Cybersecurity of hierarchical structured systems in emergency response*

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Abstract
The article considers decision-making schemes and models for threat elimination during emergencies in hierarchical systems based on information and system technologies. An analysis of publications, both classical and modern, was carried out. The relevance of a purposeful automated control systems study was shown, and the features of design using cognitive decision-making methods that would secure the possibility of avoiding structural errors were indicated. A method for assessing risks due to the cognitive component, i.e., operator errors, taking into account his intellectual characteristics, was developed, and intellectual activity cognitive coefficients tables were constructed. The application of the theory of systems and information technologies to the study of large-scale systems with a hierarchical structure of their organization, which is considered as a goal-oriented structure of interconnected subsystems for the implementation of target tasks, taking into account active attacks and threats and the cognitive component of the operator - manager, was considered.

Keywords
Information, system, structure, risk, potentially dangerous objects

1. Introduction

In modern production facilities with a complex hierarchical structure, emergencies can be caused by failures, interference, malfunctions in information management structures, production units, and technology disruptions.

In case of errors that may occur in the process of analyzing a limit or emergency situation and incorrect decisions, the dynamics of events will have catastrophic con-sequences. To prevent such a scenario, operational and technical personnel must have an appropriate level of systematized knowledge to identify hazard sources and impact factors and to build cause-and-effect relationships - the basis for analyzing the state of potentially hazardous objects (PHOs) in the hierarchical structure of the system. This system and information basis are necessary for building event development scenarios, identifying bottlenecks, and making decisions to eliminate threats and emergencies.

Operational and technical personnel must have the skills to build structural communication schemes, decompose units and assemblies, process lines and functional units, determine their critical parameters, and be able to develop action plans in normal and emergency conditions based on system and information technologies to ensure the sustainable functioning of the infrastructure.

A condition for the smooth and efficient functioning of complex systems in extreme conditions is the formed and logically ordered knowledge of the subject area in the cognitive structure of the

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neural system of the operational personnel and the skills of using them under adverse working conditions [2, 6, 7]. To solve this problem, it is necessary to develop a concept of knowledge structuring and determine the risk interval and methods of personnel selection for the implementation of a sustainable goal-oriented strategic level of management of man-made infrastructure with Π-hierarchical levels.

The study aims to develop methods for ensuring effective management of production infrastructure with a hierarchical organization in the face of a complex of active threats and internal and external conflicts, which can lead to management failure, accidents, and the collapse of the structure of a complex system.

2. References analysis

In accordance with this purpose, let's consider the works of researchers published in monographs and articles from 2011-2023.

Monograph [1] considers the problems of intelligent control using logic digital automata as the basis for creating control processes.

The monograph [3] substantiates the methods of systematics of decision-making in complex systems with robust properties to counteract strong disturbances to the system control processes.

Books [2,4,7,8] consider logical and cognitive models of management decision-making in the face of threats and information attacks on control systems.

Based on system analysis, the monograph [6] developed the concept of formation of information and intellectual operations for implementing security management strategies in the ACS.

Books [10-13] analyze models of psychological factors influencing the process of managing complex systems and evaluate multiplicative criteria.

Monographs [4, 5] consider the strategic security problems of complex systems and methods of designing an information security system under the influence of active attacks on data flows and the management process.

The monograph [9] considers the complex problem of creating automated information systems to ensure effective and sustainable management of complex hierarchical man-made complexes.

Works [14-17] consider neuro-fuzzy logic methods for building networks for processing data flows in the control process under interference conditions.

Works [18-22] consider methods of forming and making targeted decisions in the face of information attacks and logical and cognitive failures using fuzzy logic to develop algorithms for assessing the situation in complex systems.

Monograph [23] discusses methods for creating algorithms and operating automata based on the terminal logic of forming control actions.

Work [24] substantiates the use of artificial intelligence methods for data and multimedia processing, their use in decision-making procedures for control in complex systems.

Article [25] considers the problematic tasks of forming management decisions using information and intelligent technologies..

3. Main research results

The intensive development of man-made social infrastructure (industry, energy, transport, aviation, municipal systems of cities, villages, megacities, mining, oil and gas, construction) consumes large amounts of energy and material resources. To operate, they require labor resources (workers, technicians, engineers, scientists, high-level experts, advisors with strategic importance and experience in solving crisis problems).

