Development of a procedure for expert estimation of capabilities in defense planning under multicriterial conditions

Article *in* Eastern-European Journal of Enterprise Technologies · August 2020

DOI: 10.15587/1729-4061.2020.208603

4 authors, including:

Oleksandr Nesterenko
International European University

Igor Netesin
Ukrainian Scientific Centre for Development Of Information Technologies

Valery Polischuk
Ukrainian Scientific Centre for Development of Information Technology

UDC 004.5:004.6:004.89:007.51
DOI: 10.15587/1729-4061.2020.208603

DEVELOPMENT OF A PROCEDURE FOR EXPERT ESTIMATION OF CAPABILITIES IN DEFENSE PLANNING UNDER MULTICRITERIAL CONDITIONS

Improving the decision-making efficiency in defense planning based on the capabilities of military forces and means for performing purposeful tasks requires new methodological approaches and their implementation in the form of software information-analytical tools. Given the complex information environment of defense planning, it is appropriate for the variants of capabilities development options to be chosen by experts on the methodological basis of multicriterial analysis.

The research result is the development of a procedure, in which it is proposed to generate criteria and evaluate alternative options by integrating ontology, the Analytical Hierarchy Process, and the method of directed graphs. The ontological representation of the data ensures the construction of the hierarchical taxonomy of a domain and the formation of the criteria vector. The Analytical Hierarchy Process is used to conduct an expert evaluation of capabilities by their pairwise comparison against determined criteria. Experts' judgments are visualized and controlled using directed graphs. Application of the procedure will make it possible to ensure efficiency, versatility, and simplicity of technical implementation of a procedure of decision making support. The procedure was tested on the example of choosing a capability to conduct reconnaissance for the benefit of ground artillery. It was shown that the evaluation process in the expert activity is considerably simplified due to the graph visualization.

The proposed procedure introduces an innovative tool to achieve strategic goals and accomplish the basic tasks of the defense reform, which is relevant for many countries. The versatility of the procedure creates the basis for its application not only in defense but also in other force departments

Keywords: information technologies, multicriterial analysis, ontology, analytical hierarchy process, directed graphs, capabilities, defense planning

O. Nesterenko
PhD, Associate Professor
Department of Integrated Research*
E-mail: a_nest@i.ua
I. Netesin
PhD**
**Department of Analytical Research
Ukrainian Scientific Center for
Development of Information Technologies
Akademika Hlushkova ave., 44, Kyiv, Ukraine, 03680
E-mail: in@rit.org.ua
V. Polischuk
PhD**
E-mail: v.p@rit.org.ua
O. Trofymchuk
Doctor of Technical Sciences, Professor, Corresponding Member of the National Academy of Sciences of Ukraine
Department of Natural Resources*
E-mail: info@itgip.org
*Institute of Telecommunications and Global Information Space of the National Academy of Sciences of Ukraine
Chokolovsky Blvd., 13, Kyiv, Ukraine, 03186

Received date 20.05.2020
Accepted date 14.07.2020
Published date 28.08.2020

1. Introduction

In the current context, the problem of planning the development of capabilities of defense forces in counteracting the threats based on the experience of the NATO countries [1, 2] is becoming increasingly relevant. Participating countries take measures to integrate into the *Defense Planning Process (DPP)*, which implies the transition to the model of *Capability-Based Defense Planning (CBDP)*. This concept was called "the gold defense planning standard" [3] and is implemented by the *Joint Capabilities Integration and Development System* (JCIDS) [4].

The CBDP involves the formation of complex operative capabilities of armed forces to guarantee their performance of the set tasks under the determined economic conditions. The ultimate goal of the realization of this strategic perspective is to implement flexible, adaptive planning [5].

The concept of "a capability" is used to define various processes and objects – goals and tasks of defense planning;

forces and means that can accomplish the tasks set, the bodies and officials involved in the development of concepts. In military doctrines, the term "defense force capabilities" is interpreted as the ability to achieve the required result in the accomplishment of defense tasks under certain conditions under certain action scenarios and using available resources. In some of the state guidance documents, the concept of capability is clarified as the ability of a structural unit of the armed forces (defense forces) or their totality to perform certain tasks under certain conditions of the situation, resource provision meeting the established standards.

It should be mentioned, however, that quite often the capabilities are called capabilities carriers. For example, the "Mechanized battalion for the Infantry Armored Vehicle (IAV)" is called a capability, though, in fact, this battalion is a carrier of capabilities. Such capability can be characterized, for example, as the "capability to prepare and implement an attack in a strip of up to 2 km at the pace up to 25–30 km per day".

