Multicriteria evaluation offers undeniable advantages over single-criterion assessment methods. The object of the study is hierarchical systems. The subject of the study is the process of multicriteria evaluation of the state of hierarchical systems. A method for multicriteria evaluation of hierarchical systems is proposed. The originality of the method lies in the application of additional advanced procedures that allow for the following:

– verification of input data and refinement of inter-element connections within the hierarchical system using an enhanced penguin swarm algorithm. This minimizes the risk of errors resulting from incorrect data input in the assessment of the operational military (force) grouping;

– description of external and internal factors affecting the hierarchical system subject to multicriteria evaluation through the use of fuzzy cognitive models;

– adaptation to the type of hierarchical system via multilevel adjustment of the system of indicators and evaluation criteria;

– reduction of uncertainty through the use of interval-valued Pythagorean fuzzy sets, thereby improving the reliability of multicriteria assessment of hierarchical system states;

– identification of the most vulnerable elements within the hierarchical system using a fault tree analysis;

– adaptation of the membership function type depending on the system's available computational resources, which ensures compatibility with existing computational capacities.

An example of the method's application is demonstrated through the multicriteria evaluation of an operational military (force) grouping. The proposed method provides an average improvement of 35% in accuracy and efficiency, while ensuring a high convergence rate of results at the level of 93.17%

Keywords: system of indicators, vulnerability tree, penguin swarm algorithm, destabilizing factors, military (force) grouping

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DEVELOPMENT OF THE METHOD OF MULTI-CRITERIA EVALUATION OF HIERARCHICAL SYSTEMS

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1. Introduction

The assessment of the state of hierarchical systems is a complex computational task that, by its nature, is inherently multicriteria. Multicriteria evaluation offers undeniable advantages over single-criterion assessment methods and is widely used in engineering calculations, information and automated control systems, decision support systems, and more [1, 2].

These methods hold significant advantages because they allow for a comprehensive evaluation and balancing of technical [3], economic, and social criteria, integrating both quantitative and qualitative data to ensure a thorough analysis [4, 5].

Due to their transparency and simplicity in the decision-making process, multicriteria evaluation methods enable effective management of hierarchical systems [6, 7].

However, current scientific approaches to multicriteria assessment exhibit limitations in terms of accuracy and convergence [8]. These shortcomings are attributed to several factors:

– the significant influence of the human factor in the multicriteria evaluation process, which increases the subjectivity of the assessment;

– the presence of numerous heterogeneous information sources subject to evaluation, resulting in the challenge of normalizing indicators (criteria) to a unified measurement scale and/or converting them into dimensionless quantities;

– limited capacity for deep learning in systems utilizing these methods as part of their hardware and software components;

– lack of adaptation of multicriteria evaluation methods to the computational capabilities of the hardware and software systems in use;

– a large number of destabilizing factors affecting the functioning of multicriteria evaluation systems, among others.

These challenges drive the need for implementing various strategies aimed at improving the convergence speed and accuracy of multicriteria evaluation methods. One such strategy involves further refinement through the integration, comparison, and development of new procedures for their application.

2. Literature review and problem statement

In [9], an algorithm for cognitive modeling is presented, highlighting the main advantages of cognitive tools. However, a key shortcoming of this approach is the lack of consideration for the type of uncertainty regarding the state of the object under analysis.

In [10], the essence of cognitive modeling and scenario planning is explored. The authors propose a system of complementary principles for constructing and implementing scenarios, identify various approaches to scenario development, and describe the scenario modeling procedure based on fuzzy cognitive maps. Nevertheless, this approach fails to account for the type of uncertainty concerning the object's state and does not address noise in the input data.

In [11], a comprehensive analysis of core approaches to cognitive modeling is conducted. Cognitive analysis enables the study of problems involving fuzzy factors and interconnections, while also taking into account changes in the external environment and using objectively formed trends to guide strategic decisions. However, the issue of describing complex and dynamic processes remains unexplored in this study.

