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MATHEMATICS AND CYBERNETICS – APPLIED ASPECTS

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DEVELOPMENT OF A UNIVERSAL INTEGRAL CRITERION FOR CYBERNETIC CONTROL

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This study investigates the technological process of heating a liquid considered as a controlled cybernetic system for converting resources into a usable technological result. The work aims to solve a pressing task of choosing a single universal criterion for assessing the effectiveness of technological processes. The subject of research is the ELF (Normalized Efficiency Criterion) computing module, designed for an integral assessment of the effectiveness of cybernetic control over technological processes in discrete time.

This work reports designing a computing module that converts technological input parameters and corresponding price coefficients into a system of cost indicators of costs and useful effect. The proposed system allows for the reduction of heterogeneous resources and the result of the process to a single scale, which makes it possible to formalize their joint analysis and a coordinated comparison of alternative modes. Elementary cost functions and aggregated indicators of the control cycle are introduced, on the basis of which the first-level integral accumulators are formed – accumulated costs and accumulated effect.

To assess the efficiency of control over a given time interval, secondary integrators of the second level and the mode selection index are used, which reflects the excess of the integral effect over the integral costs in the inertial-accumulator sense. Within the framework of the approach, the additional benefit and resource intensity of the permissible control mode are determined, which are formed using a storage device with a reset mechanism in the case of violation of the regime conditions.

The permissibility of the mode is set by the threshold rule and the procedure for resetting the final indicators in the case of its inadmissibility, which provides a diagnostically interpreted separation of the causes of zero efficiency. The proposed structure of the computing module focuses on the analysis, diagnostics, and optimization of control modes and allows for software implementation as part of cybernetic control systems

Keywords: cybernetic system, efficiency criterion, integral assessment, cost model, regime selection

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1. Introduction

Modern controlled technological processes operate under heterogeneous input parameters, changing operating conditions, and limitations related to equipment reliability and service life. Under these conditions, the role of a cybernetic approach, focused on formalizing control objectives and developing criteria for the effectiveness of system operation over a given time interval, is increasing.

In practical control quality assessment tasks, partial KPIs (Key Performance Indicators) are widely used. These KPIs focus on individual process characteristics, such as energy consumption, productivity, and operating costs [1]. However, these indicators have a number of significant limitations.

First, most KPIs are local, instantaneous, and reflect the system's state at the current cycle or over a short time interval. In the context of inertial and cumulative processes, such assessments do not allow for an accurate assessment of the effectiveness of the control mode since the final result is formed cumulatively over time.

Second, partial KPIs characterize the effectiveness of individual resource types and do not reflect the cost structure as a whole. A situation may arise in which a mode is energy-efficient but economically unfeasible due to high material costs or accelerated equipment wear. Similarly, a high-performance mode may prove operationally unacceptable due to equipment overload or violation of process limitations.

Third, the problem of incomparability of disparate quantities with different physical natures and dimensions arises [2]. The lack of a formalized procedure for standardizing and coordinating scales makes it impossible to combine them into a single quality criterion suitable for use in automated control and optimization systems. Furthermore, most KPIs do not include mechanisms for diagnosing the causes of inefficiency, making it difficult to distinguish between the economic disadvantage of a mode and its operational impermissibility.

Thus, the task of constructing a universal criterion for control effectiveness boils down to the need to combine disparate resources and useful results, introduce an integral nature of assessment, ensure discrete computability, and incorporate mechanisms for mode selection and tolerance.

The relevance of research in the field of devising a universal integral criterion for the effectiveness of cybernetic control in discrete time is due to the lack of an integral measure for comparing different technological processes. This requires ensuring an accurate and comparable assessment of the effectiveness of control modes using disparate resources, in the presence of cost factors, and operational constraints. Devising this criterion is very important in practice for making decisions on the selection of control modes.

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2. Literature review and problem statement

Paper [3] reports the results of research on the Pontryagin maximum principle for nonlinear systems, including models with memory. A function that maximizes along the control trajectory is considered optimal. However, issues related to constructing an applied integral performance indicator for discrete process control areas remain unresolved. This requires calculating the optimum in real time and interpreting the results in engineering terms. This may be due to the high complexity of transferring continuous data to discrete computing modules without losing diagnostic properties.

Study [2] systematizes the basic principles of feedback and formalizing control objectives in engineering systems. It is shown that correctly specifying the objective and structure of the feedback is a necessary condition for the synthesis of stable control. However, the challenge of constructing a unified integral measure that allows for the comparison of modes in the presence of heterogeneous resources and operational constraints remains open. The reason is that classical schemes focus on dynamics and stability but do not define a universal "cost/benefit" criterion for process modes.

Optimal control methods were further developed in a monograph [4] tackling the analysis of nonlinear systems and control under constraints, where issues of selecting optimal system behavior under structural and operational constraints are considered. It is shown that control optimization can be performed over the horizon, taking constraints into account. However, issues of universal comparability of disparate costs and results remain unresolved: the introduction of a cost function is required, which is usually specific to the object and manually configured. This is due to the dependence of the solution quality on the selected objective function, which complicates the comparison of different processes.

Paper [5] presents the theoretical framework of MPC (Model Predictive Control) (theory, computation, and design). It is shown that constraints can be included in the optimization problem, and control quality can be formalized through a criterion. However, the problem of constructing a universal performance criterion that is simultaneously standardized, interpretable, and suitable for diagnosing the causes of performance degradation remains unresolved. This is because MPC describes the optimization mechanism for a given criterion but does not address the problem of unifying the criterion itself for heterogeneous resources and effects.

Study [6] examines adaptive optimal control methods for nonlinear systems (identifier-critic). It is shown that it is possible to learn a control strategy based on an optimization objective. However, issues of engineering interpretability and criterion unification remain unresolved: as the process changes, the feature structure, signal scale, and reward function change. The reason is the lack of a universal "quality measure" of a regime that is equally valid for different resource components (material, energy, temperature, operational).

Work [7] examines the stability and controllability of nonlinear dynamic systems using neural network models. It is shown that stability and controllability can be analyzed formally. However, the issues of jointly accounting for economic efficiency and regime acceptability remain unresolved: stability criteria do not provide a cost estimate for the transformation of resources into results. The reason is the difference in objectives: stability answers the question "can it be safely managed?" but does not answer "how profitable is the regime?"

Paper [8] reports the results of a Lyapunov stability analysis for nonlinear systems in settings that take risk-sensitive control into account. It is shown that stability can be ensured under adverse disturbances and uncertainties. However, issues related to the diagnostic differentiation of the causes of zero efficiency in a technological process remain unresolved: the absence of an effect and the prohibition of a mode due to constraints require different management decisions. This is because the classical stability framework does not introduce mechanisms for selecting modes based on "integral benefit."

Work [1] reports results on the construction and use of performance indices for energy-efficient management of industrial processes. It is shown that the KPI approach is convenient for monitoring and evaluating individual aspects of management quality. However, issues of conflicting individual indicators and their incomparability in the presence of heterogeneous resources and operational factors (e.g., energy vs. wear and tear vs. material costs) remain unresolved. This is due to the specific nature of KPIs: they measure individual aspects but do not form a single standardized measure for comparing modes.

Paper [9] proposes approaches to constructing a global criterion for the effectiveness of target operations and identifying system operations. It is shown that it is possible to formalize effectiveness through integral indicators and a cost interpretation of the result. However, the issues of integrating a mechanism for operational tolerance and diagnostic "zeroing" into a computational criterion for discrete-time process control remain unresolved. This is due to the need to link cost assessment with formal operational constraints, that is, to distinguish "unprofitable" from "impossible".

Work [10] describes a technique for selecting objects, which provides the basis for formalized selection procedures based on given criteria. It is shown that selection mechanisms can be implemented formally.

Thus, despite the significant amount of research in the field of optimal control, stability, and cost assessment, the problem of constructing a universal integrated measure of efficiency remains unresolved. This measure simultaneously:

– enables comparability of heterogeneous resources and results;

– takes into account the inertial and cumulative nature of technological processes;

– allows for discrete computational implementation;

– includes a formalized mechanism for selecting and accepting control modes.

The reasons include both the objective difficulties of formalizing heterogeneous factors within a single indicator and the lack of universal computational constructs suitable for practical application in cybernetic control systems.

All of the above allows me to conclude that it is advisable to conduct a study aimed at devising a universal integrated indicator for the effectiveness of cybernetic control over technological processes in discrete time, focused on the cost interpretation of resources and results, the integral accounting of accumulated effects and the formalized selection of acceptable control modes.

3. The aim and objectives of the study

The aim of this study is to devise a universal integrated performance criterion for cybernetic control based on a cost representation of resources and useful effects, enabling formalized assessment, selection, and software implementation of control modes in technological systems.

To achieve this goal, the following objectives are set:

– to analyze the limitations of local and cost-based performance criteria under conditions of inertial and cumulative technological processes;

– to define a system of cost coefficients and integrated indicators of accumulated costs and effects;

– to formulate the structure of a universal integrated performance criterion for discrete control time;

– to design a mechanism for mode filtering, selection, and acceptance of control modes;

– to compare the standardized ELF performance criterion with conventional partial KPIs.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of this study is the technological process of heating a liquid, considered as a controlled cybernetic system for converting resources into a useful technological result.

The process is represented as a discrete dynamic model operating over time

$$t = 0, 1, 2, \ldots,$$

where $t = 0$ corresponds to the system initialization moment (control cycle zero).

At each cycle t, the vector of technological input process variables is specified

$$x(t) = \big(v(t), e(t), \theta(t), w(t), h(t)\big), \tag{1}$$

where $v(t)$ is the material resource (volume of liquid), $e(t)$ is the energy resource, $\Theta(t)$ is the temperature resource (thermal impact), $w(t)$ is the operational resource reflecting equipment wear, and $h(t)$ is the useful result of the technological process (e.g., the volume of heated liquid).

For each input value at cycle t, a corresponding price coefficient is set

$$p(t) = \big(p_v(t), p_e(t), p_\theta(t), p_w(t), p_h(t)\big), \tag{2}$$

where $p_i(t)$ reflects the economic or conventional cost assessment of the corresponding resource or result.

The introduction of a cost representation of input resources and useful results enables the harmonization of disparate quantities on a single scale and the generation of initial data for subsequent integrated performance assessment in the ELF computing module.

The research hypothesis is as follows.

It is assumed that the efficiency of technological process control can be correctly assessed using a universal integral criterion, formed as a normalized ratio of the accumulated additional benefit to the accumulated resource intensity of the permissible mode.

It is assumed that if:

– the costs and effects of the technological process are represented on a single cost scale,

– integral indicators are formed recursively in discrete time,

– a mechanism for regime selection of permissible control trajectories is used, then a computational efficiency criterion can be constructed

$$ELF(t) = \frac{AA(t)}{RPA(t) + \varepsilon}, \tag{3}$$

where $AA(t)$ is the additional benefit of the control mode, $RPA(t)$ is the resource intensity of the admissible control mode, and ε is the regularization parameter.

It enables the comparability of heterogeneous resources, is suitable for step-by-step calculations in digital control systems, and allows for the identification of efficient and inefficient modes of technological process operation.

Before beginning the study, the following assumptions are adopted:

– all technological resources and results are non-negative

$$v(t), e(t), \theta(t), w(t), h(t) \geq 0; \tag{4}$$

– the prices of resources and results satisfy the following condition

$$p_v(t), p_e(t), p_\theta(t), p_w(t), p_h(t) \geq 0; \tag{5}$$

– the system operates in discrete time, corresponding to the measurement and decision-making steps in the digital control system;

– the ELF computing module has accumulation registers that enable the integration of indicators over time;

– price coefficients are selected to ensure the comparability of all resources and results within a single cost measurement system.

To simplify the analysis, the following assumptions were introduced during the study:

– all types of resources (material, energy, temperature, and operational) are described by a single numerical value. This value characterizes their overall contribution to the technological process;

– the cost of each resource is determined as the product of its quantity and the corresponding price coefficient. This enables the transition from physical quantities to cost assessment;

– this model does not take into account random factors and various uncertainties. All input values are known and specified at each time step;

– the structure of the technological system and the composition of the resources used do not change during the considered operating period;

– all price coefficients can correspond to both real economic values and conventional weighting parameters.

4. 2. Theoretical research methods

The following methods were used in the study:

– systems analysis of technological processes;

– mathematical modeling of dynamic systems;

– recursive accumulation of integral indicators;

– cost representation of resources and effects.

The mathematical model was constructed in discrete time and implemented the principle of accumulating cost characteristics of inputs and process effects.

The model included a system of integrated indicators at two levels, allowing for the accounting of the dynamics of cost and performance changes over time.

4. 3. Experimental conditions

The model's computational scheme provided for the sequential conversion of input process parameters into cost indicators.

At each time step, the following operations were performed:

– calculation of elementary cost indicators of resources and outputs;

– generation of total process costs;
– recursive accumulation of Level I integral indicators;
– generation of secondary Level II integral indicators.

This calculation sequence ensured a cumulative assessment of the process efficiency.

A mode selection mechanism was used to identify acceptable system operating modes. It is based on a comparison of secondary accumulated cost indicators and process effect indicators. Depending on the ratio of these values, a mode advantage indicator was generated, and the acceptability of the system operating mode was determined.

This mechanism allows for the temporal structure of the process to be taken into account and modes that do not meet the efficiency conditions to be excluded.

Based on the accumulated cost indicators, a standardized ELF control efficiency criterion was devised. The criterion was defined as the ratio of the incremental benefit of the process to the resource intensity of the permissible mode.

This criterion allows for the comparison of different operating modes of the technological process system.

4. 4. Experimental software

The mathematical model of the ELF computing module was implemented in a spreadsheet software environment.

This program included the following modules:
– calculation of resource cost indicators;
– generation of integral accumulators;
– mode selection;
– calculation of the efficiency criterion.

The software model performed a step-by-step calculation of the process indicators and generated data for further analysis.

A computational experiment was conducted to test the model's performance.

The experiment included:
– setting the input process parameters;
– calculating the indicators over time;
– recording the integral indicators and the efficiency criterion;
– preparing data for subsequent analysis.

The analysis of the ELF computing module model's performance was conducted under various operating modes of the system.

The test included:
– experiments with various input parameters;
– calculation of integrated indicators;
– verification of the stability of the efficiency criterion.

All this allowed me to confirm the validity of the model and its suitability for analyzing control modes of technological systems.

5. Results of investigating the effectiveness of the universal integral criterion of cybernetic control

5. 1. Analysis of local and cost criteria of effectiveness

To demonstrate the operability of the proposed ELF computing module, a technological process of liquid heating was considered, represented as a discrete cybernetic system for converting resources into a useful result.

At each discrete time step t, the process input values $v(t)$, $e(t)$, $\theta(t)$, $w(t)$ and the useful result $h(t)$ were generated. To standardize the disparate values, price coefficients $p_v(t)$, $p_e(t)$, $p_\theta(t)$, $p_w(t)$, $p_h(t)$ were defined, determining the cost assessment of costs and benefits.

The computational experiment included:
– generation of elementary cost indicators for the step;
– calculation of total costs and benefits;
– recursive accumulation of integral indicators of levels I and II;
– calculation of the additional benefit, the resource intensity of the permissible mode, and the standardized efficiency criterion (ELF).

A graphical representation of these values is shown in Fig. 1.

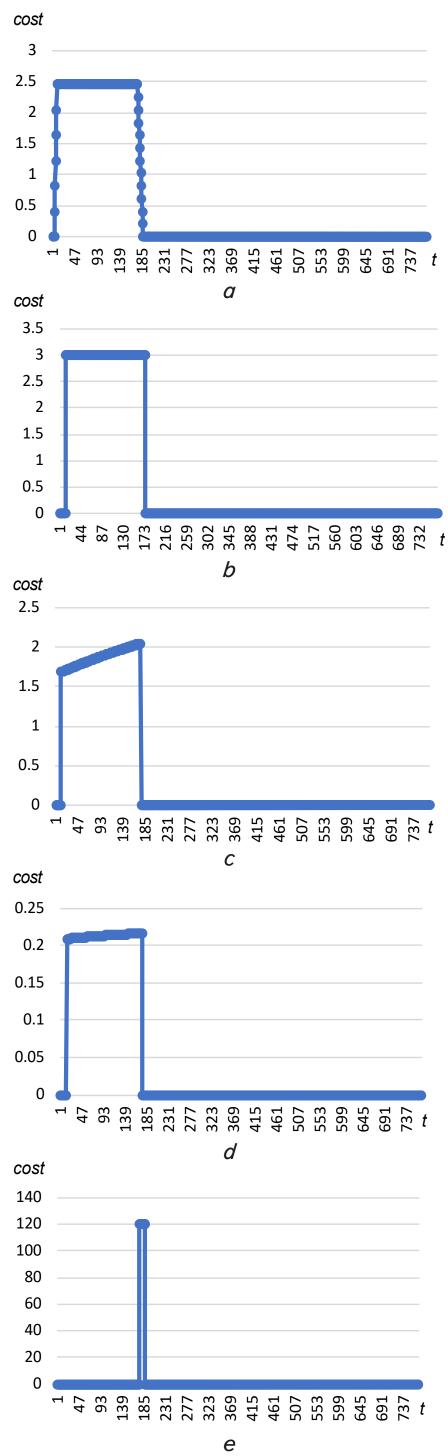

Fig. 1. Input quantities and their cost representation: *a* – cost of liquid volume $v(t)$; *b* – cost of energy consumption $e(t)$; *c* – cost of heating temperature $\theta(t)$; *d* – cost of wear $w(t)$; *d* – cost of useful result $h(t)$

To analyze the cost characteristics of resources and the effect, plots of elementary cost indicators $c_v(t)$, $c_e(t)$, $c_\theta(t)$, $c_w(t)$, $c_h(t)$ are constructed, ensuring the comparability of resources and useful results on a single scale.

5. 2. System of cost coefficients and integrated indicators of accumulated costs and effects

5. 2. 1. Cost assessment of the control cycle effect

The useful effect at cycle t was defined by $h(t)$ and converted to a cost representation using the corresponding price coefficient $p_h(t)$. The cost of a control cycle's effect was determined as the product of the useful result and its price coefficient.

Elementary cost indicators characterizing resource consumption and the generation of useful results at a control cycle were determined by the following relationships:

$$c_v(t),\ c_e(t),\ c_\theta(t),\ c_w(t), \tag{6}$$

$$c_h(t). \tag{7}$$

The total cost of the control cycle was determined by the aggregation of elementary cost indicators of resources

$$c_\Sigma(t), \tag{8}$$

And the cost assessment of the effect of the management cycle was given by the following expression

$$c_H(t). \tag{9}$$

The obtained cost indicators were used as initial data for the subsequent integral accumulation of costs and effects in the ELF computing module.

5. 2. 2. Integral assessment of accumulated costs and effects

For each resource type at cycle t, a cost estimate was generated by multiplying the corresponding resource value by its price coefficient. Integral accumulated costs and the integral accumulated effect were defined as the total cost indicators accumulated over all control cycles within the time interval under consideration.

The accumulated cost value and the accumulated effect value were calculated recurrently:

$$irc(t) = irc(t-1) + c_\Sigma(t),\ irc(0) = 0, \tag{10}$$

$$iec(t) = iec(t-1) + c_H(t),\ iec(0) = 0. \tag{11}$$

Here, $irc(t)$ is the cumulative cost estimate of costs, and $iec(t)$ is the cumulative cost estimate of the effect.

The integral indicators $irc(t)$ and $iec(t)$ were then used to generate aggregated characteristics of the control mode and calculate criterion assessments within the ELF computing module.

5. 2. 3. Resource intensity of the permissible mode

The resource intensity of the permissible control mode was defined as the integral cost characteristic of the total costs associated with implementing the control mode while observing operational and technological constraints.

Secondary integral indicators of Level II were generated recurrently:

$$sirc(t) = sirc(t-1) + irc(t),\ sirc(0) = 0, \tag{12}$$

$$siec(t) = siec(t-1) + iec(t),\ iec(0) = 0, \tag{13}$$

where $sirc(t)$ are the secondary integral cost accumulators, and $siec(t)$ are the secondary integral effect accumulators.

The resulting $sirc(t)$ and $siec(t)$ indicators were used to subsequently determine the admissibility of the management mode and generate standardized criterion assessments in the ELF computing module.

5. 2. 4. Additional benefit of the control mode

The additional benefit of the control mode was defined as the positive part of the difference between the accumulated cost effect and the accumulated costs of Level I over the considered control horizon

$$AA(t) = \max\{0, iec(t) - irc(t)\}. \tag{14}$$

The $AA(t)$ value was used to quantitatively record the presence or absence of an excess of accumulated benefits over accumulated costs and was subsequently applied in the formation of performance criteria and mode selection mechanisms in the ELF computing module.

5. 2. 5. Universal standardized efficiency criterion

The ELF universal standardized performance criterion was formed as the ratio of the incremental benefit to the resource intensity of the permissible mode, taking into account the normalizing and regularizing parameters.

To form the resource intensity of the permissible mode, an accumulator was introduced, determined recursively:

$$RPA(t) = \begin{cases} RPA(t-1) + AA(t), & siec(t) > sirc(t), \\ 0, & siec(t) \le sirc(t), \end{cases}$$

$$RPA(0) = 0. \tag{15}$$

The resource intensity of the permissible control mode at cycle t was determined by the $RPA(t)$ value.

This value was subsequently used to standardize the added benefit and calculate the universal performance criterion within the ELF computing module.

5. 2. 6. The mechanism of admissibility of control modes

To eliminate inoperable and operationally unacceptable control modes, a permissibility mechanism was introduced in the ELF computing module. This mechanism is based on verifying that economic and operational constraints are met at each control cycle.

