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2 SET OF MATHEMATICAL MODELS FOR INFORMATION SYSTEMS RESOURCE MANAGEMENT

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ABSTRACT

This section of the research proposes a set of mathematical models for the functioning of information systems. The study is based on artificial intelligence theory, fuzzy set theory, and linguistic models.

The originality of the research lies in:

– the comprehensive description of the functioning process of information systems of various types, which allows improving the accuracy of modeling for subsequent managerial decision-making;

– the description of both static and dynamic processes occurring within information systems;

– the ability to model either an individual process within an information system or to conduct complex modeling of interrelated processes taking place within it;

– the dynamic description of the process of managing the state transitions of information systems during their functioning, which enables forecasting the system's evolution N steps ahead;

– the description of the process of managing computational operations during the functioning of information systems, which allows for planning rational workloads on the hardware infrastructure;

– modeling the dependency between the availability of system resources and the level of its security;

– modeling the dynamics of resource management in the course of system functioning, thereby enabling forecasting of resource utilization;

– describing possible structural states of information systems during their operation, which makes it possible to perform not only parametric but also structural management.

The proposed set of mathematical models is advisable for solving complex information system management tasks characterized by a high degree of complexity.

KEYWORDS

Information systems, destabilizing factors, levels of functioning, integrated modeling, efficiency, reliability.

Information systems are an integral component of all spheres of human activity and are applied to solve a wide range of tasks – from entertainment to highly specialized domains [1–3].

The main tasks addressed by information systems include [3–5]:

– processing heterogeneous data in the interests of a wide range of users, regardless of their application domain;

– storing heterogeneous data for user needs;

– transmitting data between individual users (or groups of users);

– supporting decision-making by authorized individuals;

– providing prerequisites for automated (intelligent) decision-making.

The development trends of modern information systems are aimed at addressing the following conceptual challenges [4–8]:

– improving the efficiency of heterogeneous data processing;

– enhancing the reliability of heterogeneous data processing;

– ensuring fault tolerance and resilience of information systems;

– increasing the accuracy of modeling information system functioning;

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

At the same time, existing scientific approaches to the synthesis and operation of information systems demonstrate insufficient accuracy and convergence. This is primarily due to the following reasons [1–9]:

– the significant influence of the human factor in the initial configuration of information systems;

– the large number of heterogeneous information sources that must be analyzed and further processed during the functioning of information systems;

– the operation of information systems under conditions of uncertainty, which causes delays in processing;

– the presence of numerous destabilizing factors affecting the functioning of information systems, among others.

These challenges stimulate the introduction of various strategies to improve the efficiency of information systems in processing heterogeneous data. One promising approach is the enhancement of existing mathematical models (or the development of new ones) for modeling the functioning of information systems.

The analysis of works [9–71] has shown that the common shortcomings of the above-mentioned studies are as follows:

– modeling of each approach is carried out only at a separate level of information system functioning;

– within a comprehensive approach, typically only two components of information system functioning are considered, which does not allow for a full assessment of the impact of managerial decisions on further functioning;

– the listed models, which are components of the aforementioned approaches, demonstrate weak integration with one another, preventing their unification into a cohesive framework;

– the models presented employ diverse mathematical apparatuses, requiring additional mathematical transformations, which in turn increase computational complexity and reduce modeling accuracy.

The aim of this research is the development of a polymodel complex for managing information system resources. This will allow modeling the functioning of information systems at different levels of their operation to support subsequent managerial decision-making. Such an approach enables the design (or improvement) of software for modern and next-generation information systems through the integration of these models.

To achieve this aim, the following objectives have been defined:

– to develop a polymodel complex for information system resource management;

– to identify the advantages and limitations of the proposed models and outline directions for their further improvement.

The object of the study is information systems. The problem addressed in the study is improving the accuracy of modeling the functioning of information systems. The subject of the study is the functioning processes of information systems using analytical-simulation and logical-dynamic models.

The hypothesis of the study is the potential to enhance both the efficiency and accuracy of information system functioning through the integration of multiple models of information system operation.

The proposed method was modeled in the Microsoft Visual Studio 2022 software environment (USA). The hardware platform used in the research process was based on an AMD Ryzen 5 processor.

2.1 DEVELOPMENT OF A POLYMODEL COMPLEX FOR INFORMATION SYSTEM RESOURCE MANAGEMENT

2.1.1 DYNAMIC MODEL OF INFORMATION SYSTEM MOTION CONTROL

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 $E(t)=\left\|\varepsilon_{ij}(t)\right\|,\ i,j\in\left\{\overline{M}\cup\overline{M}\right\}$, referred to as the contact potential, where $\overline{M}$ – 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,

– and the spatial positions of the objects involved.

Assume the motion state of object B_i at any time moment t is defined by two vectors: $r_i^{(d)}(t)$ and $\dot{r}_i^{(d)}(t), i\in\tilde{M}=\left\{M\cup\overline{M}\right\}$. $r_i^{(d)}(t)$ 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 $x_i^{(d)}=\left\|r_i^{(d)T}\dot{r}_i^{(d)T}\right\|^T$.

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

Model of object motion process M_d

$$\dot{x}_i^{(d)}=f_i^{(d)}\left(x_i^{(d)},u_i^{(d)},t\right). \tag{2.1}$$

Constraints

$$q^{(d)}\left(x^{(d)},u^{(d)},t\right)\le 0. \tag{2.2}$$

Boundary conditions

$$h_0^{(d)}\left(x^{(d)}(T_0)\right)\le 0, h_1^{(d)}\left(x^{(d)}(T_f)\right)\le 0. \tag{2.3}$$

Quality indicators of programmed control:

$$J_1^{(d)} = \varphi^{(d)}\left(x^{(d)}(T_f)\right). \tag{2.4}$$

$$J_2^{(d)} = \int_{T_0}^{T_f} f_0^{(d)}\left(x^{(d)}(\tau), u^{(d)}(\tau), \tau\right) d\tau, \tag{2.5}$$

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

All functions in (2.1)–(2.5) 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

$$\varepsilon_{ij}(t) = \gamma_+\left\{ R_j^{(d)} - \left| r_i^{(d)}(t) - r_j^{(d)}(t) \right| \right\}, \tag{2.6}$$

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 (2.1)–(2.6), 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 (2.1)–(2.6) 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.

2.1.2 DYNAMIC MODEL OF OPERATION CONTROL IN 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:

$$\dot{x}_v^{(0,1)} = \sum_{j=1}^{m} u_{vj}^{(0,1)}; \dot{x}_{iæ}^{(0,2,v)} = \sum_{j=1}^{m} \sum_{\lambda=1}^{l_j} \varepsilon_{ij}(t) \Theta_{iæj\lambda}(t) u_{iæj\lambda}^{(0,2,v)}; \dot{x}_{vj}^{(0,3)} = u_{vj}^{(0,3)}; \tag{2.7}$$

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

Constraints:

$$\sum_{j=1}^{m} u_{vj}^{(0,1)}\left[\sum_{\alpha\in\Gamma_{v1}}\left(a_{\alpha}^{(0,1)}-x_{\alpha}^{(0,1)}(t)\right)+\prod_{\beta\in\Gamma_{v2}}\left(a_{\beta}^{(0,1)}-x_{\beta}^{(0,1)}(t)\right)\right]=0. \tag{2.8}$$

$$\sum_{\lambda=1}^{l_j} u_{iæj\lambda}^{(0,2,v)}\left[\sum_{\tilde{\alpha}\in\Gamma_{v1}}\left(a_{i\tilde{\alpha}}^{(0,2,v)}-x_{i\tilde{\alpha}}^{(0,2,v)}(t)\right)+\prod_{\tilde{\beta}\in\Gamma_{iæ2}}\left(a_{i\tilde{\beta}}^{(0,2,v)}-x_{i\tilde{\beta}}^{(0,2,v)}(t)\right)\right]=0. \tag{2.9}$$

$$\sum_{v=1}^{u} u_{vj}^{(0,1)}(t)\le 1,\forall j;\ \sum_{j=1}^{m} u_{vj}^{(0,1)}(t)\le 1,\forall j;\ u_{vj}^{(0,1)}(t)\in\left\{0,1\right\}. \tag{2.10}$$

$$u_{iæj\lambda}^{(0,2,v)}(t)\in\left\{0,u_{vj}^{(0,1)}\right\};\ u_{vj}^{(0,3)}(t)\in\left\{0,1\right\};\ u_{vj}^{(0,3)}\left(a_{js_i}^{(0,2,v)}-x_{js_j}^{(0,2,v)}(t)\right)=0. \tag{2.11}$$

Boundary conditions

$$h_0^{(o)}\left(x^{(o)}(T_0)\right)\le 0;\ h_1^{(o)}\left(x^{(o)}(T_f)\right)\le 0. \tag{2.12}$$

Quality indicators of programmed operation management:

$$J_1^{(o)}=\sum_{v=1}^{n}\sum_{j=1}^{m} u_{vj}^{(0,3)}(T_f);\ J_{<2,\alpha,v>}^{(o)}=\sum_{i=1}^{m}\sum_{j=1}^{m}\left(x_{\alpha i}^{(0,3)}(T_f)-x_{vj}^{(0,3)}(T_f)\right);\ J_3^{(o)}=T_f-\sum_{j=1} x_{nj}^{(0,1)}(T_f). \tag{2.13}$$

$$J_{<4,i,v>}^{(o)}=\sum_{v,j,\lambda,æ}\int_{T_0}^{T_f}\varepsilon_{ij}(\tau)\Theta_{iæj\lambda}(\tau)u_{iæj\lambda}^{(0,2,v)}(\tau)d\tau,\ j=1,\ldots,m;\ \lambda=1,\ldots,l_j;\ æ=1,\ldots,s_i. \tag{2.14}$$

$$J_{<5,i>}^{(o)}=\int_{T_0}^{T_f}\max_{j}\varepsilon_{ij}(\tau)d\tau, j\ne i. \tag{2.15}$$

$$J_{<6,i>}^{(o)}=\sum_{v,j,æ}\int_{T_0}^{T_f}\left[\varepsilon_{ij}(\tau)-\varepsilon_{ij}(\tau)u_{iæj\lambda}^{(0,2,v)}(\tau)\right]d\tau; \tag{2.16}$$

$$J_7^{(o)}=\sum_{i=1}^{m}\sum_{æ=1}^{s_i}\left(a_{iæ}^{(0,2,v)}-x_{iæ}^{(0,2,v)}(T_f)\right)^2; \tag{2.17}$$

$$J_8^{(o)}=\sum_{v=1}^{n}\sum_{i=1}^{m}\sum_{æ=1}^{s_i}\sum_{j=1}^{m}\sum_{\lambda=1}^{l_j}\int_{T_0}^{T_f}\tilde{\tilde{\alpha}}_{iæj\lambda}^{(v)}(\tau)u_{iæj\lambda}^{(0,2,v)}(\tau)d\tau; \tag{2.18}$$

$$J_9^{(o)} = \sum_{v=1}^{n}\sum_{i=1}^{m}\sum_{æ=1}^{s_i}\sum_{j=1}^{m}\sum_{\lambda=1}^{l_j}\int_{T_0}^{T_f}\tilde{\tilde{\beta}}_{iæ}^{(v)}(\tau)u_{iæj\lambda}^{(0,2,v)}(\tau)d\tau, \tag{2.19}$$