In [12], a method for analyzing large datasets is introduced, aimed at uncovering hidden information within big data. This method includes operations such as generating analytical baselines, reducing variables, identifying sparse features, and formulating rules. The drawbacks of this method include the inability to incorporate diverse decision-making strategies and the failure to consider the type of uncertainty in the input data.

In [13], a mechanism is described for transforming informational models of construction objects into their equivalent structural models. This mechanism automates necessary operations for converting, modifying, and supplementing data during such information exchanges. However, a major limitation of this approach is the inability to assess the adequacy and reliability of the transformation process or to perform correction of the resulting models.

In [14], the development of an analytical web platform for investigating the geographical and temporal distribution of incidents is presented. The platform features multiple dashboards with statistically significant results by region. Nevertheless, it does not allow for the assessment of the adequacy and reliability of the information transformation process and is characterized by high computational complexity. Additionally, the decision-making process lacks directional consistency.

In [15], a method for fuzzy hierarchical evaluation of library service quality is developed. This method enables quality assessment of libraries based on a set of input parameters. However, it cannot adequately assess the validity and reliability of the evaluation, nor can it determine the evaluation error.

In [16], an analysis of 30 algorithms for processing large datasets is conducted, showcasing their advantages and limitations. It is determined that big data analysis should be performed in layers, operate in real-time, and possess self-learning capabilities. Nonetheless, these methods suffer from high computational complexity and the inability to verify the adequacy of the obtained assessments.

In [17], an approach is presented for evaluating input data in decision support systems. The essence of the approach lies in clustering the base input dataset, followed by its analysis and subsequent system training. However, the approach is prone to gradual accumulation of evaluation and training errors due to the inability to assess the adequacy of the decisions made.

In [18], a data processing approach from various sources of information is presented. This method enables the handling of heterogeneous data. However, the approach suffers from low accuracy in the obtained assessments and lacks mechanisms to verify their reliability.

In [19], a comparative analysis of existing decision support technologies is conducted, including the Analytic Hierarchy Process (AHP), neural networks, fuzzy set theory, genetic algorithms, and neuro-fuzzy modeling. The advantages and limitations of these approaches are outlined, along with their application areas. It is demonstrated that AHP performs well when complete initial data is available, but due to the need for expert comparisons and selection of evaluation criteria, it carries a high degree of subjectivity. For forecasting tasks under risk and uncertainty, the use of fuzzy set theory and neural networks is considered appropriate.

In [20], the use of combined strategies of metaheuristic algorithms integrated with other components of artificial intelligence theory is discussed. However, this approach has limitations related to the low responsiveness in processing heterogeneous data when multiple metaheuristic algorithms are used simultaneously.

The analysis of works [9–20] reveals several common limitations:

– lack of capability to construct a hierarchical system of indicators for comprehensive evaluation of specialized hierarchical systems;

– failure to consider the computational resources of the system managing the evaluation process of such systems;

– absence of mechanisms for adjusting the indicator system used in managing the evaluation process;

– no selective utilization of training methods based on convolutional artificial neural networks;

– high computational complexity;

– lack of consideration for the available hardware resources in the system;

– absence of prioritized, directional search strategies.

Therefore, further research is proposed to enhance the responsiveness and effectiveness of hierarchical system state assessment through the use of multi-criteria approaches.

3.The aim and objectives of the study

The aim of this study is to develop a method for multi-criteria evaluation of hierarchical systems. This will enable increased responsiveness in assessing the state of hierarchical systems through an improved multi-criteria evaluation method with predefined reliability, facilitating the formulation of subsequent managerial decisions. As a result, it will be possible to develop (or improve) software for multi-criteria assessment of hierarchical systems.

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

– to define the algorithm for implementing the method;

– to provide a practical example of the method's application for multi-criteria assessment of the state of an operational military force grouping.

4. Materials and methods of research

The object of research is hierarchical systems. The problem addressed by this study is to improve the responsiveness of multi-criteria evaluation of hierarchical systems while ensuring a given level of reliability, regardless of the volume of incoming data. The research hypothesis is that it is possible to increase the responsiveness of multi-criteria evaluation of hierarchical systems while maintaining the required level of reliability by applying a multi-criteria assessment method.