A control mode is considered permissible if the conditions for the accumulated benefit exceeding the accumulated Level II costs and the specified operational constraints are simultaneously met

$$Admissible(t) \equiv (siec(t) > sirc(t)) \wedge (\mu(t) \le \xi(t)), \tag{16}$$

where $Admissible(t)$ is a logical indicator of the admissibility of the control mode, $siec(t)$ is the secondary accumulated effect, $sirc(t)$ is the secondary accumulated costs, $\mu(t)$ is the mode selection indicator, and $\xi(t)$ is the mode admissibility threshold.

The admissibility condition was then used to formulate the standardized performance criterion and implement the mode filtering and selection procedures in the ELF computing module.

5. 2. 7. Regime filtration and selection

After checking the permissibility of control modes, mode filtering was performed, selecting alternatives from the set of permissible modes for further evaluation using the universal standardized ELF performance criterion.

Boolean diagnostic indicators were introduced to implement the filtering and selection procedures:

$$D_{AA}(t)=\begin{cases}1, & \text{if } iec(t)-irc(t)>0,\\ 0, & \text{otherwise,}\end{cases} \quad (17)$$

$$D_{\mu}(t)=\begin{cases}1, & \text{if } siec(t)-sirc(t)>0,\\ 0, & \text{otherwise,}\end{cases} \quad (18)$$

$$D_{\mu}(t)=\begin{cases}1, & \text{if } Admissible(t),\\ 0, & \text{otherwise,}\end{cases} \quad (19)$$

$$D_{zero}(t)=1-D_{adm}(t). \quad (20)$$

Boolean diagnostic indicators: $D_{AA}(t)$ – indicator of the presence of additional benefit; $D_{\mu}(t)$ – mode selection indicator; $D_{adm}(t)$ – mode admissibility indicator; $D_{zero}(t)$ – forced zeroing indicator.

The introduced indicators were used for formalized mode filtering and implementation of mode selection procedures when calculating criterion assessments within the ELF computing module.

5. 2. 8. Regularization and computational stability

To ensure computational stability of the efficiency criterion and prevent degeneration at low resource intensity values, a regularization parameter $\varepsilon > 0$ was introduced.

The universal normalized ELF efficiency criterion was defined from the following expression:

$$ELF(t)=\begin{cases}\dfrac{AA(t)}{RPA(t)+\varepsilon}, & Admissible(t) \text{ is true,}\\ 0, & Admissible(t) \text{ is false.}\end{cases} \quad (21)$$

The introduced regularization parameter ensured the correctness of the calculations for any admissible values of the accumulated indicators.

5. 2. 9. Theorems and diagnostic consequences

Theorem 1.

If at time step t the admissibility condition for the control mode is satisfied and the incremental benefit is positive, then the universal normalized efficiency criterion is strictly positive

$$Admissible(t)\wedge AA(t)>0 \Rightarrow ELF(t)>0. \quad (22)$$

The theorem specifies sufficient conditions for the effectiveness criterion to be positive, thereby formalizing the relationship between the economic performance of a management regime and its operational feasibility. The value of the ELF criterion is positive if and only if the regime enables a stable excess of the integrated effect over the integrated costs and simultaneously satisfies the specified operational constraints.

Corollary.

Zero effectiveness of a control regime occurs if and only if either the additional benefit is zero or the control regime is unfeasible

$$ELF(t)=0 \Leftrightarrow (AA(t)=0)\vee(\neg Admissible(t)). \quad (23)$$

The resulting statements were used to formalize the diagnosis of the causes of the zero value of the performance criterion and the subsequent classification of control modes in the ELF computing module.

The modes (system state interpretation) for determining four diagnostic cases based on the combination of $D_{adm}(t)$ and $D_{AA}(t)$ indicators are given in Table 1.

Table 1

Interpretation of the system state

No.	$D_{adm}(t)$	$D_{AA}(t)$	Interpretation of the mode	Summary of indicators
A	1	1	Acceptable mode with positive benefit	$AA(t)>0,\ ELF(t)>0$
B	1	0	Acceptable mode without additional benefit	$AA(t)=0,\ ELF(t)=0$
C	0	1	Additional benefit exists, but the mode is prohibited	forcibly $ELF(t)=0$
D	0	0	The mode is prohibited and there is no benefit	forcibly $ELF(t)=0$

Commentary on the application of the regime table:

1. Case A corresponds to a control regime that is simultaneously:

– economically advantageous ($AA(t) > 0$);

– within the admissible region ($Admissible(t)$).

2. Case B corresponds to a regime that is admissible but does not yield an increase in benefit over cost. It is interpreted as a "neutral" regime.

3. Case C is diagnostically important: local advantage is present ($AA(t) > 0$), but the regime violates the tolerance constraints. This means that "advantage-based" control conflicts with the regime constraints.

4. Case D corresponds to a clearly ineffective and prohibited regime.

5. 3. The structure of the universal integral efficiency criterion for discrete-time control

5. 3. 1. Level I integral indicators

The formation of Level I integral accumulators in discrete time is illustrated in Fig. 2.

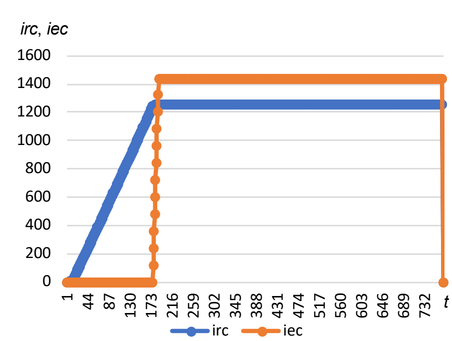

Fig. 2. Integral indicators of level I: $irc(t)$ — accumulated costs; $iec(t)$ — accumulated effect

The formation of Level I integral accumulators in discrete time t is illustrated. The irc(t) value represents the accumulated cost of the process and is calculated recursively based on the total cost of the $c_\Sigma(t)$ cycle. The $iec(t)$ value characterizes the accumulated effect in monetary terms and is determined based on the value of the useful result $c_H(t)$. The $irc(t)$ and $iec(t)$ indicators are used to subsequently calculate the additional benefit $AA(t)$ (Fig. 2).

5. 3. 2. Integral indicators of Level II

The formation of the secondary integral indicators of Level II – $sirc(t)$ and $siec(t)$ – is shown in Fig. 3.

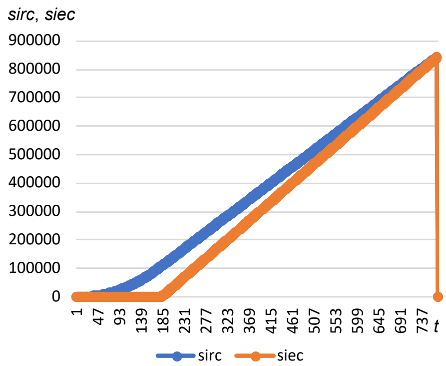

Fig. 3. Integral indicators of Level II: *sirc*(*t*) – secondary accumulated costs; *siec*(*t*) – secondary accumulated effect

These values reflect the secondary accumulation of Level II indicators and form a process performance assessment over a time interval. These indicators are used to select modes based on the consistent excess of benefits over costs.

5. 4. Designing a mechanism for performance filtering and control mode tolerance

The calculation of the performance selection indicator $\mu(t)$ is illustrated in Fig. 4.

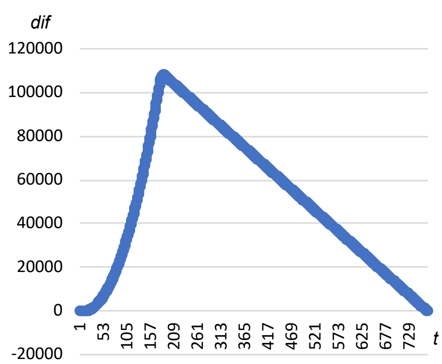

Fig. 4. Selection regime indicator

The $dif(t) \leftrightarrow \mu(t)$ quantity takes positive values in the range of modes where the secondary accumulated effect exceeds the secondary accumulated costs and is zero otherwise. This indicator is used to generate the resource intensity accumulator for the permissible mode.

The formation of the resource intensity accumulator $rpa(t)$, which determines the resource intensity of the permissible mode $RPA(t)$, is shown in Fig. 5.

The accumulator increases when the condition $siec(t) > sirc(t)$ is met and is reset to zero when this condition is violated. This mechanism is used to account for the duration of the mode's execution and is applied in calculating the efficiency criterion.

The calculation of the additional benefit $AA(t)$, defined as the positive part of the difference between the accumulated effect and the accumulated costs of level I, is shown in Fig. 6.

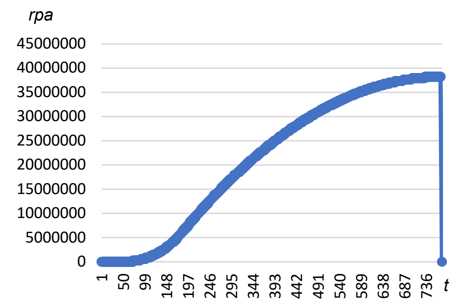

Fig. 5. Resource capacity accumulator

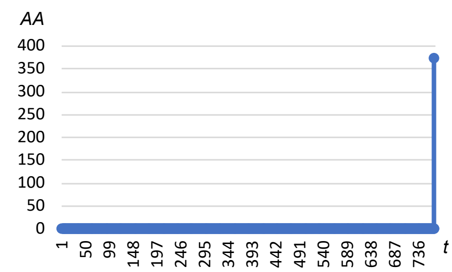

Fig. 6. Additional benefit of the control mode

The $AA(t)$ value is used as the numerator of the normalized ELF performance criterion.

The mode tolerance mechanism, defined by the threshold $dop(t) \leftrightarrow \xi(t)$ and the logical tolerance condition, is shown in Fig. 7.

This mechanism is used to limit the system's operational scope based on operational requirements and exclude unacceptable operational modes from the final efficiency calculation.

The general diagnostic logic for generating the final operational mode assessment is shown in Fig. 8.

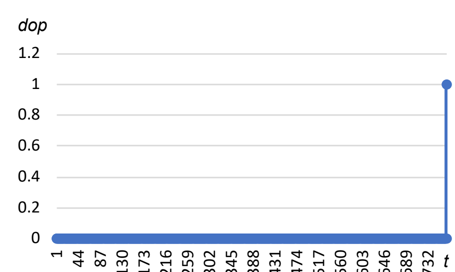

Fig. 7. Condition of control mode admissibility

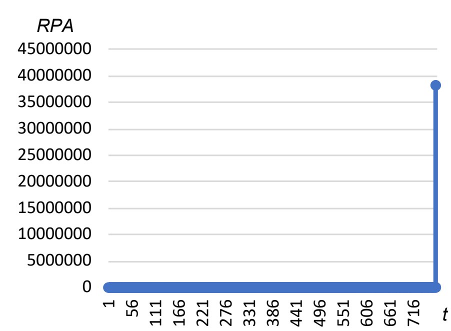

Fig. 8. Diagnostic scheme for forming the final assessment of the control mode

Regime selection generates the $\mu(t)$ a $RPA(t)$ indicators, the incremental benefit generates the $AA(t)$ value, and the tolerance condition determines the feasibility of calculating the standardized performance criterion.

The calculation of the standardized performance criterion *ELF* is shown in Fig. 9.

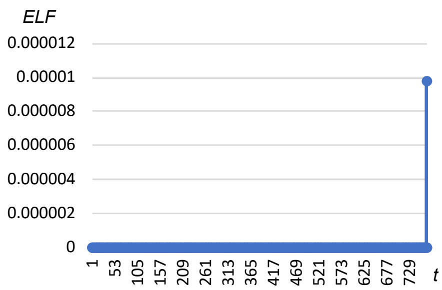

Fig. 9. Standardized criterion of control efficiency

The regularization parameter ε is used to ensure computational stability and prevent division by zero for small $RPA(t)$ values.

5. 5. Comparison of the standardized performance criterion with specific criteria

To compare the capabilities of the proposed ELF normalized performance criterion and conventional partial performance indicators (KPIs) used in process control [9, 10], a comparative analysis was performed. The results are given in Table 2.

Table 2

Results of comparing the standardized ELF performance criterion and conventional KPIs

Comparison parameter	KPI	ELF
Indicator type	Particular indicator	Generalized integral indicator
Dimensionality	Usually has the dimensionality	Dimensionless
Nature of assessment	Local (instantaneous)	Integral over time
Accounting for process inertia	Absent	Implemented through accumulation
Accounting for different resources	Limited	Full (based on the cost model)
Criteria conflict	High	Minimized
Scale dependence	High	Low
Purpose	Process monitoring	Selection and optimization of modes
Diagnosing the causes of inefficiency	Not provided	Implemented

The comparison in Table 2 demonstrates the key differences between the standardized ELF performance criterion and specific KPIs used in practice to control technological processes [9, 10].

KPIs are typically used to monitor individual process parameters and typically have physical dimensions. In contrast, the ELF criterion provides an overall, dimensionless assessment of the control mode.

Using multiple KPIs simultaneously often leads to inconsistencies between the indicators. In such a situation, it becomes difficult to select the best system operating mode. The ELF criterion, in contrast, combines the influence of various resources and process outputs into a single numerical assessment, allowing for direct comparison of different control modes.

The standardized form of the ELF criterion makes it less dependent on process scale and cost levels. Therefore, its scope of application is broader than that of conventional KPIs, which can be highly dependent on system operating conditions [9].

Furthermore, unlike instantaneous KPIs, the ELF criterion takes into account the accumulation of costs and outputs over time. This is especially important for technological processes involving inertia and cumulative effects.

To illustrate the differences between conventional performance indicators (KPIs) and the integral ELF criterion, two control modes for a liquid heating process are considered (Table 3).

The assessment is performed using the following partial performance indicators (KPIs): energy consumption E; productivity P; equipment wear W.

The integral performance criterion is also calculated

$$ELF(t)=\frac{AA(t)}{RPA(t)+\varepsilon}, \tag{24}$$

where AA – additional benefit, RPA – resource intensity of the permissible mode.

Table 3

Numerical comparison of control modes

Indicator	Mode A	Mode B
Performance P (l/min)	100	120
Energy consumption E (kWh)	50	70
Equipment wear W (arbitrary units)	20	35
Cost of result c_H	200	220
Cost of expenses c_Σ	150	210
Added value AA	50	10
Resource intensity of mode RPA	40	60
ELF	1.25	0.17

The individual KPIs reveal a contradictory picture: Mode B has higher productivity; however, it requires more energy and causes greater equipment wear.

Therefore, using individual KPIs does not allow one to definitively determine the more efficient mode.

The integrated ELF criterion takes into account the combined impact of costs and results. The calculation shows:

$$ELF_A = 1.25,$$

$$ELF_B = 0.17.$$

Therefore, Mode A is more effective, despite its lower throughput.

A numerical example demonstrates that:

– individual KPIs can yield conflicting assessments of modes;

– the integrated ELF criterion provides a unified quantitative assessment of effectiveness;

– the criterion enables formal selection of control modes.

Thus, the results confirm that the ELF criterion is not intended to replace KPIs in operational monitoring tasks, but rather complements them, forming a formalized basis for optimization, mode selection, and control decision-making in cybernetic control systems [10].

6. Discussion of results based on constructing a universal integral efficiency criterion

The results are due to the fact that all heterogeneous input resources and useful outcomes are reduced to a single cost scale and then aggregated in integral accumulators. This is confirmed by the plots of the cost indicators of resources and results (Fig. 1), in which the values are represented in comparable units. The accumulation of costs and effects at Level I (Fig. 2) enables an integral accounting of the sequence of control cycles, and secondary integration at Level II (Fig. 3) transforms the mode assessment from a local form to a mode-based one, taking into account inertia and accumulation over time. The formation of the mode selection indicator (Fig. 4) and the accumulator of resource intensity of the permissible mode (Fig. 5) defines the mechanism for identifying the range of modes for which the excess of the effect over the costs is sustainable. The additional benefit (Fig. 6) records the presence of a positive "residual" effect relative to the costs and is subsequently used in standardizing the final assessment. The role of control mode tolerance and the exclusion of unacceptable states is reflected in Fig. 7 and in the diagnostic diagram (Fig. 8), while the calculation of the normalized performance criterion and the stability of the calculations are ensured by regularization (Fig. 9). The diagnostic classification of modes based on a combination of indicators is given in Table 1 and confirms the separation of the causes of zero efficiency.

In comparison with the practice of using partial KPIs focused on individual indicators (energy, productivity, specific costs), the proposed criterion forms a single normalized mode assessment, which reduces the conflict of multi-criteria assessment and simplifies the selection of a control mode [9]. In known approaches, a cost representation is often used as a way to reduce disparate quantities to a comparable form; however, by itself, it does not solve the problem of identifying acceptable modes in the presence of operational constraints [10]. The functional difference between the proposed normalized ELF performance criterion and conventional partial performance indicators (KPIs) used in process control is the combined use of:

a) integrated accumulators;

b) selection mode;

c) mode tolerance as a separate stage that excludes unacceptable modes before calculating the final efficiency.

From the perspective of optimal control methods, classical approaches construct optimality through a functional maximized along the control trajectory and rely on recursive principles (dynamic programming) [4, 8]. In the proposed model, the criterion computational scheme is organized recursively and is compatible with a discrete control loop, ensuring applicability in practical computing modules. In terms of constraints and admissibility, the proposed tolerance mechanism is consistent with the general principles of stability and regime boundedness characteristic of feasibility analysis and sustainable operation methods [1, 3].

Constraints include conditions under which the application of the standardized ELF performance criterion can yield reproducible results:

– the requirement to specify price coefficients that define the cost scale for comparing resources and results. Changing these coefficients alters the contribution of individual input parameters to the overall performance assessment (Fig. 1);

– for the criterion to be applied correctly, the input quantities and price coefficients must be non-negative and determined at each discrete time step;

– the range of valid assessment depends on the selected mode tolerance rules and the established tolerance threshold. If the restrictions are too strict, the number of invalid modes increases, which is reflected in the diagnostics (Fig. 7, 8, Table 2);

– the repeatability of calculations is ensured by the recursive structure of the computing modules (Fig. 2–5). However, the accuracy of the final assessment depends on the completeness of the input parameter measurements and the correct recording of time steps;

– the method's shortcomings are not related to its scope of application, but to the specifics of its practical implementation;

– price coefficients can be set by experts, which introduces some subjectivity. To reduce this effect, it is promising to determine the coefficients based on statistical operating data and the economic indicators of the controlled object;

– the mode tolerance threshold and regularization parameter require adjustment. To simplify this procedure, it is advisable to use standard parameter selection rules based on the characteristic operating modes of the system and the ranges of observed data.

Diagnostic Table 2 makes it possible to identify the causes of zero efficiency but does not indicate which specific constraint was violated. This can be eliminated by expanding the set of diagnostic indicators for different groups of constraints without changing the criterion structure.

This research can be further advanced towards a standardized functionality for the deviation of the efficiency indicator. This could ensure the stability of calculations and might be used for the analysis, standardization, and comparison of different control modes.

7. Conclusions

1. This study has demonstrated that local and conventional cost indicators do not always allow for the accurate assessment of control modes in technological processes where inertia and cumulative results are important. Such indicators reflect only current or individual values and do not take into account the overall control result over time, limiting their use in selecting optimal modes.

2. A system of cost coefficients and integrated indicators of accumulated costs and effects has been designed. The proposed framework translates various resources and process results into a single scale and utilizes two-level accumulation, allowing for the inertial and cumulative nature of control processes to be taken into account.

3. The structure of a universal integrated indicator for the effectiveness of cybernetic control in discrete time has been developed. This indicator has a standardized, dimensionless form and allows for the accurate comparison of various system operating modes with different levels of costs and results. This confirms its applicability for the analysis and optimization of technological processes.

4. A mechanism for selecting and accepting control modes based on integrated indicators and threshold conditions has been designed. This mechanism allows for identifying acceptable and effective system operating modes, as well as

distinguishing between situations where a system is unprofitable and where a mode is unacceptable.

5. A comparison of the standardized integral performance criterion (ELF) and conventional partial performance indicators (KPIs) has been conducted. It is shown that, unlike KPIs, which are primarily used to monitor individual process parameters, the ELF criterion generates a generalized integral assessment of control quality and can be applied to optimization, mode selection, and software implementation in cybernetic control systems. A numerical example is presented comparing partial performance indicators with the standardized integral performance criterion. It is concluded that partial performance indicators often provide contradictory assessments of control modes.

Conflicts of interest

The author declares that he has no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The author confirms that he did not use artificial intelligence technologies when creating the current work.

Author's contribution

Igor Lutsenko: Conceptualization, Methodology, Formal analysis, Software, Validation, Investigation, Visualization, Writing – original draft, Writing – review & editing.

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DEVELOPMENT OF METHODS OF INTELLIGENT MANAGEMENT OF SECURITY PARAMETERS OF INFORMATION SYSTEMS

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The object of the study is information systems (IS). The problem that is being solved in the study is an increase in the level of IS protection. The study developed a methodology for intelligent management of IS security parameters. The originality of the study consists of:

– conducting a multi-level and systematic assessment of the state of IS security using the proposed set of analytical expressions;

– determining the influence of IS security parameters on each other when the IS security state changes due to the use of fuzzy analytical expressions;

– construction of multidimensional dependencies of the security state of the special-purpose IS, which evaluates the security of the IS based on an arbitrary number of parameters;

– assessment of IS security in conditions of incompleteness of information about evaluation parameters, which solves the dimensionality problem;

– construction of time dependences of changes in parameters that characterize the state of IS protection, which allows determining the moments of deviation of their values from the nominal;

– reducing the error of assessing the state of IS security due to the human factor through the verification of IS parameters;

– attracting additional computing resources (if necessary), which achieves the prevention of looping of the methodology;

– determination of the influence of control decisions on a separately defined parameter for assessing the state of IS security, which achieves an increase in the accuracy of control influences.

