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METHODICAL APPROACH TO ASSESSING THE STATE OF HIERARCHICAL SYSTEMS USING A METAHEURISTIC ALGORITHM

Andrii Shyshatskyi
Corresponding author
Doctor of Technical Sciences, Senior Researcher, Professor*
E-mail: ierikon13@gmail.com
Svitlana Kashkevich
Senior Lecturer*
Igor Kyrychenko
Doctor of Technical Sciences, Professor
Department of Construction and Road-Building Machinery**
Oleksiy Khakhlyuk
PhD, Associate Professor***
Volodymyr Kubrak
PhD, Lecturer***
Andrii Koval
PhD, Associate Professor
Department of Metrology and Industrial Safety**
Oleksandr Koval
PhD, Associate Professor
Department of Metrology and Industrial Safety**
Nadiia Protas
PhD, Associate Professor
Department of Information Systems and Technologies
Poltava State Agrarian University
Skovorody str., 1/3, Poltava, Ukraine, 36003
Vitalii Stryhun
Senior Researcher, Senior Test Engineer
Scientific and Research Laboratory
State Scientific Research Institute of Armament and Military Equipment Testing and Certification
Viacheslava Chornovola str., 164, Cherkasy, Ukraine, 18003
Ievgenii Kuzminov
PhD Student
Department of Computer Systems**
*Department of Intelligent Cybernetic Systems
National Aviation University
Lubomyra Huzara ave., 1, Kyiv, Ukraine, 03058
**Kharkiv National Automobile and Highway University
Yaroslava Mudroho str., 25, Kharkiv, Ukraine, 61002
***Special Department No. 1
Institute of Special Communications and Information Protection of the National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
Verkhnokliuchova str., 4, Kyiv, Ukraine, 03056

The object of the study is hierarchical systems. The subject of the study is the process of assessing the state of hierarchical systems using the advanced antlion algorithm (ALA), an advanced genetic algorithm and evolving artificial neural networks. The problem solved in the study is to increase the efficiency of assessing the state of hierarchical systems, regardless of the system hierarchy level. The originality of the study is that:

– the initial setting of ALA is carried out taking into account the type of uncertainty using appropriate correction factors for the degree of awareness of anthill location (priority search directions);

– the initial velocity of each ALA is taken into account, which allows determining the priority of search by each ALA in the specified search direction;

– the fitness of ALA hunting locations is determined, which reduces the time for assessing the state of the hierarchical system;

– the use of the procedure of global restart of the algorithm, which allows the algorithm to go beyond the current optimum and improve the exploration ability of the algorithm, which reduces the time for assessing the state of hierarchical systems;

– the possibility of clarifying the choice of an anthill at the hunting stage due to ranking anthills by the level of ant pheromone;

– improved ability to select the best ALA in comparison with random selection using an advanced genetic algorithm, which improves the reliability of assessing the state of complex hierarchical systems.

The proposed methodical approach provides a 22–25 % increase in the efficiency of assessing the state of hierarchical systems by using additional advanced procedures. The proposed methodical approach should be used to solve the problems of assessing the state of complex hierarchical systems under uncertainty and risks characterized by a high degree of complexity

Keywords: complex hierarchical systems, genetic algorithm, artificial neural networks, swarm algorithms

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1. Introduction

Evaluating complex and hierarchical systems is a complex process of determining a set of possible states for a wide range of problems, including management decision-making [1–3].

State assessments of complex and hierarchical systems are discontinuous, undifferentiated, and multimodal. Considering the above, classical gradient deterministic algorithms [4–6] are inappropriate for solving this type of problem.

The most common approaches to assessing the state of hierarchical systems are swarm intelligence algorithms (swarm algorithms). The most well-known swarm algorithms are the particle swarm optimization algorithm, artificial bee colony algorithm, firefly algorithm, ant colony optimization algorithm, wolf optimization algorithm and sparrow search algorithm [6–8].

However, most of the basic bio-inspired algorithms mentioned above are unable to maintain a balance between exploration and exploitation, resulting in poor performance for real-world complex optimization problems.

This encourages implementing various strategies to improve the convergence rate and accuracy of the basic bio-inspired algorithms.

Therefore, research on the development of new approaches to assessing the state of complex hierarchical systems is relevant.

