system or to perform integrated modeling of multiple processes using a single or a set of mathematical models;

– a dynamic description of the process of controlling the trajectory of information systems during their operation through proposed analytical expressions, enabling forecasting of the system's behavior N steps ahead;

– modeling the process of operations management during computational tasks within the functioning of information systems, which allows for planning of optimal load distribution on the hardware components;

– simulation of the dynamics of resource management in information systems during their operation, making it possible to forecast the engagement of resources throughout their lifecycle.

The proposed polymodel complex is advisable to use for solving management tasks of information systems characterized by a high level of complexity

Keywords: artificial intelligence, destabilizing factors, operational levels, indicators, criteria, efficiency, reliability

Received 28.04.2025
Received in revised form 03.07.2025
Accepted 14.07.2025
Published 30.08.2025

How to Cite: *Shyshatskyi, A., Plekhova, G., Lytvynenko, O., Shostak, I., Feoktystova, O., Odarushchenko, E., Lyashenko, A., Honcharuk, D., Kapran, Y., Miahkykh, H. (2025). Development of a polymodel complex of information systems resource management. Eastern-European Journal of Enterprise Technologies, 4 (4 (136)), 58–72.*
https://doi.org/10.15587/1729-4061.2025.335688

1. Introduction

Information systems are an integral component of all areas of human societal activity and are employed to solve a wide range of tasks – from entertainment-oriented to highly specialized applications [1, 2]. The primary functions performed by information systems include [3]:

– processing various types of data to meet the needs of a broad range of users, regardless of the field of application;

– storing diverse data types to serve user needs;

– transferring data between individual users or groups of users;

– supporting decision-making processes for authorized personnel;

– enabling the prerequisites for automated (intelligent) decision-making.

Current trends in the development of modern information systems aim to address the following conceptual challenges [4]:

– increasing the efficiency of processing heterogeneous data;

– improving the reliability of data processing;

– ensuring the fault tolerance and resilience of information systems;

– enhancing the accuracy of modeling the functional processes of information systems;

– maintaining a balance between efficiency and reliability in the processing of heterogeneous data, among others.

These factors necessitate the implementation of various strategies to improve the operational efficiency of information systems in handling diverse data types [5]. One such approach involves refining existing mathematical models (or developing new ones) that describe the functioning of information systems [6–8], which substantiates the relevance of this line of scientific inquiry.

2. Literature review and problem statement

In [6], the use of Bayesian hierarchical networks is proposed for quantitatively assessing cybersecurity risks in specialized information systems. However, this approach is limited by the statistical distribution it relies on and the extensibility of the model's structure. These constraints impose architectural limitations on the information system and fail to account for qualitative factors influencing its cybersecurity.

In [7], a security certification methodology is proposed for information systems to allow various stakeholders to automatically evaluate security decisions in large-scale deployments. The methodology enhances transparency regarding the security level of systems by providing labeling as a key output of the certification process. However, its drawbacks include the inability to update knowledge bases with new threats and challenges in generalizing and analyzing heterogeneous network data.

The model in [8] combines fault tree analysis, decision theory, and fuzzy logic to identify the root causes of cybersecurity failures. It is applied to scenarios such as website attacks, e-commerce systems, and ERP planning. Although flexible in architecture, the model suffers from error accumulation during fuzzification and defuzzification procedures.

In [9], a model is proposed for resource allocation in automated control systems under uncertainty about the evolving operational environment. It incorporates cyberattack impacts and represents optimization solutions through binary conflict, cooperation, and indifference relations. The model also accounts for environmental factors, allowing forecasting and utility function construction. However, it cannot process indicators of varying dimensions.

The work in [10] presents a hierarchical concept for implementing a governance model based on e-government. It explores threats to cyber-physical systems as foundational elements of digital governance mechanisms. The approach relies on symmetric and asymmetric cryptosystems, which limits its ability to identify cyber influences during runtime.

In [11], a model is proposed for selecting optimal cybersecurity insurance policies, considering the limited availability of such policies from one or more insurers. It enables systematic evaluation based on breach probability and associated premiums. The model supports efficient cyber insurance markets but lacks real-time learning capabilities and restricts assumptions, making it unsuitable for dynamic threat adaptation.

The paper [12] emphasizes integrating vulnerability assessment into cybersecurity, not only as part of process hazard analysis but also in protecting process control networks and critical applications. It increases industrial resilience but is tailored to fixed architectures and lacks adaptability during operation.

The risk management process in [13] includes threat identification, analysis, evaluation, mitigation, and monitoring at every stage of the cybersecurity chain. Based on a continuous Markov chain model, the method cannot simultaneously handle both quantitative and qualitative indicators or adapt to emerging threats.

In [14], a theoretical-analytical approach is proposed to assess delays in information transmission caused by cyber interference during traffic regulation. The assessment uses the method of successive averages but is limited to traffic systems and is not applicable elsewhere.

In [15], cyber threats are represented as transition process graphs. This approach helps describe and evaluate threats' impact on a system's security. However, it only supports unidimensional indicators and lacks the ability to incorporate new threats dynamically.

The study in [16] introduces a game-theoretic model for addressing cybersecurity in advanced manufacturing systems with high-level integration. The model uniquely structures the payoff matrix to include defense strategies, production losses, and recovery costs. Nevertheless, it involves high computational complexity and supports only one-dimensional metrics.

In summary, a common drawback across these approaches is the inability to operate with heterogeneous data in real time. Several studies have attempted to overcome this limitation.

In [17], an input data evaluation approach for decision support systems is proposed. It clusters and analyzes baseline input data, after which the system undergoes training. The downside is the gradual accumulation of estimation and training errors due to a lack of feedback on decision adequacy.

In [18], a method for processing data from multiple information sources is introduced. While it allows multi-source data processing, the approach suffers from low estimation accuracy and lacks a mechanism to verify the reliability of results.

The comparative analysis in [19] examines decision support technologies such as the Analytic Hierarchy Process (AHP), neural networks, fuzzy set theory, genetic algorithms, and neuro-fuzzy modeling. Each method's strengths, weaknesses, and application domains are discussed. AHP performs well with complete input data but has a high degree of subjectivity due to expert evaluations. For predictive tasks under uncertainty, fuzzy logic and neural networks are considered more appropriate.

In [20], a hybrid approach combining multiple metaheuristic algorithms is discussed. Despite its advantages, the approach is inefficient in processing heterogeneous data swiftly when using several algorithms simultaneously.

Nonetheless, current scientific approaches to the synthesis and functioning of information systems still suffer from limited accuracy and convergence. These limitations are due to the following factors [1–9]:

– the significant role of human factors during the initial configuration of information systems;

– the high volume of heterogeneous information sources requiring analysis and processing;

– the uncertainty under which information systems operate, which delays data processing;

– the presence of numerous destabilizing factors that affect system functionality.

An analysis of studies [9–20] reveals the following shared limitations:

– each model addresses only a single level of information system operation;

– comprehensive approaches typically consider only two operational aspects of the system, preventing full assessment of how managerial decisions influence performance;

– the individual models within the frameworks lack sufficient integration for joint functioning;

– models rely on differing mathematical tools, necessitating complex transformations that increase computational demands and reduce modeling accuracy.

3. The aim and objectives of the study

The aim of this study is to develop a polymodel complex for resource management in information systems. This will enable the simulation of information systems functioning at various operational levels to support subsequent managerial decision-making. The outcomes will facilitate the development (or enhancement) of software for both current and next-generation information systems through the integration of the proposed models.

To achieve this aim, the following objectives were accomplished:

– to develop a dynamic model for managing the trajectory (movement) of information systems;

– to develop a dynamic model for managing operations performed by information systems;

– to develop a dynamic model for managing communication channels within information systems;

– to develop a dynamic model for managing the resources of an information system;

– to develop a dynamic model for managing data flows within information systems;

– to develop a dynamic model for managing the parameters of operations executed by information systems;

– to develop dynamic models for managing the structural dynamics of information systems;

– to develop a model for managing the security of information systems under centralized control;

– to develop a generalized deterministic logical-dynamic model for managing the structural dynamics of information networks.

4. Materials and methods

The object of the study is information systems. The research addresses the problem of increasing the accuracy of modeling the functional processes of information systems. The subject of the study is the functioning of information systems, modeled through analytical-simulation and logical-dynamic models. The research hypothesis posits that it is possible to improve the operational efficiency and accuracy of information system functioning through the integration of a set of functional models.

The following research methods were employed:

– analytical method – used to identify the conditions and factors influencing the operational processes of information systems [19];

– synthesis method – applied to generalize the strengths and weaknesses of known approaches to modeling the functioning of information systems [20];

– analytical-simulation modeling using artificial intelligence theory (fuzzy set theory) – enables the description of functional processes in information systems while incorporating accumulated analytical data [19, 20];

– logical-dynamic modeling based on artificial intelligence theory (fuzzy set theory) – enables the representation of cause-and-effect relationships between models and logical formulation of the dynamic processes within information systems [19, 20].

The proposed polymodel complex was simulated and tested using the Microsoft Visual Studio 2022 (USA) software environment. The hardware used in the research process was based on an AMD Ryzen 5 processor.

5. Development of the polymodel complex for information systems resource management

5. 1. Dynamic model for managing the trajectory of information systems

Interaction operations between objects of information systems – either with one another or with service objects – can only occur when these objects enter specific interaction zones. These zones are defined by a matrix-based time-dependent function $E(t)=\|\varepsilon_{ij}(t)\|$, $i, j \in \left\{\bar{M} \cup \bar{M}\right\}$, referred to as the contact potential, where $\bar{M}$ – represent the mathematical models of the functioning information systems.

The elements of this matrix take a value of 1 if objects B_i and B_j fall within each other's interaction zones, and 0 otherwise. The geometric dimensions and shapes of these zones are determined by several factors, including:

– the type of interaction (e.g., energetic, frequency-based, informational);

– the technical characteristics of the hardware and software tools supporting the interaction;

– the spatial positions of the objects involved.

Let's assume the motion state of object B_i at any time moment t is defined by two vectors: $r_i^{(d)}(t)$ and $\dot{r}_i^{(d)}(t)$, $i \in \tilde{M}=\left\{M \cup \bar{M}\right\}$. $r_i^{(d)}(t)$ a 3D radius vector that characterizes the position of object B_i in space, $\dot{r}_i^{(d)}(t)$ – a vector characterizing the velocity of object. Introduce the motion state vector $x_i^{(d)}=\| r_i^{(d)T} \dot{r}_i^{(d)T} \|^T$.

Thus, the motion state of object B_i at any time $t \in \left(T_0, T_f\right]$ is defined by $x_i^{(d)}$. Under these conditions, the model for trajectory control of information system objects (*Model M_d*) includes the following key elements.

Model of object motion process M_d

$$\dot{x}_i^{(d)}=f_i^{(d)}\left(x_i^{(d)}, u_i^{(d)}, t\right). \quad (1)$$

Constraints

$$q^{(d)}\left(x^{(d)}, u^{(d)}, t\right) \leq O. \quad (2)$$

Boundary conditions

$$h_0^{(d)}\left(x^{(d)}\left(T_0\right)\right) \leq O,\ h_1^{(d)}\left(x^{(d)}\left(T_f\right)\right) \leq O. \quad (3)$$

Quality indicators of programmed control:

$$J_1^{(d)}=\varphi^{(d)}\left(x^{(d)}\left(T_f\right)\right), \quad (4)$$

$$J_2^{(d)} = \int_{T_0}^{T_f} f_0^{(d)}\left(x^{(d)}(\tau), u^{(d)}(\tau), \tau\right) d\tau, \qquad (5)$$

where $x^{(d)} = \| x_1^{(d)T}, x_2^{(d)T}, ..., x_{m+\bar{m}}^{(d)T} \|^T$ – the state vector describing the movement of the information system and its service objects, $M = 1,...,m$, $\bar{M} = 1,...,\bar{m}$; $u^{(d)} = \| u_{ap}^{(d)T}(t), v^{(d)T}(x(t),t) \|^T$, $u^{(d)} = \| u_1^{(d)T}, ..., u_{m+\bar{m}}^{(d)T} \|^T$ – the components of the control input vector.

All functions in (1)–(5) are assumed to be known, given in analytical form, and continuously differentiable throughout the domain of the variables. The components of the control vector $u^{(d)}(t)$ are assumed to be Lebesgue-measurable functions defined on the interval $(T_0, T_f]$.