The subject of the research is the process of multi-criteria assessment of the state of hierarchical systems.

Indicators used in the system of multi-criteria assessment of hierarchical systems typically vary in origin, units of measurement, and influence on the overall assessment result. To address these complexities, artificial intelligence techniques are applied, specifically:

– an improved penguin search optimization algorithm – used for input data verification and clarification of relationships between elements of the hierarchical system. This contributes to the accuracy of the resulting multi-criteria assessment. This method was selected due to its advantages in solution finding within constrained spaces, owing to the penguin agents' ability to move in a spiral pattern;

– the vulnerability tree model and interval-valued Pythagorean fuzzy sets – used to evaluate the relative importance of factors based on the probability of occurrence and severity of consequences, and to investigate the causal relationships among critical factors of the hierarchical system. These methods were chosen to ensure greater flexibility and universality in representing dependencies during assessment.

Simulation of the proposed method was conducted using the Microsoft Visual Studio 2022 (USA) software environment. The evaluation task simulated was the assessment of the state of a military (force) group. The research was carried out using AMD Ryzen 5 hardware.

The parameters of the improved algorithm are as follows:

– number of iterations: 25;

– number of agents in the algorithm's swarm: 25;

– feature space range: [–150, 150].

5. Development of a multi-criteria evaluation method for hierarchical systems

5. 1 Algorithm for implementing the multi-criteria evaluation method for hierarchical systems

The proposed method for multi-criteria evaluation of hierarchical systems consists of the following sequence of steps:

Step 1. Input of initial data. At this stage, the available input data required to initiate the multi-criteria evaluation method are entered. Specifically, the following information is provided:

– the number of constituent subsystems of the hierarchical system;

– characteristics of each subsystem (number of elements in each subsystem, number of interconnections between elements within each subsystem, type of each element including its purpose and key technical characteristics, etc.);

– the number of connections between each subsystem (or individual element) within the hierarchical system;

– the type and number of individual elements that do not belong to any subsystem of the hierarchical system.

Step 2. Verification of input data and clarification of relationships between elements of the hierarchical system. To reduce subjectivity in the evaluation results, this step involves verification of the input data and refinement of the inter-element connections within the hierarchical system. This is accomplished using the improved penguin search optimization algorithm proposed in [20].

Step 3. Description of external and internal factors influencing the hierarchical system under analysis. This stage identifies a list of external factors affecting the functioning of the hierarchical system, as well as evaluates their degree of influence. Internal factors inherent to the system are also identified. The procedure is based on the assessment method proposed in [19], which utilizes the mathematical apparatus of fuzzy cognitive models.

Step 4. Verification and refinement of the identified factors. The process of verifying and refining identified factors includes two stages. The first stage involves the use of fault tree analysis and the interval-valued Pythagorean fuzzy analytic hierarchy process (IVPF-AHP) to rank and select the most critical factors. The second stage applies the interval-valued Pythagorean fuzzy method to evaluate and visualize the causal relationships among the selected factors.

Step 4. 1. Reducing uncertainty using interval-valued Pythagorean fuzzy sets. This research proposes a combination of fuzzy set theory (specifically, Pythagorean fuzzy sets) with multi-criteria evaluation methods to structure and solve complex decision-making tasks that involve broad and hierarchically organized criteria. This combination is widely used to overcome the inaccuracies that arise from reliance on expert judgment in multi-criteria evaluation methods.