Research methods that were used to solve the problem of effective targeted management of the production hierarchical infrastructure in the face of threats, conflicts, information, and cognitive attacks:

1. Methods of system analysis of the structure and dynamics of production infrastructure components with a given goal orientation;
2. Information technologies for processing situational data on the state of active objects and their intellectual interpretation;
3. Logical and cognitive models for assessing the ability of personnel to make decisions in crisis situations;
4. Methods for assessing the risks of emergencies at the terminal control cycles using cause-and-effect diagrams.

Infrastructural man-made complexes are hybrid systems with a hierarchy of production and management structures (from man-made to strategic and global).

The development of information technologies for crisis management has its own basis.

New approaches to personnel training are based on the concept of modern scientific methods (systems analysis, crisis management, technical systems management, databases and knowledge, expert systems and computer engineering, communication and telecommunications networks (space, satellite navigation systems).

However, the foundation of the energy, metallurgy, construction, social sector, and other industries requires high-level engineering and fundamental knowledge of mathematics, physics, and thermodynamics of energy-active processes, as well as electronics and nuclear physics and automatic control systems.

Accordingly, man-made infrastructure requires comprehensive knowledge, not just digital and information technologies, to ensure its functioning and project implementation.

An important task of applying the theory of systems and information technology is to study large-scale systems with a hierarchical structure of their organization, which can be considered as a family of appropriately connected subsystems for the implementation of target tasks. From this perspective, systems theory studies the structure as an integrity that ensures the achievement of the goal [1, 4, 6]. Accordingly, all subsystems are connected through connection operators, which ensures the integrity of the functional system and determines the role of each substructure in the system structure and its purposeful behavior. This requires a revision of the classical (ACS) theory - automatic control systems and transition to a new concept - intelligent integrated control systems for man-made infrastructure (IICSMMI).

The use of system analysis, algebra of categories to represent organizational and functional components of man-made infrastructure, data processing methods of information technology to assess the state of energy-active objects, intellectual interpretation of the dynamic situation content in the state space and the target space provides an opportunity to control the functioning of technological units and assess the level of maximum loads, the risks of entering an emergency state.

The use of statistics, situational logic-cognitive analysis and cause-effect diagrams is the basis for building scenarios for the development of events in the terminal control cycles and assessing the risk of an emergency. Preventing an emergency is the main task for operational personnel with the appropriate level of knowledge, professional training, and cognitive intelligence to make targeted decisions.

Let's consider the elements of system structuring in accordance with the goal of the basic task.

Definition 1. Example text of a theorem. A generalized system $S_i \subset X_i \times Y_i$ with objects $X_i = \bigotimes_{i,j} \{X_{i,j}, j \in Ix_i\}$ $Y_i = \bigotimes_{i,j} \{Y_{i,j}, j \in Iy_i\}$ on component sets$V = (V_{i1} x \cdots x V_{in})$ and $\bar{V}_i = \{V_{i1}, \cdots V_{\text{in}}\}$ forms a structure with the set $\{X_i\}$, if it can form a connection. $\left(X_{ij} \in Zx_i\right), \{X_i\} = \otimes \left\{X_{ij}: X_{ij} \in \bar{X}_i\right\}$- input. The output object of the system $Zy_i = \otimes \left\{y_{ij}: y_{ij} \in \bar{y}_i\right\}$ There are many types of connections for each system $S_i \subset X_i \times Y_i$:$(S_i = X_i \times Y_i) \rightarrow \left\{S_{i_z} \subset \left(X_i^x \times Z_{x_i}\right) \times \left(Y_i^x \times Z_{y_i}\right)\right\}_{i=1}^{m}$, which differ by the sets $\left(Z_{X_i}, Z_{y_i}\right)$.

Accordingly, the class of connected systems can be defined in the form of a cascade connection, which reflects the class of the aggregated technological structure:

$$\bar{S}_z = \{Si_z : Si_z \subset (X_i^x \times Zx_i) \times (Y_i^x \times Zy_i)\} \quad (1)$$

and an operation of the form $o\bar{S}_z \times \bar{S}_z \to \bar{S}_z$, which defines the composition: $S_1 o S_2 = S_3$, where

$$\begin{aligned} &S_1 \subset X_1 \times (Y_1^x \times Zx_1); \mid \\ &S_2 \subset (X_2^x \times Zy_2) \times Y_2; \mid \\ &S_3 \subset (X_1 \times X_2^x) \times (Y_1^x \times Y_2); \mid x \overset{S_1}{\to} y \overset{S_2}{\to} Z \in S_3 \end{aligned} \quad (2)$$

