Selection of models for operational management of hierarchically structured systems under threats*

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Abstract

Operational management of technological production processes in complex hierarchical systems and economic complexes in the event of emergencies and natural disasters is based on operational planning and supervisory synchronous control of all system components, human resources, and unorganized masses of people in a threatening situation. Such emergencies can also include the events taking place in Ukraine during the undeclared war and the full-scale invasion of Russia with the seizure of territories and critical infrastructure of our country. It is usually difficult to predict terrorist attacks by the aggressor country, which periodically launches missile and saber attacks on our critical infrastructure, but it is possible to accurately identify such facilities that have a complex hierarchical management system and require comprehensive protection systems against both natural disasters and air defense systems. The article is focused primarily on the development of models for the operational management of complex hierarchically structured systems in the face of threats associated with emergencies, while adhering to the strategies of a goal-oriented decision-making method in crisis conditions.

Keywords

Complex process management systems, decision-making, crisis management strategy, threats, risks

1. Introduction

The most important element of managing complex integrated facilities in a hierarchical organization of the production process is to coordinate the technical level of management with the strategic level for making decisions both operationally and at the terminal time cycle of the technological process. The main problem of such systemic strategic and technical management of integrated structures (*IS*) is the construction of models and algorithms for integrated management and action planning to address target, current, and crisis situations. It is also important to increase the amount of knowledge, especially in the event of critical situations for the management of hierarchical structures, as described in [1], where the authors use the general economic database of Brazil for modeling. In a monograph devoted to modern technologies for designing automation systems for complex hierarchical objects [2], in addition to the classical methods of diagnosis, forecasting, adaptation and coordination, genetic algorithms and network structures, in particular, neural, hierarchical and fuzzy hierarchical situational-event networks, are also considered.

The problem of goal orientation in a hierarchical organization and the selection of decision makers (leaders) is addressed in [3], which focuses on the selection and training of decision makers in crisis situations.

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The issue of integrating planning and control is based on the construction of conceptual models from a set of components and the entire structure, which, accordingly, will be the basis for analyzing the current dynamics and synthesizing goal-oriented strategies for the behavior of both the operator and automated control systems in the context of identifying emergency risks [4-6].

A methodology for assessing the risk of an emergency in the security system of the information complex of printing enterprises was developed in [7], based on categorical models of the structure and dynamic state of hierarchical systems to identify attack factors and risks. The use of semantic analysis of the document text in building risk models in the threat system is considered in [8].

The development of means of protecting complex hierarchical control systems is devoted to [9] for modeling the process of building a wireless network and evaluating the effectiveness of the function of assigning a communication radius between individual nodes of a hierarchical control structure; [10,11], which describes preventive means of detecting attacks on a hierarchical control system and predicting emergency scenarios. Modern methods for analyzing general industrial control systems for hierarchical technogenic structures are presented in [12,13].

A decision support system for processing control decisions and decision makers is presented in [14], a hybrid ontology for assessing security risks for industrial control systems is developed in [15], a comparative study of methods for analyzing information security risks in complex hierarchical structures is presented in [16], and a detailed analysis of threats to banking enterprises is conducted in [17], and risk factors specific to each of the threats are identified.

Article [18] presents a model of a dynamic and iterative process in which experts discuss a multi-criteria decision-making problem in complex management structures.

However, a thorough systematic analysis of models of operational management of hierarchically structured systems in the face of active threats of resource, information and cognitive types has not yet been conducted. In the context of military operations, the importance and relevance of such scientific research of complex hierarchical control systems in crisis situations is increasing, and the choice of operational control models and the identification of factors influencing the control process allows the development of new preventive information technologies to counteract external negative factors. Taking into account previous studies of the complex of threats to complex hierarchical and dynamic systems, the proposed models can be used to identify factors of influence at different levels of the technological process hierarchy and create means to counteract external attacks on the control system as a whole.

2. Related works

A formalized description of the system should be built using the same type of mathematical apparatus (graphs, operations research, game theory, and decision making), and combined optimization algorithms should be used to dock it. Some models for solving the above problems have been considered for simulation modeling systems based on the control of hypersonic vehicles to determine the flight mechanics of GPSS [19].

Integrated systems are characterized by an n-level hierarchical structure. For the operational management of integrated automated control systems [IACS], a three-level system of strategic planning and management is effective, namely:

- situational level;
- operational level of decision-making;
- calendar level of planning the system's operation.