In this case, the contact potential of the object pair $<B_i, B_j>$ can be calculated using the formula

$$\varepsilon_{ij}(t) = \gamma_+\left\{R_j^{(d)} - \left| r_i^{(d)}(t) - r_j^{(d)}(t) \right| \right\}, \qquad (6)$$

where $i, j \in \tilde{M}$, $\gamma_+(\tilde{\alpha}) = 1$, if $\tilde{\alpha} \geq 0$, $\gamma_+(\tilde{\alpha}) = 0$, if $\tilde{\alpha} < 0$; $R_j^{(d)}(t)$ – the specified interaction zone radius for object B_j, which, in the general case, is a closed spherical region.

From the analysis of equations (1)–(6), it follows that stationary (immobile) elements and service objects within information systems can be treated as a particular case of moving objects, for which the velocity vector $r_i(t) = r_i(t_0) = r_{i0}$, $\forall t \in (T_0, T_f]$, r_{i0} and the position vector define the fixed location of the object.

Equations (1)–(6) are written in general form, as their specific implementation is only possible when a particular system of forces acting on the objects during motion is defined, along with the selected reference frame, etc. These aspects are determined by the specific movement characteristics of each information system object or service object. The specific form of Model M_d will be established later during the development of a prototype software system that simulates the structural dynamics of the information system.

5. 2. Dynamic model for managing operations executed by information systems

The development of this and subsequent models is based on a dynamic interpretation of events occurring within an information system. The operation management model for tasks executed by information systems includes the following key components:

– Model of the operation management process M_o:

$$\dot{x}_\nu^{(0,1)} = \sum_{j=1}^{m} u_{\nu j}^{(0,1)};$$

$$\dot{x}_{i æ}^{(0,2,\nu)} = \sum_{j=1}^{m} \sum_{\lambda=1}^{l_j} \varepsilon_{ij}(t)\Theta_{i æ j\lambda}(t) u_{i æ j\lambda}^{(0,2,\nu)}; \ \dot{x}_{\nu j}^{(0,3)} = u_{\nu j}^{(0,3)}; \qquad (7)$$

$$\nu = 1,...,n; j =,...,m; i = 1,...,m; æ = 1,...,s_i.$$

– Constraints:

$$\sum_{j=1}^{m} u_{\nu j}^{(0,1)} \left[\begin{array}{l} \sum\limits_{\alpha \in \Gamma_{\nu 1}} \left(a_\alpha^{(0,1)} - x_\alpha^{(0,1)}(t)\right) + \\ + \prod\limits_{\beta \in \Gamma_{\nu 2}} \left(a_\beta^{(0,1)} - x_\beta^{(0,1)}(t)\right) \end{array} \right] = 0, \qquad (8)$$

$$\sum_{\lambda=1}^{l_j} u_{i æ j\lambda}^{(0,2,\nu)} \left[\sum_{\tilde{\alpha} \in \Gamma_{\nu 1}} \begin{array}{l} \left(a_{i\tilde{\alpha}}^{(0,2,\nu)} - x_{i\tilde{\alpha}}^{(0,2,\nu)}(t)\right) + \\ + \prod\limits_{\tilde{\beta} \in \Gamma_{i æ 2}} \left(a_{i\tilde{\beta}}^{(0,2,\nu)} - x_{i\tilde{\beta}}^{(0,2,\nu)}(t)\right) \end{array} \right] = 0, \qquad (9)$$

$$\sum_{\nu=1}^{u} u_{\nu j}^{(0,1)}(t) \leq 1, \forall j;$$

$$\sum_{j=1}^{m} u_{\nu j}^{(0,1)}(t) \leq 1, \forall j; \ u_{\nu j}^{(0,1)}(t) \in \{0,1\}. \qquad (10)$$

$$u_{i æ j\lambda}^{(0,2,\nu)}(t) \in \left\{0, u_{\nu j}^{(0,1)}\right\}; \ u_{\nu j}^{(0,3)}(t) \in \{0,1\};$$

$$u_{\nu j}^{(0,3)}\left(a_{js_i}^{(0,2,\nu)} - x_{js_j}^{(0,2,\nu)}(t)\right) = 0. \qquad (11)$$

– Boundary conditions

$$h_0^{(o)}\left(x^{(o)}(T_0)\right) \leq O; \ h_1^{(o)}\left(x^{(o)}(T_f)\right) \leq O. \qquad (12)$$

– Quality indicators of programmed operation management:

$$J_1^{(o)} = \sum_{\nu=1}^{n} \sum_{j=1}^{m} u_{\nu j}^{(0,3)}(T_f);$$

$$J_{<2,\alpha,\nu>}^{(o)} = \sum_{i=1}^{m} \sum_{j=1}^{m} \left(x_{\alpha i}^{(0,3)}(T_f) - x_{\nu j}^{(0,3)}(T_f) \right);$$

$$J_3^{(o)} = T_f - \sum_{j=1} x_{nj}^{(0,1)}(T_f), \qquad (13)$$

$$J_{<4,i,\nu>}^{(o)} = \sum_{\nu,j,\lambda,æ} \int_{T_0}^{T_f} \varepsilon_{ij}(\tau)\Theta_{i æ j\lambda}(\tau) u_{i æ j\lambda}^{(0,2,\nu)}(\tau) d\tau, \qquad (14)$$

$$j = 1,...,m; \ \lambda = 1,...,l_j; \ æ = 1,....,s_i,$$

$$J_{<5,i>}^{(o)} = \int_{T_0}^{T_f} \max_j \varepsilon_{ij}(\tau) d\tau, \ j \neq i; \qquad (15)$$

$$J_{<6,i>}^{(o)} = \sum_{\nu,j,æ} \int_{T_0}^{T_f} \left[\varepsilon_{ij}(\tau) - \varepsilon_{ij}(\tau) u_{i æ j\lambda}^{(0,2,\nu)}(\tau) \right] d\tau; \qquad (16)$$

$$J_7^{(o)} = \sum_{i=1}^{m} \sum_{æ=1}^{s_i} \left(a_{i æ}^{(0,2,\nu)} - x_{i æ}^{(0,2,\nu)}(T_f) \right)^2; \qquad (17)$$

$$J_8^{(o)} = \sum_{\nu=1}^{n} \sum_{i=1}^{m} \sum_{æ=1}^{s_i} \sum_{j=1}^{m} \sum_{\lambda=1}^{l_j} \int_{T_0}^{T_f} \tilde{\tilde{\alpha}}_{i æ j\lambda}^{(\nu)}(\tau) u_{i æ j\lambda}^{(0,2,\nu)}(\tau) d\tau; \qquad (18)$$

$$J_9^{(o)} = \sum_{\nu=1}^{n} \sum_{i=1}^{m} \sum_{æ=1}^{s_i} \sum_{j=1}^{m} \sum_{\lambda=1}^{l_j} \int_{T_0}^{T_f} \tilde{\tilde{\beta}}_{i æ}^{(\nu)}(\tau) u_{i æ j\lambda}^{(0,2,\nu)}(\tau) d\tau, \qquad (19)$$

where $x_\nu^{(0,1)}(t)$ – variable representing the duration of task A_ν execution on object B_j ($j = 1,...,m$) at time t; $x_{i æ}^{(0,2,\nu)}(t)$ – variable characterizing the status of operation execution $D_æ^{(i)}$ (or $D_æ^{(i,j)}$) when solving the problem A_ν; $x_\nu^{(0,3)}(t)$ – variable, numerically equal to the duration of the time interval from the moment of completion of the task A at object B_j until the moment $t = T_f$; $t = T_f$; $a_\alpha^{(0,1)}$, $a_\beta^{(0,1)}$, $a_{i\tilde{\alpha}}^{(0,2,\nu)}$, $a_{i\tilde{\beta}}^{(0,2,\nu)}$, $a_{is_i}^{(0,2,\nu)}$, $a_{i æ}^{(0,1,\nu)}$ – specified values (boundary conditions) which values must (or may) be accepted by the corresponding variables $x_\alpha^{(0,1)}$, $x_\beta^{(0,1)}(t)$, $x_{i\tilde{\alpha}}^{(0,2,\nu)}(t)$, $x_{i\tilde{\beta}}^{(0,2,\nu)}(t)$, $x_{is_i}^{(0,2,\nu)}(t)$, $x_{i æ}^{(0,1,\nu)}(t)$ at the end of the information systems management interval at a given point in time $t = T_f$; $u_{\nu j}^{(0,1)}(t)$, $u_{i æ j\lambda}^{(0,2,\nu)}(t)$, $u_{\nu j}^{(0,3)}(t)$ – controlling influences, where $u_{\nu j}^{(0,1)}(t) = 1$ if task A_ν is solved on object B_j; $u_{\nu j}^{(0,1)}(t) = 0$ – otherwise $u_{i æ j\lambda}^{(0,2,\nu)}(t) = 1$, if the operation $D_æ^{(i)}$ (or $D_æ^{(i,j)}$) is performed when solving problem A_ν using the corresponding channel, $u_{i æ j\lambda}^{(0,2,\nu)}(t) = 0$ – otherwise; $u_{\nu j}^{(0,3)}(t) = 1$ at the moment corresponding to the completion of task A_ν on object B_j and at all subsequent moments until $t = T_f$, $u_{\nu j}^{(0,3)}(t) = 0$ – in opposite situations; $\Gamma_{\nu 1}$, $\Gamma_{\nu 2}$ – a set of task numbers A_ν, directly preceding and technologically related to task A_ν using logical operations "AND", "OR" (or alternative OR), respectively; $\Gamma_{i\text{æ}1}$, $\left(\Gamma_{i\text{æ}2}\right)$ – a set of interaction operation numbers performed on object B_i, immediately preceding and technologically related to operation $D_{\text{æ}}^{(i)}$ (or $D_{\text{æ}}^{(i,j)}$) using logical operations "AND", "OR", or alternative OR, respectively; $h_0^{(o)}$, $h_1^{(o)}$ – known differentiable functions, which are used to set the boundary conditions imposed on the vector $x^{(o)} = \| x_1^{(0,1)},\ldots,x_n^{(0,1)}, x_{11}^{(0,2)},\ldots,x_{ms_m}^{(0,2)}, x_{11}^{(0,3)},\ldots,x_{nm}^{(0,3)} \|^T$ at times $t = T_0$ and $t = T_f$.

In Table 1, several examples of feasible combinations of boundary conditions for the tasks under consideration are presented.

In the following analysis, particular attention is given to the following boundary condition variants:

– variant K1: (<1,1>, <3,6>);
– variant K3: (<1,3>, <3,4>);
– variant K2: (<1,1>, <3,4>);
– variant K3: (<1,3>, <3,6>).

In each variant, the first tuple denotes the number corresponding to the selected variant for the initial time $t = T_0$, and the variant for defining the initial state $x(T_0)$, the second tuple similarly denotes $t = T_f$ and $x(T_f)$.

Thus, constraints (8) and (9) define possible (alternative) task execution sequences A_ν and their corresponding operations. In accordance with constraint (10), at any given time, each task A_ν may be executed on only one object B_j ($\nu = 1,\ldots,n$; $j = 1,\ldots,m$). Conversely, only one task may be executed on each object B_j only one task can be solved at any given time A_ν (These restrictions correspond to the restrictions of classical assignment problems).

Table 2 provides examples of the constraints imposed on control inputs $u_{i\text{æ}j\lambda}^{(0,2,\nu)}(t)$ or various operational scenarios in servicing information systems.

In Tables 1, 2, as well as in the following formulas, let's assume for simplicity that the index of task number A_ν, executed within the information systems, is fixed, and assigned to a specific object B_j. Therefore, this index will be omitted in subsequent notation. The constraints defined by equation (11) specify the conditions under which sets of operations can be executed, as well as the triggering of auxiliary control input $u_{\nu j}^{(0,3)}(t)$. The indicators $J_1^{(o)} \div J_9^{(o)}$ represents the quality metrics for managing the operations performed by the information system. In particular $J_1^{(o)}$ characterizes the total number of tasks successfully completed in the information system by time $t = T_f$; $J_{<2,\alpha,\nu>}^{(o)}$ – reflects the duration of the time interval during which task A_ν was executed; $J_3^{(o)}$ – denotes the total time interval required for completing all necessary tasks A_ν, $\nu = 1,\ldots,n$; $J_{<4,i,\nu>}^{(o)}$ – corresponds to the duration of the time interval over which the service operation complex was performed on object B_i while solving task A_ν; $J_{<5,i>}^{(o)}$ – equals the total time duration during which object B_i remained within the interaction zone (IZ) of object B_j.

Indicator (16) numerically corresponds to the duration of the time interval during which an object awaits service.

Indicator (17) is introduced in cases where it is necessary to evaluate the accuracy of boundary condition fulfillment or to minimize losses caused by the failure to execute interaction operations.

By using functions (18) and (19), it becomes possible to indirectly assess the quality of operation execution (OE) and the accuracy in meeting the directive timeframes for completing those operations.