These three statements show cascading representation with the corresponding representation in the state space $(X^n \times T)$ will be:

$$((X_1, X_2), (Y_1, Y_2)) \in S_3 \Leftrightarrow \exists z(x_1(y_1, Z)) \in S_1((x_2, Z), y_2) \in S_2 \quad (3)$$

Definition 2. A parallel structure is defined by components with an operation that reflects the direct product of subsystems: $\overline{S_z} \times \overline{S_z} \to \overline{S_z}$ using the operation ($\oplus$) of a parallel connection in the form: $S_1 \oplus S_2 \to S_3$.

If a given system infrastructure in the form of:

$$\begin{aligned} &S_1 \subset (X_1^x \times Zx_1) \times Y_1, \\ &S_2 \subset (X_2 \times Zx_2) \times Y_2, \end{aligned} \quad (4)$$

then the parallel structure represented through the composition of substructures with a given class of functional purpose:

$$\begin{aligned} &S_3 \subset (X_1^x \times X_2^x \times Z) \times (Y_1 \times Y_2), Zx_1 = Zx_2 = Z, \\ &(((x_1, x_1, z), (y_1, y_1)) \in S_3 \Leftrightarrow ((x_1, z), y_1) \in S_1 \& ((x_2, z), y_2) \in S_2) \end{aligned} \quad (5)$$

In accordance with the concept of infrastructure targeting, a decomposition scheme of the hierarchy of units has been developed (Fig. 1).

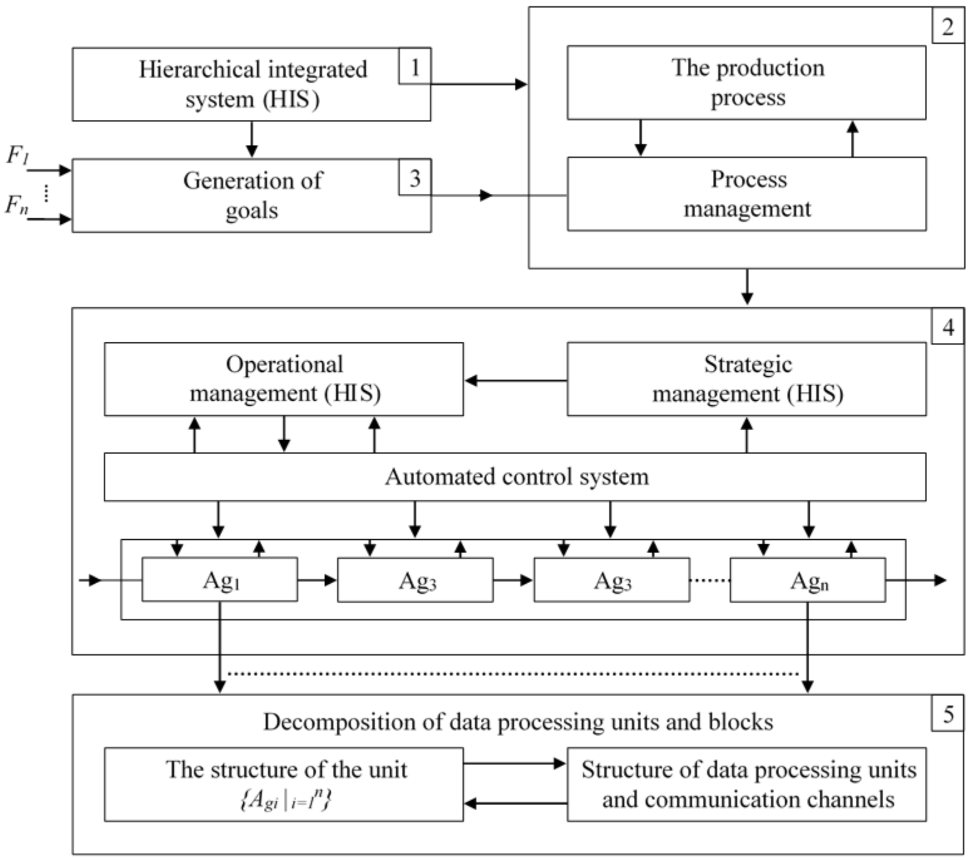

Figure 1: Scheme of sequential decomposition of an intelligent hierarchical system (IHS)

According to Fig. 1, let's define the levels of structuring of the man-made system:

1. Hierarchical integrated system that implements targeted strategic infrastructure management [2];
2. Production complex with an automatic control system.
3. The structure of the intellectual type of strategic goals generation for infrastructure functioning.
4. Technological production structure, which includes an aggregate line with production technology, an automatic process control and management system, operational management, and strategic coordination, which ensures the functioning of the infrastructure under the influence of active threats to the structure, resources, and production process.