A Pythagorean fuzzy set is defined as follows

$$P=\left\{\left\langle x,P\left(\mu_p\left(x\right),\nu_p\left(x\right)\right)\right\rangle;x\in X\right\}, \tag{1}$$

where X – a finite universe of discourse, and $\mu_p\left(x\right):X\mapsto\left[0,1\right]$ and $\nu_p\left(x\right):X\mapsto\left[0,1\right]$ – denote the degree of membership and the degree of non-membership of the element $x\in X$ to the set P. The values $\mu_p(x)$ and $\nu_p(x)$ must satisfy the following condition

$$0\le\mu_p\left(x\right)^2+\nu_p\left(x\right)^2\le 1.x\in X. \tag{2}$$

The degree of indeterminacy (or hesitation) of a Pythagorean fuzzy set with respect to the set P can be calculated as follows

$$\pi_P(x)=\sqrt{1-\mu_P(x)^2-\nu_P(x)^2}. \quad (3)$$

To more accurately represent variation and uncertainty, an interval-valued Pythagorean fuzzy set (IVPFS) is used. In this case, intervals are used instead of crisp values to describe the degree of membership, and the set $\tilde{P}$, is defined as follows

$$\tilde{P}=\left\{\left\langle x,\tilde{P}\left(\begin{matrix}\left[\mu_{\tilde{P}_L}(x),\mu_{\tilde{P}_U}(x)\right],\\ \left[\nu_{\tilde{P}_L}(x),\nu_{\tilde{P}_U}(x)\right]\end{matrix}\right)\right\rangle;x\in X\right\}, \quad (4)$$

where $\langle[\mu_{\tilde{P}_L}(x),\mu_{\tilde{P}_U}(x)],[\nu_{\tilde{P}_L}(x),\nu_{\tilde{P}_U}(x)]\rangle$ – an interval-valued Pythagorean fuzzy value $0\le\mu_{\tilde{P}_L}(x)\le\mu_{\tilde{P}_U}(x)\le\nu_{\tilde{P}_L}(x)\le\nu_{\tilde{P}_U}(x)$. $\mu_{\tilde{P}_L}(x)$ and $\nu_{\tilde{P}_L}(x)$ must satisfy the following condition

$$0\le\mu_{\tilde{P}_L}(x)^2+\nu_{\tilde{P}_L}(x)^2\le 1,\ x\in X. \quad (5)$$

The degree of indeterminacy of an interval-valued Pythagorean fuzzy set with respect to $\tilde{P}$ can be calculated as follows

$$\pi_{\tilde{P}}(x)=\left[\pi_{\tilde{P}_L}(x),\pi_{\tilde{P}_U}(x)\right]=$$
$$=\left[\sqrt{1-\mu_{\tilde{P}_U}(x)^2-\nu_{\tilde{P}_U}(x)^2},\sqrt{1-\mu_{\tilde{P}_L}(x)^2-\nu_{\tilde{P}_L}(x)^2}\right]. \quad (6)$$

Step 4. 2. Evaluation and visualization of causal relationships between the selected factors.

Given a specified interval-valued Pythagorean fuzzy set describing the causal relationships between the selected factors, the following expression is used:

$$\tilde{P}=\left(\left[\mu_{\tilde{P}_L}(x),\mu_{\tilde{P}_U}(x)\right],\left[\nu_{\tilde{P}_L}(x),\nu_{\tilde{P}_U}(x)\right]\right),$$
$$\left[\mu_{\tilde{P}_L}(x),\mu_{\tilde{P}_U}(x)\right]\subseteq[0,1],\left[\nu_{\tilde{P}_L}(x),\nu_{\tilde{P}_U}(x)\right]\subseteq[0,1],$$

and $0\le\mu_{\tilde{P}_L}(x)^2+\nu_{\tilde{P}_L}(x)^2\le 1$, with a parameter $\lambda>0$. In this case, the following operation is performed:

$$\lambda\tilde{P}=\left(\begin{matrix}\left[\begin{matrix}\sqrt{1-\left(1-\mu_{\tilde{P}_L}(x)^2\right)^{\lambda}},\\ \sqrt{1-\left(1-\mu_{\tilde{P}_U}(x)^2\right)^{\lambda}},\end{matrix}\right],\\ \left[\nu_{\tilde{P}_L}(x)^{\lambda},\nu_{\tilde{P}_U}(x)^{\lambda}\right]\end{matrix}\right), \quad (7)$$