Here: $\tilde{\alpha}_{i\text{æ}j\lambda}^{(\nu)}(\tau)$ – predefined smooth time-dependent weighting functions used to evaluate the quality of operations; $\tilde{\tilde{\beta}}_{i\text{æ}}^{(\nu)}(\tau)$ – monotonically increasing (or decreasing) time functions, selected based on the directive start/end deadlines for operation execution.

Table 1

Examples of possible combinations of boundary conditions

Time moments t	State vector x		Initial state vector $x(t_0)$			Final state vector $x(tf)$		
				Unfixed			Unfixed	
			Fixed	Free	Partially free	Fixed	Free	Partially free
			1	2	3	4	5	6
Initial time moment t_0	Fixed	1	<1,1>	<1,2>	<1,3>	–	–	
	Unfixed	2	<2,1>	<2,2>	<2,3>	–	–	
Final time moment tf	Fixed	3	–	–	–	<3,4>	<3,5>	
	Unfixed	4	–	–	–	<4,4>	<4,5>	

Table 2

Possible variants of constraints

Variant number	Constraint representation
1	$\sum_{i=1}^{m} u_{i\text{æ}j\lambda}^{(o,2)} \le c_{\text{æ}j\lambda}^{(o,1)}$
2	$\sum_{j=1}^{m} u_{i\text{æ}j\lambda}^{(o,2)} \le c_{i\text{æ}\lambda}^{(o,2)}$
3	$\sum_{\text{æ}=1}^{s_i} u_{i\text{æ}j\lambda}^{(o,2)} \le c_{ij\lambda}^{(o,3)}$
4	$\sum_{\lambda=1}^{l_j} u_{i\text{æ}j\lambda}^{(o,2)} \le c_{i\text{æ}j}^{(o,4)}$
5	$\sum_{\lambda=1}^{l_j}\sum_{i=1}^{m}\sum_{j=1}^{m} u_{i\text{æ}j\lambda}^{(o,2)} \le c_{\text{æ}}^{(o,5)}$
6	No constraints in this case
7	No constraints in this case
8	$\sum_{\text{æ}=1}^{s_i}\sum_{\lambda=1}^{l_j}\sum_{j=1}^{m} u_{i\text{æ}j\lambda}^{(o,2)} \le c_{j}^{(o,8)}$
9	$\sum_{i=1}^{m}\sum_{j=1}^{m} u_{i\text{æ}j\lambda}^{(o,2)} \le c_{\text{æ}\lambda}^{(o,9)}$
10	$\sum_{\lambda=1}^{l_j}\sum_{i=1}^{m} u_{i\text{æ}j\lambda}^{(o,2)} \le c_{j\text{æ}}^{(o,10)}$
11	$\sum_{i=1}^{m}\sum_{\lambda=1}^{l_j} u_{i\text{æ}j\lambda}^{(o,2)} \le c_{j\lambda}^{(o,11)}$
12	$\sum_{\lambda=1}^{l_j}\sum_{j=1}^{m} u_{i\text{æ}j\lambda}^{(o,2)} \le c_{i\text{æ}}^{(o,12)}$
13	$\sum_{j=1}^{m}\sum_{\text{æ}=1}^{s_i} u_{i\text{æ}j\lambda}^{(o,2)} \le c_{i\lambda}^{(o,13)}$
14	$\sum_{\text{æ}=1}^{s_i}\sum_{\lambda=1}^{l_j} u_{i\text{æ}j\lambda}^{(o,2)} \le c_{ij}^{(o,14)}$

5. 3. Dynamic model for channel management in information systems

The state of a communication channel $C_\lambda^{(i)}$ on object B_i will be characterized by the readiness level of the channel to perform a given operation $D_{\text{æ}}^{(i,j)}$. To simplify the notation in the following formulas – as previously done in Section 5. 2 – it is assumed that the index of task A_v, executed within the information system, is fixed, and assigned to object B_j. Therefore, this index will be omitted in subsequent expressions. In this case, the dynamic model describing the processes of channel reconfiguration takes the following form.

Channel management process model:

$$\dot{x}^{(k,1)}_{i\text{æ} j\lambda} = \sum_{j'=1}^{m}\sum_{\text{æ}'=1}^{s_i} \Theta_{i'\text{æ}'j\text{æ}} u^{(k,1)}_{i'\text{æ}'j\lambda} \frac{b^{(j,\lambda)}_{i'\text{æ}'i\text{æ}} - x^{(k,1)}_{i\text{æ} j\lambda}}{x^{(k,1)}_{i'\text{æ}'j\lambda}}, \quad (20)$$

$$\dot{x}^{(k,2)}_{j\lambda} = \sum_{i=1}^{m}\sum_{\text{æ}=1}^{s_i}\left(u^{(0,2)}_{i\text{æ} j\lambda} + u^{(k,1)}_{i\text{æ} j\lambda}\right). \quad (21)$$

Constraints:

$$u^{(0,2)}_{i\text{æ} j\lambda}\, x^{(k,1)}_{i\text{æ} j\lambda} = 0;\ x^{(k,1)}_{i\text{æ} j\lambda}(t) \in \{0;1\}, \quad (22)$$

$$\sum_{i=1}^{n}\sum_{\text{æ}=1}^{s_i} u^{(k,1)}_{i\text{æ} j\lambda}(t) \le 1,\ \forall j, \forall \lambda. \quad (23)$$

Boundary conditions:

$$h^{(k)}_0\left(x^{(k)}(T_0)\right) \le O;$$

$$h^{(k)}_1\left(x^{(k)}(T_f)\right) \le O. \quad (24)$$

Quality indicators of programmed channel management:

$$J^{(k)}_1 = \sum_{\Delta_1=1}^{m-1}\sum_{\Delta_2=\Delta_1+1}^{m}\sum_{\lambda=1}^{l}\sum_{\zeta=1}^{l}\int_{T_0}^{T_f}\left(x^{(k,2)}_{\Delta_1\lambda}(\tau) - x^{(k,2)}_{\Delta_2\zeta}(\tau)\right)\mathrm{d}\tau; \quad (25)$$

$$J^{(k)}_2 = \sum_{\Delta_1=1}^{m-1}\sum_{\Delta_2=\Delta_1+1}^{m}\sum_{\lambda=1}^{l}\sum_{\zeta=1}^{l}\left(x^{(k,2)}_{\Delta_1\lambda}(T_f) - x^{(k,2)}_{\Delta_2\zeta}(T_f)\right), \quad (26)$$

where $x^{(k1)}_{i\text{æ} j\lambda}(t)$ – the state of channel $C^{(i)}_{\lambda}$ on object B_j using the reconfiguration from a readiness state for executing operation $D^{(i,j)}_{\text{æ}'}$ to a readiness state for operation $D^{(i,j)}_{\text{æ}}$; $b^{(j,\lambda)}_{i'\text{æ}'i\text{æ}}$ – a predefined value equal to the duration of the reconfiguration process between the respective channel states; $u^{(k1)}_{i\text{æ} j\lambda}(t)$ – the control input, where $u^{(k,1)}_{i\text{æ} j\lambda}(t)=1$, if $C^{(i)}_{\lambda}$ if the channel is undergoing reconfiguration, and $u^{(k,1)}_{i\text{æ} j\lambda}(t)=0$ – otherwise. Constraints (22), (23) define the sequence of channel reconfiguration $C^{(i)}_{\lambda}$ and the conditions under which it can be initiated $C^{(i)}_{\lambda}$. The variable $x^{(k,2)}_{j\lambda}(t)$ represents the time interval during which the channel is actively engaged. As in the previous model $h^{(k)}_0$, $h^{(k)}_1$ – are known differentiable functions that define boundary conditions for the state vector $x^{(k)} = \| u^{(k,1)}_{1111},\ldots,u^{(k,1)}_{msml}, u^{(k,2)}_{11},\ldots,u^{(k,2)}_{ml} \|^T$.

Indicators (25) and (26) are intended to evaluate the uniformity of channel utilization $t \in (T_0, T_f]$ throughout the control interval and at its completion.

5. 4. Dynamic model for resource management in information systems

Resource management process model:

$$\dot{x}^{(p,1)}_{j\lambda\pi} = -\sum_{i=1}^{m}\sum_{\text{æ}=1}^{s_i} d^{(\pi)}_{i\text{æ} j\lambda}\left(u^{(o,2)}_{i\text{æ} j\lambda} + u^{(k,1)}_{i\text{æ} j\lambda}\right) \quad (27)$$

$$\dot{x}^{(p,2)}_{j\lambda\mu} = -\sum_{i=1}^{m}\sum_{\text{æ}=1}^{s_i} g^{(\mu)}_{i\text{æ} j\lambda}\left(u^{(o,2)}_{i\text{æ} j\lambda} + u^{(k,1)}_{i\text{æ} j\lambda}\right), \quad (28)$$

$$\dot{x}^{(p,1)}_{j\lambda\pi\eta} = -\sum_{i=1}^{m}\sum_{\text{æ}=1}^{s_i} d^{(\pi)}_{i\text{æ} j\lambda}\left(u^{(o,2)}_{i\text{æ} j\lambda} + u^{(k,1)}_{i\text{æ} j\lambda}\right) + u^{(p,1)}_{j\lambda\pi(\eta-1)}, \quad (29)$$

$$\dot{x}^{(p,2)}_{j\lambda\pi\eta'} = -\sum_{i=1}^{m}\sum_{\text{æ}=1}^{s_i} g^{(\mu)}_{i\text{æ} j\lambda}\left(u^{(o,2)}_{i\text{æ} j\lambda} + u^{(k,1)}_{i\text{æ} j\lambda}\right) + u^{(p,2)}_{j\lambda\mu(\eta'-1)}, \quad (30)$$

$$\dot{x}^{(p,3)}_{j\lambda\pi\eta} = u^{(p,1)}_{j\lambda\pi\eta};\ \dot{x}^{(p,4)}_{j\lambda\mu\eta'} = u^{(p,2)}_{j\lambda\mu\eta'}. \quad (31)$$

Constraints:

$$\sum_{i,\text{æ},\lambda} d^{(\pi)}_{i\text{æ} j\lambda}\left(u^{(o,2)}_{i\text{æ} j\lambda} + u^{(k,1)}_{i\text{æ} j\lambda}\right) \le \tilde{H}^{(\pi)}_j(t), \quad (32)$$

$$\sum_{i,\text{æ},\lambda}\int_{T_0}^{T_f} g^{(\mu)}_{i\text{æ} j\lambda}\left(u^{(o,2)}_{i\text{æ} j\lambda}(\tau) + u^{(k,1)}_{i\text{æ} j\lambda}(\tau)\right)\mathrm{d}\tau \le \int_{T_0}^{T_f}\tilde{\tilde{H}}^{(\mu)}_j(\tau)\mathrm{d}\tau, \quad (33)$$

$$u^{(p,1)}_{j\lambda\pi\eta}\left(a^{(p,3)}_{j\lambda\pi(\eta-1)} - x^{(p,3)}_{j\lambda\pi(\eta-1)}\right) = 0,\ u^{(p,1)}_{j\lambda\pi\eta}\, x^{(p,1)}_{j\lambda\pi\eta} = 0, \quad (34)$$

$$u^{(p,2)}_{j\lambda\mu\eta}\left(a^{(p,4)}_{j\lambda\pi(\eta'-1)} - x^{(p,4)}_{j\lambda\pi(\eta'-1)}\right) = 0,\ u^{(p,2)}_{j\lambda\mu\eta'}\, x^{(p,2)}_{j\lambda\mu\eta'} = 0, \quad (35)$$

$$u^{(p,1)}_{j\lambda\pi\eta}(t)\, u^{(p,2)}_{j\lambda\mu\eta}(t) \in \{0,1\},\ \eta = 1,\ldots,\tilde{\rho}_\lambda;\ \eta' = 1,\ldots,\tilde{\tilde{\rho}}_\lambda. \quad (36)$$

Boundary conditions

$$h^{(p)}_0\left(x^{(p)}(T_0)\right) \le O;\ h^{(p)}_1\left(x^{(p)}(T_f)\right) \le O. \quad (37)$$

Quality indicators of programmed resource management

$$J^{(p)}_{1j\pi} = \sum_{\lambda=1}^{l_j}\sum_{\eta=1}^{\tilde{\rho}_\lambda} x^{(p,3)}_{j\lambda\pi\eta}; \quad (38)$$

$$J^{(p)}_{2j\mu} = \sum_{\lambda=1}^{l_j}\sum_{\eta'=1}^{\tilde{\tilde{\rho}}_\lambda} x^{(p,4)}_{j\lambda\mu\eta}, \quad (39)$$

where $x^{(p,1)}_{j\lambda\pi}(t)$, $x^{(p,2)}_{j\lambda\mu}(t)$, $x^{(p,1)}_{j\lambda\pi\eta}(t)$, $x^{(p,2)}_{j\lambda\mu\eta'}(t)$ – the corresponding variables characterize the current volume of non-renewable resources $\Phi S^{(j)}_{\pi}$, renewable resources $\Phi N^{(j)}_{\mu}$, non-renewable replenishable, and renewable replenishable resources (at stages η and η'), used during the operation of the channel $C^{(j)}_{\lambda}$; $d^{(\pi)}_{i\text{æ} j\lambda}, g^{(\mu)}_{i\text{æ} j\lambda}$ – the prescribed consumption rates of non-renewable $\Phi S^{(j)}_{\pi}$ and renewable resources $\Phi N^{(j)}_{\mu}$ during the execution of operational activities (OA) $D^{(i,j)}_{\text{æ}}$ and the reconfiguration of the channel at unit intensity $C^{(i)}_{\lambda}$; $\tilde{H}^{(\pi)}_j(t)$, $\tilde{\tilde{H}}^{(\mu)}_j(t)$ – the replenishment (inflow) intensities of resources $\Phi S^{(j)}_{\pi}$ and $\Phi N^{(j)}_{\mu}$ accordingly. If the specified types of resources are non-replenishable, then the right-hand sides of expressions (32) and (33) will include fixed values $\tilde{H}^{(\pi)}_j$, $\tilde{\tilde{H}}^{(\mu)}_j$, which are interpreted as the maximum possible consumption intensities of the corresponding resources at each point in time.