Accordingly, the structure in Fig. 1 is one of the ways to represent the organization of production in the man-made infrastructure complex.

3.1. Assessment of the suitability of operational personnel for managing a targeted energy-active system

Table 1. skills assessment and a diagram of operational skills based on system analysis, information, and cognitive technologies were developed to assess the suitability of operational personnel. [8,11,19,20] (Fig. 2).

In accordance with the developed Table 1, a sequential assessment diagram was developed to determine targeted suitability for production and management activities of operational personnel in the energy and glass industry based on the authors' scientific and production experience.

The scientific and technical analysis of professional activity is based on the study of crisis problems in the control of information and measuring systems in complex industries (laser stabilizers of the molten glass surface level (T0 C - 1200-15000C) and laser systems for monitoring the concentration of coal dust after grinding in mills and feeding into power unit boilers through pipelines with a temperature (T0C = 200-6000C).

Such harsh conditions of the technological process functioning impose appropriate conditions for developing projects, their implementation and installation in industrial conditions.

The temperature in the technological shops varies according to the season (20-600C). Hardware implementation at glass plants (Kyiv, Gostomel, Rokytne, Kostopol, Lviv) and power units of Burshtyn TPP (1995-2015).

Accordingly, the level of complexity of IMS-laser control requires appropriate training of personnel (CIP - AC).

The information and measurement control and automation systems (CIP - AC) are the basis of the technological process structure and ensure compliance with the production regime and trouble-free operation of technological units (glass furnace, high-temperature steam generation boilers of the power unit) and signaling of limit situations (alarm - Alarm, pre-emergency mode - Avaria).

In accordance with the man-made infrastructure with a hierarchical production control and management process organization. At the same time, each rank level (level, strata) has requirements for the quality of knowledge, scientific and engineering training, and psychological and cognitive characteristics according to the level of responsibility and authority in the infrastructure and management hierarchy.

Accordingly, let's distinguish between service, engineering, operational, administrative, security and management, and strategic.