Modeling of the work of the proposed methodology was carried out, during which it was established that increasing the security of the IS is achieved by increasing the efficiency of decision-making at the level of 12–16% due to the use of additional procedures and ensuring the reliability (correctness) of the decisions made at the level of 0.94. This allows to avoid distortions and distortions of the information provided for decision-makers (systems)

Keywords: multidimensionality of assessment, complex systems, efficiency of decision-making, efficiency of assessment, bio-inspired algorithms

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1. Introduction

Armed conflicts of the last decade have become a catalyst for the rapid development of information technologies, including information systems (IS). IS is currently used to address both purely specific tasks in the interests of defense and national security and purely urgent issues in society.

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Below are some of the tasks that are solved by IS [1–3]:

– collecting, processing, and summarizing information coming from end users;

– storage of various types of data, their archiving, and output;

– solving individual and/or complex calculation tasks for a wide range of users;

– modeling the nature of military conflicts;

– transfer of information between IS elements, etc.

The main features of the functioning of IS for various functional purposes are [2, 4, 5]:

– constant growth in the volume of information circulating in the middle of the IS and between the IS;

– expansion of the nomenclature of means that destructively affect the process of data exchange in the middle of the IS and between the IS themselves;

– improvement of forms and methods of influencing the process of IS functioning, which negatively affects such indicators as efficiency and reliability of data exchange;

– simultaneous growth of requirements for a set of indicators characterizing the process of IS functioning;

– imperfection of the mechanisms for ensuring the security of IS in the process of their functioning, etc.

Taking into account the above, one of the urgent directions for increasing the efficiency of the functioning of complex technical systems is the development of a methodology for intelligent management of the state of security of information systems.

2. Literature review and problem statement

In work [6], it is proposed to use Bayesian hierarchical networks to determine the quantitative assessment of the level of cybersecurity risks in special-purpose IS. However, this approach is limited by the statistical distribution that can be used and by the extensibility of the model structure. This imposes restrictions on the architecture of the information system and does not take into account the qualitative factors that affect the cybersecurity of the IS.

Work [7] proposed a security certification methodology developed for ISs to enable various stakeholders to evaluate security solutions for large-scale IS deployments automatically. The methodology supports transparency regarding the level of IS safety for consumers, as the methodology provides labeling as one of the main results of the certification process. The disadvantages of the proposed approach include the inability to train knowledge bases for new threats, the problematic nature of generalization, and the analysis of various types of data circulating in the network.

Work [8] proposes a model that integrates fault tree analysis, decision theory, and fuzzy theory to establish the current causes of refusals to prevent cyberattacks. The model has been applied to assess cybersecurity risks associated with a website attack, e-commerce, and corporate resource planning, and to assess the possible consequences of such attacks. The specified model has a flexible architecture; at the same time, the disadvantages of the proposed model include the accumulation of evaluation error during the fuzzification and defuzzification procedure.

Work [9] proposes a model for the distribution of special-purpose IS resources in conditions of insufficient information about the development of the operational situation. In the specified model, mechanisms for the distribution of IS resources are proposed, taking into account the impact of cyber-attacks. This allows the representation of the solution of the vector optimization problem in binary relations of conflict, facilitation, and indifference. It also takes into account the operational situation and allows to predict the state of the IS, taking into account external influences, build utility and guaranteed gain functions, as well as a numerical optimization scheme on this set. At the same time, the specified model does not allow working with various indicators of the assessment of the functioning of the IS state.

Work [10] proposes a hierarchical concept for the introduction of a governance model based on e-government. The article examines the main threats to critical cyber-physical systems as the basis of mechanisms for performing e-government functions. This hierarchical system is based on the use of symmetric and asymmetric cryptosystems, which do not allow them to be used for the task of identifying cyber influences on IS.

Work [11] proposes a model for choosing the optimal set of cybersecurity insurance policies by a firm, given the limited number of policies offered by one or more insurance companies. The proposed model provides a risk-sharing approach that helps the root-mean-square choices of cybersecurity insurance policies in a way that contributes to an efficient cybersecurity insurance market. At the same time, the disadvantages of this approach include the impossibility of introducing new risks to the knowledge base during work and a limited number of assumptions. This makes it impossible for it to work in real time.

Work [12] discusses the importance of incorporating vulnerability analysis into cybersecurity, not only as part of process hazard analysis, but also in terms of protecting the process management network and implementing adequate safeguards in general against cyber threats. Protection level analysis is tailored to assess potential weaknesses and ensure critical applications are protected from cyber-attacks. The integration of cybersecurity into hazard and risk analysis, as well as other elements of technological process security management, is demonstrated by examples, making the plant more resistant to traditional and cyber threats. However, the proposed approach is adapted only for a clear architecture and is not intended for adjustment during operation.

The work [13] proposes a risk management process for identifying, analyzing, evaluating, responding to cyber threats, and monitoring risks at each stage of the cyber protection chain. This approach can be used in organizations that are going to implement security mechanisms to align them to current requirements or reduce cyber risks to acceptable levels. Risk assessment method based on a continuous Markov chain. At the same time, the disadvantages of the proposed method include the impossibility of simultaneous consideration of both quantitative and qualitative indicators, and the impossibility of adaptation to new threats in the system.

In the work [14], a theoretical-analytical approach to the analysis of the impact of information transmission delay in traffic regulation caused by cyber influence is proposed. The evaluation takes place using the method of consecutive averages. However, this approach is limited to use only in motion control systems and is not adapted for use in other systems.

Work [15] proposed to consider cyber security of an object in the form of a graph of transient processes. The said approach allows for describing the threats that affect the object, to determine their degree of impact on cybersecurity. Disadvantages of the proposed approach include the possibility of working only with single-dimensional values and the impossibility of adding new threats during the operation of the proposed approach.

Work [16] presents a method for creating and solving a game theory model to address cybersecurity issues specifically for advanced manufacturing systems with high-level integrated computer integration. This method introduces a unique approach to determining the content of the game's payoff matrix, including support for defense strategies, production losses, and recovery from attacks as part of the cost function. Disadvantages of the proposed method include great computational complexity and the possibility of working only with one-dimensional values.

So, summarizing the above, the general disadvantage of all these approaches is the impossibility of working with multidimensional data in real time. Several different solutions have been proposed to eliminate this shortcoming.

Work [17] presents an approach to evaluating input data for IS. The essence of the proposed approach is the clustering of the basic set of input data, their analysis, and after which the system is trained based on the analysis. The disadvantages of the mentioned approach are the gradual accumulation of evaluation and learning errors due to the lack of the possibility to evaluate the adequacy of the decisions made.

Work [18] presents an approach to data processing from various sources of information. This approach allows processing data from various sources. The disadvantages of the specified approach include the low accuracy of the received assessment and the impossibility of checking the reliability of the received assessment.

In the work [19], a comparative analysis of existing decision support technologies was carried out, namely: the method of analyzing hierarchies, neural networks, the theory of fuzzy sets, genetic algorithms, and neuro-fuzzy modeling. The advantages and disadvantages of these approaches are indicated. The areas of their application are defined. For the tasks of assessing the state of functioning of the IS state in conditions of risk and uncertainty, the use of a neuro-fuzzy approach is justified.

Work [20] states that the use of a combination of different strategies for applying metaheuristic algorithms. The disadvantages of this approach are the insufficient convergence of the obtained results when several metaheuristic algorithms are used together to assess the security of IS functioning.

The analysis of works [9–20] showed that the common shortcomings of the above-mentioned studies are:

– assessment of the state of IS security is carried out only at a separate level of their functioning, or only at a separate element of IS;

– with a comprehensive approach to assessing the state of IS security, as a rule, one or two components affecting the security of IS functioning are considered. This does not allow to fully assess the impact of management decisions on the further functioning of the IS;

– the approaches listed above (methods, techniques), provide weak integration into each other (or make it impossible at all), which does not allow them to be combined for a joint assessment of the functioning of the IS security state;

– the above approaches for assessing the state of security of IS functioning use a different mathematical apparatus, which requires appropriate mathematical transformations, which in turn increase computational complexity and reduce the accuracy of assessing the state of functional reliability of IS, etc.

All this necessitates research on the development of methods of intelligent management of information system security parameters.

3. The aim and objectives of the study

The aim of the study is to increase the security level of information systems due to the development of a methodology for intelligent management of their security parameters. This will allow comprehensive, objective, and full decision-making regarding the management of IS security parameters at different levels of their functioning (individual elements of IS).

Also, it will make it possible to develop (improve) the software of modern and promising IS by integrating the proposed methodology into the corresponding software.

To achieve this aim, the following objectives were accomplished:

– to propose the main procedures of the methodology of intelligent management of information system security parameters;

– to evaluate the effectiveness of the proposed methodology according to certain criteria.

4. Materials and methods

The object of the study is IS. The problem that is being solved in the study is an increase in the level of IS protection. The subject of the study is the process of assessing and managing the state of IS security. The hypothesis of the study is the possibility of increasing the level of IS security due to the development of a methodology for intelligent management of IS security parameters.

To carry out modeling and calculations, it is accepted that the information system performs typical calculations and computing operations under the conditions of constant influence of destructive factors. The simplifications adopted in this study are the modeling of the effectiveness of the specified methodology only on the specified composition of the information system, without taking into account other possible components of the information system.

In the course of the study, the following methods were used:

– general scientific method of analysis – for decomposing problematic issues of assessing the security level of IS when they perform tasks as intended. Also, the general scientific method of analysis is used to determine the advantages and disadvantages of known approaches to assessing the security level and managing the security level of IS when they perform tasks as intended.

– general scientific method of synthesis – to substantiate the most appropriate approaches for assessing the level of IS and managing the security level when they perform tasks as intended;

– methodical approach based on the use of fuzzy cognitive models – to determine control solutions, to manage the level of IS security. The specified improved algorithm provides the possibility of combining into a single system indicator of the security of information systems of different units of measurement and origin.

As an IS for simulation, the communication and information system of the operational grouping of troops (forces) was adopted in this study. The operational group of troops (forces) was formed according to the state of martial law (typical state). Mode of operation of the communication and information systems system – defense operation.

The organizational and personnel structure of the operational grouping of troops (forces), for modeling, includes 197 elements of the information system located on various platforms (carriers). Also, the information system of the operational grouping of troops (forces) selected for modeling includes stationary elements of the information system.

Distribution of elements of the information system, for modeling according to the main aggregate tactical and technical characteristics:

– unmanned aerial vehicles of multicopter type and type "wing" – 62;
– broadband radio access facilities – 33;
– tactical level radio communication facilities – 47;
– operational layer radio communication facilities – 13;
– satellite communications facilities – 10;
– secure field servers – 4;
– secure field personal computing machines – 28.

Generalized tactical and technical characteristics of means of destructive influence on the information system of the operational grouping of troops (forces) chosen for the computational experiment:

1. Means of radio-electronic countermeasures that simultaneously exert a destructive effect with the following tactical and technical characteristics – 4 units:

– lower/upper limit of the frequency range of radio electronic intelligence, MHz – 20...6000;
– lower/upper limit of the suppression frequency range, MHz – 20...6000;
– interference output power, W – 600;
– max. number of channels suppressed simultaneously – 12;
– the possibility of determining the coordinates of radio emitting means;
– ability to suppress channels of global satellite positioning systems NAVSTAR L1/L2/L5, GLONASS L1/L2.
– channel suppression capability, MHz GSM 900/1800, CDMA 400...530/850...895/2100...2170, UMTS 850...900/1800...2025/2110...2200, LTE 790...850/1800...1880/2600...2700; Wi-Fi 2300...2600/3400...3800/5170...6000; WiMAX 1500/2300...2500; WiMAX 2700/3400...3800;
– capability to suppress VHF and trunking systems, MHz 20...1000;
– capability to suppress satellite communications systems, MHz 1525...1559; 1616...1625; 3400...3625;
– ability to suppress control channels of unmanned aerial vehicles, MHz 440...3000/3000...6000 MHz.

2. Means of cyber influence that simultaneously exert a destructive influence on the radio channel – 12 units. Type of cyber infusion – denial of service.

A computational experiment of the proposed methodology was conducted in the Microsoft Visual Studio 2022 software environment (USA). The hardware of the research process is AMD Ryzen 5.

The general computational experiment is laid out on 151 sheets and contains information sensitive to disclosure.

5. Research results on intelligent management of security parameters of information systems

5. 1. Development of the main procedures of the methodology of intelligent management of security parameters of information systems

The method of intelligent management of IS security parameters consists of the following sequence of actions:

Action 1. Entering output data about IS.

In the specified procedure, initial data on the IS and the conditions of its functioning are entered. The following output data are entered:

– the number of electronic warfare (EW) that affect IS (both own and enemy);
– the number of means of cyber influence, the intensity of cyber influence on IS;
– type of cyber-attacks that act on IS;
– spectral-energy parameters of obstacles of EW means affecting IS;
– the number of means of fire damage that act in the line of operation of the IS;
– intensity of fire impact on IS, etc.

Action 2. Construction of a fuzzy IS security graph

$$FSCN = \langle P, S, R, U, D \rangle, \quad (1)$$

where $P = \{p_i | i = 1, \ldots, I\}$ – set of fuzzy situational signs (assessment parameters), which describe the state of IS security;

$S = \{s_j | j = 1, \ldots, J\}$ – set of fuzzy IS situations (IS risks and security threats);

$R = \left\{ r_{k_i}^{(p_i)} \mid k_i = 1, \ldots, K_i, i = 1, \ldots, I \right\}$ – set of fuzzy control decisions for managing the IS security state;

$U = \left\{ u_{j_k, j_l} \mid s_{j_k}, s_{j_l} \in S \right\}$ – set of control transitions between fuzzy situations in IS;

$D = \left\{ D_{s_{cur}, s_{tar}} \right\}$ – set of all IS routes that includes subsets $D_{s_{cur}, s_{tar}} = \left\{ d_b^{(s_{cur}, s_{tar})} \mid b = 1, \ldots, B_{s_{cur}, s_{tar}} \right\}$, $s_{cur}, s_{tar} \in S$ routes between different current (identified) s_{cur} and target s_{tar} unclear situations in IS.

Action 2. 1. Verification of a fuzzy graph.

At this stage, with the help of an improved bio-inspired algorithm [19], the fuzzy IS security graph is verified. In case of detection of deviations, the initial data is adjusted using the results of the bio-inspired algorithm.

Action 2. 2. Description of the parameters for assessing the security status of the IS state p_i, $i = 1, \ldots, I$ to describe the state of IS security.

The parameters for assessing the security status of IS are described by variables $\langle p_i, T_{p_i}, X_{p_i} \rangle$, where

$$T_{p_i} = \left\{ T_m^{(p_i)} \mid m = 1, \ldots, M \right\}$$

– term-set of variables; X_{p_i} – basic set p_i.

For submission $T_m^{(p_i)}$, $m = 1, \ldots, M$ fuzzy sets are used

$$T_m^{(p_i)} = \left\{ \left(\mu_{T_m^{(p_i)}}(x) / x \right) \right\}, x \in X_{p_i}.$$

Action 2. 3. Description of fuzzy situations of the IS security state in the form of a fuzzy set of the 2nd level:

$$\forall s_j \in S : \tilde{s}_j = \left\{ \left(\mu_{\tilde{s}_j}(\tilde{p}_j) / P \right) \right\}, p_i \in P,$$

$$\tilde{p}_i = \left\{ \left(\mu_{\tilde{p}_i}\left(T_m'^{(p_i)} \right) / T_m^{(p_i)} \right) \mid m = 1, \ldots, M \right\}, i \in \{1, \ldots, I\}. \quad (2)$$

Action 2. 4. Formation of management decisions regarding the management of IS security parameters:

$$r_{k_i}^{(p_i)} = \left\langle Tr^{\left(r_{k_i}^{(p_i)}\right)}, Er^{\left(r_{k_i}^{(p_i)}\right)}, Xr^{\left(r_{k_i}^{(p_i)}\right)} \right\rangle, \quad (3)$$

$$r_{k_i}^{(p_i)} \in R, k_i = 1,\ldots,K_i, i = 1,\ldots,I.$$

where $Tr^{\left(r_{k_i}^{(p_i)}\right)}$ – term set "of direction" influence $r_{k_i}^{(p_i)}$ on a sign p_i (IS security parameter), for example ($\{Tr_1^{\left(r_{k_i}^{(p_i)}\right)}$ – increase, $Tr_2^{\left(r_{k_i}^{(p_i)}\right)}$ – reduce, $Tr_3^{\left(r_{k_i}^{(p_i)}\right)}$ – do not change $\}$);

$Er^{\left(r_{k_i}^{(p_i)}\right)}$ – term set of degree of influence $r_{k_i}^{(p_i)}$ on a sign p_i, for example ($\{Er_1^{\left(r_{k_i}^{(p_i)}\right)}$ – very weak, $Er_2^{\left(r_{k_i}^{(p_i)}\right)}$ – weakly, $Er_3^{\left(r_{k_i}^{(p_i)}\right)}$ – strongly, $Er_4^{\left(r_{k_i}^{(p_i)}\right)}$ – very strong $\}$);

$Xr^{\left(r_{k_i}^{(p_i)}\right)}$ – scale of degree of influence $r_{k_i}^{(p_i)}$ [–1, 1].

It is the influence of the management decision $r_{k_i}^{(p_i)}$ on the sign (IS security parameter) p_i implemented by the fuzzy operation max-min- compositions between fuzzy set $\tilde{p}_i$, and a vague relationship $\tilde{r}_{k_i}^{(p_i)}$. As a result of this influence, the fuzzy value of the sign changes p_i

$$\tilde{p}'_i = \tilde{p}_i \cdot \tilde{r}_{k_i}^{(p_i)}. \quad (4)$$

The locality property of control solutions determines the number of features (IS security parameters) that change as a result of applying one control solution (the control solution is k-local if it leads to a change in the values of k features).

For fuzzy situational management of the security parameters of the IC under consideration, it is advisable to decompose k-local control solutions and present them in the form of a sequence of l-local control solutions, ordered by the degree of influence on the corresponding features. It allows:

– form and rank ordered sets of l-local control solutions corresponding to the k-local control solution, taking into account the setting of threshold values of the influence of control solutions on the dependent parameters of the IS security state;

– increase the flexibility of fuzzy graph adaptation when structurally and parametrically configuring the composite hybrid model for managing IS security parameters.

Action 3. Assessment of the indirect influence of control decisions on changing IS security parameters.

Action 3. 1. For each pair of features (for all pairwise c0ations of the influence of signs on each other, the property of transitivity is violated, then a transitive closure is performed for them, for example

$$Ef_{p_i,p_z} = Ef_{p_i,p_z} \vee Ef_{p_i,p_z}^2 \vee \ldots \vee Ef_{p_i,p_z}^1 \vee \ldots, \quad (7)$$

where $Ef_{p_i,p_z}^k = Ef_{p_i,p_z}^{k-1} \cdot Ef_{p_i,p_z}$.

If it is not possible to provide a transitive closure for any fuzzy relations, then it may be necessary to clarify them by an expert.

Action 3. 4. As a result, a generalized matrix of agreed fuzzy relations of the influence of all parameters of the IS security assessment on each other is formed:

$$Ef = \begin{vmatrix} Ef_{p_1,p_1} & Ef_{p_1,p_2} & \ldots & Ef_{p_1,p_I} \\ Ef_{p_2,p_1} & Ef_{p_2,p_2} & \ldots & Ef_{p_2,p_I} \\ \ldots & \ldots & \ldots & \ldots \\ Ef_{p_I,p_1} & Ef_{p_I,p_2} & \ldots & Ef_{p_I,p_I} \end{vmatrix}. \quad (8)$$

Action 3. 5. As a result of the application of the management decision $r_{k_i}^{(p_i)}$ the value of the IS security parameter p_i, represented by a fuzzy set $\tilde{p}_i = \left\{\left(\mu_{\tilde{p}_i}\left(T_m^{(p_i)}\right)/T_m^{(p_i)}\right) | m = 1,\ldots,M\right\}$, changes as follows

$$\tilde{p}'_i = \left\{\left(\mu_{\tilde{p}_i}\left(T_m'^{(p_i)}\right)/T_m^{(p_i)}\right) | m = 1,\ldots,M\right\}.$$

Action 3. 6. The resulting change in the IS security parameter p_i it is presented in the form of two fuzzy sets for separate consideration of positive and negative influences:

– $\delta p_i^+ = \left\{\left(\mu_{\delta p_i^+}\left(T_m^{(p_i)}\right)/T_m^{(p_i)}\right) | m = 1,\ldots,M\right\}, i \in \{1,\ldots,I\}$ – to take into account positive changes in the values of the IS security assessment parameter p_i;

– $\delta p_i^- = \left\{\left(\mu_{\delta p_i^-}\left(T_m^{(p_i)}\right)/T_m^{(p_i)}\right) | m = 1,\ldots,M\right\}, i \in \{1,\ldots,I\}$ – to take into account negative changes in the values of the IS security assessment parameter p_i.