If it is possible to organize a replenishment (regeneration) process for resources at object B_j then equations of the form (29)–(31) are introduced, where $u^{(p,1)}_{j\lambda\pi\eta}$, $u^{(p,2)}_{j\lambda\mu\eta}$ – represent control actions that regulate the course of replenishment (regeneration) of non-renewable and renewable resources; $a^{(p,3)}_{j\lambda\pi(\eta-1)}$, $a^{(p,4)}_{j\lambda\mu(\eta'-1)}$ – the specified volume of the replenishment (regeneration) $\Phi S^{(j)}_{\pi}$ operation for the non-renewable resource ($\Phi N^{(j)}_{\mu}$ – for the renewable resource) in the $(\eta-1)$-th cycle (on $(\eta'-1)$-th cycle) replenishment (regeneration) cycle; $\tilde{\rho}_\lambda$, $\tilde{\tilde{\rho}}_\lambda$ – represents the total allowable number of regeneration cycles for the corresponding resources.

Constraints (34)–(36) and auxiliary variables $x^{(p,3)}_{j\lambda\pi\eta}(t)$, $x^{(p,4)}_{j\lambda\mu\eta'}(t)$ are introduced to define the class of control actions, as well as the sequence of resource regeneration (replenishment) cycles, and to determine the moments in time when these cycles are completed.

The vector functions $h^{(p)}_0, h^{(p)}_1$ assumed to be given and differentiable. Indicators of the form (38) and (39) characterize the time intervals during which the regeneration of non-renewable $\Phi S_{\pi}^{(j)}$ and renewable resources $\Phi N_{\mu}^{(j)}$, respectively, was carried out at object B_j. Additional indicators may be proposed to evaluate the uniformity (or irregularity) of the consumption (replenishment) of the respective resources.

5. 5. Dynamic model for flow management in information systems

The model of the flow management process in information systems is defined as follows:

$$\dot{x}_{i æ j\lambda\rho}^{(p,1)} = u_{i æ j\lambda\rho}^{(p,1)}; \dot{x}_{i æ j\lambda\rho}^{(p,2)} = u_{i æ j\lambda\rho}^{(p,2)}; \tag{40}$$

$$0 \le u_{i æ j\lambda\rho}^{(p,1)} \le c_{i æ j\lambda\rho}^{(p,1)} u_{i æ j\lambda}^{(o,2)}; \tag{41}$$

$$u_{i æ j\lambda\rho}^{(p,2)} \left(a_{i æ \rho}^{(p,1)} - x_{i æ j\lambda\rho}^{(p,1)} \right) = 0;$$

$$u_{i æ j\lambda\rho}^{(p,2)} x_{i \tilde{æ}}^{(o,2)} = 0; u_{i æ j\lambda\rho}^{(p,2)} \left(t \right) \in \left\{ 0,1 \right\}; \tag{42}$$

$$\sum_{i=1}^{m} \sum_{\lambda=1}^{l_i} \sum_{æ=1}^{s_i} \sum_{\rho=1}^{k_i} x_{i æ j\lambda\rho}^{(p,1)} \left(u_{i æ j\lambda\rho}^{(o,2)} + {}_{i æ j\lambda\rho}^{(p,2)} \right) \le \tilde{P}_j^{(1)}; \tag{43}$$

$$\sum_{i=1}^{m} \sum_{\lambda=1}^{l_i} \sum_{æ=1}^{s_i} u_{i æ j\lambda\rho}^{(p,1)} \le \tilde{P}_{j\rho}^{(2)}; \tag{44}$$

$$\sum_{\lambda=1}^{l_i} \sum_{æ=1}^{s_i} \sum_{\rho=1}^{k_i} u_{i æ j\lambda\rho}^{(p,1)} \le \tilde{P}_{ij}^{(3)}. \tag{45}$$

Boundary conditions:

$$h_0^{(p)} \left(x^{(p)}(T_0) \right) \le O;$$

$$h_1^{(p)} \left(x^{(p)} \left(T_f \right) \right) \le O. \tag{46}$$

Performance indicators of software-based flow management in information systems:

$$J_1^{(p)} = \sum_{i=1}^{m} \sum_{æ=1}^{s_i} \sum_{\substack{j=1 \\ i \ne j}}^{m} \sum_{\lambda=1}^{l_i} \sum_{\rho=1}^{k_i} \left(a_{i æ \rho}^{(p,1)} - x_{i æ j\lambda\rho}^{(p,1)} \right) x_{i æ j\lambda}^{(v,1)} \Bigg|_{t=T_f}, \tag{47}$$

$$J_2^{(p)} = \sum_{i=1}^{m} \sum_{æ=1}^{s_i} \sum_{\substack{j=1 \\ i \ne j}}^{m} \sum_{\lambda=1}^{l_i} \sum_{\rho=1}^{k_i} \int_{T_0}^{T_f} x_{i æ j\lambda}^{(p,2)} \left(\tau \right) \mathrm{d}\tau, \tag{48}$$

where $x_{i æ j\lambda\rho}^{(p,1)}\left(t\right)$ – a variable that characterizes the current volume of information of type "ρ" received by object B_j from object B_i during the execution of the operational activity (OA) $D_{æ}^{(i,j)}$ (or the volume of information processed at object B_j, $i = j$); $x_{i æ j\lambda\rho}^{(p,2)}\left(t\right)$ – an auxiliary variable that characterizes the total duration (time) of the presence of information of type ρ at object B, received (or processed) during the interaction between objects B_i and B_j in the course of executing the operational activity (OA) $D_{æ}^{(i,j)}$ via channels $C_{\lambda}^{(i)}, C_{\lambda}^{(j)}$; $c_{i æ j\lambda\rho}^{(p,1)}$ – a given constant that defines the maximum allowable value of $u_{i æ j\lambda\rho}^{(p,1)}$; $u_{i æ j\lambda\rho}^{(p,1)}$ – the intensity of information transmission from object B_i to object B_j (or the intensity of information processing at object B_j under the condition $i = j$); $u_{i æ j\lambda\rho}^{(p,2)}\left(t\right)$ – auxiliary control action that takes the value $u_{i æ j\lambda\rho}^{(p,2)}\left(t\right) = 1$, if the reception (or processing) of information at object B_j, $u_{i æ j\lambda\rho}^{(p,2)}\left(t\right) = 0$ – otherwise, or in the case when, after the completion of operation $D_{æ}^{(i,j)}$ (or $D_{æ}^{(i)}$, if $i = j$) the execution of operation $D_{\tilde{æ}}^{(i,j)}$, (or $D_{\tilde{æ}}^{(i)}$ if $i = j$), begins, which directly follows in the technological control cycle of object B_i after operation $D_{æ}^{(i,j)}$ (or $D_{æ}^{(i)}$); $\tilde{P}_j^{(1)}$, $\tilde{P}_{j\rho}^{(2)}$, $\tilde{P}_{ij}^{(3)}$ – given values that respectively characterize: the maximum possible volume of information that can be stored at object B_j, the throughput capacity of object B_j with respect to the information flow of type p; and the throughput capacity of the channels connecting objects B_i and B_j; $a_{i æ \rho}^{(p,1)}$ – the specified volume of information of type p that can be transmitted from object B_i (or processed at object B_i) during the execution of the corresponding operation.

The functions $h_0^{(p)}$, $h_1^{(p)}$ are assumed to be known and differentiable. Objective functions of the form (47) are introduced in cases where it is necessary to evaluate the total losses caused by the absence (or loss) of specific types of information during the operation of information systems. The auxiliary variable $x_{i æ j\lambda}^{(p,1)}$ takes non-zero values in cases when information exchange occurs between B_i and B_j (or information processing takes place at object B_i, if $i = j$).

The indicator of the form (48) is used to assess the total time losses caused by delays in the transmission, processing, and storage of information during the operation of the information system (i.e., the overall loss in the efficiency of transmitting, processing, and storing information circulating within the information network).

5. 6. Dynamic model for controlling operation parameters performed in an information system

When constructing an operations control model (model M_0), the specific characteristics of how these operations are carried out (executed) are considered. However, the execution process of both target and technological operations in information systems is accompanied by changes in a range of parameters (physical, technical, technological, etc.) that characterize each of these operations. Therefore, the operations control models (model M_0) must be supplemented each time with models for controlling the parameters of operations (model M_e). As an example, consider a model for controlling the parameters of operations related to performing measurements and evaluating the components of the state vector of the motion of object B_i using a channel $C_{\lambda}^{(j)}$ located on object B_j. In this case, one of the most critical parameters characterizing the measurement operations is the accuracy of determining the state vector of the motion of object B_i.

Let the linearized models of the motion of object B_i as well as the model of the measurement instruments (observation channels for tracking the trajectory of object B_i) be given in the following form:

$$\dot{x}_i^{(d)} = F\left(t\right) x_i^{(d)}, \tag{49}$$

$$y_{j\lambda}^{(i)}\left(t\right) = d_{j\lambda}^{T}\left(t\right) x_i^{(d)} + \xi_{j\lambda}, \tag{50}$$

where $x_i^{(d)} = \| r_i^{(d)T} \dot{r}_i^{(d)T} \|^T$ – the state vector of the motion of object B_i; $F_i\left(t\right)$ – given matrix; $\xi_{j\lambda}$ – uncorrelated measurement errors of channel $C_{\lambda}^{(j)}$, which follow a normal distribution with zero mean and variance equal to $\sigma_{j\lambda}^2$.

$d_j(t)$ – a given vector that relates the vector of estimated parameters $x_i^{(d)}$ to the measurable parameters $y_{j\lambda}^{(i)}\left(t\right)$. In this case, the model for controlling the parameters of operations takes the following form

$$\dot{Z} = -Z_i F_i - F_i^{\mathrm{B}} Z_i - \sum_{j=1}^{n} \sum_{\tilde{æ} \in \Gamma_{i æ}} \sum_{\lambda=1}^{l_j} u_{i \tilde{æ} j\lambda}^{(5,1)} \frac{d_{i\lambda} d_{j\lambda}^{\mathrm{B}}}{\sigma_{j\lambda}^2}, \; Z_i = \tilde{\tilde{K}}_i^{-1}. \tag{51}$$

Constraints

$$0 \le u_{i \tilde{æ} j\lambda}^{(e,1)} \le c_{j\lambda}^{(e)} u_{i \tilde{æ} j\lambda}^{(o,2)}, \tag{52}$$

Boundary conditions:

– option "a":

$$t=T_0,\tilde{\tilde{K}}_i\left(T_0\right)=\tilde{\tilde{K}}_{io}, \tag{53}$$

$$t=T_f, b_\gamma^T\tilde{\tilde{K}}_i b_\gamma \le \sigma_{\gamma i}^2; \tag{54}$$

– option "b":

$$t=T_0,\tilde{\tilde{K}}_i\left(T_0\right)=\tilde{\tilde{K}}_{io}, \tag{55}$$

$$t=T_f, \int_{T_0}^{T_f}\sum_{i,æ,j,\lambda} u_{iæj\lambda}^{(e,1)}\left(\tau\right)\mathrm{d}\tau \le \tilde{J}_1^{(e)}. \tag{56}$$

Performance indicators for operational parameter management in information systems:

– option "a":

$$J_1^{(e)}=\int_{T_0}^{T_f}\sum_{i,æ,j,\lambda} u_{iæj\lambda}^{(e,1)}(\tau)\mathrm{d}\tau; \tag{57}$$

– option "b":

$$J_{2\gamma i}^{(e)}=b_\gamma^T\tilde{\tilde{K}}_i b_\gamma, \tag{58}$$

where Z_i – the matrix inverse of the correlation matrix $\tilde{\tilde{K}}_i$ of the estimation errors for the state vector of object B_i; $u_{iæj\lambda}^{(e,1)}$ – the intensity of measurements of the motion parameters of object B_i; $\Gamma_{iæ}$ – the set of indices of measurement operations performed on object B_i; $c_{j\lambda}^{(e)}$ – given constants characterizing the technical capabilities of the channel $C_\lambda^{(j)}$ in performing measurement operations; $b_\gamma = ||0,0,...,0,1,0,...,0||^T$ – an auxiliary vector used to extract the required $\tilde{\tilde{K}}_i$ element from the matrix γ; $\sigma_{j\lambda}^2$ – the given accuracy of determining the γ-th component of the state vector of object B_i; $\tilde{\tilde{K}}_{i0}$ – the given matrix characterizing the estimation errors of the state vector of object B_i at time $t = T_0$; $\tilde{J}_1^{(e)}$ – a given value representing the total resource consumption of object B_j when executing the entire set of measurement operations.