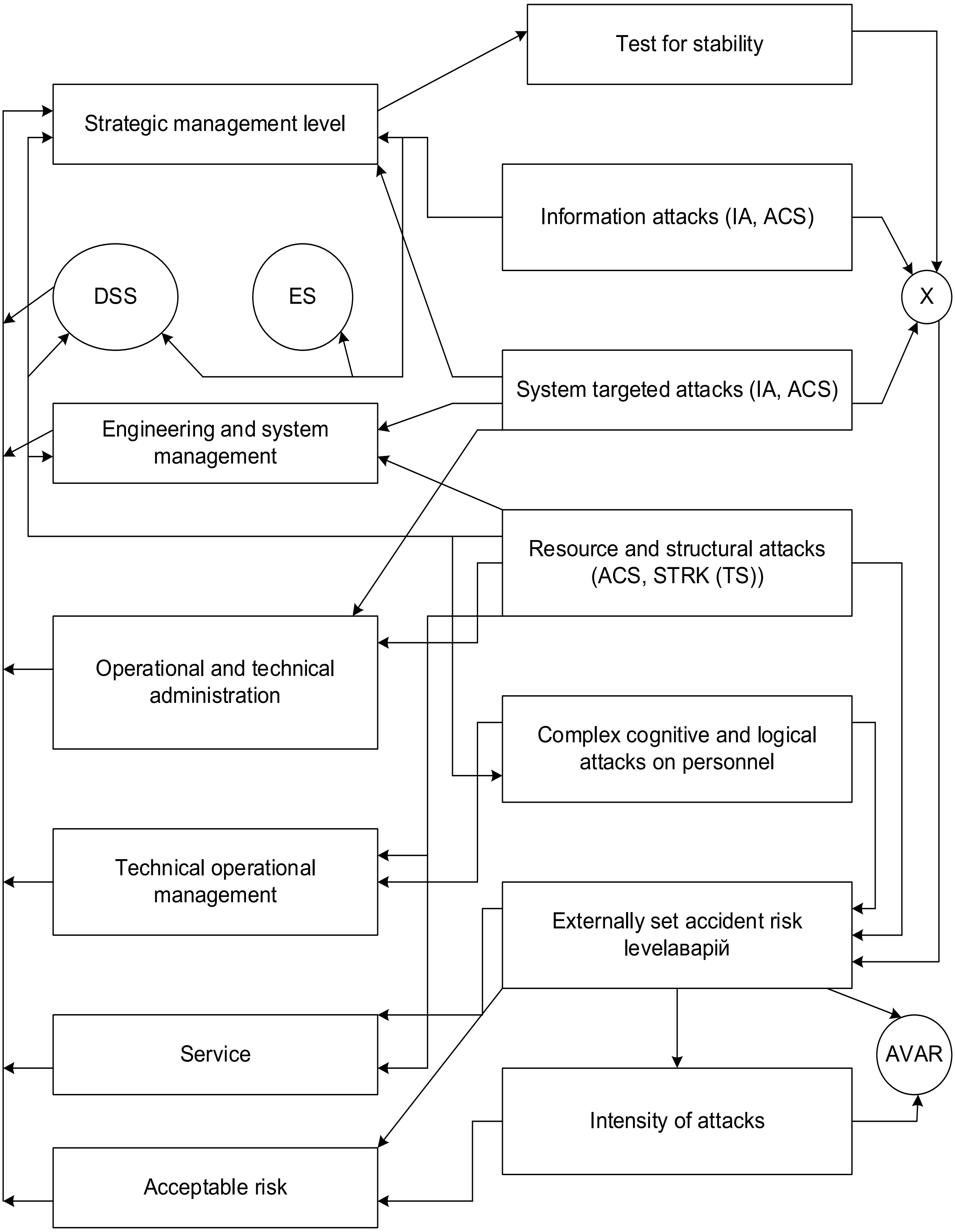

Figure 2: Scheme of formation of knowledge, systemic and cognitive failures of personnel in the performance of official tasks.

Ranking of technological infrastructure personnel by functional requirements:

$P(S_n R_1)$ - personnel for the maintenance of units and blocks;

$P(S_m R_2)$ - personnel for repair and installation works;

$P(S_k R_3)$ - personnel of laboratories of automation and control and measurement systems;

$P(S_i R_4)$ - personnel (engineers, technicians) for shift maintenance of complexes of units and power units;

$P(S_p R_5)$ - personnel for control and maintenance of automatic control systems (ACS-TP);

$P(S_{ou}R_6)$ - personnel of shift operational control of a closed-cycle technological system;
$P(S_dR_7)$ - operational and administrative personnel and document management and computer network services;
$P(S_{IS}R_8)$ - personnel for maintenance of information and automated systems;
$P(S_TR_9)$ - personnel of the chief technologist service;
$P(S_FR_{10})$ - financial and administrative management and planning personnel;
$P(S_gR_{11})$ - Chief Engineer's Service (departments, information security service, fire and technological safety service);
$P(S_ER_{12})$ - expert advisory service and DSS (decision support system) for senior management;
$P(G_nR_{13})$ - senior managers and members of the Management Board and directors, shareholders' representatives;
$P(G_nR_{14})$ - the chairman of the board and the supervisory board of the industrial complex;
$P(A_kR_{20})$ - owners (individual, team);
$P(E_RR_{dm}(SratR))$ - external teams of strategic level advisors and national and international experts (Certified by type of activity).

The requirements for technical, administrative and managerial personnel are formed in accordance with the rank.

4. Results & discussion

In accordance with the rank, test requirements for a person's cognitive, knowledge, and psychological characteristics are formed in tables and a scheme of risk situations.

Accordingly, lets provide information, logic, system and cognitive aptitude of personnel (Table 1).