2. Literature review and problem statement

The works [9–11] define the main advantages and disadvantages of cognitive algorithms. The work [9] investigated the search for hidden data arrays. The study [10] is devoted to solving the problem of interpreting analytical models. The research [11] deals with developing an analytical platform for analyzing large amounts of data. The disadvantages of these approaches include the lack of consideration of the type of uncertainty, the inability to conduct a search in different directions by several agents.

The work [12] presents an approach focused on the search for hidden information in large data sets. The method is based on analytical baselines, reducing variables, identifying sparse features and specifying rules. The disadvantages of this method include the inability to take into account various decision-making strategies, the lack of consideration of the type of uncertainty of initial data.

The work [13] presents an approach to transforming 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 shortcomings of the mentioned approach include the inability to assess the adequacy and reliability of the information transformation process, as well as to make appropriate correction of the resulting models.

The work [14] proposes a method of fuzzy hierarchical assessment, which allows assessing the quality of library services. The disadvantages of the specified method include the inability to assess the adequacy and reliability of the assessment and, accordingly, determine the assessment error.

The work [15] analyzes the 30 most common big data algorithms. It was found that the analysis of large amounts of data should be carried out in layers, take place in real time and have the opportunity for self-learning, search for a solution in different directions and take into account data noise.

The work [16] presents approaches to evaluating heterogeneous data for decision support systems based on clustering the basic set of input data, after which the system is trained based on the analysis. However, given the static architecture of artificial neural networks, an accumulation of errors occurs.

The work [17] carried out a comparative analysis of existing decision support technologies, namely: analytic hierarchy process, neural networks, fuzzy set theory, genetic algorithms and neuro-fuzzy modeling. The advantages and disadvantages of these approaches are indicated. For the problems of assessing the state of hierarchical systems under risk and uncertainty, using artificial neural networks and gradient algorithms is justified.

The work [18] developed approaches to the structural and objective analysis of the development of weakly structured systems. In this case, the problem is defined as the non-compliance of the existing state of a weakly structured system with the required one. At the same time, the disadvantages of the proposed approaches include the problem of local optimum, the lack of consideration of system computing resources, as well as the inability to conduct a search in several directions.

The work [19] reviews evolutionary bio-inspired algorithms (Particle Swarm Optimization – PSO). These algorithms have proved effective in solving a number of rather complex problems and have already undergone a number of modifications. At the same time, these procedures are not without some drawbacks that worsen the properties of the global extremum search process.

The canonical antlion algorithm is proposed in [20] for the problem of classifying infinite impulse response filters. Its operating principle depends on cooperation between ants and antlions, which use a traditional selection scheme called the roulette wheel selection scheme to test antlions for ant capturing. During optimization processes, the performance of a regular antlion is compared to the best antlion at each round of the process, guaranteeing an excellent solution. The simulation performance is evaluated by the root mean square error between the identified and actual model achievements, the root mean square deviation between the identified and actual different infinite values of the impulse filter, and the convergence rate. The proposed algorithm gives the smallest standard deviations, showing the best solutions. In addition, in the study of the *t*-test, large positive values of *t* again showed the significance of the advantage of the proposed algorithm over the comparative ones for the infinite impulse response in filter simulation.

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

– the lack of possibility of hierarchical processing of heterogeneous data;

– the lack of possibility of additional involvement of necessary system computing resources;

– the lack of consideration of the type of uncertainty and noise of data about the information circulating in the system;

– the lack of deep learning mechanisms for knowledge bases;

– the lack of priority of the search in a certain direction.

3. The aim and objectives of the study

The aim of the study is to develop a methodical approach to assessing the state of hierarchical systems using a metaheuristic algorithm. This will allow increasing the efficiency of assessing the state of hierarchical systems with a given reliability and developing 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:

– to determine procedures for implementing the methodical approach to assessing the state of hierarchical systems;

– to give an example of evaluating hierarchical systems when analyzing the operational situation of a group of troops (forces) using the proposed methodical approach.

4. Materials and methods

The object of the study is hierarchical systems. The subject of the study is the process of assessing the state of hierarchical systems using the advanced antlion algorithm (ALA), an advanced genetic algorithm and evolving artificial neural networks. The problem solved in the study is to increase the efficiency of assessing the state of hierarchical systems, regardless of the system hierarchy level.

The hypothesis of the study is the possibility of increasing the efficiency of assessing the state of hierarchical systems while ensuring the given assessment reliability at the level of 0.9.