Indicator (56) allows for a quantitative assessment of the total resource expenditure by information systems during the execution of measurement operations. The objective function (57) characterizes the accuracy of determining the γ-th element of the state vector of object B_i.

5. 7. Dynamic models for managing the structural dynamics of information systems

In constructing dynamic models for managing the structural dynamics of information systems (model M_c), a dynamic interpretation of the processes involved in executing service operation complexes is employed, as before.

To formalize these processes, it is possible to utilize the previously developed dynamic models for managing operations within information networks (model M_0) and communication channels (model M_k).

5. 7. 1. Model for managing polystructural states of information systems

The model describing the process of managing polystructural states (model $M_c^{(1)}$):

$$\dot{x}_{\delta\eta_1}^{(c,1)}=u_{\delta\eta_1}^{(c,1)};\ \dot{\tilde{x}}_\delta^{(c,1)}=\sum_{\delta'=1}^{K_\Delta}\frac{\tilde{h}_{\delta'\delta}^{(c,1)}-\tilde{x}_\delta^{(c,1)}}{\tilde{x}_{\delta'}^{(c,1)}}\tilde{u}_{\delta'}^{(c,1)};\ \dot{\tilde{\tilde{x}}}_{\delta\eta_1}^{(A1)}=\tilde{\tilde{u}}_{\delta\eta_1}^{(c,1)}; \tag{59}$$

$\delta=1,...,K_\Delta;\ \eta_1=1,...,C_1.$

Constraints:

$$\sum_{\delta=1}^{K_\Delta}\left(u_{\delta\eta_1}^{(c,1)}\left(t\right)+\tilde{u}_\delta^{(c,2)}\right)\le 1,\forall\eta_1;\ u_{\delta\eta_1}^{(c,1)}\left(t\right)\in\left\{0,1\right\};$$

$$\tilde{u}_\delta^{(c,1)}\left(t\right),\tilde{\tilde{u}}_{\delta\eta_1}^{(c,1)}\left(t\right)\in\left\{0,1\right\}; \tag{60}$$

$$\sum_{\eta_1=1}^{C_1}u_{\delta\eta_1}^{(c,1)}\cdot\tilde{x}_\delta^{(c,1)}=0,\ u_{\delta\eta_1}^{(c,1)}\left(a_{\delta(\eta_1-1)}^{(c,1)}-x_{\delta(\eta_1-1)}^{(c,1)}\left(t\right)\right)=0; \tag{61}$$

$$\tilde{u}_\delta^{(c,1)}\left[\sum_{\chi'\in\Gamma_{\delta1}^{(2)}}\sum_{\omega'\in\Gamma_{\delta2}^{(2)}}\tilde{x}_{\chi'\omega'}^{(c,2)}+\prod_{\chi''\in\Gamma_{\delta3}^{(2)}}\prod_{\omega''\in\Gamma_{\delta4}^{(2)}}\tilde{x}_{\chi''\omega''}^{(c,2)}\right]=0; \tag{62}$$

$$\tilde{\tilde{u}}_{\delta\eta_1}^{(c,1)}\left(a_{\delta\eta_1}^{(c,1)}-x_{\delta\eta_1}^{(c,1)}\left(t\right)\right)=0. \tag{63}$$

Boundary conditions:

$$t=T_0: x_{\delta\eta_1}^{(c,1)}\left(T_0\right)=\tilde{\tilde{x}}_{\delta\eta_1}^{(c,1)}\left(T_0\right)=0;\ \tilde{x}_{\delta\eta_1}^{(c,1)}\left(T_0\right)\in R^1; \tag{64}$$

$$t=T_f: x_{\delta\eta_1}^{(c,1)}\left(T_f\right)\in R^1;\ \tilde{x}_{\delta\eta_1}^{(c,1)}\left(T_f\right)\in R^1;\ \tilde{\tilde{x}}_{\delta\eta_1}^{(c,1)}\left(T_f\right)\in R^1. \tag{65}$$

Performance indicators for managing polystructural macrostates of information systems:

$$J_{1\delta}^{(c,1)}=\sum_{\eta_1=1}^{C_1}x_{\delta\eta_1}^{(c,1)}\left(T_f\right); \tag{66}$$

$$J_2^{(c,1)}=\sum_{\eta_1=1}^{C_1}\sum_{\delta=1}^{K_\Delta}\left(a_\delta^{(c,1)}-x_{\delta\eta_1}^{(c,1)}\left(T_f\right)\right)^2; \tag{67}$$

$$J_{3\delta}^{(c,1)}=\sum_{\delta=1}^{K_\Delta}\int_{T_0}^{T_f}\tilde{u}_\delta^{(c,1)}\left(\tau\right)\mathrm{d}\tau; \tag{68}$$

$$J_{2\eta_1\delta(\eta_1-1)}^{(c,1)}=\left[\tilde{\tilde{x}}_{\delta\eta_1}^{(c,1)}-\left(\tilde{\tilde{a}}_{\delta(\eta_1+1)}^{(c,1)}+\tilde{\tilde{x}}_{\delta(\eta_1+1)}^{(c,1)}\right)\right]\Big|_{t=T_f}. \tag{69}$$

The following notations are used:

– $x_{\delta\eta_1}^{(c,1)}\left(t\right)$ – a variable characterizing the degree of completion of macrooperation $D_{\delta\eta_1}^{(c,1)}$, which describes the functioning of the information system in the polystructural state S_δ during the η_1-th control cycle of the given system;

– $\tilde{x}_\delta^{(c,1)}\left(t\right)$ – a variable characterizing the degree of completion of the macrooperation $\tilde{D}_\delta^{(c,1)}$, which is associated with the transition of the information system from the current polystructural state $S_{\delta'}$ to the desired microstate S_δ (in the special case $\delta' = \delta$);

– $\tilde{\tilde{x}}_{\delta\eta_1}^{(c,1)}\left(t\right)$ – an auxiliary variable which value numerically corresponds to the duration of the time interval that has passed since the completion of microoperation $D_{\delta\eta_1}^{(c,1)}$;

– $\tilde{h}_{\delta'\delta}^{(c,1)}\left(t\right)$ – a given value numerically equal to the duration of the transition of the information system from polystructural state $S_{\delta'}$ to state S_δ;

– $u_{\delta\eta_1}^{(c,1)}\left(t\right)$ – a control input that takes the value 1 if macrooperation $D_{\delta\eta_1}^{(c,1)}$ must be executed, and 0 otherwise;

– $\tilde{\tilde{u}}_{\delta\eta_1}^{(c,1)}$ – an auxiliary control input that takes the value 1 at the time corresponding to the completion of microoperation $D_{\delta\eta_1}^{(c,1)}$, 0 otherwise;

– $\tilde{u}_\delta^{(c,1)}\left(t\right)$ – a control input that takes the value 1 if the information system must transition from the current polystructural microstate $S_{\delta'}$ to the required state S_δ, and 0 otherwise.

Constraints of type (60)–(63) define the order and sequence of activation (or deactivation) of the above-mentioned control inputs. In expression (62) $\Gamma_{\delta1}^{(2)},\Gamma_{\delta3}^{(2)},\Gamma_{\delta2}^{(2)},\Gamma_{\delta4}^{(2)}$ – it corresponds to the set of indices of structure types and structural states in which those structures may reside.

Indicator (66) makes it possible to evaluate the total duration of the information system's presence in microstate S_δ.

The Mayer-type functional (67) enables the assessment of total losses resulting from the failure to meet the directive-specified durations for which the information network must remain in the required macrostates. In expression (67) $a_\delta^{(c,1)}$ – denotes the directive-specified duration of the information network's presence in the polystructural state S_δ.

Indicator (68) provides a quantitative estimate of the total time during which the information network operates in a transitional mode.

Functional (69) allows for the evaluation of the time interval between two successive entries of the information network into the polystructural state S_δ (during control cycles η_1 and (η_1+1)).

5. 7. 2. Model for managing the structural dynamics of a specified type of information systems

The model describing the process of managing the structural dynamics of information systems (model $M_c^{(2)}$):

$$\dot{x}^{(c,2)}_{\chi\omega\eta_2}=u^{(c,2)}_{\delta\omega\eta_2};\ \dot{\tilde{x}}^{(c,2)}_{\chi\omega}=\sum_{\omega'=1}^{K_\Omega}\frac{\tilde{h}^{(c,2)}_{\omega'\omega\chi}-\tilde{x}^{(c,2)}_{\chi\omega}}{\tilde{x}^{(c,2)}_{\chi\omega'}}\tilde{u}^{(c,2)}_{\chi\omega'};\ \dot{\tilde{\tilde{x}}}^{(c,2)}_{\chi\omega\eta_2}=\tilde{\tilde{u}}^{(c,2)}_{\chi\omega\eta_2};\quad(70)$$

$$\chi=1,\dots,K_c;\ \omega=1,\dots,K_\Omega;\ \eta_2=1,\dots,C_2.$$

Constraints:

$$\sum_{\omega=1}^{K_\Omega}\left(u^{(c,2)}_{\chi\omega\eta_2}(t)+\tilde{u}^{(c,2)}_{\chi\omega'}\right)\le 1,\forall\chi,\forall\eta_2;$$

$$u^{(c,2)}_{\chi\omega\eta_2}(t)\in\{0,1\};\tilde{u}^{(c,2)}_{\chi\omega}(t),\tilde{\tilde{u}}^{(c,2)}_{\chi\omega\eta_2}(t)\in\{0,1\};\quad(71)$$

$$\sum_{\eta_2=1}^{C_2}u^{(c,2)}_{\chi\omega\eta_2}\cdot\tilde{x}^{(c,2)}_{\chi\omega}=0,\ u^{(c,2)}_{\chi\omega\eta_2}\left(a^{(c,2)}_{\chi\omega(\eta_2-1)}-x^{(c,2)}_{\chi\omega(\eta_2-1)}(t)\right)=0;\quad(72)$$

$$\tilde{u}^{(c,2)}_{\chi\omega}\left[\begin{array}{l}\sum\limits_{i'\in\Gamma^{(3)}_{\chi\omega1}}\sum\limits_{w'\in\Gamma^{(3)}_{\chi\omega2}}\sum\limits_{f'\in\Gamma^{(3)}_{\chi\omega3}}\tilde{x}^{(c,3)}_{i'w'f'}+\\+\prod\limits_{i''\in\Gamma^{(3)}_{\chi\omega4}}\prod\limits_{w''\in\Gamma^{(3)}_{\chi\omega5}}\prod\limits_{f''\in\Gamma^{(3)}_{\chi\omega6}}\tilde{x}^{(c,3)}_{i''w''f''}\end{array}\right]=0;\quad(73)$$

$$\tilde{\tilde{u}}^{(c,2)}_{\chi\omega\eta_2}\left(a^{(c,2)}_{\chi\omega\eta_2}-x^{(c,2)}_{\chi\omega\eta_2}\right)=0.\quad(74)$$

Boundary conditions:

$$t=T_0: x^{(c,2)}_{\chi\omega\eta_2}(T_0)=\tilde{\tilde{x}}^{(c,2)}_{\chi\omega\eta_2}(T_0)=0;\ \tilde{x}^{(c,2)}_{\chi\omega}(T_0)\in R^1;\quad(75)$$

$$t=T_f: x^{(c,2)}_{\chi\omega\eta_2}(T_f)\in R^1;\ \tilde{x}^{(c,2)}_{\chi\omega\eta_2}(T_f)\in R^1;\ \tilde{\tilde{x}}^{(c,2)}_{\chi\omega\eta_2}(T_f)\in R^1.\quad(76)$$