At each level, the cycles and phases of the elements of planning and implementation of the planned actions are identified, using the information base in a dialog mode. To ensure decision-making procedures under conditions of uncertainty in targeted planning, the principle of consistent disclosure of uncertainties and game situation models are used to simulate behavioral scenarios.

The classical results were obtained in [20] in the form of complexes of mathematical models and algorithms for multicriteria linear programming, taking into account resources and restrictions on them. The procedure of multicriteria control coordinates the functioning of all levels of the system.

The functional procedure for ranking local optimization criteria uses scale methods and accelerated convergence methods in optimal decision-making algorithms, which is the basis for a clear formalization of the management decision-making procedure in production conditions [21].

Lower levels of IAS can be described on the basis of modification to the object of a dynamic simulation model in both continuous and discrete mode, or in the form of piecewise linear automata [22,23].

At the level of operational management, multi-step integration procedures for assessing situations (dynamic programming and statistical theory) are used, while

- The processes of planning and decision-making based on the choice of action algorithms are revealed;
- action models are deployed in time and space in accordance with targeted plans and management strategies;
- management processes are adjusted based on the operational information received;
- a set of significant factors of influence and threats are identified and assessed.

At the same time, an important problem remains the integration of the operator into the IAS structure and into management and coordination processes. To solve this problem, two approaches are substantiated:

- simulation modeling of the IAS functioning, taking into account possible situations of failure of the modes for which optimization and adaptation strategies of the structure are introduced;
- Dynamic modeling of IACS is based on the digital representation of structure and dynamics models (graphs, signals, structure, flows), which became the basis for creating high-level modular models.

The above-mentioned approaches are logically detailed models that are problem-oriented to solve a set of tasks: analysis of the dynamics of material and information flows, integrated management and action planning, and dispatch operational control.

3. Materials and methods

The effectiveness of controlling a technological system with a distributed energy-active structure depends on the sequence of decisions in the dynamics of terminal time. Decision-making requires information about the operational situation in real time, a forecast of the process in the system, and data on past behavior (trends).

Models such as GRRAY [24] use a hierarchy of decision centers. The information for them should be hierarchically structured according to the levels of decision-making and with a certain level of reliability to minimize the risk of making an incorrect decision.

According to the above method, when synthesizing the structure of decision-making centers, it is necessary to perform a sequence of procedures and operations in accordance with the targeting strategy [7]:

- determines the type of structure of the management object that is part of the system;
- levels of management hierarchy are being formed;
- management functions are defined;
- methods and schemes for data exchange between levels are being developed;
- classes of strategies for making targeted decisions are defined;
- the types of data required for decision-making are highlighted;

- define the boundaries of acceptable management decisions at different levels of the system hierarchy;
- define the rules of operation and exchange at different levels of the hierarchy;
- The dynamics of production processes is determined.

Figure 1 shows a functional diagram of a hierarchical control system for a complex technogenic complex under threats with the definition of the levels of control of the hierarchical structure.