Capabilities carriers are military organizational structures, governing bodies, and separate means and systems, which are generally hierarchical systems. Each structural unit of defense forces can have more than one capability and each capability can be implemented by more than one structural unit. Moreover, a certain capability can be acquired by its carrier as a system by many rather than one combination of constituent elements. Capabilities carriers have properties that are characterized by both quantitative and qualitative indicators.

It is clear that such dual use of the term "capability" is related to the need to obtain the results of the CBDP in the material-technical and monetary equivalents. That is why we will subsequently use the general term "capability", taking into consideration the above dualism.

Based on the foregoing, it should be noted that the CBDP is implemented in a complex information-saturated environment. It is necessary to ensure rational decision making in it, regarding the development of military capabilities of armed forces and capabilities to accomplish certain tasks. Obviously, to do it, it is necessary to determine appropriate methodological approaches and implement them in the form of computer information and analytical tools.

At the same time, one should note that not only specialists in defense planning, but also officials of military formations are involved in expert groups. For them, expert activity is included in direct duties. There are usually tight deadlines for decision-making on choosing alternative options of capabilities.

2. Literature review and problem statement

It is recommended by the NATO directive documents to choose the option of capability development (implementation) with the involvement of experts. It is considered appropriate to use the methods of multi-dimensional criteria analysis with determining the priority (weight) and corresponding of a capability to a task as a methodological basis.

The Delphi method is proposed as one of these methods. However, this method has a series of shortcomings, narrowing the scope of its application. Its disadvantages include: significant intellectual, organizational, and technical load on the organizers of a survey; a lot of iterations in experts' work; usually considerable time of processing survey questionnaires; the condition of experts' anonymity. These shortcomings are significant just when evaluating alternatives during defense planning.

At the same time, other proven mathematical methods can be used to solve this problem. One of these methods for ranking capabilities according to certain criteria proposed in many works is to apply the expert Analytical Hierarchy Process (AHP). This method initially was designed specifically to address planning problems under conditions of unpredictable circumstances for the US Department of Defense (DoD). Now it is actively used in other spheres of activity – AHP is suitable for a wide range of applications in economy, finances, politics, resource allocation, etc. [6].

However, the formation of any expert estimates to solve such complex multi-factor problems is impossible without data modeling and data. No matter what methods of assessment of alternatives are used to support experts' decision-making in the space of various alternatives, it is necessary to ensure collection, presentation, and analysis at different levels of a significant totality of heterogeneous data. That is why different institutions of the DoD, such, for example, as the Joint Deployment Analysis Team (JDAT), provide observations, conclusions, and planning recommendations based on the collection and analysis of quantitative data.

At the same time, new types of data sources appear, data flows are applied and there is a distributed storage space in the current environment. That is why much larger data volume, in particular, non-structured is processed in combat, technical and rear service structures. Proceeding from this, the operational environment of such systems should include not only data processing and analytical tools used in the decision-making process, but also the knowledge management tools. These tools should ensure processing certain judgments, statements and assertions that carry object representations and perceptions of a Domain array (DA). In this case, data must most accurately reflect DA structuring, because the quality of the decision made depends primarily on it. This requires a thorough specification of the DA to determine clearly criteria, alternatives, and other information. Errors at the structuring stage are known to lead to the formation of false decision-making models, which lead to obtaining incorrect results.

One of the approaches, which makes it possible to solve this problem, is an ontological representation of a DA as a detailed description of a domain by means of a conceptual scheme. Such a scheme consists of a hierarchical data structure, contains information about the properties, as well as the relation between the concepts and objects of DA [7]. Formalization of relations representation in ontology makes it possible to use them for solving a wide range of problems. The ontological approach allows integrating expert knowledge based on the general understanding of information structures, ensures the repeated application of knowledge about the DA, and provides for the means of knowledge analysis. It is important that ontology provides decision-making support due to the possibility of a program–interpreted computer representation of knowledge about a specific DA. As a result, this contributes to the intellectualization of the relevant information technologies in various spheres [8, 9].

It is not surprising that many researchers and specialists offer the tools and methods for better data and processes management, among which the use of ontology-based coherent data takes an appreciable place. Thus, many researchers simultaneously consider the AHP, which is well suited for hierarchical data structures, in particular those that were formed in terms of ontologies. However, it should be noted that interconnected integrations are not used in a series of studies and projects regarding sharing ontologies and the AHP, basically, the interconnected integration is not observed. It mainly refers to preliminary preparation of ontology-based data, and then the AHP is separately applied to obtain certain estimates. It is this approach that is applied in research [10], which represents a common ontology-based architecture using a multicriteria decision-making technique to design a personalized route planning system. Originally, a general customer-oriented ontology-based architecture is constructed. The criteria that are weighted and evaluated by the AHP are separated from the constructed models. Paper [11] proposes a complex evaluation of the quality of details by the combination of the AHP and the points of evaluation features derived from ontology. In article [12], the authors represent the method of using ontology information to search for and rank Web pages using the AHP algorithm. Article [13] proposed solving the problem of estimation, ranking, and choice of ontologies for their reusing according to user's preferences. The AHP is used to model users' preferences and to find solutions with multiple criteria.