Action 3. 7. Fuzzy sets are defined δp_i^+ and δp_i^-, what are the positive and negative changes in the IS security assessment parameter p_z taking into account its interdependence with the sign p_i:

$$\delta p_i^+ = \delta p_i^+ \cdot Ef_{p_i,p_z} = \\ = \left\{\left(\mu_{\delta p_z^+}\left(T_m^{(p_z)}\right)/T_m^{(p_z)}\right) | m = 1,\ldots,M\right\}, i \in \{1,\ldots,I\}, \quad (9)$$

$$\delta p_i^- = \delta p_i^- \cdot Ef_{p_i,p_z} = \\ = \left\{\left(\mu_{\delta p_z^-}\left(T_m^{(p_z)}\right)/T_m^{(p_z)}\right) | m = 1,\ldots,M\right\}, i \in \{1,\ldots,I\}. \quad (10)$$

Action 3. 8. The indirect effect on the IS security assessment parameter is determined p_z management decision $r_{k_i}^{(p_i)}$, which directly affects the sign p_i:

$$\forall p_z \in P: \\ \tilde{p}'_z = \left\{\left(\min\left(1, \max\left(0, \begin{pmatrix} \mu_{\tilde{p}_z}\left(T_m^{(p_z)}\right) + \\ +\mu_{\delta p_z^+}\left(T_m^{(p_z)}\right) - \\ -\mu_{\delta p_z^-}\left(T_m^{(p_z)}\right) \end{pmatrix}\right)\right)/T_m^{(p_z)}\right) | m = 1,\ldots,M\right\}. \quad (11)$$

Similarly, the indirect influence of the management decision is taken into account $r_{k_i}^{(p_i)}$ but for all other vague situational signs with P.

Action 3. 9. As a result of the application of the above proposed procedure for each management decision with R a set of local control decisions is formed, ordered by the degree of their influence on dependent fuzzy situational features. Moreover, the number of these local control decisions may be limited depending on the threshold values established and the effects of the control decisions on dependent features.

The results of assessing the degree of influence of control decisions on fuzzy situational features are the basis for setting control transitions when implementing a direct approach to constructing a fuzzy graph for managing IS security parameters.

Action 4. Identification of the current unclear situation regarding the state of IS security, which is:

– firstly, in matching the feature values of the current IS security situation with the feature values of all reference fuzzy situations of the constructed fuzzy graph;

– secondly, in determining the reference fuzzy situation of the fuzzy graph, closest in a certain sense to the current situation of the IC security scenario according to the chosen method of their comparison;

– thirdly, in identifying the current fuzzy situation with the nearest fuzzy graph reference situation found.

One of the main requirements for the chosen method of comparing fuzzy situations is the possibility of establishing the degree of their closeness (similarity). This requirement is satisfied, for example, by the indicator of fuzzy equality of situations, which is well established for matching fuzzy sets of level 2 [10]

$$\theta\left(s_{cur}, s_j\right) = \underset{p_i \in P}{\wedge} \theta\left(\mu_{\tilde{s}_{cur}}\left(\tilde{p}_i\right), \mu_{\tilde{s}_j}\left(\tilde{p}_i\right)\right),$$

where:

$$\theta\left(\mu_{\tilde{s}_{cur}}\left(\tilde{p}_i\right), \mu_{\tilde{s}_j}\left(\tilde{p}_i\right)\right) = \\ = \underset{T_m^{(p_i)}}{\wedge} \theta\left(\left(\mu_{\tilde{s}_{cur}}\left(p_i\right)/T_m^{(p_i)}\right), \left(\mu_{\tilde{s}_j}\left(p_i\right)/T_m^{(p_i)}\right)\right),$$

$$\theta\left(\left(\mu_{\tilde{s}_{cur}}\left(p_i\right)/T_m^{(p_i)}\right), \left(\mu_{\tilde{s}_j}\left(p_i\right)/T_m^{(p_i)}\right)\right) = \\ = \begin{cases} \min\begin{pmatrix} \max\left(1-\left(\mu_{\tilde{s}_{cur}}\left(p_i\right)/T_m^{(p_i)}\right), \left(\mu_{\tilde{s}_j}\left(p_i\right)/T_m^{(p_i)}\right)\right) \\ \max\left(1-\left(\mu_{\tilde{s}_j}\left(p_i\right)/T_m^{(p_i)}\right), \left(\mu_{\tilde{s}_{cur}}\left(p_i\right)/T_m^{(p_i)}\right)\right) \end{pmatrix}, \\ \text{IF}\begin{pmatrix} \left(\mu_{\tilde{s}_{cur}}\left(p_i\right)/T_m^{(p_i)}\right) \notin \left(1-\sigma, \sigma\right) \\ \left(\mu_{\tilde{s}_j}\left(p_i\right)/T_m^{(p_i)}\right) \notin \left(1-\sigma, \sigma\right) \end{pmatrix}; \\ 1, \text{IF}\left(\mu_{\tilde{s}_{cur}}\left(p_i\right)/T_m^{(p_i)}\right) \in \left(1-\sigma, \sigma\right) \\ \text{OR}\left(\mu_{\tilde{s}_j}\left(p_i\right)/T_m^{(p_i)}\right) \in \left(1-\sigma, \sigma\right), \end{cases} \quad (12)$$

σ – the threshold of fuzzy equality of situations is 0.95.

The juxtaposition of fuzzy situations may be carried out based on one of the following approaches [19]:

– reduction of the multi-criteria evaluation problem to a single-criteria one based on the aggregation of the results of the comparison of individual features using different convolutions (additive, multiplicative, maximin, minimax, etc.);

– on individual or several priority features, while other features are considered additional, the matching results of which satisfy the set limit.

It is important to set fuzzy situations and determine the degree of fuzzy equality of situations in such a way that each time they are compared, there is one situation exceeding the fuzzy equality threshold.

Action 5. Determination of the target situation, strategy, and search for routes in a fuzzy graph.

Determining the target situation significantly affects the search for the best route in a fuzzy graph. At the same time, it is not always possible to predict its reach from an arbitrary current situation. This collision is resolved by adapting the fuzzy graph depending on the detected typical case of its adaptation and careful processing of routes.

Strategies for situational management of IS security parameters are formed sequences of control decisions that affect fuzzy situational features for the transition of a fuzzy graph from the current to the target situation.

As strategies of fuzzy situational management under different conditions of functioning of the fuzzy graph, the following can be chosen to achieve the target situation star, for example:

– maximizing the efficiency of IS message transmission (management strategy "Efficiency");

– minimization of the consumption of IS computing resources (management strategy "Savings");

– maximizing the reliability of messages transmitted to the IS (management strategy "Security");

– maximum average route weight – ratio of the sum of the weights of the control transitions included in the arc route to the number of these arcs according to one selected strategy (control strategy "Balanced");

– mixed strategies.

The restrictions imposed on the choice of route are requirements for intermediate situations, namely, for the composition and values of signs of unclear situations.

In order to ensure a greater possibility of choosing an appropriate fuzzy management strategy, a preliminary assessment (weighting) of each management decision is performed regarding the criteria of the relevant strategies.

Table 1 presents examples of management decisions and their weighting factors with respect to the criteria of the management strategy in question.

To achieve the target situation s_{tar} from the current one s_{cur} different routes may be involved (as a result of the execution of the corresponding sequences of control decisions), the choice of which depends on the given strategy of fuzzy situational control of the fuzzy graph.

Table 1

Management solutions and their weight solutions for various strategies for managing IS security parameters

Output situation	Final situation	Management decision	Managed parameter	The direction of influence of the management decision	The degree of influence of the management decision	Weight management solution for strategy «Security»	Weight management solution for strategy «Savings»	The weight of the control solution for the strategy «Efficiency»
...	...	...	...	...	...	...	...	...
S_k	S_5	R_{13}	p_2	Do not change	Weakly	0.9	0.1	0.2
S_k	S_j	R_{14}	p_2	Do not change	Average	0.8	0.2	0.3
...	...	...	...	...	...	...	...	...
S_4	S_3	R_{21}	p_1	Reduce	Weakly	0.8	0.7	0.5
S_4	S_6	R_{18}	p_1	Reduce	Average	0.5	0.5	0.7
S_4	S_K	R_{19}	p_1	Reduce	Strongly	0.2	0.3	0.4
...	...	...	...	...	...	...	...	...
S_2	S_3	R_c	p_m	Enlarge	Weakly	0.4	0.5	0.8
...	...	...	...	...	...	...	...	...
S_2	S_K	R_c	p_m	Enlarge	Strongly	0.1	0.9	0.6

Between the current (identified) s_{cur} but targeted s_{tar} different routes are possible by fuzzy situations of a fuzzy graph

$$\forall s_{cur}, s_{tar} \in S, s_{cur} \xrightarrow{D_{s_{cur},s_{tar}} \subset D} s_{tar} : D_{s_{cur},s_{tar}} = \\ = \left\{ d_b^{(s_{cur},s_{tar})} \mid b = 1,\ldots, B_{s_{cur},s_{tar}} \right\}, \quad (13)$$

where $B_{s_{cur},s_{tar}}$ – number of possible routes between situations s_{cur} and s_{tar}.

The choice of one or another route is carried out depending on the given strategy and is implemented in the form of the execution of a corresponding sequence of control decisions that translate a fuzzy graph through possible control transitions and intermediate situations from s_{cur} in s_{tar}.

So, after identifying the current situation s_{cur} the influence of a given management decision $r_{k_i}^{(p_i)} \in R$ on s_{cur} it is reduced to a fuzzy composition of a fuzzy set $\tilde{s}_{cur}$ and a vague relationship $\tilde{r}_{k_i}^{(p_i)}$. Then a fuzzy set is obtained $\tilde{s}_{mid}$ (defines some intermediate situation s_{mid}) mapped to fuzzy set $\tilde{s}_{fin}$ (defines a vague situation s_{fin}). If the given degree of similarity is exceeded, a conclusion is made about the transition of the fuzzy graph from the situation s_{cur} in the situation s_{fin}

$$\tilde{s}_{mid} = \tilde{s}_{cur} \cdot r_{k_i}^{(p_i)}, \tilde{s}_{fin} \approx \tilde{s}_{mid}. \quad (14)$$

After that, the assignment of the parameter of the current situation to the fuzzy graph of the reference values of the indicators can be performed s_{fin}.

Direct search and selection of routes in a fuzzy graph, taking into account the chosen strategy, can be carried out both by the iterative method and on the basis of known search algorithms in oriented weighted graphs, for example, Ford, Moore, Bellman, and Floyd.

Action 6. Adaptation of a fuzzy graph to changes in the hybrid composition model of IS.

Adaptation of a fuzzy graph is necessary if there are changes in the composite hybrid model based on the results of monitoring the state of IS components and the system in general.

Table 2 shows typical cases of fuzzy graph adaptation.

Table 2

Typical cases of fuzzy graph adaptation

A case of adaptation of a fuzzy graph	Characteristics
Case 1. Change in the set of fuzzy situational signs	Fuzzy situations, control solutions, control transitions, structure of the fuzzy graph, routes are set again
Case 2. Direct change in the composition of unclear situations	Additional control transitions are installed, the structure of the fuzzy graph is supplemented, and routes are changed
Case 3. Change in the composition of management decisions	Additional control transitions are installed, the structure of the fuzzy graph is supplemented, and routes are changed

Action 7. Determination of the amount of necessary computing resources of the IS.

In order to prevent looping of calculations on actions 1–6 of the specified technique and to increase the efficiency of calculations, the load of the IS is additionally determined. If the specified computational complexity threshold is exceeded, the number of software and hardware resources that must be additionally attracted is determined using the method proposed in work [19].

End.

5. 2. Effectiveness evaluation of the method of intelligent management of information system security parameters

In order to determine the effectiveness of the methodology of intelligent management of security parameters of information systems, its modeling was carried out when solving the task of intelligent management of security parameters of the special-purpose IS of the group of troops (forces) under the initial conditions specified in section 4.

Separate parts of the computational experiment, using the proposed method of intelligent management of IS security parameters, are given in the Tables 3, 4.

Table 3

Effectiveness evaluation of the proposed method of intelligent management of information system security parameters according to the criterion of prompt decision-making

Function name	Metrics	Canonical particle swarm algorithm [19]	Ant colony algorithm [19]	Black widow algorithm [19]	Grey wolf pack algorithm [19]	Cheetah pack algorithm [19]	Proposed methodology
1	2	3	4	5	6	7	8
U22-1	Average value	300.000	300.000	300.000	300.000	300.000	300.000
	Standard value	2.17547E-07	1.94448E-07	1.73866E-07	1.73121E-07	1.51021E-07	1.68168E-07
B22-2	Average value	400	400.265772	400.7973158	400.265772	400.3986579	399.5315429
	Standard value	4.9898E-08	1.011427534	1.621892282	1.011427535	1.216419212	1.368342398
B22-3	Average value	600.0071815	600.0644622	600.0240021	600.012832	600.031303	599.0449987
	Standard value	0.021632777	0.184980091	0.115606243	0.053463097	0.147011513	0.101164243
B22-4	Average value	826.5653461	827.3281442	823.8789639	826.3000191	826.2668486	828.7693662
	Standard value	9.13817552	8.364210734	11.30806963	8.186625055	9.136107323	9.07921317
B22-5	Average value	900.743876	900.9504411	900.9726169	900.8007883	900.5452042	899.2016312
	Standard value	0.781626306	1.424558753	1.275779755	0.903385622	0.635781924	1.578982565
B22-6	Average value	1888.524629	1874.869967	1876.294359	1847.184924	1888.926953	1855.878175
	Standard value	127.2561383	91.22185049	69.00003268	32.76980351	140.693674	29.57108747
H22-7	Average value	2027.479588	2030.758499	2029.556604	2032.238674	2028.177978	2052.128603
	Standard value	6.106897592	8.027195324	5.81348717	7.446489204	8.003968446	7.397733191

Continuation of Table 3

1	2	3	4	5	6	7	8
H22-8	Average value	2223.108804	2223.537417	2222.070633	2223.140251	2220.888475	2219.690533
	Standard value	4.749655105	2.963408213	4.895282849	3.995669404	5.451654006	5.347353983
H22-9	Average value	2510.930321	2510.930321	2536.358938	2498.216012	2523.644629	2499.216012
	Standard value	65.93880108	65.93880108	85.778947	48.38585173	77.58997694	47.38585173
C22-10	Average value	2594.615905	2596.833927	2585.256107	2591.210109	2605.304194	2618.308989
	Standard value	48.2013289	49.71807546	57.1034079	56.36586785	42.57395199	34.10382553
C22-11	Average value	2695.981932	2685.587394	2733.855734	2710.621315	2700.168413	2713.333781
	Standard value	116.3652035	110.1475838	146.333679	118.5098748	113.7913849	109.3008673
C22-12	Average value	2857.067086	2858.742176	2854.959949	2861.414681	2859.407788	2895.718769
	Standard value	9.364347909	14.88960231	5.539104327	17.96133754	15.00545163	15.34731781

Table 4

Effectiveness evaluation of the proposed methodology according to the criterion of reliability of decision-making

Function name	Metrics	Canonical particle swarm algorithm [19]	Ant colony algorithm [19]	Black widow algorithm [19]	Grey wolf pack algorithm [19]	Cheetah pack algorithm [19]	Proposed methodology
U22-1	Average value	0.66	0.73	0.67	0.68	0.8	0.94
	Standard value	0.7	0.73	0.68	0.69	0.83	0.95
B22-2	Average value	0.7	0.73	0.7	0.71	0.77	0.94
	Standard value	0.71	0.73	0.72	0.72	0.76	0.94
B22-3	Average value	0.68	0.73	0.7	0.71	0.76	0.92
	Standard value	0.69	0.73	0.69	0.73	0.77	0.93
B22-4	Average value	0.67	0.74	0.7	0.72	0.78	0.93
	Standard value	0.67	0.72	0.67	0.72	0.79	0.92
B22-5	Average value	0.6	0.71	0.64	0.73	0.8	0.93
	Standard value	0.61	0.72	0.64	0.74	0.88	0.93
B22-6	Average value	0.64	0.73	0.66	0.77	0.85	0.93
	Standard value	0.66	0.75	0.66	0.78	0.83	0.93
H22-7	Average value	0.67	0.72	0.68	0.75	0.81	0.91
	Standard value	0.68	0.71	0.69	0.74	0.83	0.94
H22-8	Average value	0.68	0.74	0.69	0.75	0.84	0.93
	Standard value	0.65	0.74	0.67	0.77	0.81	0.94
H22-9	Average value	0.64	0.75	0.66	0.69	0.83	0.94
	Standard value	0.7	0.72	0.71	0.71	0.84	0.93
C22-10	Average value	0.69	0.71	0.7	0.72	0.8	0.94
	Standard value	0.68	0.71	0.7	0.73	0.8	0.95
C22-11	Average value	0.67	0.71	0.69	0.71	0.82	0.94
	Standard value	0.67	0.72	0.68	0.74	0.91	0.94
C22-12	Average value	0.63	0.73	0.65	0.75	0.82	0.94
	Standard value	0.62	0.74	0.66	0.76	0.83	0.94

Table 4 shows the results of the assessment of the reliability of the decisions made for each of the decision optimization methods for making a decision on the management of IS security parameters.

From the analysis of Tables 3, 4, it can be concluded that the proposed technique ensures stable operation of the algorithm for the main test functions of the unimodal and multimodal form.

As can be seen from Tables 3, 4, increasing the security of IS is achieved by increasing the efficiency of decision-making at the level of 12–16% due to the use of additional procedures and ensuring the reliability of decisions made at the level of 0.94.

6. Discussion of the results of the development of the methodology of intelligent management of security parameters of information systems

The advantages of the proposed method of intelligent management of IS security parameters are the following:

– conduct a multi-level and systematic assessment of the state of IS security using the proposed set of analytical expressions. This will allow a comprehensive and objective assessment of the state of security of the IS, both its individual elements and the IS as a whole (expressions (1)–(14)), compared to works [4, 5];

– determine the influence of IS security parameters on each other when the IS security state changes due to the use of fuzzy analytical expressions (expressions (5)–(11)), compared to works [3, 7];

– construct multidimensional dependencies of the security state of the special-purpose IS (expressions (1)–(14)), which will allow to estimate the security of the IS by an arbitrary number of parameters, compared to works [9, 13];

–assess the security of the IS in conditions of incompleteness of information about the evaluation parameters (expressions (1)–(12)), which will allow solving the problem of dimensionality, compared to works [9, 12];

– build a time dependence of the change in parameters that characterize the state of security of the IS (expressions (1)–(14)), which allows to determine the moments of deviation of their values from the nominal, compared to works [11, 14];

– reduce errors in assessing the state of IS security due to the human factor during the verification of IS parameters (action 2), compared to works [4, 7];

– attract additional computing resources (if necessary) (action 7), which achieves the prevention of looping of the methodology's work, compared to research [13, 16];

– determine the influence of control decisions on a separately defined parameter for assessing the state of IS security (action 3.5–3.8), which achieves an increase in the accuracy of control influences compared to research [11, 15].

Among the disadvantages of the proposed method of IS intellectual security parameters, a slight loss of accuracy when converting security parameters to a fuzzy form should be attributed.

The proposed technique allows:

– simulate the state of IS security under the conditions of complex influence of destabilizing factors;

– identify effective measures to increase the level of IS protection;

– comprehensively assess the change in the level of IS protection during control effects on IS.

The limitations of the study are the need to take into account the delay time for collecting and proving information from IS sensors.

The proposed methodology should be used as software for automated troop control systems such as "Dzvin-AS", "Oreanda-PS", as well as integrated information systems such as "Delta".

7. Conclusions

1. The study proposes the main procedures of the method of intelligent management of information system security parameters. The features of the proposed methodology procedures are:

– conducting a multi-level and systematic assessment of the state of IS security using the proposed set of analytical expressions;

– determining the influence of IS security parameters on each other when the IS security state changes due to the use of fuzzy analytical expressions;

– constructing the multidimensional dependencies of the security state of the special-purpose IS, which evaluates the security of the IS based on an arbitrary number of parameters;

– assessing IS security in conditions of incompleteness of information about evaluation parameters, which solves the dimensionality problem;

– constructing the time dependences of changes in parameters that characterize the state of IS protection, which allows determining the moments of deviation of their values from the nominal;

– reducing the error of assessing the state of IS security due to the human factor through the verification of IS parameters;

– attracting additional computing resources (if necessary), which achieves the prevention of looping of the methodology;

– determining the influence of control decisions on a separately defined parameter for assessing the state of IS security, which achieves an increase in the accuracy of control influences.

2. The proposed technique provides an increase in IS security by increasing the efficiency of decision-making at the level of 12–16% due to the use of additional procedures and ensuring the reliability of decisions made at the level of 0.94, which is confirmed by the results of a computational experiment.

Conflict of interest

The authors declare that they have no conflict of interest in this study, including financial, personal, authorship or other nature that could affect the study and its results presented in this article.

Financing

The study was conducted without financial support.

Data availability

The manuscript has related data in the data warehouse.

Use of artificial intelligence tools

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

Authors' contributions

Hennadii Shapovalov: Conceptualization; Methodology; Project administration; Writing – original draft; Writing – review & editing; **Olha Salnikova:** Methodology; Writing; Writing – review & editing; **Yevhenii Kapran:** Writing – original draft; **Oleksii Kuvshynov:** Writing – review & editing; **Oleksii Nalapko:** Resources; Data Curation; **Viktor Yerko:** Validation; Data Curation; **Hryhorii Stepanov:** Software; Validation; Data Curation; **Ihor Borysov:** Methodology; Formal analysis; Visualization; **Oksana Dmytriieva:** Software: Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components; Validation; Data Curation; **Andrii Shyshatskyi:** Software; Validation; Data Curation.