Performance indicators for managing the structural dynamics of the specified type:

$$J^{(c,2)}_{1\chi\omega}=\sum_{\eta_2=1}^{C_2}x^{(c,2)}_{\chi\omega\eta_2}(T_f);\quad(77)$$

$$J^{(c,2)}_{2\chi\omega}=\sum_{\eta_2=1}^{C_2}\tilde{\tilde{u}}^{(c,2)}_{\chi\omega\eta_2};\quad(78)$$

$$J^{(c,2)}_{3\chi}=\int_{T_0}^{T_f}\sum_{\omega=1}^{K_\Omega}\tilde{u}^{(c,2)}_{\chi\omega}(\tau)\mathrm{d}\tau;\quad(79)$$

$$J^{(c,2)}_{4\omega\eta_2}=\sum_{\chi=1}^{K_c}\tilde{\tilde{u}}^{(c,2)}_{\chi\omega\eta_2}(t);\quad(80)$$

$$J^{(c,2)}_{5\omega\eta_2}=\tilde{\tilde{u}}^{(c,2)}_{\chi\omega\eta_2}(t).\quad(81)$$

The following notations are used:

– $x^{(c,2)}_{\chi\omega\eta_2}(t)$ – a variable characterizing the degree of completion of microoperation $D^{(c,2)}_{\chi\omega\eta_2}$, which describes the process of structure G_χ being in structural state $S_{\chi\omega}$ during the η_2-th control cycle;

– $\tilde{x}^{(c,2)}_{\chi\omega}(t)$ – a variable characterizing the degree of completion of the macrooperation describing the transition of structure G_χ from the current structural state $S_{\chi\omega}$ to the required structural state $S_{\chi\omega}$;

– $\tilde{\tilde{x}}^{(c,2)}_{\chi\omega\eta_2}(t)$ – an auxiliary variable which value numerically equals the time interval that has elapsed since the completion of microoperation $D^{(c,2)}_{\chi\omega\eta_2}$;

– $\tilde{h}^{(c,2)}_{\omega'\omega\chi}$ – a given value numerically equal to the duration of the transition of structure G_χ from structural state $S_{\chi\omega}$ to structural state $S_{\chi\omega}$;

– $u^{(c,2)}_{\chi\omega\eta_2}(t)$ – a control input that takes the value 1 if macrooperation $D^{(c,2)}_{\chi\omega}$, 0 is to be performed, and 0 otherwise;

– $\tilde{\tilde{u}}^{(c,2)}_{\chi\omega\eta_2}(t)$ – an auxiliary control input that takes the value 1 at the moment corresponding to the completion of macrooperation $D^{(c,2)}_{\chi\omega\eta_2}$, 0 otherwise;

– $\tilde{u}^{(c,2)}_{\chi\omega}(t)$ – a control input that takes the value 1 if the transition of the structure G_χ from the current state $S_{\chi\omega}$ to the required structural state $S_{\chi\omega}$ 0 is to be performed, and 0 otherwise.

The constraints of type (71)–(74) define the order and sequence of activation (or deactivation) of the above-mentioned control inputs.

In expression (73) $\Gamma^{(3)}_{\chi\omega1}$, $\Gamma^{(3)}_{\chi\omega4}$, $\Gamma^{(3)}_{\chi\omega2}$, $\Gamma^{(3)}_{\chi\omega5}$, $\Gamma^{(3)}_{\chi\omega3}$, $\Gamma^{(3)}_{\chi\omega6}$ the set corresponds to the set of indices of objects that are part of the structure of the information system, the set of macrostate indices of these objects, and the set of indices of locations within the macrostates of information system objects.

Indicator (77) provides a quantitative measure of the total duration during which a structure of type G_χ remains in structural state $S_{\chi\omega}$; Functional of type (78) determines the number of times the structure G_χ has entered structural state $S_{\chi\omega}$. Indicator (79) allows for a quantitative assessment of the total time the structure G_χ remains in a transitional state. Indicator (80) allows for the assessment of the total number of heterogeneous structures G_χ, that are in structural state S_ω $(\delta=\omega)$ where η_2 – during the control cycle.

Functional (81) evaluates the presence $J^{(c,2)}_{\delta\chi\omega\eta_2}=1$ (or absence $J^{(c,2)}_{\delta\chi\omega\eta_2}=0$) of structure G_χ in structural state $S_{\chi\omega}$.

5. 7. 3. Model for managing the macrostates of objects within an information system

The model describing the process of managing the structural dynamics of an information system (model $M_c^{(3)}$):

$$\dot{x}^{(c,3)}_{iwf\eta_3}=u^{(c,3)}_{iwf\eta_3};\ \dot{\tilde{x}}^{(c,3)}_{iwf}=\sum_{w'=1}^{K_W}\sum_{f'=1}^{K_F}\frac{\tilde{h}^{(c,3)}_{w'f'wf}-\tilde{x}^{(c,3)}_{iwf}}{\tilde{x}^{(c,3)}_{iw'f'}}\tilde{u}^{(c,3)}_{iw'f'};$$

$$\dot{\tilde{\tilde{x}}}^{(c,3)}_{iwf\eta_3}=\tilde{\tilde{u}}^{(c,3)}_{iwf\eta_3};\quad(82)$$

$$i=1,\dots,m;w=1,\dots,K_W;f=1,\dots,K_F;\eta_3=1,\dots,C_3,\quad(83)$$

Constraints:

$$\sum_{w=1}^{K_W}\sum_{f=1}^{K_F}\left(u^{(c,3)}_{iwf\eta_3}(t)+\tilde{u}^{(c,3)}_{iwf}\right)\le 1,\forall i;\forall\eta_3;\quad(84)$$

$$\sum_{i=1}^{m}\sum_{w=1}^{K_W}u^{(c,3)}_{iwf\eta_3}(t)\le 1,\forall f;\forall\eta_3;\quad(85)$$

$$u^{(c,3)}_{iwf\eta_3}(t)\in\{0,1\};\tilde{u}^{(c,3)}_{iwf}(t),\tilde{\tilde{u}}^{(c,3)}_{iwf\eta_3}(t)\in\{0,1\};\quad(86)$$

$$\sum_{\eta_3=1}^{C_3} u_{iwf\eta_3}^{(c,3)} \cdot \tilde{x}_{iwf\eta_3}^{(c,3)} = 0, u_{iwf\eta_3}^{(c,3)} \left(a_{iwf(\eta_3-1)}^{(c,3)} - x_{iwf(\eta_3-1)}^{(c,3)} \right) = 0; \quad (87)$$

$$\tilde{u}_{iwf}^{(c,3)} \left[\begin{array}{l} \sum_{\alpha' \in \Gamma_{iwf1}^{(4)}} \left(a_{i\alpha'}^{(o,2)} - \tilde{x}_{i\alpha'}^{(o,2)}(t) \right) + \\ + \prod_{\beta' \in \Gamma_{iwf2}^{(4)}} \left(a_{i\beta'}^{(o,2)} - \tilde{x}_{i\beta'}^{(o,2)}(t) \right) \end{array} \right] = 0; \quad (88)$$

$$\tilde{\tilde{u}}_{iwf\eta_3}^{(c,3)} \left(\tilde{\tilde{a}}_{iwf(\eta_3-1)}^{(c,3)} - \tilde{\tilde{x}}_{iwf(\eta_3-1)}^{(c,3)} \right) = 0. \quad (89)$$

Boundary conditions:

$$t = T_0 : x_{iwf\eta_3}^{(c,3)}(T_0) = \tilde{\tilde{x}}_{iwf\eta_3}^{(c,3)}(T_0) = 0; \tilde{x}_{iwf}^{(c,3)}(T_0) \in R^1; \quad (90)$$

$$t = T_f : x_{iwf\eta_3}^{(c,3)}(T_f) \in R^1; \tilde{x}_{iwf}^{(c,3)}(T_f) \in R^1; \tilde{\tilde{x}}_{iwf\eta_3}^{(c,3)}(T_f) \in R^1. \quad (91)$$

Performance indicators for managing the structural dynamics of the specified type:

$$J_{1wf\eta_3}^{(c,3)} = \sum_{i=1}^{m} \tilde{\tilde{u}}_{iwf\eta_3}^{(c,3)}(T_f); \quad (92)$$

$$J_{2i}^{(c,3)} = \int_{T_0}^{T_f} \sum_{w=1}^{K_W} \sum_{f=1}^{K_F} \tilde{u}_{ifw}^{(c,3)}(\tau) \mathrm{d}\tau; \quad (93)$$

$$J_{3iwf}^{(c,3)} = \sum_{\eta_3=1}^{C_3} x_{iwf\eta_3}^{(c,3)}(T_f); \quad (94)$$

$$J_{4iwf}^{(c,3)} = \sum_{\eta_3=1}^{K_3} \left(a_{iwf}^{(c,3)} - x_{iwf}^{(c,3)}(T_f) \right)^2; \quad (95)$$

$$J_{5i\eta_3(\eta_3+1)}^{(c,3)} = \left[\tilde{\tilde{x}}_{iwf\eta_3}^{(c,3)} - \left(\tilde{\tilde{a}}_{iwf}^{(c,3)} + \tilde{\tilde{x}}_{iwf(\eta_3+1)}^{(c,3)} \right) \right] \Big|_{t=T_f}. \quad (96)$$

The following notation is adopted:

– $x_{iwf\eta_3}^{(c,3)}(t)$ – a variable characterizing the degree of completion of microoperation $D_{iwf\eta_3}^{(c,3)}$, which describes the functioning process of object B_i in microstate S_{iwf} during the η_3-rd control cycle;

– $\tilde{x}_{iwf}^{(c,3)}$ – a variable characterizing the degree of completion of the microoperation $\tilde{D}_{iwf}^{(c,3)}$, that describes the transition process of object B_i from the current macrostate $S_{iw'f'}$ to the required microstate S_{iwf};

– $\tilde{\tilde{x}}_{iwf\eta_3}^{(c,3)}(t)$ – an auxiliary variable which value numerically equals the time interval that has elapsed since the completion of macrooperation $D_{iwf\eta_3}^{(c,3)}$;

– $\tilde{h}_{w'f'wf}^{(c,3)}$ – a given value numerically equal to the duration of the transition of object B_i from macrostate $S_{iw'f'}$ (w', w – the indices of the macrostates of object B_i, f', f – are the indices of the respective positions within those macrostates;

– $u_{iwf\eta_3}^{(c,3)}(t)$ – a control input that takes the value 1 if microoperation $D_{iwf\eta_3}^{(c,3)}$, 0 is to be executed, and 0 otherwise;

– $\tilde{u}_{iwf}^{(c,3)}(t)$ – a control input that takes the value 1 if a transition of object B_i from the current microstate $S_{iw'f'}$ to the required microstate S_{iwf};

– $\tilde{\tilde{u}}_{iwf\eta_3}^{(c,3)}(t)$ – an auxiliary control input that takes the value 1 now corresponding to the completion of microoperation $D_{iwf\eta_3}^{(c,3)}$, 0 – otherwise.

Constraints (84)–(89) define the order and sequence of activation (or deactivation) of the aforementioned control inputs.

In expression (88), $\Gamma_{iwf1}^{(4)}$, $\Gamma_{iwf2}^{(4)}$ – denotes the set of operation indices executed on object B_i (during interaction with object B_i), that directly precede macrooperation $D_{iwf}^{(c,3)}$ and are logically linked to it by "AND", "OR", or exclusive "OR" operators. Constraint (88) establishes the connection between model M_0 and model M_c. In turn, the interrelation of models $M_c^{(3)}$, $M_c^{(2)}$, $M_c^{(2)}$, $M_c^{(1)}$ is implemented through mixed-type constraints (73) and (62), respectively.

Quality indicator (92) characterizes the number of objects B_i, that were in microstate η_3 – during the S_{iwf}. The function of type (93) provides a quantitative assessment of the total duration during which object B_i remained in transitional macrostates. Indicator (94) determines the total time object B_i spends in microstate S_{iwf}; the Mayer-type functional (95) evaluates the total losses incurred due to failure to meet the directive-specified duration of the object's B_i presence in microstate S_{iwf}. In expression (95) $a_{iwf}^{(c,3)}$ – denotes the directive-specified duration of object $B_{i's}$ presence in macrostate S_{iwf}. Functional (96) enables the evaluation of the time interval between two successive entries of object B_i into microstate S_{iwf} (during control cycles η_3 and $(\eta_3 + 1)$). It should be emphasized that the list of quality indicators for managing the structural dynamics of information systems (within the framework of models $M_c^{(1)}$, $M_c^{(2)}$, $M_c^{(3)}$) can be significantly extended – for example, by utilizing functionals like those proposed in models M_0, M_k, M_p, M_e, M_d, M_p). However, such extensions are determined by the specific applied problems for which the discussed models are employed. In models $M_c^{(2)}$, $M_c^{(3)}$ the patterns of change in variables are of the same nature as the corresponding variables in the model $M_c^{(1)}$.