where $x_v^{(0,1)}(t)$ – variable representing the duration of task A_v execution on object B_j ($j = 1,\ldots,m$) at time t; $x_{iæ}^{(0,2,v)}(t)$ – variable characterizing the status of operation execution $D_æ^{(i)}$ (or $D_æ^{(i,j)}$) when solving the problem A_v; $x_v^{(0,3)}(t)$ – 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 $t = T_f$; $t = T_f$; $a_\alpha^{(0,1)}, a_\beta^{(0,1)}, a_{i\tilde{\alpha}}^{(0,2,v)}, a_{i\tilde{\beta}}^{(0,2,v)}, a_{is_i}^{(0,2,v)}, a_{iæ}^{(0,1,v)}$ – specified values (boundary conditions) which values must (or may) be accepted by the corresponding variables $x_\alpha^{(0,1)}, x_\beta^{(0,1)}(t)$, $x_{i\tilde{\alpha}}^{(0,2,v)}(t), x_{i\tilde{\beta}}^{(0,2,v)}(t), x_{is_i}^{(0,2,v)}(t), x_{iæ}^{(0,1,v)}(t)$ at the end of the information systems management interval at a given point in time $t = T_f$; $u_{vj}^{(0,1)}(t), u_{iæj\lambda}^{(0,2,v)}(t), u_{vj}^{(0,3)}(t)$ – controlling influences, where $u_{vj}^{(0,1)}(t)=1$ if task A_v is solved on object B_j; $u_{vj}^{(0,1)}(t)=0$ – otherwise $u_{iæj\lambda}^{(0,2,v)}(t)=1$, if the operation $D_æ^{(i)}$ (or $D_æ^{(i,j)}$) is performed when solving problem A_v using the corresponding channel, $u_{iæj\lambda}^{(0,2,v)}(t)=0$ – otherwise; $u_{vj}^{(0,3)}(t)=1$ at the moment corresponding to the completion of task A_v on object B_j and at all subsequent moments until $t = T_f$, $u_{vj}^{(0,3)}(t)=0$ – in opposite situations; Γ_{v1}, Γ_{v2} – a set of task numbers A_v, directly preceding and technologically related to task A_v using logical operations "AND", "OR" (or alternative OR), respectively; $\Gamma_{iæ1}$, $(\Gamma_{iæ2})$ – a set of interaction operation numbers performed on object B_i, immediately preceding and technologically related to operation $D_æ^{(i)}$ (or $D_æ^{(i,j)}$) 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 $x^{(o)} = \left\| x_1^{(0,1)},\ldots,x_n^{(0,1)}, x_{11}^{(0,2)},\ldots,x_{ms_m}^{(0,2)}, x_{11}^{(0,3)},\ldots,x_{nm}^{(0,3)} \right\|^{\grave{o}}$ at times $t = T_0$ i $t = T_f$.

In **Table 2.1**, 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 $t = T_f$ i $x(T_f)$.

Table 2.1 Examples of possible combinations of boundary conditions

Time moments *t*	State vector *x*		Initial state vector $x(t_0)$			Final state vector $x(tf)$		
			Fixed	Unfixed		Fixed	Unfixed	
				Free	Partially Free		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>	

Thus, constraints (2.8) and (2.9) define possible (alternative) task execution sequences A_v and their corresponding operations. In accordance with constraint (2.10), at any given time, each task A_v may be executed on only one object B_j ($v = 1,...n$; $j = 1,..,m$). Conversely, only one task may be executed on each object B_j only one task can be solved at any given time A_v (these restrictions correspond to the restrictions of classical assignment problems).

Table 2.2 provides examples of the constraints imposed on control inputs $u_{iæj\lambda}^{(0,2,v)}(t)$ or various operational scenarios in servicing information systems.

Table 2.2 Possible variants of constraints

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

In **Tables 2.1** and **2.2**, as well as in the following formulas, let's assume for simplicity that the index of task number A_v, 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 (2.11) specify the conditions under which sets of operations can be executed, as well as the triggering of auxiliary control input $u_{vj}^{(0,3)}(t)$; $J_1^{(o)} \div J_9^{(o)}$. The indicators J_k 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 $t = T_f$; $J_{<2,\alpha,v>}^{(o)}$ — reflects the duration of the time interval during which task A_v was executed.

$J_3^{(o)}$ — denotes the total time interval required for completing all necessary tasks A_v, $v = 1,\ldots,n$; $J^{(o)}_{<4,i,v>}$ — corresponds to the duration of the time interval over which the service operation complex was performed on object B_i while solving task A_v; $J^{(o)}_{<5,i>}$ — equals the total time duration during which object B_i remained within the interaction zone (IZ) of object B_j.

Indicator (2.16) numerically corresponds to the duration of the time interval during which an object awaits service.

Indicator (2.17) 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 (2.18) and (2.19), it becomes possible to indirectly assess the quality of operation execution (OE) and the accuracy in meeting the directive timeframes for completing those operations.

Where:

$\tilde{\tilde{\alpha}}^{(v)}_{iæj\lambda}(\tau)$ — predefined smooth time-dependent weighting functions used to evaluate the quality of operations;

$\tilde{\tilde{\beta}}^{(v)}_{iæ}(\tau)$ — monotonically increasing (or decreasing) time functions, selected based on the directive start/end deadlines for operation execution.

2.1.3 DYNAMIC MODEL OF 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 $D_æ^{(i,j)}$. To simplify the notation in the following formulas — as previously done — 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:

$$\dot{x}^{(k,1)}_{iæj\lambda} = \sum_{j'=1}^{m}\sum_{æ'=1}^{s_i}\Theta_{i'æ'jæ}u^{(k,1)}_{i'æ'j\lambda}\frac{b^{(j,\lambda)}_{i'æ'iæ} - x^{(k,1)}_{iæj\lambda}}{x^{(k,1)}_{i'æ'j\lambda}}, \tag{2.20}$$

$$\dot{x}^{(k,2)}_{j\lambda} = \sum_{i=1}^{m}\sum_{æ=1}^{s_i}(u^{(0,2)}_{iæj\lambda} + u^{(k,1)}_{iæj\lambda}), \tag{2.21}$$

Constraints:

$$u^{(0,2)}_{iæj\lambda}x^{(k,1)}_{iæj\lambda} = 0; \quad x^{(k,1)}_{iæj\lambda}(t) \in \{0;1\}, \tag{2.22}$$

$$\sum_{i=1}^{n}\sum_{æ=1}^{s_i}u^{(k,1)}_{iæj\lambda}(t) \le 1, \quad \forall j, \forall\lambda. \tag{2.23}$$

Boundary conditions:

$$h_0^{(k)}\left(x^{(k)}(T_0)\right) \le 0;$$

$$h_1^{(k)}\left(x^{(k)}(T_f)\right) \le 0. \qquad (2.24)$$

Quality indicators of programmed channel management:

$$J_1^{(k)} = \sum_{\Delta_1=1}^{m-1} \sum_{\Delta_2=\Delta_1+1}^{m} \sum_{\lambda=1}^{l} \sum_{\zeta=1}^{l} \int_{T_0}^{T_f} \left(x_{\Delta_1\lambda}^{(k,2)}(\tau) - x_{\Delta_2\zeta}^{(k,2)}(\tau) \right) d\tau; \qquad (2.25)$$

$$J_2^{(\hat{e})} = \sum_{\Delta_1=1}^{m-1} \sum_{\Delta_2=\Delta_1+1}^{m} \sum_{\lambda=1}^{l} \sum_{\zeta=1}^{l} \left(x_{\Delta_1\lambda}^{(\hat{e}2)}(T_f) - x_{\Delta_2\zeta}^{(\ k2)}(T_f) \right), \qquad (2.26)$$

where $x_{i æ j\lambda}^{(k,1)}(t)$ – the state of channel $C_\lambda^{(i)}$ on object B_j using the reconfiguration from a readiness state for executing operation $D_{æ'}^{(i,j)}$ to a readiness state for operation $D_{æ}^{(i,j)}$; $b_{i'æ'iæ}^{(j,\lambda)}$ – a predefined value equal to the duration of the reconfiguration process between the respective channel states; $u_{i æ j\lambda}^{(k,1)}(t)$ – the control input, where $u_{i æ j\lambda}^{(k,1)}(t) = 1$, if $C_\lambda^{(i)}$ if the channel is undergoing reconfiguration, and $u_{i æ j\lambda}^{(k,1)}(t) = 0$ – otherwise. Constraints (2.22), (2.23) define the sequence of channel reconfiguration $C_\lambda^{(i)}$ and the conditions under which it can be initiated $C_\lambda^{(i)}$. The variable $x_{j\lambda}^{(k,2)}(t)$ represents the time interval during which the channel is actively engaged. As in the previous model $h_0^{(k)}$, $h_1^{(k)}$ – known differentiable functions that define boundary conditions for the state vector $x^{(k)} = \left\| u_{1111}^{(k,1)}, \ldots, u_{msml}^{(k,1)}, u_{11}^{(k,2)}, \ldots, u_{ml}^{(k,2)} \right\|^{T}$.

Indicators (2.25) and (2.26) are intended to evaluate the uniformity of channel utilization $t \in (T_0, T_f]$ throughout the control interval and at its completion.

2.1.4 DYNAMIC MODEL OF INFORMATION SYSTEM RESOURCE MANAGEMENT

Resource management process model:

$$\dot{x}_{j\lambda\pi}^{(p,1)} = -\sum_{i=1}^{m} \sum_{æ=1}^{s_i} d_{i æ j\lambda}^{(\pi)} \left(u_{i æ j\lambda}^{(o,2)} + u_{i æ j\lambda}^{(k,1)} \right), \qquad (2.27)$$

$$\dot{x}_{j\lambda\mu}^{(p,2)} = -\sum_{i=1}^{m} \sum_{æ=1}^{s_i} g_{i æ j\lambda}^{(\mu)} \left(u_{i æ j\lambda}^{(o,2)} + u_{i æ j\lambda}^{(k,1)} \right), \qquad (2.28)$$

$$\dot{x}_{j\lambda\pi\eta}^{(p,1)} = -\sum_{i=1}^{m} \sum_{æ=1}^{s_i} d_{i æ j\lambda}^{(\pi)} \left(u_{i æ j\lambda}^{(o,2)} + u_{i æ j\lambda}^{(k,1)} \right) + u_{j\lambda\pi(\eta-1)}^{(p,1)}, \qquad (2.29)$$

$$\dot{x}^{(p,2)}_{j\lambda\pi\eta'} = -\sum_{i=1}^{m}\sum_{æ=1}^{s_i} g^{(\mu)}_{iæj\lambda}\left(u^{(o,2)}_{iæj\lambda} + u^{(k,1)}_{iæj\lambda}\right) + u^{(p,2)}_{j\lambda\mu(\eta'-1)}, \tag{2.30}$$

$$\dot{x}^{(p,3)}_{j\lambda\pi\eta} = u^{(p,1)}_{j\lambda\pi\eta};\ \dot{x}^{(p,4)}_{j\lambda\mu\eta'} = u^{(p,2)}_{j\lambda\mu\eta}. \tag{2.31}$$