At the same time, it is necessary to note that the AHP has some shortcomings, in particular, those regarding sensitivity to the clarity of determining the list of alternatives and limitations. It is also usually necessary to minimize the drawback, which is associated with the relations of consistency as an indicator of the quality of expert estimates. Due to this, the search for the method of multicriteria analysis, which is best suited for a problem, is expanded either by the modified AHP or by other methods. This is proposed, for example, in paper [14], which focuses on the development of a system of decision-making support regarding the software choice. An attempt to propose a way to represent the AHP ontologically was made in paper [15]. The proposed method not only specifies the concepts and their interrelations but also implements the mechanisms of assessment of priority and consistency in the AHP through appropriate reasoning rules.

In addition, as it may be seen as a result of analysis of the existing solutions, the issue of ontology and AHP application in administrative management, particularly, in the defense planning area, is considered in a limited way. Among some examples, it is possible to note the paper [16], which offers a solution to the problem of object arrangement in a military logistic system. Two stages of solving the problem of maximizing the average usefulness of buildings given to objects are based on the application of the AHP. Article [17] presents a model that relates to determining the necessary capabilities and the options for their development in accordance with possible scenarios of security threats. The model takes into consideration the significant parameters of scenarios, necessary capabilities, and cost parameters for ranking the variants of capability development with the aim of the optimum choice of a variant. An expert estimation is used to determine parameters and their values. Article [18] states that insufficient awareness of the corporate data landscape affects the ability to manage data. This, in turn, affects the overall quality of data in organizations. The article aims to offer large organizations the tools and the methods for better understanding data, processes, and organizational features by using the linked data ontology. The structure of intelligent agents for modeling possible capabilities development scenarios is proposed in paper [19]. The issues of ontologies, which, as noted, are necessary to develop to solve similar problems, are basic in this research. Article [20] deals with the problem of determining the main approaches to the application of ontologically controlled information systems in the administrative control area, in particular, for solving the problem of capability-based estimation in the defense planning process.

The main conclusion of the conducted analysis is that such approaches make it possible to find acceptable decisions only in case the state of a domain is clearly specified, its mathematical description is given in the form of the predetermined sets of concepts and their properties, and highly qualified specialists have to act as experts. This peculiarity is related to the fact that expert groups that are responsible for the execution of such work usually include officials of military structures, who find it difficult to understand assessment procedures. In addition, in practice, there is not always an opportunity for experts to use the determined (available) technical characteristics of the samples of weapons and military equipment (military means).

That is why under modern conditions, it is extremely important to provide the military units with a simple and at the same time scientifically grounded capability evaluation procedure. This procedure should allow experts to choose promptly (sometimes even in field conditions) the capabilities or other components of defense planning using a simple unified procedure. In this case, the made choice must create the conditions to accomplish the set tasks in the best possible way.

All this makes it possible to argue that it is advisable to conduct a study dedicated to further improvement of the typical expert decision-making process in complex multicriteria problems.

3. The aim and objectives of the study

The aim of this study is to create a procedure to enhance the effectiveness of the solution of a multicriterial problem of capability assessment in defense planning.

To accomplish the aim, the following tasks were set:

– to check the possibility of application of the procedure based on the integration of an ontological model, which describes the management domain, the Analytical hierarchy process, and visualization on graphs;

– to develop a description of the process of solving a multicriteria evaluation problem in the terminology of the proposed procedure;

– to propose a scheme of practical realization of the obtained solutions based on the typical tasks in the structure of a military administration body.

4. Studying the possibility of ontology integration, the analytical hierarchy process, and visualization on graphs

Any multicriterial problem can be represented by a hierarchical system. At its lower level, an object is estimated by a criteria vector, formed by the decomposition of its properties. At the upper level, an object's estimate, on the whole, is formed using the composition mechanism. In this connection, the approach to solving a multicriterial problem of choosing an alternative at decision making must meet the following requirements:

1) to apply the concept of the "vector" approach to the evaluation of alternatives. At this, it is desirable that the depth of decomposition (hierarchy) of properties (characteristics, criteria) of alternatives should result in the achievement of their quantitative values;

2) to envisage a pairwise comparison of alternatives by separate properties using both qualitative and quantitative natural or artificial characteristics with impossible violation of conditions of transitive coordination of experts' judgments. This is accomplished by their control and increasing objectivity in the formation of characteristics vectors based on the representation of a corresponding DA as a specific data model;

3) to ensure the implementation of a composition of expert estimates at different hierarchy levels by the method of nested scalar convolutions.