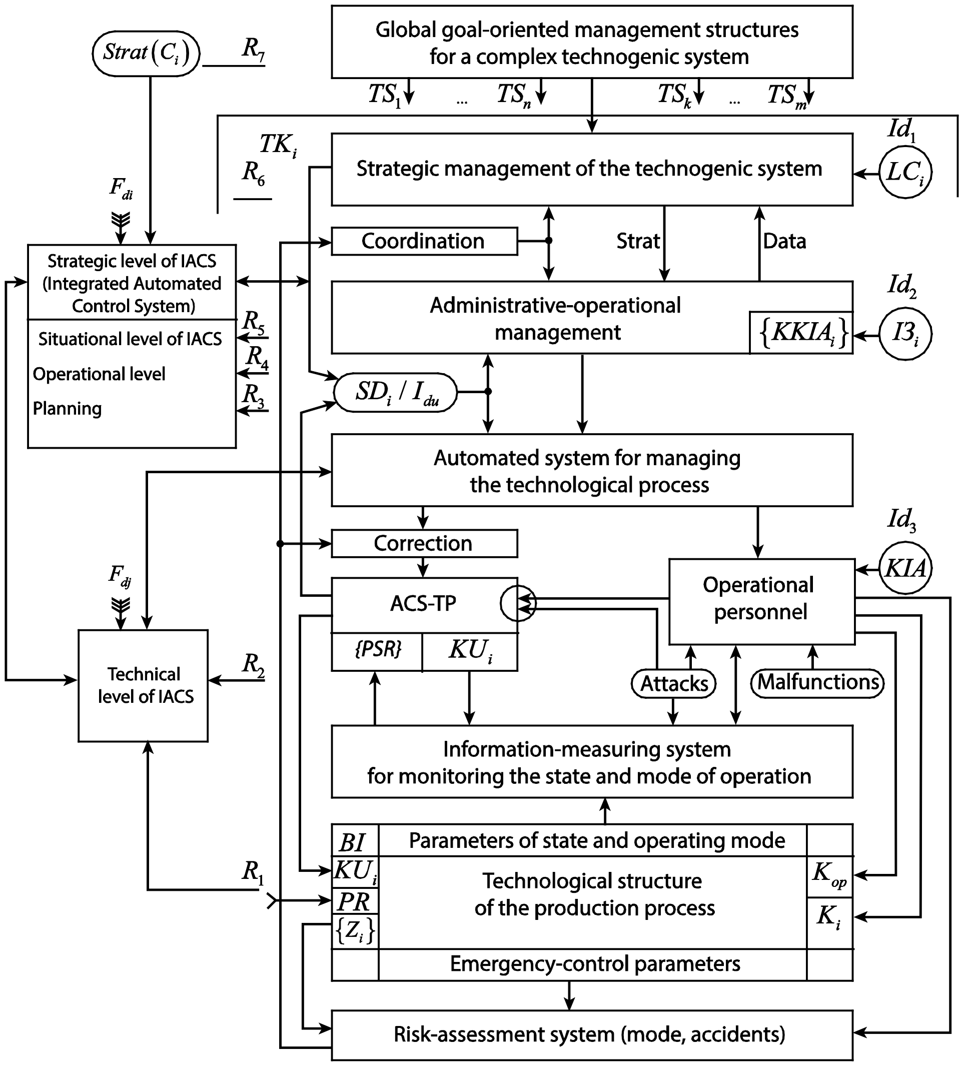

Figure 1: Hierarchical structure of the management system of the technogenic complex in the face of threats.

The efficiency of decision-making by the system is based on the use of sufficient and necessary scientifically correct information both from the object about the situation in real time and from the integrated database and knowledge. This information is divided into [25]:

- current information that is received automatically;
- information generated by the operator based on the analysis of data flows;
- a priori information from the knowledge and data base;
- the information is provided by the designer in diagrams, mnemonic diagrams, and documentation;
- the information is processed and archived by the operator, which requires the elasticity of adaptive signal and data processing structures, their algorithmic and software.

Notation in Fig. 1: R_i - levels of management of the hierarchical structure; F_{di}, F_{dj} - factors of action of information and technical threats, respectively; $Strat(C_i)$ - strategic management goals; LC_i - local management goals; $\text{I}З_i$ - information threats to the management process; KIA_i - cognitive information agent (decision maker in crisis situations); $\{KU_i(KIA_i)\}$ - management teams; $KIA_i\, SD_i/I_{du}$ - data exchange process control kernel; PSR - parameters of the system state and operating modes; K_{op}, K_i - control of the organization of the technological process and intermediate stages of production, respectively; PR - decision-making; $\{Z_i\}$ - a set of threats affecting the production system; ACS - automated process control system.

According to the requirements of decision-making procedures, information in data streams is classified [26]:

- information on the structure and characteristics of the components of the control object (CO) (link graphs, channels, sensors, flows);
- information on the dynamics of the MA and ACS;
- information about the external environment, its parameters and characteristics;
- information about disturbances and threats;
- information on the objectives of the MA and ACS, quality criteria and limitations;
- information on permissible and optimal strategies for planning and managing actions under conditions of uncertainty of performance criteria and information about the impact of threats and disturbances.

When making targeted decisions, situations arise when there is insufficient information about the behavior of the system as a whole. Unpredictable stochastic threats arise, and active elements (persons) with regulated freedom of action and behavior in making non-standard decisions and performing actions intervene in the control system. In such cases, the classical theories of probability, games, optimal control, identification, and adaptation do not provide the appropriate logic for action planning. Therefore, for such cases of management in IASU, it is important to form the appropriate information support, which includes [5,7]:

- a set of information in arrays and data streams, documents, signals;
- methods of organizing, structuring, and storing data arrays;
- operational data: administrative, economic, technological, regulatory;
- information on the functional relationships of the system elements and blocks;
- logical and mathematical elements of decision-making procedures (logic of decisions and actions);
- prompt display of information about the system status and the progress of processes;
- methods of storing control programs (models of strategies and tactics of targeted actions of algorithms).