Simulation of the proposed methodical approach was carried out in the MathCad 14 software environment (USA). The problem solved during the assessment was to assess the elements of the operational situation of a group of troops (forces). The hardware of the research process is AMD Ryzen 5.

The object of assessment was an operational group of troops (forces). The operational group of troops (forces) formed on the basis of an operational command with a standard composition of forces and means according to the wartime staff, and with a range of responsibilities under current regulations.

Initial data for determining the composition of the operational group of troops (forces) and elements of its operational structure using the methodical approach:

– number of information sources about the state of the hierarchical system – 3 (radio monitoring means, remote earth sensing tools and unmanned aerial vehicles). To simplify the modeling, the same number of each tool was taken – 4 tools each;

– number of informational features for determining the state of the hierarchical system – 12. These parameters include: affiliation, type of organizational and staff formation, priority, minimum width along the front, maximum width along the front. The number of personnel, the minimum depth along the flank, the maximum depth along the flank, the number of weapons and military equipment (WME) samples, the number of types of WME samples and the number of communication means, the type of operational structure are also taken into account;

– options for organizational and staff formations – company, battalion, brigade.

Parameters of the methodical approach:

– number of iterations – 100;

– number of individuals in the flock – 25;

– range of the feature space – [–100, 100].

The study uses ALA to assess the state of hierarchical systems, and to select ALA – an advanced genetic algorithm. For ALA training, an advanced algorithm for training evolving artificial neural networks is used. The antlion optimizer was chosen due to the possibility of using different search strategies depending on the available computing resources of the system. Evolving artificial neural networks allow learning not only the parameters but also the architecture of the system.

5. Development of a methodical approach to assessing the state of hierarchical systems using a metaheuristic algorithm

5. 1. Procedures for implementing the methodical approach to assessing the state of hierarchical systems using a metaheuristic algorithm

The antlion algorithm (ALA) is based on simulating the way antlions dig anthills to hunt ants in the natural environment. The procedures underlying the proposed methodical approach include the following sequence of steps:

Step 1. Entering initial data. At this stage, the main parameters of the algorithm are defined, such as:

– type of problem being solved;

– number of agents in the population;

– number of variables characterizing the problem being solved;

– available computing resources of the system;

– complexity of the hierarchical system to be evaluated;

– parameters of the advanced genetic algorithm (selection parameters, mutations), number of individuals;

– type of uncertainty about the hierarchical system (complete uncertainty, partial uncertainty, complete awareness);

– volume and type of the training sample;

– volume and type of the test sample;

– architecture of an artificial neural network, etc.

Step 2. Creating the ALA flock. The ALA population X_i (i= =1, 2, ..., n) is initiated. ALA create a population defined by the matrix X. The initial ALA population in the algorithm is created taking into account uncertainty. ALA are search agents in the solution space. This provides candidate values for problem variables based on their positions in the search space described by a vector.

The arrangement of ALA is carried out taking into account uncertainty [2, 19] (1):

$$X=\begin{bmatrix} X_1 \\ . \\ . \\ . \\ X_i \\ . \\ . \\ . \\ X_N \end{bmatrix}_{N\times m} = \begin{bmatrix} x_{1,1}\times\iota_{1,1} & \cdots & x_{1,d}\times\iota_{1,d} & \cdots & x_{1,m}\times\iota_{1,m} \\ \vdots & & \vdots & & \vdots \\ x_{i,1}\times\iota_{i,1} & \cdots & x_{i,d}\times\iota_{i,d} & \cdots & x_{i,m}\times\iota_{i,m} \\ \vdots & & \vdots & & \vdots \\ x_{N,1}\times\iota_{N,1} & \cdots & x_{N,d}\times\iota_{N,d} & \cdots & x_{N,m}\times\iota_{N,m} \end{bmatrix}_{N\times m}, \quad (1)$$

where X is the ALA population matrix, X_i is the i-th member of the ALA flock (solution candidate), $x_{i,d}$ is the d-th dimension in the search space (solution variable), N is the number of ALA, m is the number of solution variables describing the state a complex hierarchical system.

Step 3. Assigning numbers to each ALA in the flock, i, $i\in[0, S]$. This step allows determining a set of parameters for finding a solution for each ALA.

Step 4. Determining the initial velocity of ALA.

The initial velocity v_0 of each ALA is determined by the following expression:

$$v_i=\left(v_1,v_2...v_S\right), v_i=v_0. \quad (2)$$

The process of updating the ALA population is based on simulating two strategies: the exploration phase and the exploitation phase.