Table 1
Information, logic, system and cognitive aptitude of personnel

№	Name	Code	KF	α_{risk}
1.	Ability to take active management actions	ZAd	0.5-1	$\alpha_r < 0.2$
2.	Targeted to the recognition situation	CSitПS	0.8-1	$\alpha_r < 0.25$
3.	Reaction and active factors	Rek (AF)	0.6-1	$\alpha_r < 0.5$
4.	Encouraging goal-oriented activities	CDi	0.7-1	$\alpha_r < 0.3$
5.	Building sets of target alternatives	C(Di)	0.9-1	$\alpha_r < 0.25$
6.	Choosing strategies	VStrarU	0.8-1	$\alpha_r > 0.5$
7.	Subconscious choice of goal orientation	ПSv(Ci)	0.7-1	$\alpha_r > 0.5$
8.	Targeted selection	V (Ci)	0.8-1	$\alpha_r < 0.2$
9.	Conscious risk assessment	α_{risk}	0.7-1	$\alpha_r < 0.25$

10.	Formation of situations images in the system under threats	FIcon Sit	0.6-1	$\alpha_r > 0.5$
11.	Understanding the essence of situation image in information attacks	Sens (Icon)	0.7-1	$\alpha_r > 0.5$
12.	Realizing the image essence of the target situation	Sens (Ci)	0.7-1	$\alpha_r > 0.5$
13.	Targeted operations in the face of threats	Di(Ci/Ui)	0.5-1	$\alpha_r > 0.5$
14.	Confidence in their actions	$K_V sp$	0.8-1.0	$\alpha_r > 0.2$
15.	Complex confidence (knowledge, intelligence)	$S_g K_V(A_i)$ $ZpK_V(A_j)$	0.7-1.0 0.6-1.0	$\alpha_r > 0.2$ $\alpha_r > 0.3$
16.	Self-confidence in your knowledge	$SK_V(A_i)$	0,8-1,0	$\alpha_r > 0.5$
17.	Professional self-confidence	$S_Z K_V(A_i)$	0,8-1,0	$\alpha_r > 0.7$
18.	Trust of external experts in the person	$R_d(A_i)$	0,2-1,0	$\alpha_r > 0.5$
19.	Professional trust in the personality of a cognitive agent	$K_{ZP}(A_i)$	0,2-1,0	$\alpha_r > 0.5$
20.	Self-confidence in the ability to solve the problem	$K_{cogn}(A_i)$ $K_{du}(A\ )$	0,75-1,0 0,8-1,0	$\alpha_r > 0.8$
21.	Determination to act in the face of risk	$K_d(D_{risk})$	0,85-1,0 0,9-1,0	$\alpha_r > 0.75$

Table 2
Ranking table of the level of scientific and technical knowledge based on the results of specialized industry tests, which are formed on the basis of the study

№	Points	K_V	K_d	α_{risk}
1.	Systemic background knowledge	0,0-100	0,1-1,0	0,1-0,5
2.	Engineering and technical examples	0,2-100	0,5-1,0	>0.5
3.	Operational management	50-100	0,6-1,0	>0.7
4.	Strategic level	80-100	0,7-1,0	>0.75

Table 3

Ranking table of the level of professional aptitude based on the results of logical, cognitive and psychological tests of personnel screening

№	Test control points	Amount of points	Confidence factor K(B)	Risks a_v
1.	Excellent	88-100	0,9-1,0	0,05-0,1
2.	Very good	81-88	0,7-0,85	0,1-0,2
3.	Good	71-80	0,55-0,65	0,1-0,25
4.	Satisfactorily	51-70	0,3-0,5	0,3-0,6
5.	Unacceptably	0-51	0,0-0,01	0,9-1,0

On the basis of the developed risk assessments (α_{risk}) and the introduced cognitive coefficients (K_d) - trust and coefficients of knowledge requirements (K_V), the methods of assessing professional suitability are substantiated. On the basis of (Table 1), a diagram for assessing the target suitability of personnel for managerial activities in the hierarchical structure of a man-made system has been developed as a basis for maintaining the level of cybersecurity under the influence of information attacks and threats, which can lead to disorientation in the situation and its incorrect assessment in the formation and decision-making.