The target picture of the system [7] is formed on the basis of the normative-algorithmic model [NAM] as a set of information model of the control object and algorithms for data processing and management decision-making consistent with the organizational structure.

Normative-algorithmic management models with organizational structure. The NAM model reflects the processes occurring in the object and the management system with sufficient accuracy to achieve the goals. The NAM defines the mechanism (logical and mathematical) of the management system functioning as a team of decision makers who implement the normative technology and algorithm for achieving management goals in a hierarchical structure.

The information and organizational structure of the NAM includes the following components:

- schemes of control loops for the implementation of processes (logical and mathematical);
- decision-making and processing of details;

- diagrams of typical organizational structures;
- technological route cooperation maps of algorithms for performing management actions;
- organizational scientific and technical documentation;
- mathematical models for optimizing functional, algorithmic, organizational and technological structures of objects and control systems;
- logical and mathematical models of management processes and algorithms for solving management problems (strategies).

4. Experimental research

The expert representation of the hierarchical level of management within the formed knowledge base is as follows [6]

$$\mathrm{M[DS]_{R=h}} = \left\{\mathrm{B_e^k(P, t_h)} \otimes \mathrm{B_e^k(U, t_h)} \otimes \mathrm{B_e^k(t, t_{n-1})}\right\} \otimes \mathrm{B_e^k(S, t_n), K} \in \mathrm{N_n} \quad (1)$$

where *(p, u, d, s)* are variables in the planning and management processes at level *h* with the volume of elements, N_n $\otimes$ are communication operators, $B_e^k(*)$ are operators for describing elements in the linguistic base of the expert system, $M[DS]_{R=h}$ is a model of a dynamic system of level *h*.

The planning process operators for the level *n* phase are displayed in the form [1]:

$$\exists DS_{R=h}: \left(\vec{X}^n, \vec{Z}^n\right) \rightarrow \vec{X}: \overline{P^k}[t_h] = \overline{\Pi^k}\left(\{X^k[t_h]\}, \overline{Z^u}(t_h), \overline{R^k}(t_{h+1}), \overline{n^k}(t_h), F^*(t_h)\right) \quad (2)$$

where $\overline{\Pi^\mathrm{k}}$ is the vector-function of the planning procedure, $\left(\overline{P^k}, \overline{R^k}\right)$ is the planning components with bounde $\mathrm{d\overline{r_i}} \in \mathrm{R^k}, \overline{\mathrm{n^k}}$ is the parameter matrix, $(\vec{\mathrm{X}}, \vec{\mathrm{Z}})$ is the input and state vectors of the system at the h-level.

Output vector $\vec{\mathrm{Y}}$ reflects the implementation of the control plan [7, 8] $\vec{\mathrm{Y}}[\mathrm{t_n}] = \overline{\mathrm{P^k}}[\mathrm{t_n}]$, i.e., the functional planning procedures are performed by the operator based on information about the system state:

$$\left\{\overline{X^k}[t_h], \overline{Z^k}[t_h], \overline{R^k}[t_{h+1}], \overline{P_c^k}[t_h]\right\} \; Alg\;(PL) \rightarrow \left\{\overline{P^k}\left[t_h \rightarrow t_{h+1}/U_n^i\right]\right\} \quad (3)$$

where $\overline{\mathrm{P_c^k}}$ is a set of expert system tips.

The linear operators of the plan's links by levels of the system hierarchy are determined based on the representation:

$$\overline{R^k}[t_{h+1}] = \lambda^{k+1}\overline{P^{k+1}}[t_{h+1}] \quad (4)$$

$$\overline{X^k}[t_h] = \pi^k\overline{P^k}\left[t_h/U_{h-1,h+1}\right] \quad (5)$$

where $\lambda^{\mathrm{k+1}} = \mathrm{quasidiag} \otimes \left\{\lambda_1^\mathrm{k} \;\ldots\; \lambda_\mathrm{n}^\mathrm{k}\right\}$ is the block-diagonal matrix of connections in the system structure at the k-level.

The local element of planning control actions can be expressed as a model [9].