Step 5. Selecting the best ALA.

The fitness of each ALA is determined in each iteration using the advanced genetic algorithm proposed in [12].

Step 6. Preliminary assessment of the ALA search area. In this procedure, the natural language search area is determined precisely by the halo of ALA existence, where ants live.

Step 7. Classification of ant nests.

The location of the best anthill (the smallest anthill with the smallest number of ants) is (FS_{ht}), which is nearby and requires the least energy to find and retrieve. The largest anthill, with the largest number of ants, is denoted as FS_{at}.

Other single ants are denoted as FS_{nt}:

$$FS_{ht}=FS(\text{sorte\_index}(0.8)), \quad (3)$$

$$FS_{at}(1{:}3)=\text{FS}(\text{sorte\_index}(1{:}3)), \quad (4)$$

$$FS_{nt}(1{:}\ NP-4)=\text{FS}(\text{sorte\_index}(4{:}\ NP)). \quad (5)$$

Step 8. Determining the amount of available system computing resources.

The amount of computing resources available for calculations is determined [20].

Step 9. Exploration (prey encirclement).

The positions of ALA are directly dependent on the position of their prey. The position of each ant in each dimension is updated by a random walk. This random walk is described by the following mathematical expression:

$$x(t)=\begin{bmatrix} 0,\ cumsum\left(2t\left(t_1\right)\right)-1, cumsum\left(2t\left(t_2\right)\right)-1, \\ ..., cumsum\left(2t\left(t_T\right)\right)-1 \end{bmatrix}, \quad (6)$$

where T is the maximum number of iterations, t_i is the t-th iteration, *cumsum* is the cumulative summation, and $r(t)$ is a random function calculated as follows:

$$r(t)=\begin{cases} 1 & rand \geq 0.5, \\ 0 & rand < 0.5, \end{cases} \quad (7)$$

where t is the iteration index and *rand* is a randomly generated number in [0, 1].

The total population of ants on the search plane hunted by ALA is described by the matrix:

$$M_{ant}=\begin{bmatrix} \overrightarrow{Ant_1} \\ \overrightarrow{Ant_2} \\ \cdot \\ \cdot \\ \overrightarrow{Ant_n} \end{bmatrix}, \quad (8)$$

where n is the number of ants in the population.

The value of anthills in this study is identified as the value of the decision made in relation to the optimization problem, stored in the following vector:

$$M_{oa}=\begin{bmatrix} f\left(\overrightarrow{Ant_1}\right) \\ f\left(\overrightarrow{Ant_2}\right) \\ \cdot \\ \cdot \\ \cdot \\ f\left(\overrightarrow{Ant_n}\right) \end{bmatrix}, \quad (9)$$

Each antlion is represented by a position vector and a target vector as follows:

$$\overrightarrow{Antlion_i}=\left[A_{i,1}, A_{i,1}, ..., A_{i,d}\right], \quad (10)$$

where $Antlion_i$ is the i-th antlion, $A_{i,d}$ is the position of the i-th ant in the d-th dimension:

$$M_{Antlion}=\begin{bmatrix} \overrightarrow{Antlion_1} \\ \overrightarrow{Antlion_2} \\ \cdot \\ \cdot \\ \overrightarrow{Antlion_n} \end{bmatrix}, \quad (11)$$

$$M_{oal}=\begin{bmatrix} f\left(\overrightarrow{Antlion_1}\right) \\ f\left(\overrightarrow{Antlion_2}\right) \\ \cdot \\ \cdot \\ \cdot \\ f\left(\overrightarrow{Antlion_n}\right) \end{bmatrix}, \quad (12)$$

where n is the number of ants in the population.

Step 10. Checking the formation of the global optimum. The algorithm is checked for reaching the global optimum by a certain criterion for assessing the state of complex hierarchical systems [12].

Step 11. Global restart procedure.

This step improves the ability of the algorithm to go beyond the current optimum [19].

Step 12. Hunting phase (exploitation).

To determine the anthill priority, the anthill with the highest ant pheromone value (with more ants) is chosen for the ALA attack:

$$P_{ij}^k=\begin{cases} \dfrac{\left(\tau_{ij}\right)^{\alpha}\left(\eta_{ij}\right)^{\beta}}{\sum_{h\notin tabu_k}\left(\tau_{ih}\right)^{\alpha}\left(\eta_{ih}\right)^{\beta}}, & j\notin tabu_k, \\ 0, & \text{otherwise}, \end{cases} \quad (13)$$

where τ_{ij} and η_{ij} are the intensity of pheromone evaporation, the duration of the route between anthills i and j, respectively. The relative value of τ_{ij} and η_{ij} is determined by parameters α and β, respectively.