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CREATING A POLYMODEL FRAMEWORK FOR THE CONSTRUCTION OF INTELLIGENT DECISION SUPPORT SYSTEMS

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Intelligent decision support systems (IDSS) are the object of the study. The research problem is to improve the accuracy of the mathematical description of the process of processing heterogeneous data in IDSS. The subject of the study is a mathematical description of the processes of processing heterogeneous data in IDSS. The proposed polymodel complex for the construction of IDSS solutions, which allows:

– systemically represent the relationship between IDSS construction models in the course of their calculation and computing tasks;

– simulate the process of functioning of the IDSS, due to the use of an algebraic (formal) approach to object-oriented modeling and design of the IDSS;

– determine the rational tactical and technical indicators of the IDSS for solving specific calculation and computing tasks, due to the multi-level description of the order of construction of the IDSS;

– make the transition from one type of data representation in IDSS to another due to the presence of appropriate mathematical transformations;

– multidimensional to describe the process of processing heterogeneous data in IDSS, due to the use of a multidimensional matrix model of IDSS data;

– approach the solution of computational-calculation tasks in IDSS by using an interconnected set of mathematical models of IDSS construction;

– formalize the process of constructing IDSS, which allows combining IDSSs using different algorithmic and software. The disadvantages of the proposed polymodel complex include the need to adapt the mathematical apparatus to the specific operating conditions of the IDSS.

The proposed polymodel complex should be used for the construction of IDSS to solve general and specialized calculation tasks, as well as to solve the task of integrating various types of IDSS

Keywords: system modeling, data representation, decision-making, multidimensionality of data description

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1. Introduction

Intelligent decision support systems (IDSS) are the basis for building modern information systems, automated systems, and computing systems for various functional purposes [1–3]. IDSS is used to solve a wide range of tasks in various areas [4, 5]:

– intellectualization of decision support processes by decision makers;

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– increasing the reliability of decisions made due to multifactorial, multi-criteria, and multi-parameter assessment of available information for analysis;

– processing of large arrays of information circulating in information systems, automated systems of various functional purposes, of different origins and units of measurement;

– forecasting the development of events, as well as their consequences, etc.

The basis of any IDSS is mathematical support, which is later transformed into algorithmic and software for performing the tasks set before them [6–8].

This prompts the search for new solutions for the development of mathematical support for modern IDSS to increase the efficiency of their assigned tasks [9].

One of these approaches is the use of algebraic models of the functioning of the IDSS, which will allow to substantiate approaches to data approximation, optimize the use of IDSS resources, and carry out appropriate formalizations of heterogeneous data processing processes in the IDSS [10, 11].

Therefore, the study devoted to the development of new approaches to the construction of IDSS is relevant.

2. Literature review and problem statement

Work [12] presents an approach focused on searching for hidden information in large data sets. The method is based on analytical baselines, variable reduction, rarefied feature detection, and rule formation. The disadvantages of this method include the impossibility of taking into account different decision-making strategies, and the lack of taking into account the type of uncertainty of the initial data. In the study, not enough attention was paid to the principles and procedure of calculations, their effectiveness according to a certain criterion, and a comparative assessment of the specified approach was not carried out in comparison with the known ones.

Works [13, 14] provide an approach to the transformation of information models of objects to their equivalent structural models. This mechanism is designed to automate the necessary conversion, modification, and addition operations during such information exchange. The disadvantages of this approach include the impossibility of assessing the adequacy and reliability of the information transformation process, as well as carrying out appropriate corrections of the obtained models. In the study, not enough attention was paid to the principles and procedure of calculations, their effectiveness according to a certain criterion, and a comparative assessment of the specified approach was not carried out in comparison with the known ones.

In work [15], a method of fuzzy hierarchical evaluation is proposed, which allows for an assessment of the quality of library service. The disadvantages of the specified method include the impossibility of assessing the adequacy and reliability of the assessment and determining the assessment error accordingly. In the study, not enough attention was paid to the principles and procedure of calculations, their effectiveness according to a certain criterion, and a comparative assessment of the specified approach was not carried out in comparison with the known ones.

In work [16], an analysis of the 30 most common Big Data algorithms was carried out. It was established that the analysis of large data sets should be carried out layer by layer, take place in real time, and be able to self-learn, find a solution in different directions, and take into account the noise of the data.

Works [17, 18] present approaches for evaluating various types of data for support and decision-making systems based on the clustering of a basic set of input data, after which system training takes place based on the analysis. However, given the static architecture of artificial neural networks, an accumulation of error occurs.

In the work [19], a comparative analysis of existing decision support technologies was carried out, namely: the method of analyzing hierarchies, neural networks, the theory of fuzzy sets, genetic algorithms, and neuro-fuzzy modeling. The advantages and disadvantages of these approaches are indicated. For the tasks of assessing the state of hierarchical systems in conditions of risk and uncertainty, the use of the theory of artificial neural networks and gradient algorithms is justified.

In work [20], approaches to the structural-target analysis of the development of weakly structured systems are developed. At the same time, the problem is defined as the inconsistency of the existing state of the weakly structured system with the necessary one. At the same time, the disadvantages of the proposed approaches include the problem of local optimum, the lack of consideration of the system's computing resources, as well as the inability to conduct searches in several directions.

Analyzing scientific research [12–20] showed that the common shortcomings of the above-mentioned research are:

– not enough attention is paid to the effectiveness of the mathematical apparatus that forms the basis of their work;

– there is no systematic consideration of the mathematical apparatus, its advantages and disadvantages compared to known ones;

– there is no order of transition from one principle of data submission to another in the IDSS;

– using only one type of mathematical apparatus to solve computational tasks in IDSS.

Taking into account the above, all this allows to state that it is expedient to conduct a study devoted to the development of mathematical and algorithmic support for the construction of intelligent decision support systems.

3. The aim and objectives of the study

The aim of the study is to develop a polymodel complex for building intelligent decision support systems. This will make it possible to increase the reliability of the assessment of the state of objects with a given efficiency and the development of subsequent management decisions. This will make it possible to develop software for intelligent decision support systems.

To achieve the aim, the following objectives were set:

– cite the basic concepts and definitions of universal algebra and algebraic systems in IDSS and develop an intuitive approach to object-oriented IDSS modeling;

– propose an algebraic (formal) approach to object-oriented modeling and IDSS design;

– provide an object-oriented approach to the development of IDSS data models and to develop a multidimensional matrix model of IDSS data;

– establish the correspondence of set-theoretic and multidimensional-matrix models of IDSS data;

– develop an axiomatic approach to the formalization of data models for IDSS.

4. Materials and methods

The object of the study is IDSS. The subject of the study is a mathematical description of the processes of processing heterogeneous data in IDSS.

The hypothesis of the study is the possibility of increasing the accuracy of transformations during the processing of heterogeneous data in IDSS.

The study is based on algebraic models for formalizing the structure of heterogeneous data processing tasks in IDSS, finding optimal strategies for heterogeneous data processing, and forecasting the results of their processing under conditions of limitations.

The limitations adopted in this study are that only the identified destabilizing factors, the distribution law of which is known, are taken into account during the modeling. To simplify modeling and calculations, it is accepted that IDSS performs typical calculations and computing operations under conditions of constant influence of destructive factors.

5. Polymodel complex for building intelligent decision support systems

5. 1. Basic concepts and definitions of universal algebraic systems, an intuitive approach to object-oriented modeling

As the basis of object-oriented models of IDSS, which will allow formalizing the representation of data and their transformation operations, concepts such as universal algebra and universal algebraic system are used in the future, the known definitions of which are given below.

Definition 1. Let A – some nonempty set. Partially defined function $y = F(x_1, ..., x_n)$, $(y, x_1, \dots, x_n) \in A$ called n-ary partial operation on A. If the function is defined everywhere, they talk about n- ary operation.

Definition 2. System $U_A = <A, \Omega>$, consisting of the main set A and the set of partial operations defined on it $\Omega = \{F_s^{n_s}\}$ $(s = 1, 2, ...)$, it is called a partial universal algebra with a signature Ω.

Definition 3. Universal algebras U_A and U_B, in which the signatures are specified, respectively Ω and Ω' they are called the same type. This becomes possible if such a one-to-one correspondence between signatures can be established Ω and Ω', in which any operation $F \in \Omega$ and the corresponding operation $F' \in \Omega'$ will be n-ary with the same n.

Let two universal algebras of the same type be given $U_A = <A, \Omega>$ and $U_B = <B, \Omega>$ with basic sets A and B.

Definition 4. Display $\varphi: A \to B$ it is called a homomorphic mapping of algebra U_A in algebra U_B, if for any elements of IDSS $a_1, \dots, a_n \in A$ and arbitrary n-ary operations $F \in \Omega$ the ratio is performed $\varphi(F(a_1, ..., a_n)) = F(\varphi(a_1), ..., \varphi(a_n))$, where $\varphi(a_i) = b_i$ and $b_i \in B(i = 1, \dots, n)$. Algebras U_A and U_B they are called homomorphic.

If between the main sets A and B an unambiguous correspondence is established, then the display φ it is called an isomorphic mapping, and algebras U_A and U_B they are called isomorphic.

Definition 5. Let $\pi(x_1, ..., x_n)$, $x_1, \dots, x_n \in A$ – n-local predicate, $\Pi = \{\pi_s^{n_s}\}$ $(s = 1, 2, ...)$ – predicate signature. System $U_A = <A, \Pi, \Omega>$ it is called a universal algebraic system.

Homomorphic and isomorphic dependencies can also be established between universal algebraic systems. For this, it is necessary to establish a correspondence between the signatures of the predicates, similar to the one established between the signatures of the IDSS operations.

Cases where a single main set can be dispensed with when constructing a formal model of a task solved by IDSS do not occur often, since objects in the subject area have a complex structure, for the description of which many different types of parameters are used. Multibasic algebras are used to model such subject areas.

Definition 6. System $U_M = <M, \Omega>$, consisting of a family of basic sets $M = \{A_\alpha\}$ $(\alpha = 1, 2, ...)$ and signatures Ω operations defined on the family M. Each in this family n-ary operation with Ω is a mapping of the Cartesian product n sets from the family M in the plural from the same family $A_{\alpha_1} \times \dots \times A_{\alpha_n} \to A_{\alpha_r}$, it is called a polybasic algebra.

Definition 7. System, $U_M = <M, \Pi, \Omega>$ where Π – signature n-local predicates $\pi : A_{\alpha_1} \times \dots \times A_{\alpha_n} \to \{0,1\}$, it is called a polybasic algebra system.

Homomorphic and isomorphic mappings can be established between polybasic algebras and algebraic systems, just as between monobasic ones. The following are examples of some frequently encountered data types that can be represented as polybasic algebraic systems.

Example 1. Let $U_S = <S, Z_0; \Pi; \Omega>$ – a system consisting of a set of lines S and sets of nonnegative integers Z_0. Signature Ω consists of operations:

– Ⓛ: $S \to Z_0$ – line length;

– Ⓟ: $S \times S \to Z_0$ – substring position s_1 in line s_2;

– ?+?+: $S \times S \to S$ – concatenation (clutching) of rows s_1 and s_2;

– Ⓒ: $S \times Z_0 \times Z_0 \to S$ – selection from a line s_1, starting from the position i, substring s_2 lengths l.

Predicate signature Π may include predicates:

– π_1: "line s – empty" (does not contain any character);

– π_2: "line s_1 precedes the line s_2".

Example 2. Ordinary matrix algebra is very important from the point of view of mass data processing in IDSS for example, a universal two-basic algebraic system $U_M = <M, R, \Pi, \Omega>$, where M – a set of matrices, and R – a set of real numbers (matrix elements). Signature Ω universal two-basic algebraic system U_M it looks like this:

– $+ : R \times R \to R$ – additive operation on matrix elements;

– $\times : R \times R \to R$ – multiplicative operation on matrix elements;

– ?'?' $: M \to M$ – matrix transpose;

– $\times : R \times M \to M$ – multiplying a matrix by a number;

– $+ : M \times M \to M$ – matrix sum;

– $\times : M \times M \to M$ – product of matrices;

– Ⓓ: $M \to R$ – matrix determinant.

Predicate signature Π can contain predicates such as a "matrix M degenerate" or "matrix M_1 can be multiplied by the matrix M_2".

Next, polybasic algebraic systems will be used as an apparatus for building data models in IDSS, the properties of which satisfy the tasks set in the work.

The basis of the object-oriented approach in IDSS is the concept of abstract data type (ADT).

Definition 8. Intuitively, ADT is a construction of data representation in IDSS, in which the following elements are grouped into one concept:

– the set of operations (actions) in IDSS;

– the set (one or more) of objects to which these operations apply;

– protection, or the ability of the relevant IDSS to protect the internal representation of the ADT from actions not explicitly specified in its definition (that is, to hide it from the ADT user).

Definition 9. In IDSS ADT is a two-part design:

– interface containing the name of the conditioned ADT, the names of the operations indicating their argument types and values;

– descriptions of the operations and objects with which these operations work.

This description is called concrete, in contrast to the abstract description made by means of a higher level. A specific description is also called an ADT implementation or presentation. Thanks to protection, only the names listed in the interface are available; that is, they can be used by other components of the program external to the ADT.

In the future, algebraic definitions of ADT and specific descriptions for each ADT will be used in the creation of IDSS data models. The ADT interface is a list of variables that take values on the main ADT sets and operations defined on these sets and take values in one of them. In the implementation of ADT, variables are assigned names, and their types are determined. Operations are matched with software implementation (procedures and functions), consisting of two parts:

– declarative, in which each function implementing the operation is given a name and given a description of its interface (a list of formal parameters is given);

– imperative, which is the body of a partial algorithm that implements this function.

To solve the tasks set in the work, the conjugation of data models and calculation models by the method of establishing correspondence between these models, the intuitive definition of ADT is not enough. Therefore, a strict definition of ADT must be used.

5. 2. Algebraic (formal) approach to object-oriented modeling and design

From an intuitive definition, it follows that ADT combines data sets in IDSS and operations on them under one name with which it is possible to set a description of the properties and procedures of transformation of a real object from a certain subject area, that is, build its formal model. The concept of a multi-basic algebraic system is used to clearly and unambiguously define ADT.

Definition 10. Abstract data type IDSS (object or class) – a universal monobasic or multibasic algebraic system.

This definition allows to consider any, including monobasic, universal algebras and algebraic systems, as ADTs. Despite its brevity, it fully corresponds to the intuitive definition. The following example clearly illustrates this.

Example 3. When solving various computational and logical tasks, such as finding the shortest paths, determining the availability of graph vertices, and disassembly, the universal single-base algebra system – monoid is often used to determine the data.

A monoid is a set *M*, on which the binary operation is specified (*), and two conditions are met:

– for any three elements $x \in M,\ y \in M,\ z \in M\ (x*(y*z)) = ((x*y)*z$ – operation associativity;

– there is such an element $e \in M$, what is called a neutral element that for any $x \in M,\ x*e = x = e*x$.

The monoid is designated as a triad of the species $U_M = <M;*;e>$. The monoid defined in this way can be considered as a basic ADT, that is, the highest level of abstraction, to which different implementations correspond, each of which corresponds to a specific task or a specific class of tasks:

– $U_R = <R;+;0>$ – the set of real numbers with addition operation;

– $U_R = <R;\times;1>$ – the set of real numbers with the multiplication operation;

– $U_R = <R;\min;+\infty>$ – a set of positive real numbers with the operation of finding the minimum of two numbers and a neutral element (+∞), which in software implementations usually corresponds to the largest value in the type;

– $U_B = <B;\vee;0>$ – plural $B = \{0,\ 1\}$ with disjunction operation;

– $U_S = <S;+;\varnothing>$ – the set of character strings of arbitrary length with the operation of concatenating (coupling) strings and the neutral element "empty string" (a string that does not contain any character).

The encapsulation property is satisfied because in each implementation of the basic ADT, the main set is precisely indicated, and the operation is defined as algebraic, that is, closed on the main set.

All the above implementations of the monoid inherit the properties inherent in the basic ADT; that is, the inheritance property is also satisfied.

Finally, for the operations of two implementations of the monoid, the sign (+) is used to denote two operations of different content (compilation of real numbers and concatenation of strings). That is, the property of operations polymorphism is satisfied.

Example 4. Of the many operations for constructing an example of a universal polybasic algebraic system, only one – the compute method is chosen. This provides simplicity of example, but does not limit commonality. The operation is implemented by a function that is defined on the following sets:

– the set of all tables *T*;

– the set of lines of a special type S_E, containing expressions based on aggregate functions (sum, mean, maximum and similar);

– the set of lines of a special type S_F, containing logical expressions – table row filters.

Since the type of the result of the operation is determined by the type of the result of calculating the expression from S_E, to ensure commonality, it is given by type *object*. That is, the result can be given a value of any type specified by the user. It can be assumed that the type *object* corresponds to the concept of a universal set *U*, that is, a set fixed within the solvable problem and containing as elements all the objects considered in this theory. Then the operation can be defined as a function $Compute: T \times S_E \times S_F \to U$. Class DataTable defined as a multibasic universal algebraic system $U_{DT} = <T;S_E;S_F;U;Compute;\Pi>$. The definition of predicates depends on the task being solved. For example, a "filter expression acquires a truth value on more than half of the rows of the table".

Examples 3 and 4 clearly demonstrate the correspondence of two definitions of ATD: intuitive and strict (algebraic).

5. 3. An object-oriented approach to model development, a multidimensional-matrix data model

To develop IDSS data models that meet the requirements, namely: compliance with high-level data models and calculation models, procedurality, parallelism of algebraic operations, possibility of optimization of requests, and object orientation, it is necessary to choose basic ADTs.

The specified ADTs must have properties that will be sufficient so that, using the inheritance mechanism, it would be possible to build the necessary universal algebras or algebraic systems for use as data models.

Among the set of arbitrary ADTs, it is proposed to consider a specific ADT, hereinafter called an abstract algebraic machine.

Definition 11. An abstract algebraic machine is a two-basic algebraic system of the form $E = <S, T, \Omega, \Pi>$. Basis S it is called a structure, and the base T – type.

The structure is some construction composed of instances of this type. Examples of such structures are vectors, matrices, and graphs. The choice of structure and type is determined by the features of the solved task. Moreover, for some classes of tasks, several types can correspond to one structure. The following example illustrates this situation.

Example 5. To solve the IDSS of the tasks named in the example, finding the shortest paths, determining the accessibility of the vertices of the graph, and knotting a method based on the algorithm for calculating the transitive closure of a square matrix can be applied M.

Transitive matrix closure M it is calculated according to the following formula: $M^* = \sum_{i=1}^{K} M^i,\ M^i \neq Z$ for everyone $i \leq K$ and $M^{K+1} = Z$ where Z – zero matrix.

In this case, the abstract algebraic machine has the following form $E_M =< M; X; \Omega; \Pi >$, where X – type, and M – a set of square matrices composed of type elements.

Minimum type requirement X consists in on X two algebraic operations were defined, one of which is interpreted as additive and the other – as multiplicative.

That is, the type X there must be, according to each of these operations, at least an algebraic structure called a groupoid. In real problems, the types can be quite complex algebraic structures, such as rings and fields. The following are formal definitions and descriptions of signature operations Ω abstract algebraic machine E_M:

– ?+?+: $X \times X \to X$ – additive operation on matrix elements;

– ?×?×: $X \times X \to X$ – multiplicative operation on matrix elements;

– ?′?′: $M \to M$ – matrix transpose;

– +: $M \times M \to M$ – matrix sum;

– ×: $M \times M \to M$ – product of matrices;

– Ⓓ: $M \to X$ – matrix determinant.

In real tasks, IDSS in the role of type X there can be such sets as:

– in the "knotting task" – the set of nonnegative real numbers R^0, with additive addition operation and multiplicative multiplication operation of numbers, $\Omega = \{+, \times\}$;

– in the task of calculating the shortest paths in the graph –, the set of positive real numbers R^+, with the additive operation of calculating the minimum of two numbers, and the multiplicative operation of addition, $\Omega = \{\min, +\}$;

– in the task of determining the availability of vertices in the graph, the set $\{0, 1\}$ with additive disjunction operation and multiplicative conjunction operation, $\Omega = \{\vee, \wedge\}$.

Operations on matrices included in the signature of operations Ω, are implemented by well-known sequential and parallel standard algorithms, which will be discussed later.

The importance of the considered example lies, first of all, in the fact that it clearly shows the presence of universal two-basic algebraic systems that have quality. Quality can be formulated as the possibility of replacing one main set, namely the type and operations on its elements, while preserving another set and algorithms that implement operations on its elements. This fact can be formulated in the form of an obvious statement.

Statement 1. Let S – structure, and $T_1, \ldots, T_n$ – types acceptable for this structure. Then $T_1, \ldots, T_n$ – universal systems of the same type (s).

The practical value of universal algebraic machines is that the essence of operations on elements of the structure S does not change when the essence of operations on type elements changes T. If types $T_1, \ldots, T_n$ – homomorphic or isomorphic universal algebraic systems, it becomes possible to adjust operations on the structure on the simplest type of data. The structure adjusted in this way becomes the basic ADT, from which specific ADTs (implementations) designed to solve IDSS tasks on complex data types can be generated. Next, the method of constructing binary operations on tuples is considered, without which it is impossible to construct binary operations on data aggregates that are used as elements of the structure (relationships, data, multidimensional matrices). In different data models, these tuple operations, given explicitly or implicitly, are interpreted either additively or multiplicatively. The proposed method made it possible to make explicit formal descriptions of binary operations on tuples. Next, the definition of a tuple generally accepted in mathematics is used.

Definition 12. Tuple – the final set $(t_1, \ldots, t_n)$ lengths n (where n – a non-negative integer), each element of which t_i belongs to some type $T_i\,(1 \leq i \leq n)$. Zero tuples play an important role in data models. In the future, the zero-tuple is perceived as a tuple consisting only of neutral elements of types $T_1, \ldots, T_n$.