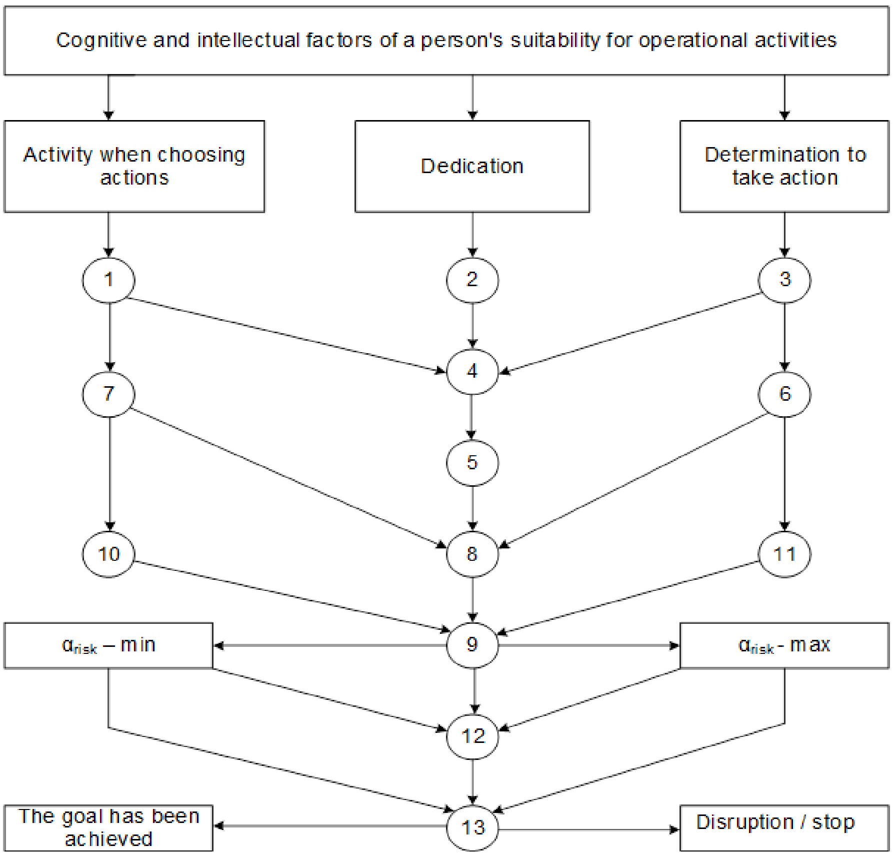

Figure 3: Scheme of formation of knowledge, systemic and cognitive failures of personnel in the performance of official tasks.

The diagram (Fig. 3) of goal suitability assessment and preliminary studies and schemes (Figs. 1-3) are the basis for the construction of professionally oriented tests.

4.1. Prospects for research on the problems of managerial stress resistance and professional engineering and technical activity

The current stage of society development, industrial infrastructure, and social and communal conglomerates is characterized by a set of regional and global problems. The problems that have developed in the infrastructure of society, global ecosystems, energy, transport and the entire economic and industrial complex are becoming increasingly complex and cannot be solved by simple, deregulatory solutions.

The growing process of informatization of technologies and society (start-up technologies, the Internet, artificial intelligence, process automation, intelligent technologies, global data and knowledge bases) cannot ensure the mass welfare of the population, as this requires a certain level of education, not self-deception of opportunities. The low level of managerial culture at all levels of the hierarchy and the educational base leads to strategic mistakes of global and local accidents of the systemic type (e.g., Chornobyl, Yokohama, dam breaks, environmental disasters, Saano-Shushenska TPP), which are characterized by resource, financial and large losses of population.

The war leads to the collapse of infrastructure and large population losses, the ruin of social, communal and strategic structures. These problems can be solved only through the constructive use of material and energy resources, labor, and scientific and engineering potential to upgrade infrastructure. This problem can be solved with effective management at different levels of the hierarchy of state infrastructure organizations, raising the level of professionalism on the basis of modernized educational programs of training and vocational education, selection of managerial personnel on the basis of new concepts of testing and aptitude assessment, taking into account cognitive, psychological and intellectual characteristics to assess the ability to each type of professional activity.

5. Conclusion

Depending on the system structure and the situation, there are changes in the state of the hierarchical system in the terminal space [Tm×TR] in relation to the dynamics of the pace of events, which leads to the thickening of situations on the real-time axis and to the occurrence of an emergency in case of untimely adoption of protection measures. Therefore, for the rapid elimination of emergencies, it is necessary to develop: structural diagrams of technological processes; models, schemes for data selection and processing; methods of classifying situations and making decisions; schemes for the development of possible event scenarios; schemes of personnel behavior and instructions for emergency response based on information and system technologies.

On the basis of the proposed approach, using the logic of actions and the theory of situational management, models of the structure of systems for active control of technological processes under conditions of dynamic disturbances on objects both of the systemic, structural, and cognitive-informational types were developed. The concept of goal orientation and coordination of logical and cognitive models of forming control decisions of a system with a hierarchical structure under the influence of threats and information attacks as a basis for the synthesis of robust decision-making strategies in crisis emergency situations were substantiated.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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