Constraints:

$$\sum_{i,æ,\lambda} d^{(\pi)}_{iæj\lambda}\left(u^{(o,2)}_{iæj\lambda} + u^{(k,1)}_{iæj\lambda}\right) \le \tilde{H}^{(\pi)}_{j}(t), \tag{2.32}$$

$$\sum_{i,æ,\lambda}\int_{T_0}^{T_f} g^{(\mu)}_{iæj\lambda}\left(u^{(o,2)}_{iæj\lambda}(\tau) + u^{(k,1)}_{iæj\lambda}(\tau)\right)d\tau \le \int_{T_0}^{T_f}\tilde{\tilde{H}}^{(\mu)}_{j}(\tau)d\tau, \tag{2.33}$$

$$u^{(p,1)}_{j\lambda\pi\eta}\left(a^{(p,3)}_{j\lambda\pi(\eta-1)} - x^{(p,3)}_{j\lambda\pi(\eta-1)}\right) = 0,\ u^{(ð,1)}_{j\lambda\pi\eta}\, x^{(ð,1)}_{j\lambda\pi\eta} = 0, \tag{2.34}$$

$$u^{(ð,2)}_{j\lambda\mu\eta}\left(d^{(ð,4)}_{j\lambda\pi(\eta'-1)} - x^{(ð,4)}_{j\lambda\pi(\eta'-1)}\right) = 0,\ u^{(p,2)}_{j\lambda\mu\eta'}\, x^{(p,2)}_{j\lambda\mu\eta'} = 0, \tag{2.35}$$

$$u^{(p,1)}_{j\lambda\pi\eta}(t)u^{(p,2)}_{j\lambda\mu\eta}(t) \in \{0,1\},\ \eta = 1,\ldots,\tilde{\rho}_{\lambda};\ \eta' = 1,\ldots,\tilde{\tilde{\rho}}_{\lambda}. \tag{2.36}$$

Boundary conditions

$$h^{(p)}_{0}\left(x^{(p)}(T_0)\right) \le 0;\ h^{(p)}_{1}\left(x^{(p)}(T_f)\right) \le 0. \tag{2.37}$$

Quality indicators of programmed resource management:

$$J^{(p)}_{1j\pi} = \sum_{\lambda=1}^{l_j}\sum_{\eta=1}^{\tilde{\rho}_{\lambda}} x^{(p,3)}_{j\lambda\pi\eta}; \tag{2.38}$$

$$J^{(p)}_{2j\mu} = \sum_{\lambda=1}^{l_j}\sum_{\eta'=1}^{\tilde{\tilde{\rho}}_{\lambda}} x^{(p,4)}_{j\lambda\mu\eta'}, \tag{2.39}$$

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 $C^{(j)}_{\lambda}$; $d^{(\pi)}_{iæj\lambda}$, $g^{(\mu)}_{iæj\lambda}$ – 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) $D^{(i,j)}_{æ}$ 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 (2.32) and (2.33) 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 (2.29)–(2.31) 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 (η-1)-th cycle (on (η›-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 (2.34)–(2.36) 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 (2.38) and (2.39) characterize the time intervals during which the regeneration of non-renewable $\Phi S^{(j)}_{\pi}$ and renewable resources $\Phi N^{(j)}_{\mu}$, 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.

2.1.5 DYNAMIC MODEL OF FLOW MANAGEMENT IN INFORMATION SYSTEMS

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

$$\dot{x}^{(p,1)}_{iæj\lambda\rho} = u^{(p,1)}_{iæj\lambda\rho}; \ \dot{x}^{(p,2)}_{iæj\lambda\rho} = u^{(p,2)}_{iæj\lambda\rho}; \tag{2.40}$$

$$0 \le u^{(p,1)}_{iæj\lambda\rho} \le c^{(p,1)}_{iæj\lambda\rho} u^{(o,2)}_{iæj\lambda}; \tag{2.41}$$

$$u^{(p,2)}_{iæj\lambda\rho}\left(a^{(p,1)}_{iæ\rho} - x^{(p,1)}_{iæj\lambda\rho}\right) = 0; \ u^{(p,2)}_{iæj\lambda\rho} x^{(p,2)}_{i\tilde{æ}} = 0; \ u^{(p,2)}_{iæj\lambda\rho}(t) \in \{0,1\}; \tag{2.42}$$

$$\sum_{i=1}^{m}\sum_{\lambda=1}^{l_i}\sum_{æ=1}^{s_i}\sum_{\rho=1}^{k_i} x^{(p,1)}_{iæj\lambda\rho}\left(u^{(o,2)}_{iæj\lambda\rho} + {}^{(o,2)}_{iæj\lambda\rho}\right) \le \tilde{P}^{(1)}_{j}; \tag{2.43}$$

$$\sum_{i=1}^{m}\sum_{\lambda=1}^{l_i}\sum_{æ=1}^{s_i} u^{(p,1)}_{iæj\lambda\rho} \le \tilde{P}^{(2)}_{j\rho}; \tag{2.44}$$

$$\sum_{\lambda=1}^{l_i}\sum_{æ=1}^{s_i}\sum_{\rho=1}^{k_i} u^{(p,1)}_{iæj\lambda\rho} \le \tilde{P}^{(3)}_{ij}. \tag{2.45}$$

Boundary conditions:

$$h^{(p)}_0\left(x^{(p)}(T_0)\right) \le 0;$$

$$h^{(p)}_1\left(x^{(p)}(T_f)\right) \le 0. \tag{2.46}$$

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

$$J_1^{(p)} = \sum_{i=1}^{m}\sum_{æ=1}^{s_i}\sum_{\substack{j=1 \\ i\neq j}}^{m}\sum_{\lambda=1}^{l_i}\sum_{\rho=1}^{k_i}\left(a_{iæ\rho}^{(p,1)} - x_{iæj\lambda\rho}^{(p,1)}\right)x_{iæj\lambda}^{(p,1)}\Bigg|_{t=T_f}, \tag{2.47}$$

$$J_2^{(p)} = \sum_{i=1}^{m}\sum_{æ=1}^{s_i}\sum_{\substack{j=1 \\ i\neq j}}^{m}\sum_{\lambda=1}^{l_i}\sum_{\rho=1}^{k_i}\int_{T_0}^{T_f} x_{iæj\lambda}^{(p,2)}(\tau)d\tau, \tag{2.48}$$

where $x_{iæj\lambda\rho}^{(p,1)}(t)$ — 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, $i = j$); $x_{iæj\lambda\rho}^{(p,2)}(t)$ — 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) $D^{(i,j)}$ via channels $C_\lambda^{(i)}, C_\lambda^{(j)}$; $c_{iæj\lambda\rho}^{(p,1)}$ — a given constant that defines the maximum allowable value of $u_{iæj\lambda\rho}^{(p,1)}$; $u_{iæj\lambda\rho}^{(p,1)}$ — 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 $i = j$); $u_{iæj\lambda\rho}^{(p,2)}(t)$ — auxiliary control action that takes the value $u_{iæj\lambda\rho}^{(p,2)}(t) = 1$, if the reception (or processing) of information at object Bj, $u_{iæj\lambda\rho}^{(p,2)}(t) = 0$ — 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; $a_{iæ\rho}^{(p,1)}$ — 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 (2.47) 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 $x_{iæj\lambda}^{(p,1)}$ 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 (2.48) 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).

2.1.6 DYNAMIC MODEL OF PARAMETER CONTROL OF OPERATIONS CONDUCTED IN THE 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:

$$\dot{x}_i^{(d)} = F(t)x_i^{(d)}, \tag{2.49}$$

$$y_{j\lambda}^{(i)}(t) = d_{j\lambda}^T(t)x_i^{(d)} + \xi_{j\lambda}, \tag{2.50}$$

where $x_i^{(d)} = \left\| r_i^{(d)T} \dot{r}_i^{(d)T} \right\|^T$ – the state vector of the motion of object B_i; $F_i(t)$ – 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 $y_{j\lambda}^{(i)}(t)$. In this case, the model for controlling the parameters of operations takes the following form

$$\dot{Z} = -Z_i F_i - F_i^T Z_i - \sum_{j=1}^{n} \sum_{\text{æ} \in \Gamma_{i\text{æ}}} \sum_{\lambda=1}^{l_j} u_{i\text{æ}j\lambda}^{(e,1)} \frac{d_{i\lambda} d_{j\lambda}^T}{\sigma_{j\lambda}^2}, Z_i = \tilde{\tilde{K}}_i^{-1}. \tag{2.51}$$

Constraints

$$0 \le u_{i\tilde{\text{æ}}j\lambda}^{(e,1)} \le c_{j\lambda}^{(e)} u_{i\text{æ}j\lambda}^{(o,2)}. \tag{2.52}$$

Boundary conditions:

– option "a":

$$t = T_0,\ \tilde{\tilde{K}}_i(T_0) = \tilde{\tilde{K}}_{io}, \tag{2.53}$$

$$t = T_f,\ b_\gamma^{\grave{o}} \tilde{\tilde{K}}_i b_\gamma \le \sigma_{\gamma i}^2; \tag{2.54}$$

– option "b":

$$t = T_0,\ \tilde{\tilde{K}}_i(T_0) = \tilde{\tilde{K}}_{io}, \tag{2.55}$$

$$t = T_f,\ \int_{T_0}^{T_f} \sum_{i,\tilde{æ},j,\lambda} u_{i\tilde{æ}j\lambda}^{(e,1)}(\tau)d\tau \le \tilde{J}_1^{(e)}, \tag{2.56}$$

Performance indicators for operational parameter management in information systems:

– option "a"

$$J_1^{(e)} = \int_{T_0}^{T_f} \sum_{i,\tilde{æ},j,\lambda} u_{i\tilde{æ}j\lambda}^{(e,1)}(\tau)d\tau; \tag{2.57}$$

– option "b"

$$J_{2\gamma i}^{(e)} = b_\gamma^T \tilde{\tilde{K}}_i b_\gamma, \tag{2.58}$$

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; $u_{i\tilde{æ}j\lambda}^{(e,1)}$ – the intensity of measurements of the motion parameters of object B_i; $\Gamma_{i\tilde{æ}}$ – 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; $b_\gamma = \|0,0,\ldots,0,1,0,\ldots,0\|^T$ – 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 (2.56) allows for a quantitative assessment of the total resource expenditure by information systems during the execution of measurement operations.

The objective function (2.57) characterizes the accuracy of determining the γ-th element of the state vector of object B_i.

2.1.7 DYNAMIC MODELS OF STRUCTURAL DYNAMICS MANAGEMENT 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_O) and communication channels (model M_K).