Let $T_1, \ldots, T_n$ – the set of basic sets of universal algebras or algebraic systems, which are called simple types in programming languages. These are, for example, fixed or floating point numbers, strings, as well as types obtained from simple types by adding new operations. Let $x_1, \ldots, x_p, y_1, \ldots, y_q$, $(0 \leq p, q \leq n, p + q = n)$ – a set of variables, each of which acquires a value in one and only one of the sets $T_1, \ldots, T_n$.

On these sets, the system of functions is defined

$$f^{j}_{\alpha_1,\ldots,\alpha_k,\beta_1,\ldots,\beta_l}\begin{pmatrix} x_{\alpha_1},\ldots,x_{\alpha_k}, \\ y_{\beta_1},\ldots,y_{\beta_l}\end{pmatrix} : \begin{pmatrix} T_{\alpha_1}\times\ldots\times T_{\alpha_k}\times \\ \times T_{\beta_1}\times\ldots\times T_{\beta_l}\end{pmatrix} \to T_i.$$

Inequalities are performed here $1 \leq k \leq p$, $1 \leq l \leq q$, $j > 0$ and $1 \leq i \leq n$. Next, a shortened entry of these functions will be used – $f^{j}_{\alpha_1,\ldots,\alpha_k,\beta_1,\ldots,\beta_l}$.

Definition 13. Let tuple c_1 lengths p and tuple c_2 lengths q composed of variables $x_1, \ldots, x_p$ and $y_1, \ldots, y_q$ accordingly. Then the cortege c_3 lengths r, built according to the rule $(f^{1}_{\alpha_1,\ldots,\alpha_k,\beta_1,\ldots,\beta_l}, \ldots, f^{r}_{\alpha_1,\ldots,\alpha_k,\beta_1,\ldots,\beta_l})$, can be considered as the result of a binary operation on tuples c_1 and c_2 $(c_3 = c_1 * c_2)$. If the function is defined on all elements of tuples c_1 and c_2, that is the designation used $f^{j}_{c_1,c_2}$.

The semantics of the operation on tuples (additivity or multiplicativity) is determined by the semantics of the operation, defined over a structure, the types of elements of which can be tuples c_1, c_2 and c_3.

The following example shows the construction of binary operations on tuples.

Example 6. Let S – the set of lines, a R^+ – the set of positive real numbers. Variables (attributes) A, B, C, D acquire meaning in the set S, and variables X, Y – in the plural R^+. Cortezhi c_1 and c_2 have schemes c_1 (A, B, C, X) and c_2 (B, C, D, Y). Functions $f^{2}_{c_1,c_2}(d) = d, (d \in D)$ they allow to build a motorcade $c_3 = c_1 \times c_2$ with scheme c_3 (A, D, Z), where $Z = X \times Y$, and takes values in the set R^+. In this way, the multiplicative operation on tuples is determined. If c_{31}, c_{32}, c_{33} – tuples with a scheme $c_3(A, D, Z)$, then functions:

$$f^{1}_{c_{31},c_{32}}(c_{31}.a) = c_{31}.a, (a \in A), \tag{1}$$

$$f^{2}_{c_{31},c_{32}}(c_{31}.d) = c_{31}.d, (d \in D), \tag{2}$$

$$f^3_{c_{31},c_{32}}\left(c_{31}.z,\, c_{32}.z\right)=c_{31}.z\times c_{32}.z,\left(z\in Z\right), \quad (3)$$

determine the additive operation on tuples $c_{33} = c_{31} + c_{32}$.

Similarly, the considered functions can be used to construct algebras of elements of IDSS structures (data and multidimensional matrices) in set-theoretic and multidimensional-matrix models.

In some models, when constructing binary operations on elements of the structure, a situation may arise when the result tuple is formed from only one operand tuple. This is impossible in a multidimensional matrix model, because there are all possible elements in the matrix, including zero tuples. But in the relational and set-theoretic model, relations and data, as a rule, do not contain strings and records consisting only of neutral elements. Therefore it is advisable to consider two more types of functions $f^j_{\alpha_1,\ldots,\alpha_k,0}(x_{\alpha_1},\ldots,x_{\alpha_k}):(T_{\alpha_1}\times\ldots\times T_{\alpha_k})\rightarrow T_j$ and $f^j_{0,\beta_1,\ldots,\beta_l}(y_{\beta_1},\ldots,y_{\beta_l}):(T_{\beta_1}\times\ldots\times T_{\beta_l})\rightarrow T_j$, which will allow to design operations that form a tuple-result from only one tuple-operand. The use of these operations ensures the unity of the formal recording of algorithms of binary operations on structures. An abbreviated entry of these functions looks like: $f^j_{0,\beta_1,\ldots,\beta_l}$, $f^j_{\alpha_1,\ldots,\alpha_k,0}$.

The proposed method defines various additive and multiplicative operations on tuples and, at the same time, obtains various universal algebras or algebraic systems. The properties of the constructed operations make up a list of axioms of these algebraic systems. Thanks to this, there is a possibility of formal construction of arbitrary universal algebraic systems of tuples in accordance with the requirements of real tasks.

The method of constructing a universal algebraic system for tuples will be used later to construct the second main set (type) in matrix algebraic machines. It will also be used to prove the isomorphism of the data models considered in the work.

The multidimensional-matrix data model considered below was proposed in order to solve the problems of increasing the efficiency of data processing in IDSS. Often, in practice, optimization of one step leads to deterioration of the characteristics of another. This happens because:

– it is difficult to efficiently construct a multidimensional structure even from data placed in analogous structures unless special algebraic operations on these structures are used;

– most modern methods of optimizing data processing processes in IDSS in various data models are based on a heuristic approach, which does not allow effective use of specific properties of multidimensional data structures and operations on them.

Solving these problems is possible based on the use of an algebra of multidimensional matrices, the properties of which allow solving the listed problems. Algebra operations of multivariate matrices are quite easily implemented on parallel computing complexes with different architectures. One of the most important properties of the algebra of multivariate matrices is the possibility of constructing optimal IDSS data processing processes based on the use of formal optimization methods, for example, fuzzy logic.

Matrices are usually understood as structured sets of elements of simple types. Next, multidimensional matrices are considered, the elements of which can belong to arbitrary data types. The main and only requirement is that two algebraic operations must be defined on these types: additive and multiplicative. This means that the types of matrix elements must be at least groupoids for each of the operations defined on them.

This approach allows to use such standard structural types as vectors and matrices to create matrices, although the use of multidimensional matrices deprives such constructions of practical meaning. In principle, different ADTs can be used as types of matrix elements. In order to achieve the goals, set in the work, it is especially important that in order to build a multidimensional-matrix data model, ADTs designed in accordance with the specified requirement for different types of tuples can be used to build a multidimensional-matrix data model.

Definition 14. Let – $i_1, \ldots, i_p$ a set of indices gaining values from 1 to n_α ($\alpha = 1, \ldots, p$) accordingly. Then p- the dimensional matrix is a collection $T=\{a_{i_1,\ldots,i_p}\}$ elements of some type, on which additive and multiplicative operations are defined.

Thus, p – the dimensional matrix contains $n_1 \times\ldots\, n_p$ elements. For multivariate matrices, notation is used $A=||a_{i_1,\ldots,i_p}||$. The algebra signature of multivariate matrices contains the unary operations of transpose, section, convolution, and binary operations of assembly and multiplication. The following are definitions of these operations.

Transposition. Matrix $A'=||a_{i_{\alpha_1},\ldots,i_{\alpha_p}}||$, which elements are related to those of the matrix $A=||a_{i_1,\ldots,i_p}||$ ratio $a_{i_{\alpha_1},\ldots,i_{\alpha_p}}=a_{i_1,\ldots,i_p}$, where $(i_1, \ldots, i_p)$ $(i_{\alpha_1},\ldots,i_{\alpha_p})$ – some permutation of the indices $(i_1, \ldots, i_p)$, it is called transposed with respect to the matrix A according to this permutation.

Visually p – the dimensional matrix can be represented as a p-dimensional parallelepiped or hypercube. Hence, the transposition operation can be interpreted as the rotation of this parallelepiped or hypercube.

Crossing. Two variants of this operation are possible. In the first, the dimension of the matrix decreases, while in the second, it remains.

Simple m-fold intersection. Let in m indices $(1 \le m \le p)$ sets of indices $(i_1, \ldots, i_p)$ matrices are fixed by one value. For simplicity and without limitation of commonality, these will be assumed to be indices $(i_1, \ldots, i_m)$. $(p - m)$-dimensional matrix $||A_{(i_1^0,\ldots,i_m^0,i_{m+1}^0,\ldots,i_p)}||$, consisting only of those elements of the matrix $A=||a_{i_1,\ldots,i_p}||$, in which indices $(i_1, \ldots, i_p)$ have a single fixed value $(i_1^0,\ldots,i_m^0)$, it is called simple m-multiple cross-section of the matrix A orientations $(i_1, \ldots, i_p)$.

Example 7. Let $A=||a_{i_1i_2i_3i_4}||$ – a four-dimensional matrix, all indices of which acquire the value 1, 2. If to fix the value of two indices $i_1 = 2$ and $i_2 = 1$, then a two-time simple cross-section of the matrix is obtained A orientations (i_1, i_2), which is a two-dimensional matrix of the form:

$$A_{(i_1,i_2)}=\begin{Vmatrix} a_{2111} & a_{2112} \\ a_{2121} & a_{2122} \end{Vmatrix}\begin{pmatrix} i_1=2 \\ i_2=1 \end{pmatrix}.$$

If to fix the value of one index $i_2 = 2$, then a one-time simple cross-section of the matrix is obtained A orientations (i_2), which is a three-dimensional matrix of the form:

$$A_{(i_2)}=\begin{matrix} i_1,i_3 \\ \downarrow \end{matrix}\ \overset{i_4\ \rightarrow}{\begin{Vmatrix} a_{1211} & a_{1212} \\ a_{1221} & a_{1222} \\ \hline a_{2211} & a_{2212} \\ a_{2221} & a_{2222} \end{Vmatrix}}\left(i_2=2\right). \quad (4)$$

Intersection with fixed index values. Let be in the set of index values $(i_1, \ldots, i_m)$ $(1 \le m \le p)$ sets of indices $(i_1, \ldots, i_p)$ matrices $A=||a_{i_1,\ldots,i_p}||$ recorded in more than one value.

This means that any index i_k $(1 \le k \le m)$ accepts t_k $(1 < t_k < n_k)$ values from the set $(1, \ldots, n_k)$. p-dimensional matrix $A_{(i_1,\ldots,i_m)}$, consisting only of those elements of the matrix $A=||a_{i_1,\ldots,i_p}||$, in which indices $(i_1, \ldots, i_m)$ accepted accordingly $t_1, \ldots, t_k$ values, called m-multiple intersection of orientation $(i_1, \ldots, i_m)$ with fixed values of matrix indices A.

Obviously, that m-multiple cross-section of the matrix A can be considered as a matrix built from simple m-multiple sections.

Example 8. Let $A = \| a_{i_1 i_2 i_3 i_4} \|$ – a four-dimensional matrix in which all indices take values (1, 2, 3). With the help of double sections, this matrix can be presented in the form:

$$A_{(i_2)} = \begin{matrix} i_1 \\ \downarrow \end{matrix} \overset{i_2 \ \rightarrow}{\left\| \begin{array}{ccc|ccc|ccc} a_{1111} & a_{1112} & a_{1113} & a_{1211} & a_{1212} & a_{1213} & a_{1311} & a_{1312} & a_{1313} \\ a_{1121} & a_{1122} & a_{1123} & a_{1221} & a_{1222} & a_{1223} & a_{1321} & a_{1322} & a_{1323} \\ a_{1131} & a_{1132} & a_{1133} & a_{1231} & a_{1232} & a_{1233} & a_{1331} & a_{1332} & a_{1333} \\ \hline a_{2111} & a_{2112} & a_{2113} & a_{2211} & a_{2212} & a_{2213} & a_{2311} & a_{2312} & a_{2313} \\ a_{2121} & a_{2122} & a_{2123} & a_{2221} & a_{2222} & a_{2223} & a_{2321} & a_{2322} & a_{2323} \\ a_{2131} & a_{2132} & a_{2133} & a_{3231} & a_{2232} & a_{2233} & a_{2331} & a_{2332} & a_{2333} \\ \hline a_{3111} & a_{3112} & a_{3113} & a_{3211} & a_{3212} & a_{3213} & a_{3311} & a_{3312} & a_{3313} \\ a_{3121} & a_{3122} & a_{3123} & a_{3221} & a_{3222} & a_{3223} & a_{3321} & a_{3322} & a_{3323} \\ a_{3131} & a_{3132} & a_{3133} & a_{3231} & a_{3232} & a_{3233} & a_{3331} & a_{3332} & a_{3333} \end{array} \right\|}. \quad (5)$$

Matrix A is a four-dimensional hypercube. If to fix the values of the indices $i_1 = (1, 2)$ and $i_2 = (2, 3)$ then as a result of performing the section operation of the matrix A turns into a four-dimensional parallelepiped of the form:

$$A_{(i_1,i_2)} = \begin{matrix} i_1 \\ \downarrow \end{matrix} \overset{i_2 \ \rightarrow}{\left\| \begin{array}{cc|cc} a_{1111} & a_{1113} & a_{1311} & a_{1313} \\ a_{1121} & a_{1123} & a_{1321} & a_{1323} \\ a_{1131} & a_{1133} & a_{1331} & a_{1333} \\ \hline a_{2111} & a_{2113} & a_{2311} & a_{2313} \\ a_{2121} & a_{2123} & a_{2321} & a_{2323} \\ a_{2131} & a_{2133} & a_{2331} & a_{2333} \end{array} \right\|} \begin{pmatrix} i_1 = (1,2) \\ i_2 = (2,3) \end{pmatrix}. \quad (6)$$

A combined version of this operation is also possible, when a simple cross-section is performed in the index part, and an intersection with a fixed set of index values is performed in the part. In this case, the dimension of the result matrix is less than the dimension of the operand matrix by the number of indices, according to which a simple cross-section is made.

Convolution. Let the partition of the set of matrix indices be given $A = \| a_{i_1,\ldots,i_p} \|$ on totality $l = (l_1, \ldots, l_k)$ and $c = (c_1, \ldots, c_\mu)$, $\kappa + \mu = p$. Matrix ${}^{\mu}A = \| a_l \|$, which elements are related to those of the matrix $A = \| a_{lc} \|$ ratio $a_l = \sum_{(c)} a_{lc}$, called μ-rolled up matrix and is denoted ${}^{\mu}A = \left\| \sum_{(c)} a_{lc} \right\|$. Breakdown indices $l = (l_1, \ldots, l_k)$ they are called free indices, and partition indices $c = (c_1, \ldots, c_\mu)$ – cell indices.

Example 9. Let $A = \| a_{i_1 i_2 i_3 i_4} \|$ – a four-dimensional matrix, all indices of which take the value 1, 2. If $\kappa = \mu = 2$, $l_1 = i_1$, $l_2 = i_2$ – free indices and $c_1 = i_3$, $c_2 = i_4$ – Kelly indices, then the matrix ${}^{2}A = \left\| \sum_{(c)} a_{lc} \right\|$ looks like:

$${}^{2}A = \left\| \begin{array}{cc} \sum_{i_3=1}^{2} \sum_{i_4=1}^{2} a_{11 i_3 i_4} & \sum_{i_3=1}^{2} \sum_{i_4=1}^{2} a_{12 i_3 i_4} \\ \sum_{i_3=1}^{2} \sum_{i_4=1}^{2} a_{21 i_3 i_4} & \sum_{i_3=1}^{2} \sum_{i_4=1}^{2} a_{22 i_3 i_4} \end{array} \right\|. \quad (7)$$

Adding. The sum of two p-dimensional matrices $A = \| a_{i_1,\ldots,i_p} \|$ and $B = \| b_{i_1,\ldots,i_p} \|$ with the same sets of indices $i_1, \ldots, i_p$ called p-dimensional matrix $C = \| c_{i_1,\ldots,i_p} \|$ with the same set of indices, the elements of which are calculated according to the formula $c_{i_1,\ldots,i_p} = a_{i_1,\ldots,i_p} + b_{i_1,\ldots,i_p}$.

Multiplication. Let the matrices $A = \| a_{i_1,\ldots,i_p} \|$ and $B = \| b_{i_1,\ldots,i_p} \|$ p and q-measured accordingly. The sets of indices of these matrices $i_1, \ldots, i_p$ and $i_1, \ldots, i_q$ they are divided into four groups containing, respectively κ, λ, μ and ν indices ($\kappa, \lambda, \mu, \nu \geq 0$). And $\kappa + \lambda + \mu = p$, and $\kappa + \lambda + \mu = q$.

Designations are used for the obtained index groups: $l = (l_1, \ldots, l_k)$, $s = (s_1, \ldots, s_\lambda)$, $c = (c_1, \ldots, c_\mu)$ and $m = (m_1, \ldots, m_\nu)$. Then matrices A and B can be submitted in the form $A = \| a_{lsc} \|$ and $B = \| b_{scm} \|$. Group indices s and c in matrices A and B completely match. Just like in the convolution operation, partition indices c they are called Kelly. Breakdown indices s they are called scott's, and the division indices m, as are the breakdown indices l, – free.

Matrix $C = \| c_{lsm} \|$, the elements of which are calculated according to the formula $c_{lsm} = \sum_{(c)} a_{lsc} \times b_{scm}$ it is called the product of matrices A and B.

The algorithm for implementing this operation is as follows:

– multiplies all pairs of elements in which the values of the indexes of the groups completely coincide s and c;

– sum all products with the same values of group indices c.

The product of multidimensional matrices is called (λ, μ)-collapsed product is denoted by ${}^{\lambda,\mu}(A \times B)$. From definition (λ, μ)-collapsed product follows that for any pair of multidimensional matrices, many different products can be constructed by selecting different values λ and μ.

The number of all possible (λ, μ)-collapsed products p-dimensional matrix A on q-dimensional matrix B it is calculated according to the formula

$$N_{p,q} = \sum_{\lambda+\mu=0}^{\min(p,q)} \frac{p!}{\lambda!\mu!(p-\lambda-\mu)!} \cdot \frac{q!}{\lambda!\mu!(q-\lambda-\mu)!}. \quad (8)$$

Example 10. The example demonstrates different options (λ, μ) – the convolved product of two three-dimensional matrices. Let a set of indices be given i_1, i_2, i_3, i_4, dimensions which ones $n_1, n_2, n_3, n_4 = 2$. Then three-dimensional matrices $A = \| a_{i_1 i_2 i_3} \|$ and $B = \| b_{i_2 i_3 i_4} \|$ look like

$$A = \overset{i_1 (1,2) \rightarrow}{\left\| \begin{array}{cc|cc} a_{111} & a_{112} & a_{211} & a_{212} \\ a_{121} & a_{122} & a_{221} & a_{222} \end{array} \right\|}$$

and

$$B = \overset{i_1 (1,2) \rightarrow}{\left\| \begin{array}{cc|cc} b_{111} & b_{112} & b_{211} & b_{212} \\ b_{121} & b_{122} & b_{221} & b_{222} \end{array} \right\|}. \quad (9)$$

Among the possible (λ, μ)-convolved products of matrices A and B will be as follows: four-dimensional matrix $C = {}^{2,0}(A \times B)|^{i_2,i_3} = \| c_{i_1,i_2,i_3,i_4} \|$, the elements of which are calculated according to the formula $c_{i_1,i_2,i_3,i_4} = a_{i_1,i_2,i_3} \times b_{i_2,i_3,i_4}$ index values match for all i_2, i_3.

This matrix has the form:

$$C=\left\|\begin{array}{cc|cc} a_{111}\times b_{111} & a_{111}\times b_{112} & a_{121}\times b_{211} & a_{121}\times b_{212}\\ a_{112}\times b_{121} & a_{112}\times b_{122} & a_{122}\times b_{221} & a_{122}\times b_{222}\\ \hline a_{211}\times b_{111} & a_{211}\times b_{112} & a_{221}\times b_{211} & a_{221}\times b_{212}\\ a_{212}\times b_{121} & a_{212}\times b_{122} & a_{222}\times b_{221} & a_{222}\times b_{222}\end{array}\right\|. \quad (10)$$

In this case, matrix multiplication is performed without convolution, because there are no Kelly indices.

Three-dimensional matrix $C={}^{1,1}(A\times B)\Big|_{i_2}^{i_3}=\left\|c_{i_1,i_3,i_4}\right\|$, the elements of which are calculated according to the formula $c_{i_1,i_3,i_4}=\sum_{i_2=1}^{2}a_{i_1,i_2,i_3}\times b_{i_2,i_3,i_4}$.

This matrix has the form:

$$C=\left\|\begin{array}{cc|cc} a_{111}\times b_{111}+a_{121}\times b_{211} & a_{111}\times b_{112}+a_{121}\times b_{212} & a_{211}\times b_{111}+a_{221}\times b_{211} & a_{211}\times b_{112}+a_{221}\times b_{212}\\ a_{112}\times b_{121}+a_{122}\times b_{221} & a_{112}\times b_{122}+a_{122}\times b_{222} & a_{212}\times b_{121}+a_{222}\times b_{221} & a_{212}\times b_{122}+a_{222}\times b_{222}\end{array}\right\|. \quad (11)$$

The three-dimensional matrix is obtained because the cell index i_2 when folded, it is removed from the set of indices common to both matrices.

Two-dimensional matrix $C={}^{0,2}(A\times B)\Big|_{i_2,i_3}=\left\|c_{i_1,i_4}\right\|$, the elements of which are calculated according to the formula: $c_{i_1,i_4}=\sum_{i_2=1}^{2}\sum_{i_3=1}^{2}a_{i_1,i_2,i_3}\times b_{i_2,i_3,i_4}$.