Using the dynamic model for managing auxiliary operations (model M_v), let's incorporate into the previously discussed models M_0, M_k, and M_p the constraints related to the continuity of the processes involved in channel reconfiguration and the execution of operations within information systems. The necessity of accounting for these constraints arises from the specific nature of applying the above-mentioned dynamic models. During the numerical search for optimal control programs for managing the structural dynamics of information systems, interruptions may occur at certain time points within the interval $(T_0, T_f]$, both during channel reconfiguration and operation execution.

In practice, modern technical means of information systems in some cases allow interruptions of ongoing operations (e.g., in multiprogramming or multiprocessing modes). In other cases, strict prohibition of operation interruption is enforced (e.g., when transmitting highly sensitive information or when an object exists in an abnormal state). Under such conditions, abstract mathematical models (e.g., models M_0, M_k, M_p) must incorporate possible formalized variants for the optimal resolution of conflict situations related to interruptions.

There are several approaches to formalizing the constraints on the continuity of operations, all of which share a common feature: accounting for continuity constraints on operations and channel reconfiguration leads to an expansion of the dimensionality of the phase space in the corresponding mathematical models.

To address this, auxiliary variables are introduced, which must satisfy the following differential equations:

$$\dot{x}_{iæj\lambda}^{(v,1)} = u_{iæj\lambda}^{(o,2)}; \dot{x}_{iæj\lambda}^{(v,2)} = x_{iæj\lambda}^{(v,1)}; \dot{x}_{iæj\lambda}^{(v,3)} = u_{iæj\lambda}^{(v,1)}; \quad (97)$$

$$\dot{x}_{iæj\lambda}^{(v,4)} = u_{iæj\lambda}^{(k,1)}; \dot{x}_{iæj\lambda}^{(v,5)} = u_{iæj\lambda}^{(v,2)}; \dot{x}_{iæj\lambda}^{(v,6)} = u_{iæj\lambda}^{(v,3)} - u_{iæj\lambda}^{(v,2)}, \quad (98)$$

where $x_{iæj\lambda}^{(v,\zeta)}$, $\zeta = 1...6$ – auxiliary variables, and $u_{iæj\lambda}^{(v,1)}$, $u_{iæj\lambda}^{(v,2)}$, $u_{iæj\lambda}^{(v,3)}$ – auxiliary control actions, which must satisfy the following constraints:

$$u_{iæj\lambda}^{(v,1)}\left(a_{iæ}^{(o,2)}-\sum_{i=1}^{m}\sum_{\lambda=1}^{l}x_{iæj\lambda}^{(v,1)}\right)=0, \quad (99)$$

$$u_{iæj\lambda}^{(v,2)}x_{iæj\lambda}^{(v,4)}=0,\ u_{iæj\lambda}^{(v,3)}x_{iæj\lambda}^{(v,1)}=0; \quad (100)$$

$$u_{iæj\lambda}^{(v,1)}(t)\in\{0,1\},\ u_{iæj\lambda}^{(v,2)}(t)\in\{0,1\},\ u_{iæj\lambda}^{(v,3)}(t)\in\{0,1\}. \quad (101)$$

Constraints (99) and (100) define a possible variant of "activating" the auxiliary control actions $u_{iæj\lambda}^{(v,1)}(t), u_{iæj\lambda}^{(v,2)}(t), u_{iæj\lambda}^{(v,3)}(t)$.

Taking the above into account, the first approach to formalizing continuity conditions reduces to the formulation of isoperimetric conditions of the following form:

$$\int_{T_0}^{T_f}\left(1-u_{iæj\lambda}^{(k,1)}\right)x_{iæj\lambda}^{(v,4)}x_{iæj\lambda}^{(k,1)}\left(a_{iæ}^{(o,2)}-x_{iæ}^{(o,2)}\right)\mathrm{d}\tau=0, \quad (102)$$

$$\int_{T_0}^{T_f}\left(1-u_{iæj\lambda}^{(o,1)}\right)x_{iæj\lambda}^{(v,1)}x_{iæj\lambda}^{(k,1)}\left(a_{iæ}^{(o,2)}-x_{iæ}^{(o,2)}\right)\mathrm{d}\tau=0, \quad (103)$$

where $x_{iæj\lambda}^{(v,1)}(t_0)=x_{iæj\lambda}^{(v,4)}(t_0)=0$, $x_{iæj\lambda}^{(v,1)}(T_f)\in R^1$, $x_{iæj\lambda}^{(v,4)}(T_f)\in R^1$ – the set of real numbers. Relations (102) and (103) define, respectively, the constraints on the continuity of executing the channel reconfiguration C_λ^j operation $D_{æ}^{(i,j)}$. It should be noted that the constraints on the continuity of operations related to the replenishment (regeneration) of stored and non-renewable resources are formulated in the same way as for interaction operations.

An alternative approach to formalizing the continuity constraints of operations and channel reconfiguration in information systems may also be proposed. These constraints, when expressed as additional boundary conditions, are written as follows:

$$\left.\left\{\left[x_{iæj\lambda}^{(v,3)}x_{iæj\lambda}^{(v,1)}+\frac{\left(a_{iæ}^{(o,2)}\right)^2}{2}-x_{iæj\lambda}^{(v,2)}\right]^2 x_{iæj\lambda}^{(v,1)}\right\}\right|_{t=T_f}=0, \quad (104)$$

$$\left.\left(x_{iæj\lambda}^{(v,6)}-x_{iæj\lambda}^{(v,4)}\right)^2\right|_{t=T_f}=0.$$

Subject to the condition, $x_{iæj\lambda}^{(v,\zeta)}(T_0)=0$, $x_{iæj\lambda}^{(v,\zeta)}(T_f)\in R^1$.

In expression (104), the value of the product $x_{iæj\lambda}^{(v,3)}x_{iæj\lambda}^{(v,1)}$ is numerically equal to the area under the integrand curve corresponding to the solution of the first equation in formula (97) over the time interval $(t'_{iæj\lambda}, T_f]$ where $t'_{iæj\lambda}$, t – the moment when the operation $D_{æ}^{(i,j)}$, performed by the channel, is completed C_λ^j.

The value of $(a_{iæ}^{(o,2)})^2/2$ is numerically equal to the area under the integrand curve corresponding to the solution of the first equation in formula (97) over the time interval $\left(T_0, t'_{iæj\lambda}\right]$, assuming that the interaction operation (OA) was executed without interruption using the resources of a single channel C_λ^j. From the analysis of expression (104), it follows that in the case where the OA $D_{æ}^{(i,j)}$ was executed by channel C_λ^j without interruptions, the difference between the values inside the square brackets equals zero. Otherwise (if OA $D_{æ}^{(i,j)}$ was interrupted), this difference is non-zero. To account for cases in which the channel C_λ^j is not scheduled to perform OA $D_{æ}^{(i,j)}$ within the interval $(T_0, T_f]$, an additional multiplier is introduced into expression (104) $x_{iæj\lambda}^{(v,1)}$, which takes the value zero at time $t = T_0$.

5. 8. Model for managing the security of information systems under centralized control

The purpose of developing a model for managing the security of information networks is as follows:

– to model the allocation of the required number of resources for each element of the information network in response to a specific type of cyberattack, within a limited time interval;

– to model the number of engaged resources in each element of the information system, as well as to model the number of available (free) resources in the system.

The need for additional resource allocation is assumed to be deterministic and time-dependent. Such resource allocation planning accounts for constraints on resource levels (preventing shortages or overutilization), as well as the minimization of total costs, including redistribution between the elements of the information system.

To model the security management process of information systems, the following notations are introduced:

$N = i|i = 1,\dots,n$: the set of n service requests within each element of the information system;

$P = 0_p|0_p = 0_1,\dots, 0_m$: the set of m total information system resources;

$N_{p=} i|i = 0_p$, $1\dots n$: the set representing n service requests, where node 0_p represents a particular information system element p that supplies resources;

$R = r|r = 1,\dots u$: the set of u types of information system resources used for protection against a specific type of cyberattack;

$V = v|v = 1,\dots k$: the set of k homogeneous information channels with capacity Q and their respective bandwidth.

Resource reserves and consumption in the information system:

– $H_p^{L,r}$, $h_i^{L,r}$, $H_p^{E,r}$, $h_i^{E,r}$: the cost of maintaining the readiness of information system resources in element p for the benefit of element i;

– $I_{p0}^{L,r}$, $L_{i0}^{L,r}$, $I_{p0}^{E,r}$, $L_{i0}^{E,r}$: the initial level of information system resources of type r in element p intended for element i;

– C_p^L, c_i^L, C_p^E, c_i^E : the maximum volume of information system resources in element p allocated for element i;

– D_{pit}^r : the required amount of resources to be delivered from element p to satisfy the needs of element $i \in N$ during the period $t \in T$.

Costs associated with the transfer of computing resources between information system elements:

The distance between information system elements $i \in N_p$, $j \in N_p$, d_{ij}^p.

– w_L^r and w_E^r : weighting coefficients of utilized and unused resources of type r within the information system;

– e_r: the cost of allocating one unit of information system resources;

– s_r: the cost of utilizing resources of type r from another element of the information system.

Information system resource maintenance costs:

– g_r: the cost of maintaining a single unit of information system resource of type r.

The model for managing the security of information systems within a closed information system – comprising multiple elements that supply available resources and multiple elements that utilize them – is described as follows

$$\begin{aligned}\min &\sum_{i\in N}\sum_{t\in T}\sum_{r\in R}\left(h_i^{Lr}L_{it}^{Lr}+h_i^{Er}L_{it}^{Er}\right)+\\ &+\sum_{p\in P}\sum_{t\in T}\sum_{r\in R}\left(H_p^{L,r}I_{pt}^{Lr}+H_p^{Er}I_{pt}^{Er}\right)+\\ &+\sum_{p\in P}\sum_{t\in T}\sum_{r\in R}e_r n_t^{p,r}+\sum_{p\in P}\sum_{t\in T}\sum_{p'\in P}\sum_{r\in R}g_r F_{pt}^{p'r}+\\ &+\sum_{i\in N}\sum_{p\in P}\sum_{p'\in P}\sum_{t\in T}\sum_{r\in R}s_r W_{ip't}^{pr}+\\ &+\sum_{p\in P}\sum_{t\in T}\sum_{i\in N_p}\sum_{j\in N_p}\left(a\sum_{v\in V}x_{ijvt}^p+\sum_{r\in R}b\left(w_L^r X_{ijt}^{pr}+w_E^r E_{ijt}^{pr}\right)d_{ij}^p\right),\end{aligned} \quad (105)$$

subject to the following conditions:

$$L_{pit}^{Lr} = L_{pit-1}^{Lr} + \sum_{p' \in P} Q_{pit}^{p'r} - D_{pit}^{r},$$

$$\forall i \in N, t \in T, p \in P, r \in R, \quad (106)$$

$$I_{pt}^{Lr} = I_{pit-1}^{Lr} - \sum_{i \in N} \sum_{p' \in P} Q_{pit}^{p'r} + \sum_{p' \in P} F_{pt}^{p'r},$$

$$\forall t \in T, p \in P, r \in R, \quad (107)$$

$$L_{it}^{Er} = L_{it-1}^{Er} - \sum_{p \in P} Z_{it}^{pr} + \sum_{p \in P} D_{pit}^{r} - \sum_{p \in P} \sum_{p' \in P} W_{ip't}^{pr},$$

$$\forall i \in N, t \in T, r \in R, \quad (108)$$

$$I_{pt}^{Er} = I_{pt-1}^{Er} + \sum_{i \in N} Z_{it}^{pr} - \sum_{p' \in P} F_{pt}^{p'r} + n_t^{pr} + \sum_{p' \in P} W_{ip't}^{pr},$$

$$\forall p \in P, t \in T, r \in R, \quad (109)$$

$$\sum_{i \in N_p, i \neq j} \left(X_{ijt}^{pr} - X_{jit}^{pr} \right) = \sum_{p' \in P} Q_{pjt}^{p'r},$$

$$\forall j \in N, p \in P, t \in T, r \in R, \quad (110)$$

$$\sum_{i \in N_p, i \neq j} \left(E_{jit}^{pr} - E_{ijt}^{pr} \right) = Z_{jt}^{pr} + \sum_{p' \in P} W_{jp't}^{pr},$$

$$\forall j \in N, p \in P, t \in T, r \in R, \quad (111)$$

$$0 \le \sum_{p \in P} \sum_{r \in R} L_{pit}^{Lr} \le c_i^L \; \forall i \in N, t \in T, \quad (112)$$

$$0 \le \sum_{r \in R} I_{pt}^{Lr} \le C_p^L, \forall p \in P, t \in T, \quad (113)$$

$$0 \le \sum_{p \in P} \sum_{r \in R} L_{pit}^{Er} \le c_i^E, \forall i \in N, t \in T, \quad (114)$$

$$0 \le \sum_{r \in R} I_{pt}^{Er} \le C_p^E, \forall p \in P, t \in T, \quad (115)$$

$$\sum_{p \in P} \sum_{r \in R} \left(X_{ijt}^{pr} + E_{ijt}^{pr} \right) \le Q \sum_{p \in P} \sum_{v \in V} x_{ijvt}^{p}, \forall i, j \in N_p, t \in T, \quad (116)$$

$$\sum_{i \in N_p} \sum_{v \in V} x_{ijvt}^{p} \le 1, \forall j \in N, p \in P, t \in T, \quad (117)$$

$$\sum_{i \in N_p i \neq j} x_{ijvt}^{p} = \sum_{i \in N_p i \neq j} x_{jivt}^{p}, \forall vs. \in V, j \in N_p, p \in P, t \in T, \quad (118)$$

$$\sum_{j \in N} x_{0_p jvt}^{p} \le 1, \forall vs. \in V, p \in P, t \in T. \quad (119)$$

The analytical expressions presented above form the foundation for managing the security of information systems under centralized control.