2.1.7.1 MODEL OF POLYSTRUCTURAL STATE MANAGEMENT OF INFORMATION SYSTEMS

The model describing the process of managing polystructural states (model $M_{\tilde{n}}^{(1)}$):

$$\dot{x}_{\delta\eta_1}^{(c,1)} = u_{\delta\eta_1}^{(c,1)};\ \dot{\tilde{x}}_{\delta}^{(c,1)} = \sum_{\delta'=1}^{K_\Delta} \frac{\tilde{h}_{\delta'\delta}^{(c,1)} - \tilde{x}_{\delta}^{(c,1)}}{\tilde{x}_{\delta'}^{(c,1)}} \tilde{u}_{\delta'}^{(c,1)};\ \dot{\tilde{\tilde{x}}}_{\delta\eta_1}^{(c,1)} = \tilde{\tilde{u}}_{\delta\eta_1}^{(c,1)}; \tag{2.59}$$

$$\delta = 1,\dots,K_\Delta;\ \eta_1 = 1,\dots,Œ_1.$$

Constraints:

$$\sum_{\delta=1}^{K_\Delta}\left(u_{\delta\eta_1}^{(c,1)}(t) + \tilde{u}_{\delta}^{(c,2)}\right) \le 1, \forall \eta_1;\ \ u_{\delta\eta_1}^{(c,1)}(t) \in \{0,1\};\ \ \tilde{u}_{\delta}^{(c,1)}(t), \tilde{\tilde{u}}_{\delta\eta_1}^{(c,1)}(t) \in \{0,1\}; \tag{2.60}$$

$$\sum_{\eta_1=1}^{?_1} u_{\delta\eta_1}^{(c,1)} \cdot \tilde{x}_{\delta}^{(c,1)} = 0,\ \ u_{\delta\eta_1}^{(c,1)}\left(a_{\delta(\eta_1-1)}^{(c,1)} - x_{\delta(\eta_1-1)}^{(c,1)}(t)\right) = 0; \tag{2.61}$$

$$\tilde{u}_{\delta}^{(c,1)}\left[\sum_{\chi'\in\Gamma_{\delta1}^{(2)}}\ \sum_{\omega'\in\Gamma_{\delta2}^{(2)}} \tilde{x}_{\chi'\omega'}^{(c,2)} + \prod_{\chi''\in\Gamma_{\delta3}^{(2)}}\ \prod_{\omega''\in\Gamma_{\delta4}^{(2)}} \tilde{x}_{\chi''\omega''}^{(c,2)}\right] = 0; \tag{2.62}$$

$$\tilde{\tilde{u}}_{\delta\eta_1}^{(c,1)}\left(a_{\delta\eta_1}^{(c,1)} - x_{\delta\eta_1}^{(c,1)}(t)\right) = 0. \tag{2.63}$$

Boundary conditions:

$$t = T_0 : x_{\delta\eta_1}^{(c,1)}(T_0) = \tilde{\tilde{x}}_{\delta\eta_1}^{(c,1)}(T_0) = 0;\ \ \tilde{x}_{\delta\eta_1}^{(c,1)}(T_0) \in R^1; \tag{2.64}$$

$$t = T_f : x_{\delta\eta_1}^{(c,1)}(T_f) \in R^1;\ \ \tilde{x}_{\delta\eta_1}^{(c,1)}(T_f) \in R^1;\ \ \tilde{\tilde{x}}_{\delta\eta_1}^{(c,1)}(T_f) \in R^1. \tag{2.65}$$

Performance indicators for managing polystructural macrostates of information systems:

$$J_{1\delta}^{(c,1)} = \sum_{\eta_1=1}^{Œ_1} x_{\delta\eta_1}^{(c,1)}(T_f); \tag{2.66}$$

$$J_{2}^{(c,1)} = \sum_{\eta_1=1}^{Œ_1}\sum_{\delta=1}^{K_\Delta}\left(a_{\delta}^{(c,1)} - x_{\delta\eta_1}^{(c,1)}(T_f)\right)^2; \tag{2.67}$$

$$J_{3\delta}^{(c,1)} = \sum_{\delta=1}^{K_\Delta}\int_{T_0}^{T_f} \tilde{u}_{\delta}^{(c,1)}(\tau)d\tau; \tag{2.68}$$

$$J_{2\eta_1\delta(\eta_1-1)}^{(c,1)} = \left[\tilde{\tilde{x}}_{\delta\eta_1}^{(c,1)} - \left(\tilde{\tilde{a}}_{\delta(\eta_1+1)}^{(c,1)} + \tilde{\tilde{x}}_{\delta(\eta_1+1)}^{(c,1)}\right)\right]\Bigg|_{t=T_f}. \tag{2.69}$$

The following notations are used: $x^{(c,1)}_{\delta\eta_1}(t)$ — a variable characterizing the degree of completion of macrooperation $D^{(c,1)}_{\delta\eta_1}$, 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; $\tilde{x}^{(c,1)}_{\delta}(t)$ — a variable characterizing the degree of completion of the macrooperation $\tilde{D}^{(c,1)}_{\delta}$, 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 $\delta' = \delta$); $\tilde{\tilde{x}}^{(c,1)}_{\delta\eta_1}(t)$ — an auxiliary variable which value numerically corresponds to the duration of the time interval that has passed since the completion of microoperation $D^{(c,1)}_{\delta\eta_1}$; $\tilde{h}^{(c,1)}_{\delta'\delta}(t)$ — a given value numerically equal to the duration of the transition of the information system from polystructural state $S_{\delta'}$ to state S_δ; $u^{(c,1)}_{\delta\eta_1}(t)$ — a control input that takes the value 1 if macrooperation $D^{(c,1)}_{\delta\eta_1}$ must be executed, and 0 otherwise; $\tilde{\tilde{u}}^{(c,1)}_{\delta\eta_1}$ — an auxiliary control input that takes the value 1 at the time corresponding to the completion of microoperation $D^{(c,1)}_{\delta\eta_1}$, and 0 otherwise; $\tilde{u}^{(c,1)}_{\delta}(t)$ — 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 (2.60)–(2.63) define the order and sequence of activation (or deactivation) of the above-mentioned control inputs. In expression (2.62) $\Gamma^{(2)}_{\delta 1}, \Gamma^{(2)}_{\delta 3}, \Gamma^{(2)}_{\delta 2}, \Gamma^{(2)}_{\delta 4}$, it corresponds to the set of indices of structure types and structural states in which those structures may reside.

Indicator (2.66) makes it possible to evaluate the total duration of the information system's presence in microstate S_δ.

The Mayer-type functional (2.67) 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 (2.67) $a^{(c,1)}_{\delta}$, — denotes the directive-specified duration of the information network's presence in the polystructural state S_δ.

Indicator (2.68) provides a quantitative estimate of the total time during which the information network operates in a transitional mode.

Functional (2.69) 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 η1 and (η1+1)).

2.1.7.2 MODEL OF DYNAMICS MANAGEMENT OF STRUCTURES OF A GIVEN TYPE OF INFORMATION SYSTEMS

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

$$\dot{x}^{(c,2)}_{\chi\omega\eta_2} = u^{(c,2)}_{\delta\omega\eta_2};\ \dot{\tilde{x}}^{(c,2)}_{\chi\omega} = \sum_{\omega'=1}^{K_\Omega} \frac{\tilde{h}^{(c,2)}_{\omega'\omega\chi} - \tilde{x}^{(c,2)}_{\chi\omega}}{\tilde{x}^{(c,2)}_{\chi\omega'}} \tilde{u}^{(c,2)}_{\chi\omega'};\ \dot{\tilde{\tilde{x}}}^{(c,2)}_{\chi\omega\eta_2} = \tilde{\tilde{u}}^{(c,2)}_{\chi\omega\eta_2}; \tag{2.70}$$

$$\chi = 1,\dots,K_C;\ \omega = 1,\dots,K_\Omega;\ \eta_2 = 1,\dots,Œ_2.$$

Constraints:

$$\sum_{\omega=1}^{K_\Omega}\left(u^{(c,2)}_{\chi\omega\eta_2}(t) + \tilde{u}^{(c,2)}_{\chi\omega'}\right) \le 1, \forall\chi, \forall\eta_2;\ u^{(c,2)}_{\chi\omega\eta_2}(t) \in \{0,1\};\ \tilde{u}^{(c,2)}_{\chi\omega}(t), \tilde{\tilde{u}}^{(c,2)}_{\chi\omega\eta_2}(t) \in \{0,1\}; \tag{2.71}$$

$$\sum_{\eta_2=1}^{Œ_2} u_{\chi\omega\eta_2}^{(c,2)} \cdot \tilde{x}_{\chi\omega}^{(c,2)} = 0, \; u_{\chi\omega\eta_2}^{(c,2)} \left(a_{\chi\omega(\eta_2-1)}^{(c,2)} - x_{\chi\omega(\eta_2-1)}^{(c,2)}(t) \right) = 0; \tag{2.72}$$

$$\tilde{u}_{\chi\omega}^{(c,2)} \left[\sum_{i' \in \Gamma_{\chi\omega 1}^{(3)}} \sum_{w' \in \Gamma_{\chi\omega 2}^{(3)}} \sum_{f' \in \Gamma_{\chi\omega 3}^{(3)}} \tilde{x}_{i'w'f'}^{(c,3)} + \prod_{i'' \in \Gamma_{\chi\omega 4}^{(3)}} \prod_{w'' \in \Gamma_{\chi\omega 5}^{(3)}} \prod_{f'' \in \Gamma_{\chi\omega 6}^{(3)}} \tilde{x}_{i''w''f''}^{(c,3)} \right] = 0; \tag{2.73}$$

$$\tilde{\tilde{u}}_{\chi\omega\eta_2}^{(c,2)} \left(a_{\chi\omega\eta_2}^{(c,2)} - x_{\chi\omega\eta_2}^{(c,2)} \right) = 0. \tag{2.74}$$

Boundary conditions:

$$t = T_0 : x_{\chi\omega\eta_2}^{(c,2)}(T_0) = \tilde{\tilde{x}}_{\chi\omega\eta_2}^{(c,2)}(T_0) = 0; \; \tilde{x}_{\chi\omega}^{(c,2)}(T_0) \in R^1; \tag{2.75}$$

$$t = T_f : x_{\chi\omega\eta_2}^{(c,2)}(T_f) \in R^1; \; \tilde{x}_{\chi\omega\eta_2}^{(c,2)}(T_f) \in R^1; \; \tilde{\tilde{x}}_{\chi\omega\eta_2}^{(c,2)}(T_f) \in R^1; \tag{2.76}$$

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

$$J_{1\chi\omega}^{(c,2)} = \sum_{\eta_2=1}^{Œ_2} x_{\chi\omega\eta_2}^{(c,2)}(T_f); \tag{2.77}$$

$$J_{2\chi\omega}^{(c,2)} = \sum_{\eta_2=1}^{Œ_2} \tilde{\tilde{u}}_{\chi\omega\eta_2}^{(c,2)}; \tag{2.78}$$

$$J_{3\chi}^{(c,2)} = \int_{T_0}^{T_f} \sum_{\omega=1}^{K_\Omega} \tilde{u}_{\chi\omega}^{(c,2)}(\tau) d\tau; \tag{2.79}$$

$$J_{4\omega\eta_2}^{(c,2)} = \sum_{\chi=1}^{K_C} \tilde{\tilde{u}}_{\chi\omega\eta_2}^{(c,2)}(t); \tag{2.80}$$

$$J_{5\omega\eta_2}^{(c,2)} = \tilde{\tilde{u}}_{\chi\omega\eta_2}^{(c,2)}(t). \tag{2.81}$$

The following notations are used: $x_{\chi\omega\eta_2}^{(c,2)}(t)$ – a variable characterizing the degree of completion of macrooperation $D_{\chi\omega\eta_2}^{(c,2)}$, which describes the process of structure G_χ being in structural state $S_{\chi\omega}$ during the η_2-th control cycle; $\tilde{x}_{\chi\omega}^{(c,2)}(t)$ – 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 $S_{\chi\omega'}$; $\tilde{\tilde{x}}_{\chi\omega\eta_2}^{(c,2)}(t)$ – an auxiliary variable which value numerically equals the time interval that has elapsed since the completion of microoperation $D_{\chi\omega\eta_2}^{(c,2)}$; $\tilde{h}_{\omega'\omega\chi}^{(c,2)}$ – a given value numerically equal to the duration of the transition of structure G_χ from structural state $S_{\chi\omega}$ to structural state $S_{\chi\omega'}$; $u_{\chi\omega\eta_2}^{(c,2)}(t)$ – a control input that takes the value 1 if macrooperation $D_{\chi\omega}^{(c,2)}$, 0 is to be performed, and 0 otherwise; $\tilde{\tilde{u}}_{\chi\omega\eta_2}^{(c,2)}(t)$ – an auxiliary control input that takes the value 1 at the moment corresponding to the completion of macrooperation $D_{\chi\omega\eta_2}^{(c,2)}$, and 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 (2.71)–(2.74) define the order and sequence of activation (or deactivation) of the above-mentioned control inputs.