Among the existing methods of multicriteria analysis, the analytical hierarchy process, which can be used not only to choose alternatives but also to determine the relative importance of characteristics themselves meets these requirements most of all. To apply the AHP in problems of defense capabilities assessment, it is necessary:

1) firstly, to determine the previous enumeration of capabilities (that is, alternatives to choose from) to perform the set task;

2) then, to construct a dominant hierarchy of criteria – those properties of capabilities carriers, which significantly affect the accomplishment of this task;

3) for experts to carry out a pairwise comparison of alternatives giving the estimates of the advantages of one alternative over the other by each criterion using the special T. Saaty scale;

4) to generalize these estimates using scalar (linear) convolution, taking into consideration the significance (weight) of the criteria and, possibly, the competence (weight) of experts. This will make it possible to obtain summary estimates (rating) for each alternative and thus carry out their ranking.

To ensure the processing of this hierarchy along with attribute descriptions by computer tools, it is advisable to present it in the form of an ontological model.

The main components of the DA ontology are usually classes (concepts), relations (properties, attributes), functions, axioms, incidents (concepts-individuals), where classes determine abstract groups, collections, or sets of objects (system elements or concepts).

As one knows, in general, the domain ontology is formally represented as an ordered three $O=\langle X, R, F\rangle$, where X is a set of concepts (concepts, terms) of a domain, R is the set of relations and properties between them, F is the function of interpretation (definition) of X and/or R. Boundary cases of the sets of this expression in different combinations of values of X, R and F give different variants of ontological constructions from simple vocabulary to taxonomy and complete ontology – the formal conceptual structure of knowledge base. To solve the applied problems in the DA according to the ontology construction procedure and taking into consideration its certain functional completeness and the formality degree, the so-called thematic (domain) ontology is usually separated. These are such ontologies, in which the sets of concepts and conceptual relations are as complete as possible, and attribute descriptions – axioms, definitions, and restrictions on the subjects of a given DA are added to interpretation functions. The ontologies of the problems that are used in software development designed to solve specific problems are constructed above them.

The scheme of a formal model of thematic ontology OT is described as $OT=\langle X, R, F, A(D,L)\rangle$, where additionally:

– A is the finite set of axioms, used to write down always true statements (definitions, limitations) in the thematic terms of the DA;

– D is the set of additional definitions of concepts in the thematic terms of the DA;

– L is the set of limitations that determines the region of actions of concept structures of the determined theme area of the DA.

The basic system component of the ontological system is taxonomy. It reflects a certain hierarchy of interaction of concepts, which is assigned by means of binary relations determining the nature of the interaction between the ontology concepts. Taxonomy can be supplemented by interpretation functions – a special case of relations, in which the n-th element of the relation is uniquely determined (n–1) by the preceding elements, as well as the axioms used to record always true expressions. They can be included in the ontology, for example, to determine complex limitations to attribute values, to arguments of relations, to check the correctness of the data described in the ontology, or to ensure logical conclusions.

In this connection, the ontological capability-based system of defense planning can be primarily represented by a series of taxonomies describing the components of force planning by the characteristics of their capabilities.

The combination of these taxonomies into a single ontological system by establishing relations between their concepts forms an information space, which should provide experts with the comprehensive and clear support of their activities on the evaluation of alternatives on an objective basis.

During the formation of ontologies in the operational decision-making environment, we will determine a set of limitations L as the one, which makes it possible to distinguish from the set of concepts X the subset B that may be divided into subsets $B_k=\left\{x_{ij}^{(k)}\right\}|L,$ that can intersect, which will be called the set of alternatives characteristics (Fig. 1). All elements x_{ij} of each set B_k must have the property of a certain advantage, which makes it possible to choose the necessary tautology at the stages of solving decision support problems. That is, in such problems, the set of limitations permits the construction of a set of alternative concepts based on determining a taxonomic structure of the ontology.

Properties of ontology objects can be used as criteria, according to which experts can choose one or another alternative from the set of possible alternatives.