Step 13. Checking the stop criterion. Checking the maximum number of iterations, if the maximum number of iterations is not reached, the behavior of generating new locations and checking conditions is repeated.

Step 14. Training ALA knowledge bases.

To train the knowledge bases of each ALA, the training method based on evolving artificial neural networks developed in [2] is used.

The end of the algorithm.

5. 2. Example of applying the methodical approach to assessing the state of hierarchical systems using a metaheuristic algorithm

The efficiency of the methodical approach is compared with the swarm optimization algorithms, using a set of CEC2019 test functions listed in Table 1. The efficiency assessment criterion is the speed of decision-making (ms) with a given assessment reliability (0.9).

Table 1

Comparison of the proposed methodical approach with other swarm algorithms for a defined set of test functions

Type of CEC2019 test functions	Value	Particle swarm optimization algorithm	Ant colony optimization algorithm	Black widow optimization algorithm	Grey wolf optimization algorithm	Bee colony algorithm	Canonical antlion algorithm	Proposed methodical approach
F1	Better	6.2501	4.4884	4.103	4.4136	6.2606	5.0994	2.7698
	Average	8.1507	6.2966	5.309	5.1521	6.2606	8.1594	2.7698
	Standard	7.33	6.01	6.2	6.4	7.838	7.7192	3.3712
F2	Better	545.9192	5.6911	4.8556	4.2197	4.0557	4.2739	3.2141
	Average	2689.105	6.91	4.9935	55.3157	4.8087	4.9449	4.6568
	Standard	1741.300	0.94	0.02708	106.434	0.33374	0.17328	0.64381
F3	Better	2.3979	2.4361	1.9805	1.1634	1.4104	2.9411	1.4173
	Average	7.2501	4.4884	4.103	4.4136	6.2606	5.0994	2.7698
	Standard	1.9616	1.2868	0.766	2.2871	2.6603	1.0752	0.62451
F4	Better	9.2209	10.0576	38.8009	12.248	4.1414	29.1901	3.9849
	Average	27.9446	25.5342	57.3153	24.843	28.4397	44.8217	16.6629
	Standard	11.0734	8.7901	6.9365	10.7428	15.7463	8.8591	11.1345
F5	Better	1.5511	1.4833	29.405	1.1339	1.0497	2.1918	1.0074
	Average	11.428	1.7597	72.0211	9.5542	1.115	3.7237	1.0641
	Standard	13.5064	0.18663	19.4782	9.0179	0.061305	1.1233	0.050987
F6	Better	1.9552	3.1214	8.5015	1.7038	1.3443	6.2846	1.0041
	Average	6.7367	5.9982	10.5902	5.2258	3.9784	9.1707	3.0444
	Standard	2.4593	1.2484	0.77804	1.7237	1.5453	1.3384	1.268
F7	Better	308.3668	249.343	1208.30	309.912	83.4932	399.241	126.6386
	Average	1102.474	832.301	1623.67	810.994	894.644	1206.1076	508.5085
	Standard	355.712	265.703	130.086	376.011	339.8851	290.3894	230.6677
F8	Better	805.925	811.990	837.627	809.783	804.9748	816.6299	802.0457
	Average	825.7583	824.501	848.282	824.769	825.9996	832.6092	815.3867
	Standard	10.1005	7.4753	6.0262	9.2526	8.9454	8.4370	9.9757
F9	Better	1.1616	1.1532	1.5475	1.2025	1.1683	1.3514	1.0359
	Average	1.3579	1.4924	1.9341	1.3228	1.3786	1.6591	1.1378
	Standard	0.0999	0.1697	0.1336	0.0928	0.1442	0.1545	0.0522
F10	Better	1436.99	1274.08	1641.75	1325.81	1204.19	1818.69	1139.99
	Average	1937.94	1861.89	2362.49	1828.64	1819.19	2217.23	1505.39
	Standard	349.35	275.94	194.21	344.89	267.68	216.92	229.69

As can be seen from Table 1, a 22–25 % increase in the efficiency of assessing the state of hierarchical systems is achieved by using additional procedures.