5. 8. 1. Mathematical model for managing the security of information systems in self-organization mode

In the self-organization mode model, there is no pooling of shared resources among the elements of the information system $W_{ip't}^{pr} = F_{pt}^{p'r} = 0$ for $p' \neq p, \forall p, p' \in P, i \in N, t \in T, r \in R$. Each element of the information system independently manages its own resources with respect to the elements acting as resource requesters. Thus, the mathematical model is solved independently for each IS element that supplies resources, and the costs to be minimized include expenses associated with maintaining an adequate level of IS resources and transportation costs for their delivery. The model is described as follows

$$\min \sum_{i \in N} \sum_{t \in T} \sum_{r \in R} \left(h_i^{Lr} L_{it}^{Lr} + h_i^{Er} L_{it}^{Er} \right) +$$
$$+ \sum_{t \in T} \sum_{r \in R} \left(H_p^{L,r} I_{pt}^{Lr} + H_p^{Er} I_{pt}^{Er} \right) +$$
$$+ \sum_{t \in T} \sum_{r \in R} e_r n_t^{p,r} + \sum_{p \in P} \sum_{t \in T} \sum_{p' \in P} \sum_{r \in R} g_r F_{pt}^{p'r} +$$
$$+ \sum_{t \in T} \sum_{i \in N_p} \sum_{j \in N_p} \left(a \sum_{v \in V} x_{ijvt}^{p} + \sum_{r \in R} b \left(w_L^r X_{ijt}^{pr} + w_E^r E_{ijt}^{pr} \right) d_{ij}^{p} \right). \quad (120)$$

The objective function aims to minimize the total cost incurred by the IS element p in maintaining the necessary resources in readiness for delivery to each requester. This includes the cost of keeping resources available for use, as well as the fixed and variable transportation costs required for their delivery.

These costs depend on:

$$L_{pit}^{Lr} = L_{pit-1}^{Lr} + Q_{pit}^{r} - D_{pit}^{r}, \forall i \in N, t \in T, r \in R, \quad (121)$$

$$I_{pt}^{Lr} = I_{pt-1}^{Lr} - \sum_{i \in N} Q_{pit}^{r} + F_{pt}^{r}, \forall t \in T, r \in R, \quad (122)$$

$$L_{it}^{Er} = L_{it-1}^{Er} - \sum_{p \in P} Z_{it}^{pr} + \sum_{p \in P} D_{pit}^{r}, \forall i \in N, t \in T, r \in R, \quad (123)$$

$$I_{pt}^{Er} = I_{pt-1}^{Er} + \sum_{i \in N} Z_{it}^{pr} - F_{pt}^{r} + n_t^{pr}, \forall t \in T, r \in R, \quad (124)$$

$$\sum_{i \in N_p, i \neq j} \left(X_{ijt}^{pr} - X_{jit}^{pr} \right) = Q_{pjt}^{r}, \forall j \in N, t \in T, r \in R, \quad (125)$$

$$\sum_{i \in N_p, i \neq j} \left(E_{jit}^{pr} - E_{ijt}^{pr} \right) = Z_{jt}^{pr}, \forall j \in N, t \in T, r \in R, \quad (126)$$

$$0 \le \sum_{p \in P} \sum_{r \in R} L_{pit}^{Lr} \le c_i^L, \forall i \in N, t \in T, \quad (127)$$

$$0 \le \sum_{r \in R} I_{pt}^{Lr} \le C_p^L, \forall t \in T, \quad (128)$$

$$0 \le \sum_{p \in P} \sum_{r \in R} L_{pit}^{Er} \le c_i^E, \forall i \in N, t \in T, \quad (129)$$

$$0 \le \sum_{r \in R} I_{pt}^{Er} \le C_p^E, \forall t \in T, \quad (130)$$

$$\sum_{p \in P} \sum_{r \in R} \left(X_{ijt}^{pr} + E_{ijt}^{pr} \right) \le Q \sum_{p \in P} \sum_{v \in V} x_{ijvt}^{p}, \forall i, j \in N_p, t \in T, \quad (131)$$

$$\sum_{i \in N_p} \sum_{v \in V} x_{ijvt}^{p} \le 1, \forall j \in N, t \in T, \quad (132)$$

$$\sum_{i \in N_p i \neq j} x_{ijvt}^{p} = \sum_{i \in N_p i \neq j} x_{jivt}^{p}, \forall vs. \in V, j \in N_p, t \in T, \quad (133)$$

$$\sum_{j \in N} x_{0_p jvt}^{p} \le 1, \forall vs. \in V, t \in T, \quad (134)$$

Q_{pit}^{r} : the quantity of information system resources of type r, owned by supplier p, that were delivered to client i during period t; F_{pt}^{r} : the quantity of available information system resources of type r, owned by supplier p, that were replenished with products at their level during period t.

5. 9. Generalized deterministic logic-dynamic model for managing the structural dynamics of information networks

An analysis of previously developed models for managing structural dynamics shows that, in general, the generalized deterministic dynamic model for managing the structural dynamics of an information system (Model M) can be represented in the following form:

$$\dot{x} = f(x,u,t), \tag{135}$$

$$h_0(x(T_0)) \le O,\ h_1(x(T_f)) \le O, \tag{136}$$

$$q^{(1)}(x,u) = O,\ q^{(2)}(x,u) = O, \tag{137}$$

$$J_i = J_i(x(t),u(t),t) = \\ = \varphi_i(x(t_f)) + \int_{T_0}^{T_f} f_{0i}(x(\tau),u(\tau),\tau)\,\mathrm{d}\tau, i = 1,\dots I_M, \tag{138}$$

where x – the generalized state vector of the multistructural configuration of the information system; u – the generalized control input vector; h_0, h_1 – known vector functions used to define the initial data for the control problem of the structural dynamics of the information system at time $t = T_0$ and the terminal (desired) values of the system state vector at the end of the control interval ($t = T_f$). It should be noted that the boundary conditions in the previously formulated structural dynamics control problems of the information system may be either fixed at both ends of the phase trajectory $x(t)$ or variable. The vector functions $q^{(1)}$, $q^{(2)}$ define the fundamental spatiotemporal, technical, and technological constraints imposed on the functioning process of the information system.

6. Discussion of the results of the polymodel complex operation

The conducted analysis shows that all sets of indicators used to assess the quality of structural dynamics management in information systems can be categorized into the following groups:

J_1 – indicators assessing the operational efficiency of the information system;

J_2 – indicators assessing the throughput capacity of the information system;

J_3 – indicators assessing the quality of operations (tasks) performed as part of the technological control cycles;

J_4 – indicators assessing resource consumption during the functioning of the information system;

J_5 – indicators assessing the flexibility of structural configurations of the information system (structural and functional self-organization indicators);

J_6 – indicators assessing the resilience (survivability) of the information system;

J_7 – indicators assessing the interference resistance of the information system;

J_8 – indicators assessing the reliability of the information system during its target deployment;

J_9 – indicators assessing the security (protection level) of the information system.

The developed model M (135)–(138) is a deterministic, nonlinear, non-stationary, finite-dimensional differential dynamic system with a reconfigurable structure.

The conducted research has demonstrated that, depending on the chosen application method for the information system, structural dynamics management tasks can be formulated as multi-criteria decision-making problems.

The advantages of the proposed polymodel complex include:

– a comprehensive description of the functioning of different types of information systems (expressions (1)–(138)), which improves the accuracy of system modeling for managerial decision-making, in comparison with [6, 9];

– the ability to describe both static and dynamic processes occurring within information systems (expressions (1)–(138)), surpassing the scope of [8, 10];

– support for modeling individual processes or integrated simulations of multiple processes within information systems (expressions (1)–(138)), compared to studies [5–16];

– a dynamic description of the trajectory control process of information systems during operation (expressions (1)–(6)), enabling N-step forecasting of the system's motion, compared to [7, 13];

– modeling of operations management during computational tasks within system functionality (expressions (7)–(26), Tables 1, 2), allowing for rational hardware load planning, compared to [12, 14];

– modeling of dynamic resource management within information systems (expressions (27)–(39)), enabling forecasting of system resource engagement, compared to [11, 18];

– analytical description of flow control processes in information systems (expressions (40)–(48)), supporting flow distribution based on specified criteria, compared to [12, 13];

– modeling of computational operations based on defined parameters (expressions (49)–(58)), improving the accuracy of system computation modeling, compared to [2, 8];

– description of possible structural states of information systems during operation (expressions (59)–(104)), enabling both parametric and structural control, compared to [6, 15];

– modeling the relationship between available resources and system security state (expressions (105)–(138)), compared to [9, 17].

The proposed polymodel complex is recommended for managing information systems with a high level of complexity.

Limitations of the study include the need to account for time delays in collecting and delivering information from system components.

Identified drawbacks of the proposed polymodel complex are:

– the inability to account for the degree of uncertainty in data circulating within information systems;

– higher computational complexity compared to existing approaches.

The proposed polymodel complex enables:

– comprehensive modeling of information system operations;

– identification of effective measures to improve system performance;

– acceleration of heterogeneous data processing while ensuring the required reliability of decision-making;

– reduction of computational resource usage in decision support systems.

Future research directions include developing a set of methodologies for analyzing and forecasting the state of information systems under the influence of destabilizing factors.

7. Conclusions

1. A dynamic model for managing the trajectory of information systems has been proposed. It enables the formulation of new analytical dependencies reflecting the impact of destabilizing factors on the system's trajectory during topology reconfiguration, improving the accuracy of this phenomenon's description by 17%.

2. A dynamic model for managing operations performed by information systems has been introduced. This model

increases the efficiency of establishing analytical dependencies in operation management by 13%.

3. A dynamic model for managing communication channels in information systems has been developed. It improves the accuracy of channel management processes by 16%.

4. A dynamic model for managing the resources of information systems has been designed. It introduces new analytical dependencies for resource management processes and reduces the number of required system resources under equal conditions by 15%.

5. A dynamic model for managing data flows in information systems has been proposed. It reduces the hardware load of information systems by 12% through newly defined analytical dependencies for flow management.

6. A dynamic model for managing the parameters of operations within an information system has been introduced. This model enhances the reliability of parameter management by 14% due to the flexible configuration of the parameter set used.

7. A dynamic model for managing the structural dynamics of information systems has been developed. It increases the accuracy of describing the structural reconfiguration process by 18%, owing to a greater number of descriptive parameters.

8. A model for managing the security of information systems under centralized control has been developed. It improves system protection by 23% through a flexible set of indicators characterizing the state of security.

9. A generalized deterministic logical-dynamic model for managing the structural dynamics of information networks has been proposed. This model facilitates the representation of interconnections among individual models within the polymodel complex.

Conflict of interest

The authors declare that there is no conflict of interest related to this study, including financial, personal, authorship, or any other type of conflict that could have influenced the study or its results as presented in this article.

Financing

This study was conducted without any financial support.

Data availability

The manuscript includes associated data stored in a data repository.

Use of artificial intelligence tools

The authors confirm that no artificial intelligence technologies were used in the preparation of the presented work.

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