This matrix has the form:

$$C=\left\|\begin{array}{c|c} a_{111}\times b_{111}+a_{111}\times b_{112}+a_{121}\times b_{211}+a_{121}\times b_{212} & a_{211}\times b_{111}+a_{211}\times b_{112}+a_{221}\times b_{211}+a_{221}\times b_{212}\\ a_{112}\times b_{121}+a_{112}\times b_{122}+a_{111}\times b_{221}+a_{122}\times b_{222} & a_{212}\times b_{121}+a_{212}\times b_{122}+a_{222}\times b_{221}+a_{222}\times b_{222}\end{array}\right\|. \quad (12)$$

The operations on multivariate matrices defined in this way make it possible to construct a two-basic algebraic system or ADT, which is called an abstract algebraic multivariate machine.

The peculiarity of building operations on matrix elements is that neutral elements of the type are clearly present in matrices.

Therefore, these operations are built based on a defined system of functions

$$f^{j}_{\alpha_1,\ldots,\alpha_k,\beta_1,\ldots,\beta_l}\left(x_{\alpha_1},\ldots,x_{\alpha_k},y_{\beta_1},\ldots,y_{\beta_l}\right).$$

Let M – be the set of multidimensional matrices, and E – be the set of their elements, which is determined for each specific subject area. Next, a list of IDSS operations included in the signature of operations of this algebraic system is given. Unary operations specify mapping $M\to M$, and binary – displays $M\times M\to M$.

Structure operations: T – transposition; S – intersection; C – convolution; + – adding; × – (λ, μ)-collapsed product.

Type operations (over structure elements): ?+?+ – additive; ?×?× – multiplicative.

In predicate signatures Π includes the following predicates:

– z: $M\to\{0, 1\}$; matrix X contains only neutral elements of the type;

– ac: $M\times M\to\{0, 1\}$; matrices X and Y compatible by addition;

– mc: $M\times M\to\{0, 1\}$; matrices X and Y compatible by multiplication.

In addition, in cases where the elements of the matrices – tuples, predicates are set on many elements of the matrices (type) *pred*, *eq*, *succ*: $E\times E\to\{0,1\}$, which specify binary relations of warning, equivalence and following.

Then the abstract multidimensional matrix machine is given as follows:

$$M_{am}=\left\langle\begin{array}{l}M,E;T,S,C,+,\times,?+?+,?\times?\times;\\ z,\ ac,\ mc,pred,eq,succ\end{array}\right\rangle. \quad (13)$$

Further, the work considers the methods of building an abstract multidimensional machine, based on the generalization of parallel algorithms that implement operations on matrices into multidimensional matrices.

5. 4. Establishing the correspondence of set-theoretic and multidimensional matrix data models

The correspondence of the operations of the set-theoretic and multidimensional model for IDSS can be established as shown in the Table 1.

Definition 15. Multidimensional matrix $A=\left\|a_{i_1,\ldots,i_p}\right\|$ it is called a logical multidimensional matrix (LMM), if its elements belong to the set {0,1} and over these, the additive disjunction operation and the multiplicative conjunction operation are defined.

Transpose and cross-section operations are independent of the type of matrix elements, and therefore their definitions remain unchanged for LMM. In the definitions of other operations, the formulas that calculate the values of the LMM elements of the operation result change.

Convolution: if $B={}^{\mu}A$, that's it $b_l=\underset{(c)}{\vee}a_{lc}$, where l – a set of free, and c – Kelly indices.

Addition: if $C=A+B$, that's it $c_{i_1,\ldots,i_p}=a_{i_1,\ldots,i_p}\circ b_{i_1,\ldots,i_p}$, where $\circ$ – a binary logical operation that is perceived as an additive operation; (λ, μ)-collapsed product: if $C={}^{\lambda,\mu}(A\times B)$, that's it $c_{lsm}=\underset{(c)}{\vee}a_{lsm}\wedge b_{scm}$.

Table 1

Correspondence of algebraic operations in set-theoretic and multidimensional-matrix models of IDSS data

Theoretically, a multiple model (data algebra)	Multidimensional matrix model (algebra of multidimensional matrices)	Operation type
Sorting	Transposition	unary
Sampling	m-multiple section	unary
Compression	Convolution	unary
Fusion of strictly ordered data	Adding	binary
Merging of unordered data	(λ, μ)-collapsed product	binary

Statement 2. Each type of data corresponds to a single LMM.

Let XK – be data strictly ordered by the set of keys $K=\{K_1, \ldots, K_p\}$. Since the set of key values is finite, it is possible to number all the values of each key and thereby match each key K_α index $i_\alpha=(1, \ldots, n_\alpha)$. Then each instance of the set of keys $K^* = \{K_1^*, \ldots, K_p^*\}$ one and only one set of index values corresponds $(i_1^0, \ldots, i_p^0)$.

This means that between the set of all instances of the set of keys K file X_K and a set of all sets of index values $(i_1, \ldots, i_p)$ mutually unambiguous correspondence has been established. Let the instance of the set of keys $K^* = \{K_1^*, \ldots, K_p^*\}$ corresponds to a set of index values $(i_1^0, \ldots, i_p^0)$. Then the equivalence class X_{K^*} it is possible to match the LMM element $X = \left\| x_{i_1, \ldots, i_p} \right\|$, the value of which is determined by the formula:

$$x_{i_1^0, \ldots, i_p^0} = \begin{cases} 0, \text{ if } X_{K^*} = \Theta, \\ 1, \text{ if } X_{K^*} \neq \Theta. \end{cases} \quad (14)$$

Since the data X_K strictly ordered, each of its equivalence classes contains either a single definite record or a universal indefinite record. Therefore, for this method of constructing a LMM, each strictly ordered array of data corresponds to a single LMM. However, a situation is possible in which the same LMM corresponds to several different data arrays, each containing data from a different subject area. That is, the constructed mapping of the set of strictly ordered data to the set of LMM is unambiguous.

In the following three statements, it is assumed that X – the set of strictly ordered data, M – the LMM set, $\varphi: X \to M$ – unambiguous mapping of a set of strictly ordered data to a set of LMM.

Statement 3. If X_K – data strictly ordered by a set of keys $K = \{K_1, \ldots, K_p\}$, and $A = \left\| a_{i_1, \ldots, i_p} \right\|$ – its corresponding LMM $(\varphi(X_K) = A)$ and $\begin{pmatrix} K_1, \ldots, K_p \\ K_{\alpha_1}, \ldots, K_{\alpha_p} \end{pmatrix}$, $\begin{pmatrix} i_1, \ldots, i_p \\ i_{\alpha_1}, \ldots, i_{\alpha_p} \end{pmatrix}$ the same permutations of data keys and LMM indices, then φ (sort $(X_K)) = A'$, provided that sorting and transposing are performed according to given permutations of keys and indices.

This statement follows directly from the definitions of data sorting and multidimensional matrix transposition operations.

Statement 4. Let X_K – data strictly ordered by a set of keys $K = \{K_1, \ldots, K_p\}$, $A = \left\| a_{i_1, \ldots, i_p} \right\|$ – their corresponding LMM $(\varphi(X_K) = \text{A})$ and predicate $\pi(K)$ fixes the value of the keys $K_1, \ldots, K_m \in K(m < p)$, which indices correspond to $(i_1, \ldots, i_m)$ LMM A.

Then the data obtained from the data X_K as a result of applying to it a sampling operation according to the predicate $\pi(K)$, a single LMM corresponds $A_{(i_1, \ldots, i_m)}$, obtained from the matrix A m-multiple intersection of orientation $(i_1, \ldots, i_m)$, i.e. $\varphi(sel(X_K, \pi(K))) = A_{(i_1, \ldots, i_m)}$.

It is enough to consider the validity of this statement for the case when the predicate $\pi(K)$ fixes a single instance of each key $K_1, \ldots, K_m$. Then to each fixed instance K_j^* key K_j corresponds to a single value i_j^* index i_j $(j = 1, \ldots, m)$, and there is a simple one m-multiple section $A_{(i_1, \ldots, i_m)} = \left\| a_{i_1, \ldots, i_p} \right\| \begin{pmatrix} i_1 = i_1^* \\ \cdots \\ i_m = i_m^* \end{pmatrix}$ LMM $A = \left\| a_{i_1, \ldots, i_p} \right\|$.

If X_{K^*} – data equivalence class X_K, such that in an instance of the set of keys K^* key instances $K_1^*, \ldots, K_m^*$ fixed predicate $\pi(K)$, and instances of other keys – arbitrarily, this equivalence class corresponds to the LMM element A

$$a_{i_1^*, \ldots, i_m^*, i_{m+1}^0, \ldots, i_p^0} = \begin{cases} 0, \text{ if } X_{K^*} = \Theta_{K^*}, \\ 1, \text{in the other case.} \end{cases} \quad (15)$$

But this element will also belong to the simple m-multiple section $A_{(i_1, \ldots, i_m)}$. So, to all the selected data equivalence classes X_K the only elements of this section of the LMM will correspond A. However, m-multiple section can be constructed from the corresponding simple ones m-multiple section. If predicate $\pi(K)$ fixes at least one instance of each of the keys $K_1, \ldots, K_m$, then it is possible to get all the necessary simple sections, and then build the necessary LMM from them using the LMM addition operation. From what has been said, the validity of statement 4 follows.

Statement 5. Let X_K – data strictly ordered by multiple keys $K = \{K_1, \ldots, K_p\}$, $A = || a_{i_1, \ldots, i_p} ||$ – its corresponding LMM $(\varphi(X_K) = A)$, $M = \{K_1, \ldots, K_m\}$, $(m < p)$ – the subset of a set of keys M, by what data X_M not strictly ordered. Then given $Y_M = quant(X_M)$ a single convolution of LMM corresponds A, i.e. $\varphi(quant(X_M)) = {}^{\mu}A$.

According to the definition of the compression operation, equivalence classes of strictly ordered data *quant* (X_M) they come out according to the formula $Y_{M^*} = f(X_{M^*})$, where $f(X_{M^*})$ – a function implementing a group operation on each equivalence class corresponding to an instance of a set of keys M^*. That is, the set of data records X_K, what keys $K_1, \ldots, K_m$ have the same values, turns into a single data record Y_M. Each record from this population corresponds to an LMM element A $a_{i_1^*, \ldots, i_m^*, i_{m+1}^0, \ldots, i_p^0} = 1$. Then $a_{i_1^*, \ldots, i_m^*} = \bigvee_{(i_{m+1}, \ldots, i_p)} a_{i_1^*, \ldots, i_m^*, i_{m+1}^0, \ldots, i_p^0} = 1$. So, $\varphi(quant(X_M)) = {}^{\mu}A$.

Statement 6. Let X_K and Y_K – data strictly ordered by multiple keys $K = \{K_1, \ldots, K_p\}$, $A = || a_{i_1, \ldots, i_p} ||$ and $B = || b_{i_1, \ldots, i_p} ||$ – their corresponding LMM $(\varphi(X_K) = A$ and $\varphi(Y_K) = B)$. Then the result of the strictly ordered data merger operation X_K and Y_K a single LMM corresponds $C = || c_{i_1, \ldots, i_p} ||$ such that $C = A + B$.

Depending on the task to be solved for the formation of equivalence classes (records) of data – of the result of merging strictly ordered data X_K and Y_K functions are constructed that generate an equivalence class containing either a real or a universal indefinite entry. Similarly, as an additive operation on LMM elements A and B one of sixteen logical operations is selected. It forms the LMM element of the result based on the equivalence class of the result data and according to the rules for forming the LMM – image of the data when displayed φ.

Thus, the data – of the result of the merger operation is strictly ordered data X_K and Y_K a single LBM corresponding to, equal to the sum of the LMM A and B with additive operation $\circ$ above the elements of the matrices. That is $\varphi(ms(X_K, Y_K)) = A +_{(\circ)} B$. Operation sign $+_{(\circ)}$ read as LMM addition operation with additive operation $\circ$ above their elements.

Example 11. The operations of merging strictly ordered data, which implement set-theoretic union and intersection operations, correspond to the operations of assembling multivariate matrices with additive operations on elements: disjunction $(\vee)$ that conjunction $(\wedge)$.

Statement 7. Let X_L and Y_M – data strictly ordered by multiple keys $L = \{L_1, \ldots, L_p\}$ and $M = \{M_1, \ldots, M_p\}$ and the condition is fulfilled $L \cap M \neq \varnothing$, and let $K = \{K_1, \ldots, K_r\}$, $(r < p + q)$ – set of keys associated with sets L and M ratio: $K \subseteq L \cup M$, $K \cap L \neq \varnothing$, $K \cap M \neq \varnothing$ (data $X_{K \cap L}$ and $X_{K \cap M}$ not strictly ordered by their sets of keys). $A = || a_{i_1, \ldots, i_p} ||$ and $B = || b_{i_1, \ldots, i_r} ||$ – data-relevant $X_{K \cap L}$ and $X_{K \cap M}$ LMM $(\varphi(X_{K \cap L}) = A$ and $\varphi(X_{K \cap M}) = B)$. Then given Z_K – the result of the merger operation is not strictly ordered by the set of keys K given X_K and Y_K a single multidimensional matrix corresponds $C = || c_{i_1, \ldots, i_r} || = {}^{\lambda, \mu}(A \times B)$.

According to the definition of the merge operation of non-strictly ordered data, the set of keys K consists of three subsets:

– L' – keys belonging only to a set of keys L;

– M' – keys belonging only to a set of keys M;

– T – keys belonging to both sets of keys L and M.

When building an operation ${}^{\lambda,0}(A\times B)$ it can be assumed that the keys of subsets L' and M' correspond to free LMM indices A and B (breakdown indices l and m). The keys correspond to subsets T – scott indices of LMM A and B (breakdown indices s). Equivalence class $Z_{K^*}\neq\Theta_{K^*}$ only if the classes corresponding to it equivalence $X_{(L'\cup T)^*}\neq\Theta_{(L'\cup T)^*}$ and $Y_{(M'\cup T)^*}\neq\Theta_{(M'\cup T)^*}$.

Then elements LMM A and B, corresponding to these equivalence classes, have a value of 1. So the result of the conjunction of these elements will also have a value of 1. That is, the equivalence class corresponding to this element $Z_{K^*}\neq\Theta_{K^*}$.

If the function $f(X_{(K\cap L)^*}, X_{(K\cap M)^*})$ implements a group operation, then the operation of merging ordered non-strictly data includes a data compression operation Z_K, as a result of which data is obtained $Z_{K'}$ (plural keys K' there is a subset of the set of keys K, i.e $K'\subset K$). In this case, the parts of the keys of the subset T LMM cell indices correspond A and B (breakdown indices c), and merge operations of not strictly ordered data X_L and Y_M the operation corresponds (λ, μ)-collapsed product of the matrices corresponding to them. That is, $\varphi(mns(X_{K\cap L}, X_{K\cap M})) = {}^{\lambda,\mu}(A\times B)$.

5. 5. Axiomatic approach to formalizing data models

The axiomatic method of formalization of mass data processing (MDP) for IDSS is considered below. The axiomatic method is used to formalize an object transformation operation by describing the resulting object from transforming the original objects. That is, it provides a description of the objects and their transformation operations according to the principle: "which should be the result of operations on operand objects, regardless of what the reality of these objects is and how this operation is performed".

The algebraic method allows for constructive descriptions of object structures and operation algorithms. The structure of objects is defined either strictly, using mathematical terminology, or by analogy with known structures. For example, in a file model, a file is defined in the language of set theory, and in relational terms, a similar object looks to be a set according to a table.

Algorithms are also defined either by natural language description or by using formalization tools inherent in theoretical and practical programming. That is, the principle is inherent to the algebraic method: "after applying an operation according to a known algorithm to an object (s) with a known structure, an object result with a given structure" is obtained.

For example, relational computation is nothing more than an axiomatic description of objects (relationships) and operations of transforming one relation into another. This allows to determine what relation should be obtained as a result of applying a given operation on operand relations. In relational algebra, an object is structured as a comparison in the form of tables, and operations on relations are usually given as verbal (intuitive) descriptions. In multivariate-matrix algebra, which is homomorphic to relational algebra, each relation corresponds to a multivariate matrix, which can be considered a highly structured object. Strict formal algorithms are given for all operations.

Next, the formalization of MDPs for set-theoretic (file) relational and multidimensional matrix data models is considered. In the future, all of them will be considered a single formal (axiomatic) theory T. It will be considered defined if the following conditions are met:

– given defined finite set of symbols called theory symbols, T;

– defines the finite sequences of the symbols of the theory forming the set T^*, which is called expressions of the theory T.

The set of symbols of the axiomatic theory T for MDP [17, 19] contains two types of symbols:

1. Common symbols:

– digits: 0, …, 9;

– upper and lower case letters: a, b, …, A, B, …;

– letters with indexes: a_1, a_2, …, A_1, A_2, …

2. Special symbols of two classes:

– therms (objects) of the theory T, which are defined as letters or sequences of letters;

– formulas (ratio) of the theory T.

Intuitively, the terms are the notation of objects, and the formulas are the notation of statements in what can be done with these objects. There is usually an effective procedure that allows each expression to determine whether it is a formula. In this theory, this procedure is given by a recursive relation. The formulas thus defined can be interpreted differently in different models of theory T. These are set-theoretic, (file), multidimensional-matrix and relational models of IDSS data.

In these data models, there are the terminological differences, but also different ways of representing objects and different algorithms of their transformation operations. Table 2 shows interpretations in different data models of some formulas that will be used in the construction of axioms.

Table 2

Examples of interpretation of formulas

Formulas and their values in data models		
Set theory	Multidimensional-matrix	Multidimensional-relational
A_i, a_i		
Record field, field value	Set (type of elements), value of the element	Attribute, attribute value
$(a_{1,\dots,} a_n)$		
Instance of data recording	Multidimensional matrix element	Cortege
$\mathscr{K}\left(A_1,\dots,A_k\right)R\left(A_1,\dots,A_k,A_{k+1},\dots,A_n\right)$		
$X_K = (F_1, \dots, F_n)$ – data with type recording $(F_1, \dots, F_n)$ and plural keys $K = (F_1, \dots, F_k)$;	M – multidimensional matrix with indices $i_1, \dots, i_k$	Relationship $R(A_1, \dots, A_k)$ with scheme $(A_1, \dots, A_n)$ and the constituent key $A_1, \dots, A_k$
$f(A_1, \dots, A_n)$		
n-ary operation on data recording fields	Additive operation on elements of a multidimensional matrix	n-ary operation defined on attribute domains $A_1, \dots, A_n$
$f_{a_1,\dots,a_k}\left(A_{k+1},\dots,A_n\right)$		
n-ary an operation on fields of a group of data records with the same instance of a set of keys	Multiplicative operation on multidimensional matrices with Kelly indices $i_{1,\dots,} i_k$	n-ary group operation defined on attribute domains $A_{k+1}, \dots, A_n$
${}^{so}\left(\mathscr{K}\left(A_1,\dots,A_k\right)R\left(A_1,\dots,A_k,A_{k+1},\dots,A_n\right)\right)$		

A defined set of formulas called axioms (or schemes of axioms) of theory T is highlighted. Formulas that are axioms for mass data processing are discussed later:

A1) Strict order axiom

$$
\begin{aligned}
&{}^{so}\left(\mathscr{K}\left(A_1,\ldots,A_k\right)R\left(A_1,\ldots,A_k,A_{k+1},\ldots,A_n\right)\right)=\\
&=\left\{\begin{pmatrix}a_1,\ldots,a_k,\\ a_{k+1},\ldots,a_n\end{pmatrix}\mid\forall\begin{pmatrix}a_1,\ldots,a_k,\\ a_{k+1},\ldots,a_n\end{pmatrix}\neg\left(\exists\begin{pmatrix}a_1,\ldots,a_k,\\ a'_{k+1},\ldots,a'_n\end{pmatrix}\right)\right\}.
\end{aligned}
\tag{16}
$$

This axiom means that objects of type $(a_1, \ldots, a_k, a_{k+1}, \ldots, a_n)$ are in the facility R no more than once. It gives a description of the data aggregate as a set.

A2) The axiom is not strict orderliness

$$
\begin{aligned}
&{}^{nso}\left(\mathscr{K}\left(A_1,\ldots,A_k\right)R\left(A_1,\ldots,A_k,A_{k+1},\ldots,A_n\right)\right)=\\
&=\left\{\begin{pmatrix}a_1,\ldots,a_k,\\ a_{k+1},\ldots,a_n\end{pmatrix}\mid\forall\begin{pmatrix}a_1,\ldots,a_k,\\ a_{k+1},\ldots,a_n\end{pmatrix}\exists\begin{pmatrix}a_1,\ldots,a_k,\\ a'_{k+1},\ldots,a'_n\end{pmatrix}\right\}.
\end{aligned}
\tag{17}
$$

This axiom means that objects of type $(a_1, \ldots, a_k, a_{k+1}, \ldots, a_n)$ may occur in an object R no more than once, that is, the set of data is defined as a factor of a set (multiple). Interpretations of axioms A1 and A2 in the data models, it is given in the Table 2.