In expression (2.73) $\Gamma^{(3)}_{\chi\omega1},\Gamma^{(3)}_{\chi\omega4};\Gamma^{(3)}_{\chi\omega2},\Gamma^{(3)}_{\chi\omega5};\Gamma^{(3)}_{\chi\omega3},\Gamma^{(3)}_{\chi\omega6}$, 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 (2.77) 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 (2.78) determines the number of times the structure G_χ has entered structural state $S_{\chi\omega}$. Indicator (2.79) allows for a quantitative assessment of the total time the structure G_χ remains in a transitional state. Indicator (2.80) 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 (2.81) 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 *y* in structural state $S_{\chi\omega}$.

2.1.7.3 MODEL OF MACROSTATE MANAGEMENT OF OBJECTS WITHIN THE INFORMATION SYSTEM

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

$$\dot{x}^{(c,3)}_{iwf\eta_3}=u^{(c,3)}_{iwf\eta_3};\ \dot{\tilde{x}}^{(c,3)}_{iwf}=\sum_{w'=1}^{K_W}\sum_{f'=1}^{K_F}\frac{\tilde{h}^{(c,3)}_{w'f'wf}-\tilde{x}^{(c,3)}_{iwf}}{\tilde{x}^{(c,3)}_{iw'f'}}\tilde{u}^{(c,3)}_{iw'f'};\tag{2.82}$$

$$\dot{\tilde{\tilde{x}}}^{(c,3)}_{iwf\eta_3}=\tilde{\tilde{u}}^{(c,3)}_{iwf\eta_3};\ i=1,\dots,m; w=1,\dots,K_W; f=1,\dots,K_F; \eta_3=1,\dots,Œ_3 .\tag{2.83}$$

Constraints:

$$\sum_{w=1}^{K_W}\sum_{f=1}^{K_F}\left(u^{(c,3)}_{iwf\eta_3}(t)+\tilde{u}^{(c,3)}_{iwf}\right)\le 1,\forall i;\forall\eta_3;\tag{2.84}$$

$$\sum_{i=1}^{m}\sum_{w=1}^{K_W}u^{(c,3)}_{iwf\eta_3}(t)\le 1,\forall f;\forall\eta_3;\tag{2.85}$$

$$u^{(c,3)}_{iwf\eta_3}(t)\in\{0,1\};\ \tilde{u}^{(c,3)}_{iwf}(t),\tilde{\tilde{u}}^{(c,3)}_{iwf\eta_3}(t)\in\{0,1\};\tag{2.86}$$

$$\sum_{\eta_3=1}^{Œ_3}u^{(c,3)}_{iwf\eta_3}\cdot\tilde{x}^{(c,3)}_{iwf\eta_3}=0,\ u^{(c,3)}_{iwf\eta_3}\left(a^{(c,3)}_{iwf(\eta_3-1)}-x^{(c,3)}_{iwf(\eta_3-1)}\right)=0;\tag{2.87}$$

$$\tilde{u}^{(c,3)}_{iwf}\left[\sum_{\alpha'\in\Gamma^{(4)}_{iwf1}}\left(a^{(o,2)}_{i\alpha'}-\tilde{x}^{(o,2)}_{i\alpha'}(t)\right)+\prod_{\beta'\in\Gamma^{(4)}_{iwf2}}\left(a^{(o,2)}_{i\beta'}-\tilde{x}^{(o,2)}_{i\beta'}(t)\right)\right]=0;\tag{2.88}$$

$$\tilde{\tilde{u}}^{(c,3)}_{iwf\eta_3}\left(\tilde{\tilde{a}}^{(c,3)}_{iwf(\eta_3-1)}-\tilde{\tilde{x}}^{(c,3)}_{iwf(\eta_3-1)}\right)=0. \tag{2.89}$$

Boundary conditions:

$$t=T_0: x^{(c,3)}_{iwf\eta_3}(T_0)=\tilde{\tilde{x}}^{(c,3)}_{iwf\eta_3}(T_0)=0;\ \tilde{x}^{(c,3)}_{iwf}(T_0)\in R^1; \tag{2.90}$$

$$t=T_f: x^{(c,3)}_{iwf\eta_3}(T_f)\in R^1;\ \tilde{x}^{(c,3)}_{iwf}(T_f)\in R^1;\ \tilde{\tilde{x}}^{(c,3)}_{iwf\eta_3}(T_f)\in R^1; \tag{2.91}$$

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

$$J^{(c,3)}_{1wf\eta_3}=\sum_{i=1}^{m}\tilde{\tilde{u}}^{(c,3)}_{iwf\eta_3}(T_f); \tag{2.92}$$

$$J^{(c,3)}_{2i}=\int_{T_0}^{T_f}\sum_{w=1}^{K_W}\sum_{f=1}^{K_F}\tilde{u}^{(c,3)}_{ifw}(\tau)d\tau; \tag{2.93}$$

$$J^{(c,3)}_{3iwf}=\sum_{\eta_3=1}^{Œ_3}x^{(c,3)}_{iwf\eta_3}(T_f); \tag{2.94}$$

$$J^{(c,3)}_{4iwf}=\sum_{\eta_3=1}^{K_3}\left(a^{(c,3)}_{iwf}-x^{(c,3)}_{iwf}(T_f)\right)^2; \tag{2.95}$$

$$J^{(c,3)}_{5i\eta_3(\eta_3+1)}=\left[\tilde{\tilde{x}}^{(c,3)}_{iwf\eta_3}-\left(\tilde{\tilde{a}}^{(c,3)}_{iwf}+\tilde{\tilde{x}}^{(c,3)}_{iwf(\eta_3+1)}\right)\right]\Bigg|_{t=T_f}. \tag{2.96}$$

The following notation is adopted: $x^{(c,3)}_{iwf\eta_3}(t)$ – a variable characterizing the degree of completion of microoperation $D^{(c,3)}_{iwf\eta_3}$, which describes the functioning process of object B_i in microstate S_{iwf} during the η_3-rd control cycle; $\tilde{x}^{(c,3)}_{iwf}$ – a variable characterizing the degree of completion of the microoperation $\tilde{D}^{(c,3)}_{iwf}$, that describes the transition process of object B_i from the current macrostate $S_{iw'f'}$ to the required microstate S_{iwf}; $\tilde{\tilde{x}}^{(c,3)}_{iwf\eta_3}(t)$ – an auxiliary variable which value numerically equals the time interval that has elapsed since the completion of macrooperation $D^{(c,3)}_{iwf\eta_3}$; $\tilde{h}^{(c,3)}_{w'f'wf}$ – 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; $u^{(c,3)}_{iwf\eta_3}(t)$ – a control input that takes the value 1 if microoperation $D^{(c,3)}_{iwf\eta_3}$, 0 – to be executed, and 0 otherwise; $\tilde{u}^{(c,3)}_{iwf}(t)$ – 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}; $\tilde{\tilde{u}}^{(c,3)}_{iwf\eta_3}(t)$ – an auxiliary control input that takes the value 1 now corresponding to the completion of macrooperation $D^{(c,3)}_{iwf\eta_3}$, 0 – otherwise.

Constraints (2.84)–(2.89) define the order and sequence of activation (or deactivation) of the aforementioned control inputs.

In expression (2.88), $\Gamma^{(4)}_{iwf1},\Gamma^{(4)}_{iwf2}$ – denotes the set of operation indices executed on object B_i (during interaction with object B_j), that directly precede macrooperation $D^{(c,3)}_{iwf}$ and are logically linked to it by "AND", "OR", or exclusive "OR" operators. Constraint (2.88) 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 (2.73) and (2.62), respectively.

Quality indicator (2.92) characterizes the number of objects B_i, that were in microstate η_3 - during the S_{iwf}. The function of type (2.93) provides a quantitative assessment of the total duration during which object B_i remained in transitional macrostates. Indicator (2.94) determines the total time object B_i spends in microstate S_{iwf}; the Mayer-type functional (2.95) 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 (2.95) $a_{iwf}^{(c,3)}$, – denotes the directive-specified duration of object B_i's presence in macrostate S_{iwf}. Functional (2.96) 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_f). 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:

$$\dot{x}_{i\text{æ}j\lambda}^{(v,1)} = u_{i\text{æ}j\lambda}^{(o,2)}; \quad \dot{x}_{i\text{æ}j\lambda}^{(v,2)} = x_{i\text{æ}j\lambda}^{(v,1)}; \quad \dot{x}_{i\text{æ}j\lambda}^{(v,3)} = u_{i\text{æ}j\lambda}^{(o,1)}; \tag{2.97}$$

$$\dot{x}_{i\text{æ}j\lambda}^{(v,4)} = u_{i\text{æ}j\lambda}^{(k,1)}; \quad \dot{x}_{i\text{æ}j\lambda}^{(v,5)} = u_{i\text{æ}j\lambda}^{(v,2)}; \quad \dot{x}_{i\text{æ}j\lambda}^{(v,6)} = u_{i\text{æ}j\lambda}^{(v,3)} - u_{i\text{æ}j\lambda}^{(v,2)}, \tag{2.98}$$

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

$$u_{i æ j\lambda}^{(v,1)}\left(a_{iæ}^{(o,2)}-\sum_{i=1}^{m}\sum_{\lambda=1}^{l}x_{iæ j\lambda}^{(v,1)}\right)=0, \tag{2.99}$$

$$u_{iæ j\lambda}^{(v,2)}x_{iæ j\lambda}^{(v,4)}=0,\quad u_{iæ j\lambda}^{(v,3)}x_{iæ j\lambda}^{(v,1)}=0; \tag{2.100}$$

$$u_{iæ j\lambda}^{(v,1)}(t)\in\{0,1\},\quad u_{iæ j\lambda}^{(v,2)}(t)\in\{0,1\},\quad u_{iæ j\lambda}^{(v,3)}(t)\in\{0,1\}. \tag{2.101}$$

Constraints (2.99) and (2.100) define a possible variant of "activating" the auxiliary control actions $u_{iæ j\lambda}^{(v,1)}(t), u_{iæ j\lambda}^{(v,2)}(t), u_{iæ j\lambda}^{(v,3)}(t)$.