$$\lambda\tilde{P}=\left(\begin{matrix}\left[\mu_{\tilde{P}_L}(x)^{\lambda},\mu_{\tilde{P}_U}(x)^{\lambda}\right],\\ \left[\begin{matrix}\sqrt{1-\left(1-\nu_{\tilde{P}_L}(x)^2\right)^{\lambda}},\\ \sqrt{1-\left(1-\nu_{\tilde{P}_U}(x)^2\right)^{\lambda}}\end{matrix}\right]\end{matrix}\right). \quad (8)$$

$$\tilde{P}=\left(\left[\mu_{\tilde{P}_L}(x),\mu_{\tilde{P}_U}(x)\right],\left[\nu_{\tilde{P}_L}(x),\nu_{\tilde{P}_U}(x)\right]\right),$$
$$\left[\mu_{\tilde{P}_L}(x),\mu_{\tilde{P}_U}(x)\right]\subseteq[0,1],$$
$$\left[\nu_{\tilde{P}_L}(x),\nu_{\tilde{P}_U}(x)\right]\subseteq[0,1],$$

and

$$0\le\mu_{\tilde{P}_L}(x)^2+\nu_{\tilde{P}_L}(x)^2\le 1.$$

Given two interval-valued Pythagorean fuzzy sets $\tilde{P}_1=\left([a_1,b_1],[c_1,d_1]\right)$ and $\tilde{P}_2=\left([a_2,b_2],[c_2,d_2]\right)$ the following operation is performed:

$$\tilde{P}_1\oplus\tilde{P}_2=$$
$$=\left(\left[\sqrt{a_1^2+a_2^2-a_1^2a_2^2,b_1^2+b_2^2-b_1^2b_2^2}\right],\left[c_1c_2,d_1d_2\right]\right), \quad (9)$$

$$\tilde{P}_1\oplus\tilde{P}_2=$$
$$=\left(\left[a_1a_2,b_1b_2\right],\left[\sqrt{c_1^2+c_2^2-c_1^2c_2^2,d_1^2+d_2^2-d_1^2d_2^2}\right]\right). \quad (10)$$

Step 5. Vulnerability analysis of a subsystem (or individual element) of a hierarchical system.

Vulnerability tree analysis is widely used to identify potential root causes, referred to as basic events, as well as to determine the probability of an unexpected event, known as the top event. The top event is located at the top of the tree, whereas basic events are found at the bottom. Basic events (BEs) in the vulnerability tree are considered statistically independent and are connected using logical operators (AND/OR).

The vulnerability tree analysis involves both qualitative and quantitative assessments. Within the scope of qualitative analysis, the vulnerability tree establishes and explains the theoretical interrelationships between the vulnerability structure and basic events based on the logic of "AND" and "OR". In quantitative assessment, basic events and their logical relationships are identified to construct a logical expression of the vulnerability tree. The probability of the top event can be quantitatively calculated based on the probabilities of each risk factor.

In this study, the vulnerability tree is used to analyze the causal relationships among the identified factors and to rank them based on the probability of occurrence. The probability of the top event is assessed using equations (11)–(13), derived based on the principles of Boolean algebra:

$$P_{OR}=1-\prod_{i=1}^{n}\left(1-P_i\right), \quad (11)$$

$$P_{AND}=\prod_{i=1}^{n}P_i, \quad (12)$$

$$P_{TE}=\prod_{j\in M}\left(1-\prod_{BE_i\in Q_j}^{n}\left(1-P_i\right)\right), \quad (13)$$

where P_i – the probability of occurrence of the basic event BE_i; Q_j – a group of basic events BE_i.

To assess the importance of each basic event, its contribution to the probability of the top event is calculated. This information is of significant value to decision-makers as it helps identify the most vulnerable points in the system. As a result, decision support systems can effectively pinpoint the factors that most frequently lead to failures and require increased attention.