It can be seen that the methodical approach is able to converge to the true value for most unimodal functions with the fastest convergence speed and the highest accuracy, while the convergence results of the ant colony optimization algorithm are far from satisfactory.

6. Discussion of the results of developing a methodical approach to assessing the state of hierarchical systems using a metaheuristic algorithm

The advantages of the proposed methodical approach are due to the following:

– the initial setting of ALA is carried out taking into account the type of uncertainty (Step 2) using appropriate correction factors for the degree of awareness of anthill location, compared to [9, 14, 20];

– the initial velocity of each ALA is taken into account (Step 4), which allows determining the priority of search by each ALA in the specified search direction, compared to [9–15];

– the fitness of ALA hunting locations is determined, which reduces the time for assessing the state of the hierarchical system (Step 6), compared to [14, 16, 17];

– the degree of data noise in the process of updating the ALA position (Steps 9–12) is taken into account, which reduces the time for assessing the state of hierarchical systems, compared to [9–15];

– use of the procedure of global restart of the algorithm, which allows the algorithm to go beyond the current optimum and improve the exploration ability of the algorithm (Step 11), which reduces the time for assessing the state of hierarchical systems, compared to [9–15];

– universality of solving the problem of assessing the state of hierarchical ALA systems due to the hierarchical nature of their description (Steps 1–14, Table 1), compared to [9, 12–18];

– the possibility of simultaneous search for a solution in different directions (Steps 1–14, Table 1);

– adequacy of the results obtained (Steps 1–14), compared to [9–20];

– the possibility of clarifying the choice of an anthill at the hunting stage (Step 12) due to ranking anthills by the level of ant pheromone, compared to [9, 12–18];

– improved ability to select the best ALA in comparison with random selection using an advanced genetic algorithm (Step 5), compared to [9–15]. This improves the reliability of assessing the state of hierarchical systems;

– the ability to avoid the local extremum problem (Steps 1–14);

– the possibility of deep learning of ALA knowledge bases (Step 14), compared to [9–20].

The disadvantages of the proposed methodical approach include:

– loss of informativeness when processing heterogeneous data due to constructing the membership function;

– lower accuracy of processing homogeneous data due to gradient search;

– loss of credibility of the obtained solutions when searching for a solution in several directions simultaneously;

– lower assessment accuracy compared to other assessment approaches.

The specified methodical approach will allow you:

– to assess the state of complex hierarchical systems;

– to determine effective measures for increasing the efficiency of assessing the state of complex hierarchical systems while maintaining the given reliability;

– to reduce the use of computing resources of decision support systems.

The limitations of the study are the need for an initial database on the state of hierarchical systems, the need to take into account the delay time for collecting and communicating information from intelligence sources.

The proposed methodical approach should be used to solve the problems of assessing the state of complex hierarchical systems under uncertainty and risks characterized by a high degree of complexity.

This study is a further development of research aimed at developing methodological principles for increasing the efficiency of processing heterogeneous data published earlier [2, 4–6, 12, 20].

Areas of further research should be aimed at reducing computing costs while processing heterogeneous data in special-purpose systems.

7. Conclusions

1. Procedures for implementing a methodical approach to assessing the state of complex hierarchical systems were determined, due to additional and advanced procedures, which allows you:

– to take into account the type of uncertainty and noise;

– to implement adaptive strategies for searching for ALA hunting sources;

– to determine the hunting strategy taking into account the available computing resources of the system and assessment priority;

– to take into account the available computing resources of the decision support system;

– to change the area of search by individual ALA;

– to change the velocity of ALA movement in the specified search direction;

– to carry out the initial setting of ALA taking into account the type of uncertainty;

– to conduct a local and global search taking into account the degree of uncertainty and noise of data;

– to conduct training of knowledge bases, which is carried out by training the synaptic weights of the artificial neural network, the type and parameters of the membership function, as well as the architecture of individual elements and the architecture of the artificial neural network as a whole;

– to perform classification of ant nests according to assessment priority;

– to adjust the ALA attack route by ranking ant nests according to the level of ant pheromones;

– to avoid the problem of local extremum.

2. An example of applying the proposed methodical approach when solving the problem of determining the composition of an operational group of troops (forces) and elements of its operational structure is provided. This example showed a 22–25 % increase in the efficiency of assessing the state of hierarchical systems by using additional advanced procedures.

Conflict of interest

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

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Data availability

The manuscript has associated data in the data repository.

Use of artificial intelligence

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

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