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

$$\int_{T_0}^{T_f}\left(1-u_{iæ j\lambda}^{(k,1)}\right)x_{iæ j\lambda}^{(v,4)}x_{iæ j\lambda}^{(k,1)}\left(a_{iæ}^{(o,2)}-x_{iæ}^{(o,2)}\right)d\tau=0, \tag{2.102}$$

$$\int_{T_0}^{T_f}\left(1-u_{iæ j\lambda}^{(o,1)}\right)x_{iæ j\lambda}^{(v,1)}x_{iæ j\lambda}^{(v,1)}\left(a_{iæ}^{(o,2)}-x_{iæ}^{(o,2)}\right)d\tau=0, \tag{2.103}$$

where $x_{iæ j\lambda}^{(v,1)}(t_0)=x_{iæ j\lambda}^{(v,4)}(t_0)=0,\ x_{iæj\lambda}^{(v,1)}(T_f)\in R^1, x_{iæj\lambda}^{(v,4)}(T_f)\in R^1$ – the set of real numbers. Relations (2.102) and (2.103) 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:

$$\left.\left\{\left[x_{iæ j\lambda}^{(v,3)}x_{iæ j\lambda}^{(v,1)}+\frac{\left(a_{iæ}^{(o,2)}\right)^2}{2}-x_{iæ j\lambda}^{(v,2)}\right]^2 x_{iæ j\lambda}^{(v,1)}\right\}\right|_{t=T_f}=0, \tag{2.104}$$

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

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

In expression (2.104), the value of the product $x_{iæ j\lambda}^{(v,3)}x_{iæ j\lambda}^{(v,1)}$ is numerically equal to the area under the integrand curve corresponding to the solution of the first equation in formula (2.97) over the time interval $(t'_{iæ j\lambda}, T_f]$ where $t'_{iæ j\lambda}$, t – the moment when the operation $D_æ^{(i,j)}$, performed by the channel, is completed C_λ^j.

The value $\frac{\left(a_{iæ}^{(o,2)}\right)^2}{2}$ is numerically equal to the area under the integrand curve corresponding to the solution of the first equation in formula (2.97) over the time interval $(T_0, t'_{iæj\lambda}]$, 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 (2.104), 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 $D_æ^{(i,}$ 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 (2.104) $x_{iæj\lambda}^{(v,1)}$, which takes the value zero at time $t = T_0$.

2.1.8 MODEL OF INFORMATION SYSTEM SECURITY MANAGEMENT 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:

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

$P = 0p|0p = 01,\ldots, 0m$: the set of m total information system resources;

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

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

$V = \upsilon|\upsilon = 1,\ldots k$: 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^{r}_{pit} : 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^p_{ij}.

w^r_L and w^r_E: 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

$$\min\sum_{i\in N}\sum_{t\in T}\sum_{r\in R}(h_i^{Lr}L_{it}^{Lr}+h_i^{Er}L_{it}^{Er})+\sum_{p\in P}\sum_{t\in T}\sum_{r\in R}(H_p^{L,r}I_{pt}^{Lr}+H_p^{Er}I_{pt}^{Er})+$$
$$+\sum_{p\in P}\sum_{t\in T}\sum_{r\in R}e_r n_t^{p,r}+\sum_{p\in P}\sum_{t\in T}\sum_{p'\in P}\sum_{r\in R}g_r F_{pt}^{p'r}+\sum_{i\in N}\sum_{p\in P}\sum_{p'\in P}\sum_{t\in T}\sum_{r\in R}s_r W_{ip't}^{pr}+$$
$$+\sum_{p\in P}\sum_{t\in T}\sum_{i\in N_p}\sum_{j\in N_p}(a\sum_{v\in V}x_{ijvt}^{p}+\sum_{r\in R}b(w_L^r X_{ijt}^{pr}+w_E^r E_{ijt}^{pr})d_{ij}^{p}), \tag{2.105}$$

subject to the following conditions:

$$L_{pit}^{Lr}=L_{pit-1}^{Lr}+\sum_{p'\in P}Q_{pit}^{p'r}-D_{pit}^{r}\quad \forall i\in N, t\in T, p\in P, r\in R, \tag{2.106}$$

$$I_{pt}^{Lr}=I_{pit-1}^{Lr}-\sum_{i\in N}\sum_{p'\in P}Q_{pit}^{p'r}+\sum_{p'\in P}F_{pt}^{p'r},\ \forall t\in T, p\in P, r\in R, \tag{2.107}$$

$$L_{it}^{Er}=L_{it-1}^{Er}-\sum_{p\in P}Z_{it}^{pr}+\sum_{p\in P}D_{pit}^{r}-\sum_{p\in P}\sum_{p'\in P}W_{ip't}^{pr},\quad \forall i\in N, t\in T, r\in R, \tag{2.108}$$

$$I_{pt}^{Er}=I_{pt-1}^{Er}+\sum_{i\in N}Z_{it}^{pr}-\sum_{p'\in P}F_{pt}^{p'r}+n_t^{pr}+\sum_{p'\in P}W_{ip't}^{pr}\quad \forall p\in P, t\in T, r\in R, \tag{2.109}$$

$$\sum_{i\in N_p, i\neq j}(X_{ijt}^{pr}-X_{jit}^{pr})=\sum_{p'\in P}Q_{pjt}^{p'r},\ \forall j\in N, p\in P, t\in T, r\in R, \tag{2.110}$$

$$\sum_{i\in N_p, i\neq j}(E_{jit}^{pr}-E_{ijt}^{pr})=Z_{jt}^{pr}+\sum_{p'\in P}W_{jp't}^{pr}\quad \forall j\in N, p\in P, t\in T, r\in R, \tag{2.111}$$

$$0\le\sum_{p\in P}\sum_{r\in R}L_{pit}^{Lr}\le c_i^{L}\quad \forall i\in N, t\in T, \tag{2.112}$$

$$0\le\sum_{r\in R}I_{pt}^{Lr}\le C_p^{L},\quad \forall p\in P, t\in T, \tag{2.113}$$

$$0 \le \sum_{p\in P}\sum_{r\in R} L_{pit}^{Er} \le c_i^E, \ \ \forall i \in N, t \in T, \tag{2.114}$$

$$0 \le \sum_{r\in R} I_{pt}^{Er} \le C_p^E, \ \ \forall p \in P, t \in T, \tag{2.115}$$

$$\sum_{p\in P}\sum_{r\in R}(X_{ijt}^{pr} + E_{ijt}^{pr}) \le Q\sum_{p\in P}\sum_{v\in V} x_{ijvt}^{p}, \ \ \forall i, j \in N_p, t \in T, \tag{2.116}$$

$$\sum_{i\in N_p}\sum_{v\in V} x_{ijvt}^{p} \le 1, \ \ \forall j \in N, p \in P, t \in T, \tag{2.117}$$

$$\sum_{i\in N_p i\ne j} x_{ijvt}^{p} = \sum_{i\in N_p i\ne j} x_{jivt}^{p}, \ \ \forall vs. \in V, j \in N_p, p \in P, t \in T, \tag{2.118}$$

$$\sum_{j\in N} x_{0_p jvt}^{p} \le 1, \ \ \forall vs. \in V, p \in P, t \in T. \tag{2.119}$$

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

2.1.8.1 MATHEMATICAL MODEL OF INFORMATION SYSTEM SECURITY MANAGEMENT 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 $p' \ne p, \forall p, p' \in P, i \in N, t \in T, r \in R$. 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

$$\begin{aligned} \min \sum_{i\in N}\sum_{t\in T}\sum_{r\in R}(h_i^{Lr}L_{it}^{Lr} + h_i^{Er}L_{it}^{Er}) + \sum_{t\in T}\sum_{r\in R}(H_p^{L,r}I_{pt}^{Lr} + H_p^{Er}I_{pt}^{Er}) + \\ + \sum_{t\in T}\sum_{r\in R} e_r n_t^{p,r} + \sum_{p\in P}\sum_{t\in T}\sum_{p'\in P}\sum_{r\in R} g_r F_{pt}^{p'r} + \\ + \sum_{t\in T}\sum_{i\in N_p}\sum_{j\in N_p}(a\sum_{v\in V} x_{ijvt}^{p} + \sum_{r\in R} b(w_L^r X_{ijt}^{pr} + w_E^r E_{ijt}^{pr})d_{ij}^{p}). \end{aligned} \tag{2.120}$$

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:

$$L_{pit}^{Lr} = L_{pit-1}^{Lr} + Q_{pit}^{r} - D_{pit}^{r}, \quad \forall i \in N, t \in T, r \in R, \tag{2.121}$$

$$I_{pt}^{Lr} = I_{pt-1}^{Lr} - \sum_{i \in N} Q_{pit}^{r} + F_{pt}^{r}, \quad \forall t \in T, r \in R, \tag{2.122}$$

$$L_{it}^{Er} = L_{it-1}^{Er} - \sum_{p \in P} Z_{it}^{pr} + \sum_{p \in P} D_{pit}^{r}, \quad \forall i \in N, t \in T, r \in R, \tag{2.123}$$

$$I_{pt}^{Er} = I_{pt-1}^{Er} + \sum_{i \in N} Z_{it}^{pr} - F_{pt}^{r} + n_{t}^{pr}, \quad \forall t \in T, r \in R, \tag{2.124}$$

$$\sum_{i \in N_p, i \neq j} (X_{ijt}^{pr} - X_{jit}^{pr}) = Q_{pjt}^{r}, \quad \forall j \in N, t \in T, r \in R, \tag{2.125}$$

$$\sum_{i \in N_p, i \neq j} (E_{jit}^{pr} - E_{ijt}^{pr}) = Z_{jt}^{pr}, \quad \forall j \in N, t \in T, r \in R, \tag{2.126}$$

$$0 \le \sum_{p \in P} \sum_{r \in R} L_{pit}^{Lr} \le c_{i}^{L}, \quad \forall i \in N, t \in T, \tag{2.127}$$

$$0 \le \sum_{r \in R} I_{pt}^{Lr} \le C_{p}^{L}, \quad \forall t \in T, \tag{2.128}$$

$$0 \le \sum_{p \in P} \sum_{r \in R} L_{pit}^{Er} \le c_{i}^{E}, \quad \forall i \in N, t \in T, \tag{2.129}$$

$$0 \le \sum_{r \in R} I_{pt}^{Er} \le C_{p}^{E}, \quad \forall t \in T, \tag{2.130}$$

$$\sum_{p \in P} \sum_{r \in R} (X_{ijt}^{pr} + E_{ijt}^{pr}) \le Q \sum_{p \in P} \sum_{v \in V} x_{ijvt}^{p}, \quad \forall i, j \in N_p, t \in T, \tag{2.131}$$

$$\sum_{i \in N_p} \sum_{v \in V} x_{ijvt}^{p} \le 1, \quad \forall j \in N, t \in T, \tag{2.132}$$

$$\sum_{i \in N_p i \neq j} x_{ijvt}^{p} = \sum_{i \in N_p i \neq j} x_{jivt}^{p}, \quad \forall vs. \in V, j \in N_p, t \in T, \tag{2.133}$$

$$\sum_{j \in N} x_{0_p jvt}^{p} \le 1, \quad \forall vs. \in V, t \in T, \tag{2.134}$$

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*.

2.1.9 GENERALIZED DETERMINISTIC LOGICAL–DYNAMIC MODEL OF STRUCTURAL DYNAMICS MANAGEMENT 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:

$$\dot{x} = f(x, u, t), \tag{2.135}$$

$$h_0(x(T_0)) \le 0, \ \ h_1(x(T_f)) \le 0, \tag{2.136}$$

$$q^{(1)}(x, u) = 0, \ \ q^{(2)}(x, u) = 0, \tag{2.137}$$

$$J_i = J_i\left(x(t), u(t), t\right) = \varphi_i\left(x(t_f)\right) + \int_{T_0}^{T_f} f_{0i}\left(x(\tau), u(\tau), \tau\right) d\tau, i = 1, \ldots l_M, \tag{2.138}$$

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.