To identify and prioritize the most critical basic events leading to the top event, Birnbaum's importance measure is applied. The Birnbaum importance measure is a key metric based on fault tree analysis, used to assess the criticality of individual components or events in a system. It quantitatively evaluates each basic event's contribution to the occurrence of the top event. Formally, the Birnbaum Importance Measure (BIM) for a specific basic event is calculated as follows

$$\mathrm{IM}_{\mathrm{BE}_i}^{\mathrm{BIM}}=P\left(\mathrm{TE}|\mathrm{BE}_i=1\right)-\mathrm{P}\left(\mathrm{TE}|\mathrm{BE}_i=0\right), \quad (14)$$

where $\mathrm{IM}_{\mathrm{BE}_i}^{\mathrm{BIM}}$ – the Birnbaum importance value for the basic event BE_i.

Once the BIM values for all basic events have been computed, they can be sorted by their importance level. A higher BIM value indicates a higher significance of the corresponding basic event in causing the top event.

Step 6. Ranking the influencing factors of the hierarchical system.

The application of fault tree analysis and interval-valued Pythagorean fuzzy sets provides two types of relative importance weights and corresponding rankings. To ensure a balanced evaluation that accounts for both the severity of vulnerabilities and their likelihood of occurrence, a correction weight is introduced. This weight is used to harmonize both indicators, resulting in an updated ranking of factors. The most important factors for further analysis are selected based on this new ranking

$$MR_i = w \cdot R_i^1 + \left(1 - w\right) \cdot R_i^2, \quad (15)$$

where MR_i – the combined rank value for factor i, R_i^1 – the rank of factor i, obtained from fault tree analysis, R_i^2 – the rank of factor i, obtained from the interval-valued Pythagorean fuzzy set method, and w – the correction weight that determines the influence of each aspect.

After that, the failure-inducing factors can be re-sorted based on the combined ranking.

5. 2. Example of applying the proposed method for multi-criteria evaluation of a hierarchical system's state

To determine the effectiveness of the proposed method, a simulation was conducted to solve the problem of multi-criteria evaluation of the condition of a military grouping (forces), based on the initial conditions set out in Section 4.

Individual components of the computational experiment using the proposed method are presented in Tables 1, 2.

Table 1

Results of membership function calculations for decisions based on rules.