A3) Sample axiom

$$
\begin{aligned}
&{}^{sel}R\left(A_1,\ldots,A_k,A_{k+1},\ldots,A_n\right)\Pi\left(a_1,\ldots,a_k\right)=\\
&=\left\{\begin{pmatrix}a_1,\ldots,a_k,\\ a_{k+1},\ldots,a_n\end{pmatrix}\in\begin{pmatrix}A_1,\ldots,A_k,\\ A_{k+1},\ldots,A_n\end{pmatrix}\mid\Pi\left(a_1,\ldots,a_k\right)\right\}.
\end{aligned}
\tag{18}
$$

This axiom gives a description of a subset of a data aggregate, which elements satisfy the condition defined by the predicate $\Pi(a_1, \ldots, a_k)$. This subset is formed as a result of the application of the sampling operation $^{(sel)}$ to the data aggregate $R(A_1, \ldots, A_k, A_{k+1}, \ldots, A_n)$. In the data model, it corresponds to the sampling operation, the multidimensional-matrix data model, the cross-section operation of the multidimensional matrix, in the relational data model – operator SELECT.

A4) Compression axiom

$$
\begin{aligned}
&\left({}^{nso}\left(\mathscr{K}\left(A_1,\ldots,A_k\right)R\left(A_1,\ldots,A_k,B_{k+1},\ldots,B_m\right)\right)\right)=\\
&=\left\{\begin{pmatrix}a_1,\ldots,a_k,\\ f_{a_1,\ldots,a_k}\left(B'_{k+1},\ldots,B'_m\right)\end{pmatrix}\mid B'_{k+1}\subset B_{k+1},\ldots,B'_m\subset B_m\right\}.
\end{aligned}
\tag{19}
$$

This axiom gives a description of the data aggregate to be derived from the data aggregate $R(A_1, \ldots, A_k, B_{k+1}, \ldots, B_m)$ after applying the operation $f_{a_1,\ldots,a_k}(B'_{k+1},\ldots,B'_m)$. This function applies to all groups of its elements in which the values of the variables $A_1, \ldots, A_k$ coincide.

A new data aggregate is formed as a result of applying an operation to the data aggregate $R(A_1, \ldots, A_k, B_{k+1}, \ldots, B_m)$. In the set-theoretic data model, this axiom corresponds to the operation of compressing non-strictly ordered data, in the multivariate-matrix – convolution, in the relational one – *select ... group by ...* to the relation in the first normal form.

A5) Merge axiom with strict ordering of data aggregates

$$
\begin{aligned}
&{}^{so}\left(\mathscr{K}\left(A_1,\ldots,A_k\right)R_1\left(A_1,\ldots,A_k,B_{k+1},\ldots,B_m\right)\right)\oplus\\
&\oplus{}^{so}\left(\mathscr{K}\left(A_1,\ldots,A_k\right)R_2\left(A_1,\ldots,A_k,C_{k+1},\ldots,C_n\right)\right)=\\
&=\left\{\left(a_1,\ldots,a_k,f\left(b_{k+1},\ldots,b_m,c_{k+1},\ldots,c_n\right)\right)\right\}.
\end{aligned}
\tag{20}
$$

This axiom gives a description of the data aggregate to be derived from the data aggregates $R_1(A_1, \ldots, A_k, B_{k+1}, \ldots, B_m)$ and $R_2(A_1, \ldots, A_k, C_{k+1}, \ldots, C_n)$ after applying the operation $f(b_{k+1}, \ldots, b_m, c_{k+1}, \ldots, c_n)$ to elements with the same values $a_1, \ldots, a_k$.

A new data aggregate is formed as a result of the operation $(\oplus)$ to these data aggregates.

A6) Merge axiom with non-strict ordering of data aggregates

$$
\begin{aligned}
&{}^{nso}\left(\mathscr{K}\left(A_1,\ldots,A_k\right)R_1\left(A_1,\ldots,A_k,B_{k+1},\ldots,B_m\right)\right)\otimes\\
&\otimes{}^{nso}\left(\mathscr{K}\left(A_1,\ldots,A_k\right)R_2\left(A_1,\ldots,A_k,C_{k+1},\ldots,C_n\right)\right)=\\
&=\left\{\begin{aligned}&\left(\begin{aligned}&a_1,\ldots,a_k,\\ &f_{a_1,\ldots,a_k}\begin{pmatrix}B'_{k+1},\ldots,B'_m,\\ C'_{k+1},\ldots,C'_n\end{pmatrix}\end{aligned}\right)\mid B'_{k+1}\subset B_{k+1},\ldots,B'_m\subset B_m,\\ &C'_{k+1}\subset C_{k+1},\ldots,C'_n\subset C_n\end{aligned}\right\}.
\end{aligned}
\tag{21}
$$

This axiom gives a description of the data aggregate to be derived from the data aggregates $R_1(A_1, \ldots, A_k, B_{k+1}, \ldots, B_m)$ and $R_2(A_1, \ldots, A_k, C_{k+1}, \ldots, C_n)$ after applying the operation $f_{a_1,\ldots,a_k}\left(B'_{k+1},\ldots,B'_m,C'_{k+1},\ldots,C'_n\right)$ to groups of elements with the same values $a_1,\ldots,a_k$. A new data aggregate is formed as a result of the application of operation ( ) to these data aggregates.

Thus, using these axioms constructed using definitions, property ops of data aggregates and operations with them are constructed.

6. Discussion of the results on the development of a polymodel complex for the construction of intelligent decision support systems

The proposed polymodel complex for building intelligent decision support systems allows:

– systemically represent the relationship between IDSS construction models in the course of their calculation and computing tasks;

– carry out the simulation of the process of functioning of the IDSS, due to the use of an algebraic (formal) approach to object-oriented modeling and design of the IDSS;

– determine the rational tactical and technical indicators of the IDSS for solving specific calculation and computing tasks, due to the multi-level description of the IDSS construction order;

– make the transition from one type of data representation in IDSS to another due to the presence of appropriate mathematical transformations;

– multidimensional to describe the process of processing heterogeneous data in IDSS, due to the use of a multidimensional matrix model of IDSS data;

– approach universally the solution of computational-calculation tasks in IDSS by using an interconnected set of mathematical models for constructing IDSS;

– formalize the process of constructing IDSS, which allows combining IDSSs using different algorithmic and software.

The advantages of the proposed polymodel complex are due to the following:

– system representation of the relationship between IDSS construction models during their performance of calculation and calculation tasks (expressions (1)–(21)), compared to works [12, 19];

– the ability to carry out simulations of the process of IDSS functioning, through the use of an algebraic (formal) approach to object-oriented IDSS modeling and design, in comparison with works [11, 14];

– to determine the rational tactical and technical indicators of the IDSS for solving specific calculation and computing tasks, due to the multi-level description of the order of construction of the IDSS, (expressions (1)–(21), Tables 1, 2), compared to works [9, 13];

– the possibility of making a transition from one type of data representation in IDSS to another due to the presence of appropriate mathematical transformations (Tables 1, 2), compared to works [9, 11];

– by multidimensional representations of the process of processing heterogeneous data in IDSS, due to the use of a multidimensional matrix model of IDSS data in comparison with works [13, 15];

– versatility to approach the solution of computational-calculation problems in IDSS by using an interconnected set of mathematical models for constructing IDSS (expressions (1)–(21), Tables 1, 2), in comparison with works [13, 18];

– a high degree of formalization of the IDSS construction process, which allows combining IDSS s using different algorithmic and software (expressions (16)–(21), Table 2) in comparison with works [12, 14];

– by the adequacy of the obtained results (expressions (1)–(21), Tables 1, 2), compared to works [16, 17].

The disadvantages of the proposed polymodel complex include the need to adapt the proposed mathematical apparatus to the specific conditions of the functioning of the IDSS.

The proposed polymodel complex should be used for the IDSS construction to solve general and specialized calculation tasks, as well as to solve the task of integrating various types of IDSS.

The limitations of the study are the need to have an initial database on the peculiarities of the IDSS functioning.

Areas of further study should be directed to reducing computing costs when processing various types of data in IDSS.

7. Conclusions

1. The basic concepts and definitions of universal algebra and algebraic systems in IDSS are given and an intuitive approach to object-oriented modeling of IDSS is developed. This allows to outline the list of basic concepts and definitions used in IDSS, and also allows to simplify the modeling of the process of functioning of IDSS.

2. An algebraic (formal) approach to object-oriented modeling and design of IDSS is proposed. This approach allows to formulate a list of basic mathematical procedures to the object-oriented simulation of the IDSS life cycle, regardless of the type and tasks performed by them.

3. An object-oriented approach to the development of IDSS data models is presented and a multidimensional matrix model of IDSS data is developed. This makes it possible to form a scientifically based approach to the order of development of IDSS data models, including in a multidimensional-matrix form.

4. Correspondences of set-theoretic and multidimensional-matrix models of IDSS data have been established. The proposed correspondences make it possible to flexibly make the transition from one form of data presentation in the IDSS to another, which significantly increases the degree of convergence of various types of IDSS.

5. An axiomatic approach to the formalization of data models for IDSS has been developed. This approach makes it possible to increase the unambiguity of data processing in IDSS when formalizing models of IDSS functioning. The proposed polymodel complex should be used for the IDSS construction to solve general and specialized calculation tasks, as well as to solve the task of integrating various types of IDSS.

Conflict of interest

The authors declare that they have no conflict of interest in this study, including financial, personal, authorship or other nature that could affect the study and its results presented in this article.

Financing

The study was conducted without financial support.

Data availability

The manuscript has related data in the data warehouse.

Use of artificial intelligence tools

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

Authors' contributions

Nina Kuchuk: Conceptualization; Methodology; Project administration; Writing – original draft; Writing – review & editing; **Leonid Artushin**: Methodology; Writing; Writing – review & editing; **Yurii Zhuravskyi**: Writing – original draft; **Iraida Stanovska**: Writing – review & editing; **Oleksiy Kononov**: Resources; Data Curation; **Nadiia Protas**: Validation; Data Curation; **Serhii Neronov**: Software; Validation; Data Curation; **Serhii Shostak**: Methodology; Formal analysis; Visualization; **Anton Nikitenko**: Software: Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components; Validation; Data Curation; **Andrii Veretnov**: Software; Validation; Data Curation.

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ABSTRACT AND REFERENCES

MATHEMATICS AND CYBERNETICS – APPLIED ASPECTS

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DEVELOPMENT OF A UNIVERSAL INTEGRAL CRITERION FOR CYBERNETIC CONTROL (p. 6–15)

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This study investigates the technological process of heating a liquid considered as a controlled cybernetic system for converting resources into a usable technological result. The work aims to solve a pressing task of choosing a single universal criterion for assessing the effectiveness of technological processes. The subject of research is the ELF (Normalized Efficiency Criterion) computing module, designed for an integral assessment of the effectiveness of cybernetic control over technological processes in discrete time.

This work reports designing a computing module that converts technological input parameters and corresponding price coefficients into a system of cost indicators of costs and useful effect. The proposed system allows for the reduction of heterogeneous resources and the result of the process to a single scale, which makes it possible to formalize their joint analysis and a coordinated comparison of alternative modes. Elementary cost functions and aggregated indicators of the control cycle are introduced, on the basis of which the first-level integral accumulators are formed – accumulated costs and accumulated effect.

To assess the efficiency of control over a given time interval, secondary integrators of the second level and the mode selection index are used, which reflects the excess of the integral effect over the integral costs in the inertial-accumulator sense. Within the framework of the approach, the additional benefit and resource intensity of the permissible control mode are determined, which are formed using a storage device with a reset mechanism in the case of violation of the regime conditions.

The permissibility of the mode is set by the threshold rule and the procedure for resetting the final indicators in the case of its inadmissibility, which provides a diagnostically interpreted separation of the causes of zero efficiency. The proposed structure of the computing module focuses on the analysis, diagnostics, and optimization of control modes and allows for software implementation as part of cybernetic control systems.

Keywords: cybernetic system, efficiency criterion, integral assessment, cost model, regime selection.

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DEVELOPMENT OF METHODS OF INTELLIGENT MANAGEMENT OF SECURITY PARAMETERS OF INFORMATION SYSTEMS (p. 16–25)

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The object of the study is information systems (IS). The problem that is being solved in the study is an increase in the level of IS protection. The study developed a methodology for intelligent management of IS security parameters. The originality of the study consists of:

– conducting a multi-level and systematic assessment of the state of IS security using the proposed set of analytical expressions;

– determining the influence of IS security parameters on each other when the IS security state changes due to the use of fuzzy analytical expressions;

– construction of multidimensional dependencies of the security state of the special-purpose IS, which evaluates the security of the IS based on an arbitrary number of parameters;

– assessment of IS security in conditions of incompleteness of information about evaluation parameters, which solves the dimensionality problem;

– construction of time dependences of changes in parameters that characterize the state of IS protection, which allows determining the moments of deviation of their values from the nominal;

– reducing the error of assessing the state of IS security due to the human factor through the verification of IS parameters;

– attracting additional computing resources (if necessary), which achieves the prevention of looping of the methodology;

– determination of the influence of control decisions on a separately defined parameter for assessing the state of IS security, which achieves an increase in the accuracy of control influences.

Modeling of the work of the proposed methodology was carried out, during which it was established that increasing the security of the IS is achieved by increasing the efficiency of decision-making at the level of 12–16% due to the use of additional procedures and ensuring the reliability (correctness) of the decisions made at the level of 0.94. This allows to avoid distortions and distortions of the information provided for decision-makers (systems).

Keywords: multidimensionality of assessment, complex systems, efficiency of decision-making, efficiency of assessment, bio-inspired algorithms.

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CREATING A POLYMODEL FRAMEWORK FOR THE CONSTRUCTION OF INTELLIGENT DECISION SUPPORT SYSTEMS (p. 26–38)

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Intelligent decision support systems (IDSS) are the object of the study. The research problem is to improve the accuracy of the mathematical description of the process of processing heterogeneous data in IDSS. The subject of the study is a mathematical description of the processes of processing heterogeneous data in IDSS. The proposed polymodel complex for the construction of IDSS solutions, which allows:

– systemically represent the relationship between IDSS construction models in the course of their calculation and computing tasks;

– simulate the process of functioning of the IDSS, due to the use of an algebraic (formal) approach to object-oriented modeling and design of the IDSS;

– determine the rational tactical and technical indicators of the IDSS for solving specific calculation and computing tasks, due to the multi-level description of the order of construction of the IDSS;

– make the transition from one type of data representation in IDSS to another due to the presence of appropriate mathematical transformations;

– multidimensional to describe the process of processing heterogeneous data in IDSS, due to the use of a multidimensional matrix model of IDSS data;

– approach the solution of computational-calculation tasks in IDSS by using an interconnected set of mathematical models of IDSS construction;

– formalize the process of constructing IDSS, which allows combining IDSSs using different algorithmic and software. The disadvantages of the proposed polymodel complex include the need to adapt the mathematical apparatus to the specific operating conditions of the IDSS.

The proposed polymodel complex should be used for the construction of IDSS to solve general and specialized calculation tasks, as well as to solve the task of integrating various types of IDSS.

Keywords: system modeling, data representation, decision-making, multidimensionality of data description.

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АНОТАЦІЇ

MATHEMATICS AND CYBERNETICS – APPLIED ASPECTS

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РОЗРОБКА УНІВЕРСАЛЬНОГО ІНТЕГРАЛЬНОГО КРИТЕРІЯ КІБЕРНЕТИЧНОГО УПРАВЛІННЯ (с. 6–15)

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Об'єктом дослідження є технологічний процес нагрівання рідини, що розглядається як керована кібернетична система перетворення ресурсів на корисний технологічний результат. Робота направлена на вирішення проблеми вибора єдиного універсального критерія для оцінювання ефективності технологічних процесів. Предметом дослідження в даній роботі є обчислювальний блок ELF (Normalized Efficiency Criterion – нормалізований показник ефективності), призначений для інтегральної оцінки результативності кібернетичного управління технологічними процесами в дискретному часі.

Роботу присвячено розробленню обчислювального блока, який здійснює перетворення технологічних вхідних параметрів і відповідних цінових коефіцієнтів у систему вартісних показників витрат і корисного ефекту. Запропонована система забезпечує приведення різнорідних ресурсів і результату процесу до єдиного масштабу, що дає змогу формалізувати їх спільний аналіз та узгоджене порівняння альтернативних режимів. Уводяться елементарні вартісні функції та агреговані показники такту управління, на основі яких формуються інтегральні накопичувачі першого рівня – накопичені витрати й накопичений ефект.

Для оцінювання ефективності управління на заданому часовому інтервалі застосовуються вторинні інтегратори другого рівня та показник селекції режимів, що відображає перевищення інтегрального ефекту над інтегральними витратами в інерційно-накопичувальному сенсі. У межах підходу визначаються додаткова вигода і ресурсоємність допустимого режиму управління, які формуються з використанням накопичувача з механізмом скидання у разі порушення режимних умов.

Допустимість режиму задається пороговим правилом і процедурою обнулення підсумкових показників у разі його недопустимості, що забезпечує діагностично інтерпретоване розділення причин нульової ефективності. Запропонована структура обчислювального блока орієнтована на аналіз, діагностику та оптимізацію режимів управління й допускає програмну реалізацію у складі кібернетичних систем управління.

Ключові слова: кібернетична система, критерій ефективності, інтегральна оцінка, вартісна модель, режимна селекція.

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РОЗРОБКА МЕТОДИКИ ІНТЕЛЕКТУАЛЬНОГО УПРАВЛІННЯ ПАРАМЕТРАМИ ЗАХИЩЕНОСТІ ІНФОРМАЦІЙНИХ СИСТЕМ (с. 16–25)

Г. М. Шаповалов, О. Ф. Сальнікова, О. В. Кувшинов, Є. С. Капран, О. Л. Налапко, О. І. Дмитрієва, І. В. Борисов, В. Б. Єрко, Г. С. Степанов, А. В. Шишацький

Об'єктом дослідження є інформаційні системи (ІС). Проблема, яка вирішується в дослідженні, є підвищення рівня захищеності ІС. В дослідженні проведено розробку методики інтелектуального управління параметрами захищеності ІС. Оригінальність дослідження полягає у:

– проведенні багаторівневої та системної оцінку стану захищеності ІС за допомогою запропонованої сукупності аналітичних виразів;

– визначенні впливу параметрів захищеності ІС один на одного при зміні стану захищеності ІС за рахунок використання нечітких аналітичних виразів;

– побудові багатовимірних залежностей стану захищеності ІС спеціального призначення, чим здійснюється оцінка захищеності ІС за довільною кількістю параметрів;

– оцінці захищеності ІС в умовах неповноти інформації про параметри оцінки, чим вирішується проблему розмірності;

– побудові часових залежностей зміни параметрів, які характеризують стан захищеності ІС, чим дозволяється визначити моменти відхилення їх значень від номінального;

– зменшенні помилки оцінювання стану захищеності ІС, що обумовлені людським фактором за рахунок верифікації параметрів ІС;

– залученні додаткових обчислювальних ресурсів (у разі необхідності), чим досягається недопущення зациклювання роботи методики;

– визначенні впливу управляючих рішень на окремо визначений параметр оцінки стану захищеності ІС, чим досягається підвищення точності здійснення управляючих впливів.

Проведено моделювання роботи запропонованої методики, в ході якого встановлено, що підвищення захищеності ІС досягається за рахунок підвищення оперативності прийняття рішень на рівні 12–16% за рахунок використання додаткових процедур та забезпечення достовірності (правильності) прийнятих рішень на рівні 0.94. Це дозволяє уникнути викривлень та спотворень інформації, що надається для осіб (систем) що приймають керуючі рішення.

Ключові слова: багатовимірність оцінки, складні системи, оперативність прийняття рішень, оперативність оцінки, біоінспіровані алгоритми.

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РОЗРОБКА ПОЛІМОДЕЛЬНОГО КОМПЛЕКСУ ПОБУДОВИ ІНТЕЛЕКТУАЛЬНИХ СИСТЕМ ПІДТРИМКИ ПРИЙНЯТТЯ РІШЕНЬ (с. 26–38)

Н. Г. Кучук, Л. М. Артюшин, Ю. В. Журавський, І. І. Становська, О. А. Кононов, Н. М. Протас, С. В. Шостак, С. М. Неронов, А. П. Нікітенко, А. О. Веретнов

Об'єктом дослідження є інтелектуальні системи підтримки прийняття рішень (ІСППР). Проблема, яка вирішується в дослідженні, є підвищення точності математичного опису процесу обробки гетерогенних даних в ІСППР. Предметом дослідження є математичний опис процесів обробки гетерогенних даних в ІСППР. Запропонований полімодельний комплекс побудови ІСППР рішень, що дозволяє:

– системно представити взаємозв'язок між моделями побудови ІСППР в ході виконання ними розрахунково-обчислювальних завдань;

– провести моделювання процесу функціонування ІСППР, за рахунок використання алгебраїчного (формального) підходу до об'єктно-орієнтованого моделювання та проектування ІСППР;

– визначити раціональні тактико-технічні показники ІСППР для вирішення конкретних розрахунково-обчислювальних завдань, за рахунок багаторівневого опису порядку побудови ІСППР;

– здійснити перехід від одного типу представлення даних в ІСППР до іншого за рахунок наявності відповідних математичних перетворень;

– багатовимірно описати процес обробки гетерогенних даних в ІСППР, за рахунок використання багатовимірно-матричної моделі даних ІСППР;

– універсально підійти до вирішення обчислювально-розрахункові завдання в ІСППР за рахунок використання взаємопов'язаної сукупності математичних моделей побудови ІСППР;

– формалізувати процес побудови ІСППР, що дозволяє об'єднати ІСППР, що використовують різне алгоритмічне та програмне забезпечення. До недоліків запропонованого полімодельного комплексу слід віднести необхідність адаптації запропонованого математичного апарату під конкретні умови функціонування ІСППР.

Запропонований полімодельний комплекс доцільно використовувати для побудови ІСППР для вирішення загальних так і спеціалізованих розрахункових завдань, а також вирішення завдання інтеграції різнотипних ІСППР.

Ключові слова: моделювання систем, представлення даних, прийняття рішень, багатовимірність опису даних.