Notation in Figure 2: Alg PL - algorithm of the unit structure functioning; $\overline{\mathrm{Z_i}}$ - parameter of the unit's operating mode; $\mathrm{P_m^k}$ - information input; $\mathrm{K_i}$ - coefficients of influence on the unit's mode; $\overline{\mathrm{X_m^i}}$ - operator of information data processing; $\pi_\mathrm{n}^\mathrm{i} = \mathrm{quasidiag} \otimes \left\{\pi_\mathrm{n}^\mathrm{l} \;\ldots\; \pi_\mathrm{n}^\mathrm{m}\right\}$ operator of horizontal links presented in the form of a block matrix, responsible for generating data on the system state; $\mathrm{D_n}$ - operator of generating parameters for controlling the unit's mode.

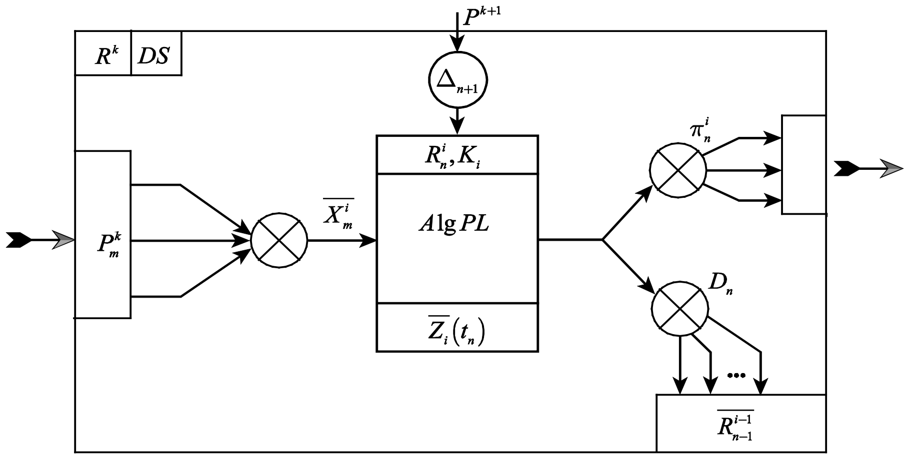

Figure 2: Model of local targeted actions to control the energy-active unit of a technological system.

4.1. Results

The equation of system dynamics in the mode of targeted planning can be expressed as a differential time representation in the space of object states.

$$\frac{dy}{dx} = A_0(t, \bar{x}, \bar{y})\vee(t) + B_0(t, \bar{x}, \bar{y}) \tag{6}$$

The model of control actions can be specified in the form:

$$\forall t \in [t_0, t_1] \subset T_m: I_0\big(\bar{Y}(t), \bar{X}(t), \bar{U}(t)\big) = \int_{t_0}^{t_1} F_0[\bar{Y}(t), \bar{X}(t), \bar{U}(t)]dt \tag{7}$$

where A, B_0, F_0 - matrix structural functions; $\bar{X}$, $\bar{Y}$ - vectors of states of elements of level K; $\bar{U}$ - control vector; I(t) - objective function (target area).

We find the control of $U(t) \subset strat(u/c_i)$ based on the Pontryagin-Belman dynamic programming method.

Accordingly, the operators of the technological link in the structure of the process control system are expressed in the form of matrix equations for state and control.

$$\overline{X_k}(t_0) = g\overline{Y_{k_0}}(t_0) + H\overline{X_{10}}(t_0); \tag{8}$$

$$\overline{Y_{k_0}}(t_0) = L\overline{Y_{k_0}}(t_0) + M\overline{X_{10}}(t_0); \tag{9}$$

$$\overline{P^k}(t_n) = \overline{\Pi^k}(t_0) + (\overline{X^k}(t_n), \overline{Z^k}(t_n)); \tag{10}$$

$$\overline{U^k}(t_n) = \overline{\Pi^k}\{\overline{Z^k}(t_n), \overline{Y^k}(t_n), \overline{P^k}(t_n), \overline{\Lambda^k}(t_n)\}, \tag{11}$$

where (g, H, L, M) - structural matrices; $\overline{P^k}(\quad)$ - action plan; $\overline{U^k}(\quad)$ - management.

Based on the foregoing, it follows that an important feature of operational planning and management is a limited time limit for making and implementing decisions regarding the target in the event of unpredictable changes in the state of the system and object under the influence of threats and disturbances.

The smallest element of the production process is an operation, and its implementation requires the availability of an operation object and resources, as well as additional information about the logic of the operational cycle. In other words, operational management according to the above consists of two phases:

- planning targeted actions;
- real-time action management.