No. Rules	Results of membership function calculations of decisions based on rules											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.0007	0.045	0.048	0.04	0.066	0.032	0.007	0.005	0.009	0.049	0.063	0.044
2	0.061	0.039	0.116	0	0.126	0.158	0.147	0.018	0.072	0.137	0.162	0.163
3	0.065	0.041	0.05	0.027	0.011	0.058	0.033	0.04	0.045	0.056	0.067	0.046
4	0.095	0.074	0.153	0.068	0.004	0.1	0.0018	0.169	0.0052	0.053	0.046	0.163
5	0.174	0.0147	0.083	0.083	0.076	0.002	0.102	0.083	0.162	0.116	0.09	0.105
6	0.028	0.057	0.019	0.036	0.047	0.038	0.025	0.028	0.0029	0.005	0.036	0.063
7	0.061	0.067	0.056	0.045	0.012	0.014	0.0007	0.012	0.022	0.056	0.069	0.00216
8	0.197	0.219	0.211	0.232	0.197	0.203	0.057	0.07	0.119	0.13	0.138	0.0054
9	0	0.122	0.124	0.157	0.243	0.003	0.262	0.208	0	0.165	0.084	0.151
10	0.146	0.079	0.142	0.076	0.005	0.121	0.107	0.121	0.114	0.091	0.049	0.139
11	0.165	0.139	0.065	0.044	0.07	0.1	0.083	0.163	0.061	0.165	0.133	0.086
12	0.026	0.039	0.001	0.006	0.043	0.021	0.036	0.013	0.014	0.034	0.02	0.03
13	0.035	0.006	0.037	0.04	0.021	0.038	0.004	0.0005	0.033	0.017	0.021	0.017
14	0.0054	0.003	0.033	0.021	0.007	0.028	0.029	0.0076	0.05	0.033	0.017	0.038
15	0.049	0.009	0.012	0.021	0.033	0.03	0.044	0.023	0.024	0.034	0.018	0.041
16	0.03	0.042	0.027	0.019	0.014	0.047	0.029	0.011	0.036	0.023	0.05	0.033
17	0.021	0.0005	0.031	0.028	0.032	0.047	0.031	0.02	0.024	0.012	0.02	0.032
18	0.03	0.008	0.016	0.044	0.02	0.036	0.016	0.048	0.05	0.014	0.035	0.0086
19	0.026	0.039	0.038	0.014	0.003	0.002	0.031	0.011	0.031	0.0076	0.034	0.013
20	0.007	0.046	0.049	0.033	0.015	0.007	0.049	0.023	0.05	0.016	0.03	0.034
21	0.042	0.026	0.026	0.025	0.037	0.029	0.027	0.021	0.015	0.01	0.041	0.00758
22	0.126	0.027	0.017	0.315	0.033	0.096	0.206	0.305	0.093	0.146	0.116	0.00332
23	0.391	0.462	0.616	0.443	0.077	0.231	0.0064	0.077	0.616	0.109	0.237	0.61
24	0.132	0.005	0.04	0.002	0.035	0.139	0.063	0.0088	0.112	0.118	0.109	0.037
25	0.14	0.125	0.044	0.139	0.13	0.074	0.107	0.125	0.1	0.054	0.021	0.158
26	0.041	0.047	0.02	0.026	0.008	0.016	0.025	0.019	0.043	0.031	0.04	0.049
27	0.022	0.014	0.041	0.037	0.034	0.046	0.013	0.027	0.022	0.011	0.042	0.012
28	0.038	0.008	0.015	0.011	0.018	0	0.017	0.033	0.018	0.042	0.043	0.023
29	0.037	0	0.039	0.015	0.035	0.004	0.021	0.017	0.039	0.031	0.004	0.05
30	0.007	0.028	0.011	0.031	0.012	0.048	0.021	0.026	0.032	0.036	0.033	0.026
31	0.032	0.011	0.007	0.018	0.033	0.036	0.04	0.011	0.038	0.024	0.018	0.045
32	0.041	0.02	0.05	0.027	0.008	0.017	0.05	0.024	0.031	0.045	0.034	0.022
33	0.022	0.019	0.039	0.049	0.043	0.000	0.045	0.029	0.0025	0.016	0.013	0.037
34	0.042	0.048	0.011	0.02	0.013	0.042	0.006	0.0035	0.014	0.0056	0.049	0.049
35	0.05	0.032	0.032	0.037	0.027	0.014	0.005	0.046	0.038	0.02	0.037	0.039
36	0.081	0.044	0.049	0.102	0.016	0.146	0.053	0.114	0.133	0.054	0.054	0.086
37	0.139	0.153	0.025	0.172	0.014	0.142	0.025	0.114	0.063	0.04	0.091	0.135
38	0.019	0.044	0.012	0.004	0.03	0.047	0.008	0.024	0.05	0.033	0.008	0.0015
39	0.023	0.034	0.041	0.003	0.015	0.015	0.05	0.048	0.018	0.036	0.035	0.027
40	0.034	0.063	0.056	0.023	0.085	0.045	0.025	0.0073	0.012	0.113	0.078	0.036
41	0.045	0.016	0.023	0.027	0.032	0.006	0.027	0.011	0.036	0.045	0.038	0.041
42	0.018	0.013	0.019	0.038	0.05	0.021	0.023	0.03	0.028	0.024	0.015	0.045
43	0.0005	0.031	0.033	0.028	0.047	0.023	0.0005	0.035	0.0066	0.034	0.044	0.031
Defense	0.174	0.147	0.153	0.083	0.126	0.158	0.147	0.169	0.162	0.137	0.162	0.163
Counterattack	0.391	0.462	0.616	0.443	0.243	0.231	0.262	0.305	0.616	0.165	0.237	0.61
Stabilization actions	0.139	0.153	0.056	0.172	0.14	0.142	0.05	0.114	0.063	0.113	0.091	0.135
Error	0.42	0.334	0.174	0.347	0.609	0.636	0.569	0.525	0.178	0.729	0.617	0.197

The complete computational experiment comprises more than 140 pages; only a selected part of it is presented in this section.