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.

CONCLUSIONS

As a result of the conducted research, a polymodel complex was developed, comprising analytica-simulation and logical-dynamic models for managing the motion, channels, resources, complexes, and parameters of target functions, as well as supporting operations, flows, and structures of information systems. In generalized form, this polymodel complex was represented as a multilevel alternative dynamic system graph with a reconfigurable structure.

The first advantage of the proposed generalized description lies in its ability to ensure, at the conceptual, model-algorithmic, informational, and software levels of detail, correct alignment (according to the criteria of homomorphisms and dynamomorphisms of relations) of the mathematical (analytical-simulation) models of structural dynamics management of information systems (both real and virtual-software) with their logical-algebraic and logical-linguistic analogues (models) constructed on the basis of intelligent information technologies. Unlike existing scenario-based behavioral models of information system functioning, which are built on finite-state automata and simulation descriptions, the proposed logical-dynamic approach makes it possible, at a constructive level, to address both the synthesis of technologies for information system functioning and the tasks of integrated planning of information processes occurring within them, thereby ensuring the effective functioning of the Industrial Internet of Things.

The second advantage of the proposed polymodel complex is its ability to uniformly (using the same mathematical structures) provide a formal description of both the tasks of integrated modeling of information system management processes and the tasks of planning their operations, plan correction (re-planning), as well as the tasks of real-time control and monitoring of their state. This ensures correct inter-model coordination with a unified language for describing the analyzed processes.

Overall, the dynamic interpretation of processes for managing the elements and subsystems of information systems proposed by the authors makes it possible to significantly reduce the dimensionality of these software control tasks (through recurrent model descriptions), to decompose and parallelize the initial planning and management tasks of information systems, and to improve the efficiency of solving such tasks when using modern multiprocessor and multicore computers. It also enhances the stability of the computational process associated with solving the tasks of planning and managing information systems.

Consideration of uncertainty factors within the developed polymodel complex is proposed using combined approaches, based on the authors' technologies of integrated modeling. These are oriented both toward analytical-simulation modeling of possible scenarios of proactive information system management programs at the execution stage — with subsequent correction and implementation of the required level of various types of redundancy (functional, technical, temporal, etc.) — and toward the construction and analysis of approximated reachability regions in the space of criterial functions and interval-defined perturbations.

Such approaches make it possible to identify the most robust proactive management programs for information systems.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

USE OF ARTIFICIAL INTELLIGENCE

The authors confirm that they did not use artificial intelligence technologies in creating the submitted work.

REFERENCES

1. Dudnyk, V., Sinenko, Y., Matsyk, M., Demchenko, Y., Zhyvotovskyi, R., Repilo, I. et al. (2020). Development of a method for training artificial neural networks for intelligent decision support systems. Eastern-European Journal of Enterprise Technologies, 3 (2 (105)), 37–47. https://doi.org/10.15587/1729-4061.2020.203301
2. Sova, O., Shyshatskyi, A., Salnikova, O., Zhuk, O., Trotsko, O., Hrokholskyi, Y. (2021). Development of a method for assessment and forecasting of the radio electronic environment. EUREKA: Physics and Engineering, 4, 30–40. https://doi.org/10.21303/2461-4262.2021.001940
3. Pievtsov, H., Turinskyi, O., Zhyvotovskyi, R., Sova, O., Zvieriev, O., Lanetskii, B., Shyshatskyi, A. (2020). Development of an advanced method of finding solutions for neuro-fuzzy expert systems of analysis of the radioelectronic situation. EUREKA: Physics and Engineering, 4, 78–89. https://doi.org/10.21303/2461-4262.2020.001353
4. Zuiev, P., Zhyvotovskyi, R., Zvieriev, O., Hatsenko, S., Kuprii, V., Nakonechnyi, O. et al. (2020). Development of complex methodology of processing heterogeneous data in intelligent decision support systems. Eastern-European Journal of Enterprise Technologies, 4 (9 (106)), 14–23. https://doi.org/10.15587/1729-4061.2020.208554
5. Kuchuk, N., Mohammed, A. S., Shyshatskyi, A., Nalapko, O. (2019). The Method of Improving the Efficiency of Routes Selection in Networks of Connection with the Possibility of Self-Organization. International Journal of Advanced Trends in Computer Science and Engineering, 8 (1.2), 1–6. https://doi.org/10.30534/ijatcse/2019/0181.22019
6. Shyshatskyi, A., Zvieriev, O., Salnikova, O., Demchenko, Ye., Trotsko, O., Neroznak, Ye. (2020). Complex Methods of Processing Different Data in Intellectual Systems for Decision Support System. International Journal of Advanced Trends in Computer Science and Engineering, 9 (4), 5583–5590. https://doi.org/10.30534/ijatcse/2020/206942020
7. Pozna, C., Precup, R.-E., Horvath, E., Petriu, E. M. (2022). Hybrid Particle Filter–Particle Swarm Optimization Algorithm and Application to Fuzzy Controlled Servo Systems. IEEE Transactions on Fuzzy Systems, 30 (10), 4286–4297. https://doi.org/10.1109/tfuzz.2022.3146986

8. Yang, X.-S., Deb, S. (2013). Cuckoo search: recent advances and applications. Neural Computing and Applications, 24 (1), 169–174. https://doi.org/10.1007/s00521-013-1367-1
9. Mirjalili, S. (2015). The Ant Lion Optimizer. Advances in Engineering Software, 83, 80–98. https://doi.org/10.1016/j.advengsoft.2015.01.010
10. Yu, J. J. Q., Li, V. O. K. (2015). A social spider algorithm for global optimization. Applied Soft Computing, 30, 614–627. https://doi.org/10.1016/j.asoc.2015.02.014
11. Mirjalili, S., Mirjalili, S. M., Lewis, A. (2014). Grey Wolf Optimizer. Advances in Engineering Software, 69, 46–61. https://doi.org/10.1016/j.advengsoft.2013.12.007
12. Koval, V., Nechyporuk, O., Shyshatskyi, A., Nalapko, O., Shknai, O., Zhyvylo, Y. et al. (2023). Improvement of the optimization method based on the cat pack algorithm. Eastern-European Journal of Enterprise Technologies, 1 (9 (121)), 41–48. https://doi.org/10.15587/1729-4061.2023.273786
13. Gupta, E., Saxena, A. (2015). Robust generation control strategy based on Grey Wolf Optimizer. Journal of Electrical Systems, 11, 174–188.
14. Chaman-Motlagh, A. (2015). Superdefect Photonic Crystal Filter Optimization Using Grey Wolf Optimizer. IEEE Photonics Technology Letters, 27 (22), 2355–2358. https://doi.org/10.1109/lpt.2015.2464332
15. Nuaekaew, K., Artrit, P., Pholdee, N., Bureerat, S. (2017). Optimal reactive power dispatch problem using a two-archive multi-objective grey wolf optimizer. Expert Systems with Applications, 87, 79–89. https://doi.org/10.1016/j.eswa.2017.06.009
16. Koval, M., Sova, O., Orlov, O., Shyshatskyi, A., Artabaiev, Y., Shknai, O. et al. (2022). Improvement of complex resource management of special-purpose communication systems. Eastern-European Journal of Enterprise Technologies, 5 (9 (119)), 34–44. https://doi.org/10.15587/1729-4061.2022.266009
17. Ali, M., El-Hameed, M. A., Farahat, M. A. (2017). Effective parameters' identification for polymer electrolyte membrane fuel cell models using grey wolf optimizer. Renewable Energy, 111, 455–462. https://doi.org/10.1016/j.renene.2017.04.036
18. Zhang, S., Zhou, Y. (2017). Template matching using grey wolf optimizer with lateral inhibition. Optik, 130, 1229–1243. https://doi.org/10.1016/j.ijleo.2016.11.173
19. Khouni, S. E., Menacer, T. (2023). Nizar optimization algorithm: a novel metaheuristic algorithm for global optimization and engineering applications. The Journal of Supercomputing, 80 (3), 3229–3281. https://doi.org/10.1007/s11227-023-05579-4
20. Saremi, S., Mirjalili, S., Lewis, A. (2017). Grasshopper Optimisation Algorithm: Theory and application. Advances in Engineering Software, 105, 30–47. https://doi.org/10.1016/j.advengsoft.2017.01.004
21. Braik, M. S. (2021). Chameleon Swarm Algorithm: A bio-inspired optimizer for solving engineering design problems. Expert Systems with Applications, 174, 114685. https://doi.org/10.1016/j.eswa.2021.114685
22. Thamer, K. A., Sova, O., Shaposhnikova, O., Yashchenok, V., Stanovska, I., Shostak, S. et al. (2024). Development of a solution search method using a combined bio-inspired algorithm. Eastern-European Journal of Enterprise Technologies, 1 (4 (127)), 6–13. https://doi.org/10.15587/1729-4061.2024.298205
23. Yapici, H., Cetinkaya, N. (2019). A new meta-heuristic optimizer: Pathfinder algorithm. Applied Soft Computing, 78, 545–568. https://doi.org/10.1016/j.asoc.2019.03.012

24. Duan, H., Qiao, P. (2014). Pigeon-inspired optimization: a new swarm intelligence optimizer for air robot path planning. International Journal of Intelligent Computing and Cybernetics, 7 (1), 24–37. https://doi.org/10.1108/ijicc-02-2014-0005
25. Shyshatskyi, A., Romanov, O., Shknai, O., Babenko, V., Koshlan, O., Pluhina, T. et al. (2023). Development of a solution search method using the improved emperor penguin algorithm. Eastern-European Journal of Enterprise Technologies, 6 (4 (126)), 6–13. https://doi.org/10.15587/1729-4061.2023.291008
26. Yang, X. S (2012). Flower pollination algorithm for global optimization. Unconventional computing and natural computation. Berlin, Heidelberg: Springer, 240–249. https://doi.org/10.1007/978-3-642-32894-7_27
27. Gomes, G. F., da Cunha, S. S., Ancelotti, A. C. (2018). A sunflower optimization (SFO) algorithm applied to damage identification on laminated composite plates. Engineering with Computers, 35 (2), 619–626. https://doi.org/10.1007/s00366-018-0620-8
28. Mehrabian, A. R., Lucas, C. (2006). A novel numerical optimization algorithm inspired from weed colonization. Ecological Informatics, 1 (4), 355–366. https://doi.org/10.1016/j.ecoinf.2006.07.003
29. Qi, X., Zhu, Y., Chen, H., Zhang, D., Niu, B. (2013). An idea based on plant root growth for numerical optimization. Intelligent Computing Theories and Technology. Berlin, Heidelberg: Springer, 571–578. https://doi.org/10.1007/978-3-642-39482-9_66
30. Bezuhlyi, V., Oliynyk, V., Romanenko, I., Zhuk, O., Kuzavkov, V., Borysov, O., Korobchenko, S., Ostapchuk, E., Davydenko, T., Shyshatskyi, A. (2021). Development of object state estimation method in intelligent decision support systems. Eastern-European Journal of Enterprise Technologies, 5 (3 (113)), 54–64. https://doi.org/10.15587/1729-4061.2021.239854
31. Mahdi, Q. A., Shyshatskyi, A., Prokopenko, Y., Ivakhnenko, T., Kupriyenko, D., Golian, V. et al. (2021). Development of estimation and forecasting method in intelligent decision support systems. Eastern-European Journal of Enterprise Technologies, 3 (9 (111)), 51–62. https://doi.org/10.15587/1729-4061.2021.232718
32. Sova, O., Radzivilov, H., Shyshatskyi, A., Shevchenko, D., Molodetskyi, B., Stryhun, V. et al. (2022). Development of the method of increasing the efficiency of information transfer in the special purpose networks. Eastern-European Journal of Enterprise Technologies, 3 (4 (117)), 6–14. https://doi.org/10.15587/1729-4061.2022.259727
33. Zhang, H., Zhu, Y., Chen, H. (2013). Root growth model: a novel approach to numerical function optimization and simulation of plant root system. Soft Computing, 18 (3), 521–537. https://doi.org/10.1007/s00500-013-1073-z
34. Labbi, Y., Attous, D. B., Gabbar, H. A., Mahdad, B., Zidan, A. (2016). A new rooted tree optimization algorithm for economic dispatch with valve-point effect. International Journal of Electrical Power & Energy Systems, 79, 298–311. https://doi.org/10.1016/j.ijepes.2016.01.028
35. Murase, H. (2000). Finite element inverse analysis using a photosynthetic algorithm. Computers and Electronics in Agriculture, 29 (1-2), 115–123. https://doi.org/10.1016/s0168-1699(00)00139-3
36. Zhao, S., Zhang, T., Ma, S., Chen, M. (2022). Dandelion Optimizer: A nature-inspired metaheuristic algorithm for engineering applications. Engineering Applications of Artificial Intelligence, 114, 105075. https://doi.org/10.1016/j.engappai.2022.105075