A generalized description of an operation of type j is an expression:

$$A_{op}^{j}(U_{l=1}^{m}) = \{r_j, \Omega_j^-, \Omega_j^+ \mid A\lg(\Omega_j^- \rightarrow \Omega_j^+)\}, \tag{12}$$

where A_{op}^{j} - active operation; r_j - resource type; Ω_j^+ - operation resources; $A\lg()$ - transformation algorithm for performing the operation; $U_{l=1}^{m}$ - command to start actions.

In this representation, the model of processes in the system will be a grid of operational actions (Figure 3).

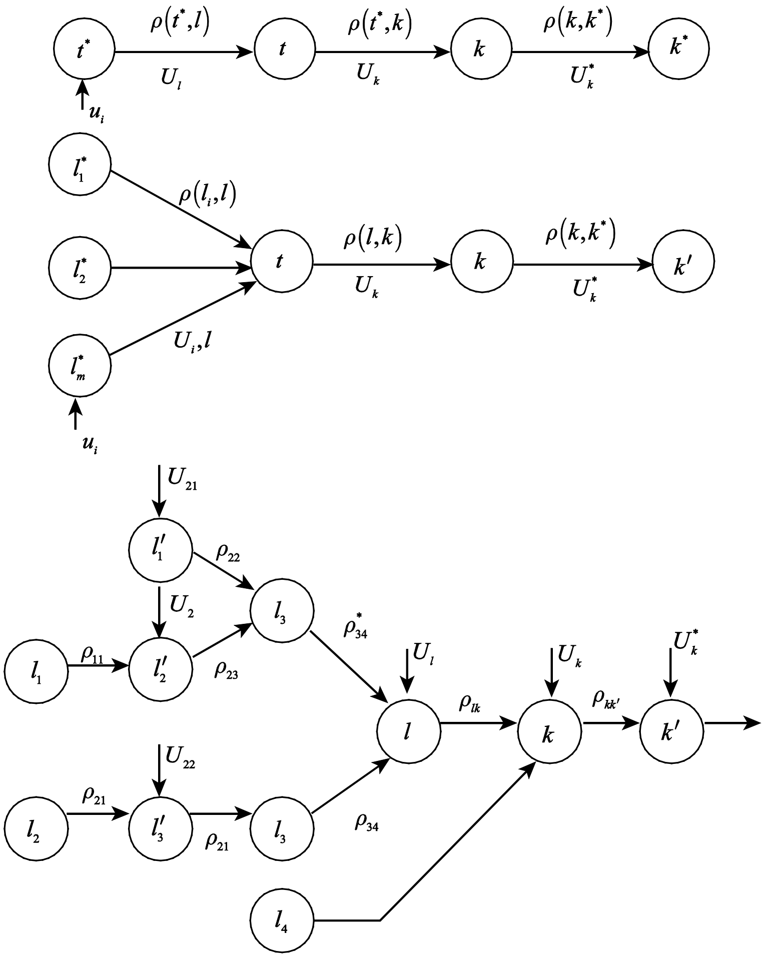

Figure 3: Categorical representation of the operational action model, where $\rho_{lk}=M_d\,(A_{op}, SL_i, SL_k, t_l, t_k, U_l)$; U - management and corrective actions; $\rho_{i,j}$ - functions of interconnection; t,l,k - categorical chart operator indices.

5. Conclusions

The paper solves the scientific and applied task of developing a methodology for selecting and building models of the structure of hierarchical control systems for complex anthropogenic objects in the face of threats and attacks based on the use of categorical representations of system dynamics in the mode of targeted planning. The possibility of determining the strategic and technical levels of the hierarchy of management of a technogenic system on the basis of the proposed functional diagram of a hierarchical management system of a complex technogenic complex under threats is substantiated.

The scientific novelty of the study is as follows:

- the categorical representation of the model of local targeted actions for controlling the energy-active unit of a technological system based on the algorithm of the functioning of the unit structure and the operator of forming the parameters for controlling the unit mode was improved;

- for the first time, a functional diagram of a control system for a complex technogenic complex under threats has been developed with the definition of levels of management and control of the technological process parameters of the production structure;
- categorical representations of the system process model in the form of diagrams of operational data processing and decision-making in the block structure of a complex object with channels for information and management flows and the negative impact of threats on the management process are proposed.

The practical significance of the results obtained is that the proposed method of identifying threats at the hierarchical levels of management of complex technogenic processes allows determining the risk of emergencies and, accordingly, carrying out operational management in solving decision-making tasks to prevent crisis situations.

Further study of the problem is seen in improving the protection of complex hierarchical systems and assessing the risk of their functioning under the influence of active threats.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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