Table 2

Comparative results of the process of assessing the state of the troop (force) grouping

–	Using the method	Without using the method
Speed of the assessment process of troop grouping state		
Best case	49–303 sec	56–507.1 sec
Worst case	255.1–2501.5 sec	382.8–3977 sec
Reliability of obtained decisions		
Best case	0.89–1.0	0.64–0.85
Worst case	0.77–1.0	0.617–0.75

From the analysis of Table 2, it can be concluded that the proposed method provides an increase in accuracy and speed on average by 35%, while ensuring a high convergence of the obtained results at the level of 93.17%.

6. Discussion of the results of the multi-criteria assessment method

The advantages of the proposed method are due to the following:

– verification of the input data and refinement of the relationships between elements of the hierarchical system (Step 2) is carried out using an improved penguin swarm algorithm, compared to works [6, 7]. This allows minimizing errors caused by incorrect data input for the assessment of the operational troop grouping (forces);

– description of external and internal factors affecting the hierarchical system subject to multi-criteria evaluation using fuzzy cognitive models (Step 3), compared to works [10, 11];

– adaptability to the type of hierarchical system through multi-level adaptation of the system of indicators and evaluation criteria (Steps 1–6), compared to works [9, 17];

– reduction of uncertainty by using interval Pythagorean fuzzy sets (Step 4. 1), which leads to increased reliability of the multi-criteria assessment of the hierarchical system state, compared to works [10, 11];

– ability to identify the most vulnerable elements of the hierarchical system using a fault tree (Step 5), compared to works [13, 14];

– ability to adapt the membership function type depending on the available computational resources of the system, thus ensuring adaptation to the available computational resources (Step 4), compared to works [13, 16];

– adaptability to simultaneously search for solutions in different directions (Step 2).

Disadvantages of the proposed method include:

– lower accuracy of evaluation for an individual evaluation criterion;

– loss of reliability of obtained decisions when searching for solutions in several directions simultaneously.

The proposed method enables:

– conducting multi-criteria assessment of the state of hierarchical systems regardless of the structure of the hierarchical system being assessed;

– identifying vulnerable points in hierarchical systems that are the primary targets for intervention;

– improving the speed and accuracy of the multi-criteria assessment of the state of hierarchical systems;

– reducing uncertainty in the multi-criteria assessment of the state of hierarchical systems;

– reducing the use of computational resources of decision support systems.

The limitations of the study include the need to account for time delays in collecting and delivering information from components of hierarchical systems.

The proposed approach is advisable to use for solving the task of multi-criteria assessment of the state of hierarchical systems characterized by a high degree of complexity.

7. Conclusions

1. An algorithm for implementing the method has been defined, which, thanks to additional and improved procedures, allows:

– verification of input data and refinement of relationships between elements of the hierarchical system using an improved penguin swarm algorithm. This minimizes errors due to incorrect data input for assessing the operational troop grouping (forces);

– description of external and internal factors affecting the hierarchical system subject to multi-criteria evaluation using fuzzy cognitive models;

– adaptation to the type of hierarchical system by multi-level adaptation of the system of indicators and evaluation criteria;

– reduction of uncertainty using interval Pythagorean fuzzy sets, thus increasing the reliability of the multi-criteria assessment of the state of hierarchical systems;

– identification of the most vulnerable elements of the hierarchical system using a fault tree;

– adaptation of the type of membership function depending on the available computational resources of the system, ensuring adaptation to available computational resources.

2. An example of the use of the proposed method was conducted on the multi-criteria assessment of the operational troop grouping (forces), demonstrating that the proposed method provides an average increase in accuracy and speed by 35%, while ensuring high convergence of the obtained results at the level of 93.17%.

Conflict of interest

The authors declare that they have no conflicts of interest regarding this study, including financial, personal, authorship, or other relationships that could influence the study and its results presented in this article.

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Data availability

The manuscript has associated data in a data repository.

Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used in the creation of this work.

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