37. Paliwal, N., Srivastava, L., Pandit, M. (2020). Application of grey wolf optimization algorithm for load frequency control in multi-source single area power system. Evolutionary Intelligence, 15 (1), 563–584. https://doi.org/10.1007/s12065-020-00530-5
38. Dorigo, M., Blum, C. (2005). Ant colony optimization theory: A survey. Theoretical Computer Science, 344 (2-3), 243–278. https://doi.org/10.1016/j.tcs.2005.05.020
39. Poli, R., Kennedy, J., Blackwell, T. (2007). Particle swarm optimization. Swarm Intelligence, 1 (1), 33–57. https://doi.org/10.1007/s11721-007-0002-0
40. Bansal, J. C., Sharma, H., Jadon, S. S., Clerc, M. (2014). Spider Monkey Optimization algorithm for numerical optimization. Memetic Computing, 6 (1), 31–47. https://doi.org/10.1007/s12293-013-0128-0
41. Yeromina, N., Kurban, V., Mykus, S., Peredrii, O., Voloshchenko, O., Kosenko, V. et al. (2021). The Creation of the Database for Mobile Robots Navigation under the Conditions of Flexible Change of Flight Assignment. International Journal of Emerging Technology and Advanced Engineering, 11 (5), 37–44. https://doi.org/10.46338/ijetae0521_05
42. Maccarone, A. D., Brzorad, J. N., Stone H. M. (2008). Characteristics And Energetics Of Great Egret And Snowy Egret Foraging Flights. Waterbirds, 31 (4), 541–549. https://doi.org/10.1675/1524-4695-31.4.541
43. Ramaji, I. J., Memari, A. M. (2018). Interpretation of structural analytical models from the coordination view in building information models. Automation in Construction, 90, 117–133. https://doi.org/10.1016/j.autcon.2018.02.025
44. Pérez-González, C. J., Colebrook, M., Roda-García, J. L., Rosa-Remedios, C. B. (2019). Developing a data analytics platform to support decision making in emergency and security management. Expert Systems with Applications, 120, 167–184. https://doi.org/10.1016/j.eswa.2018.11.023
45. Chen, H. (2018). Evaluation of Personalized Service Level for Library Information Management Based on Fuzzy Analytic Hierarchy Process. Procedia Computer Science, 131, 952–958. https://doi.org/10.1016/j.procs.2018.04.233
46. Chan, H. K., Sun, X., Chung, S.-H. (2019). When should fuzzy analytic hierarchy process be used instead of analytic hierarchy process? Decision Support Systems, 125, 113114. https://doi.org/10.1016/j.dss.2019.113114
47. Osman, A. M. S. (2019). A novel big data analytics framework for smart cities. Future Generation Computer Systems, 91, 620–633. https://doi.org/10.1016/j.future.2018.06.046
48. Nechyporuk, O., Sova, O., Shyshatskyi, A., Kravchenko, S., Nalapko, O., Shknai, O. et al. (2023). Development of a method of complex analysis and multidimensional forecasting of the state of intelligence objects. Eastern-European Journal of Enterprise Technologies, 2 (4 (122)), 31–41. https://doi.org/10.15587/1729-4061.2023.276168
49. Merrikh-Bayat, F. (2015). The runner-root algorithm: A metaheuristic for solving unimodal and multimodal optimization problems inspired by runners and roots of plants in nature. Applied Soft Computing, 33, 292–303. https://doi.org/10.1016/j.asoc.2015.04.048
50. Poliarush, O., Krepych, S., Spivak, I. (2023). hybrid approach for data filtering and machine learning inside content management system. Advanced Information Systems, 7 (4), 70–74. https://doi.org/10.20998/2522-9052.2023.4.09

51. Balochian, S., Baloochian, H. (2019). Social mimic optimization algorithm and engineering applications. Expert Systems with Applications, 134, 178–191. https://doi.org/10.1016/j.eswa.2019.05.035
52. Lenord Melvix, J. S. M. (2014). Greedy Politics Optimization: Metaheuristic inspired by political strategies adopted during state assembly elections. 2014 IEEE International Advance Computing Conference (IACC), 1157–1162. https://doi.org/10.1109/iadcc.2014.6779490
53. Moosavian, N., Roodsari, B. K. (2014). Soccer League Competition Algorithm, a New Method for Solving Systems of Nonlinear Equations. International Journal of Intelligence Science, 4 (1), 7–16. https://doi.org/10.4236/ijis.2014.41002
54. Hayyolalam, V., Pourhaji Kazem, A. A. (2020). Black Widow Optimization Algorithm: A novel meta-heuristic approach for solving engineering optimization problems. Engineering Applications of Artificial Intelligence, 87, 103249. https://doi.org/10.1016/j.engappai.2019.103249
55. Abualigah, L., Yousri, D., Abd Elaziz, M., Ewees, A. A., Al-qaness, M. A. A., Gandomi, A. H. (2021). Aquila Optimizer: A novel meta-heuristic optimization algorithm. Computers & Industrial Engineering, 157, 107250. https://doi.org/10.1016/j.cie.2021.107250
56. Hodlevskyi, M., Burlakov, G. (2023). Information technology of quality improvement planning of process subsets of the spice model. Advanced Information Systems, 7 (4), 52–59. https://doi.org/10.20998/2522-9052.2023.4.06
57. Askari, Q., Younas, I., Saeed, M. (2020). Political Optimizer: A novel socio-inspired meta-heuristic for global optimization. Knowledge-Based Systems, 195, 105709. https://doi.org/10.1016/j.knosys.2020.105709
58. Mohamed, A. W., Hadi, A. A., Mohamed, A. K. (2019). Gaining-sharing knowledge based algorithm for solving optimization problems: a novel nature-inspired algorithm. International Journal of Machine Learning and Cybernetics, 11 (7), 1501–1529. https://doi.org/10.1007/s13042-019-01053-x
59. Gödri, I., Kardos, C., Pfeiffer, A., Váncza, J. (2019). Data analytics-based decision support workflow for high-mix low-volume production systems. CIRP Annals, 68 (1), 471–474. https://doi.org/10.1016/j.cirp.2019.04.001
60. Harding, J. L. (2013). Data quality in the integration and analysis of data from multiple sources: some research challenges. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-2/W1, 59–63. https://doi.org/10.5194/isprsarchives-xl-2-w1-59-2013
61. Orouskhani, M., Orouskhani, Y., Mansouri, M., Teshnehlab, M. (2013). A Novel Cat Swarm Optimization Algorithm for Unconstrained Optimization Problems. International Journal of Information Technology and Computer Science, 5 (11), 32–41. https://doi.org/10.5815/ijitcs.2013.11.04
62. Karaboga, D., Basturk, B. (2007). A powerful and efficient algorithm for numerical function optimization: artificial bee colony (ABC) algorithm. Journal of Global Optimization, 39 (3), 459–471. https://doi.org/10.1007/s10898-007-9149-x
63. Fister, I., Fister, I., Yang, X.-S., Brest, J. (2013). A comprehensive review of firefly algorithms. Swarm and Evolutionary Computation, 13, 34–46. https://doi.org/10.1016/j.swevo.2013.06.001
64. Sova, O., Radzivilov, H., Shyshatskyi, A., Shvets, P., Tkachenko, V., Nevhad, S. et al. (2022). Development of a method to improve the reliability of assessing the condition of the monitoring object in spe-

cial-purpose information systems. Eastern-European Journal of Enterprise Technologies, 2 (3 (116)), 6–14. https://doi.org/10.15587/1729-4061.2022.254122

65. Khudov, H., Khizhnyak, I., Glukhov, S., Shamrai, N., Pavlii, V. (2024). The method for objects detection on satellite imagery based on the firefly algorithm. Advanced Information Systems, 8 (1), 5–11. https://doi.org/10.20998/2522-9052.2024.1.01
66. Owaid, S. R., Zhuravskyi, Y., Lytvynenko, O., Veretnov, A., Sokolovskyi, D., Plekhova, G. et al. (2024). Development of a method of increasing the efficiency of decision-making in organizational and technical systems. Eastern-European Journal of Enterprise Technologies, 1 (4 (127)), 14–22. https://doi.org/10.15587/1729-4061.2024.298568
67. Tyurin, V., Bieliakov, R., Odarushchenko, E., Yashchenok, V., Shaposhnikova, O., Lyashenko, A. et al. (2023). Development of a solution search method using an improved locust swarm algorithm. Eastern-European Journal of Enterprise Technologies, 5 (4 (125)), 25–33. https://doi.org/10.15587/1729-4061.2023.287316
68. Yakymiak, S., Vdovytskyi, Y., Artabaiev, Y., Degtyareva, L., Vakulenko, Y., Nevhad, S. et al. (2023). Development of the solution search method using the population algorithm of global search optimization. Eastern-European Journal of Enterprise Technologies, 3 (4 (123)), 39–46. https://doi.org/10.15587/1729-4061.2023.281007
69. Mohammed, B. A., Zhuk, O., Vozniak, R., Borysov, I., Petrozhalko, V., Davydov, I. et al. (2023). Improvement of the solution search method based on the cuckoo algorithm. Eastern-European Journal of Enterprise Technologies, 2 (4 (122)), 23–30. https://doi.org/10.15587/1729-4061.2023.277608
70. Raskin, L., Sukhomlyn, L., Sokolov, D., Vlasenko, V. (2023). Multi-criteria evaluation of the multifactor stochastic systems effectiveness. Advanced Information Systems, 7 (2), 63–67. https://doi.org/10.20998/2522-9052.2023.2.09
71. Arora, S., Singh, S. (2018). Butterfly optimization algorithm: a novel approach for global optimization. Soft Computing, 23 (3), 715–734. https://doi.org/10.1007/s00500-018-3102-4