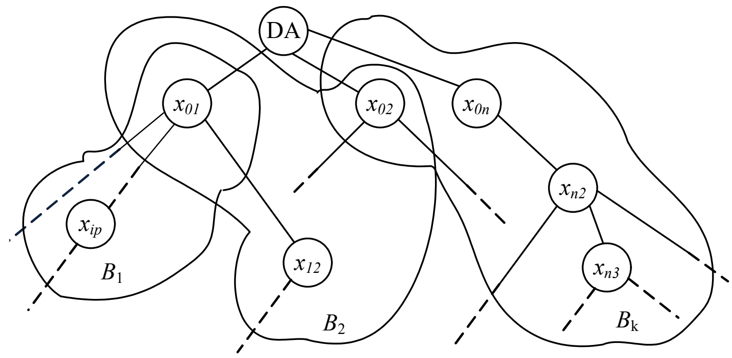

Fig. 1. General diagram of the formation of the vector of alternatives choice criteria using ontological data: DA – domain array, x_{ij} – ontology concepts, B_k – criteria vector

Attribute descriptions (properties) of criteria can be represented in an ontological database in the form of frames, whose slots contain appropriate numerical or linguistic data. This data should be used by experts to support decision making in relation to the evaluation of alternatives.

Thus, the necessary information support for solving the problem of criteria formation and choosing alternatives can be in the application by experts of the ontological model of the DA based on interpretational functions of choice. These functions are constructed with the help of hyper-relations over the concepts of a taxonomic ontology structure and their properties.

Proceeding to the AHP, it is necessary to note that in this method the hierarchical structure of the problem of choosing alternatives is a graphical representation in the form of an inverted tree. In this structure, each element, except the topmost, depends on one or more elements located above. Using information from a database constructed on the ontological model that was considered above, such a hierarchy can be formed based on sets *B*, which are formed taking into consideration the set of limitations *L*.

The main procedure of the AHP is a pairwise comparison of alternatives by experts.

A significant problem that often arises using a pairwise comparison is a possible disagreement of experts' statements while estimating alternatives. Designate $Cr \succ Cq$, if alternative *Cr* has a general advantage over alternative *Cq*, and $Cr \sim Cq$, if they are equal. Thus, there can be situations when an expert, according to a certain criterion, estimated alternatives as $(Cr \succ Cq)\&(Cq \succ Cs)$, and at the same time $Cs \succ Cr$. In the general case, coordination of relations is considered cardinal, when in the matrix above $a_{rq} * a_{qs} = a_{rs}$, and/or transitive, when if $(Cr \succ Cq)\&(Cq \succ Cs)$, it is compulsory that $Cr \succ Cs$. In the AHP, cardinal coordination (which is impossible to achieve completely, even if all actual numbers are used in the scale) is determined after the estimation. For this purpose, one determines the main (maximum) eigenvalue λ_{max} of reverse symmetrical matrix $N \times N$, where *N* is the number of alternatives and calculates so-called coordination index: $CI=(\lambda_{max}-N)/(N-1)$. If relative coordination (*RC*) as the ratio of *CI* to the average random index of a matrix of the same order exceeds 10–20 % (which is often the case), it is recommended to review an expert statement.

When applying the AHP, the number of computation tables, depending on the number of alternatives, characteristics, and experts usually proves to be rather substantial. This is especially due to the repeated computations in case of significant cardinal disagreement. Besides, the transitive agreement is not verified in the AHP. That is why to ensure visualization in the elaboration of tables and to maintain coordination, it is proposed synchronously with filling comparative tables to visualize the process of filling in the form of a directed graph. At the same time, it ensures the transitivity control.

The vertices of the specified graph will correspond to the alternatives, and the edge with the arrow – arc (*Cr*, *Cq*), which will go from vertex *Cr* to vertex *Cq*, if $Cr \succ Cq$. Since all selected alternatives are compared pairwise, at the end of the procedure of filling the table, all vertices will be joined with arcs. The resulting graph will be a complete directed graph, which in the graph theory is called a tournament. According to the algorithm, at steps 1 and 2, two comparisons are made and corresponding vertices and arcs are drawn. If estimates are equal, they have a combined name (for example, *Cr*/*Cq*). Then, after each step it is checked if there are arc (*Cr*, *Cq*) and arc (*C*q, *Cs*), arc (*Cr*, *Cs*) is added. That is, the so-called transitive closure of a graph is performed – all such triangles are closed (Fig. 2).

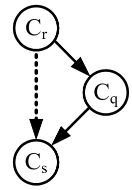

Fig. 2. Illustration of the process of the transitive closure of a graph

This operation can be performed, for example, using a simple Floyd-Warsholl algorithm, according to which a series of disjunctions is performed over the lines of the matrix of adjacency to the oriented graph.

Thus, the general scheme, which reflects the essence of the proposed integration procedure can be presented in Fig. 3.

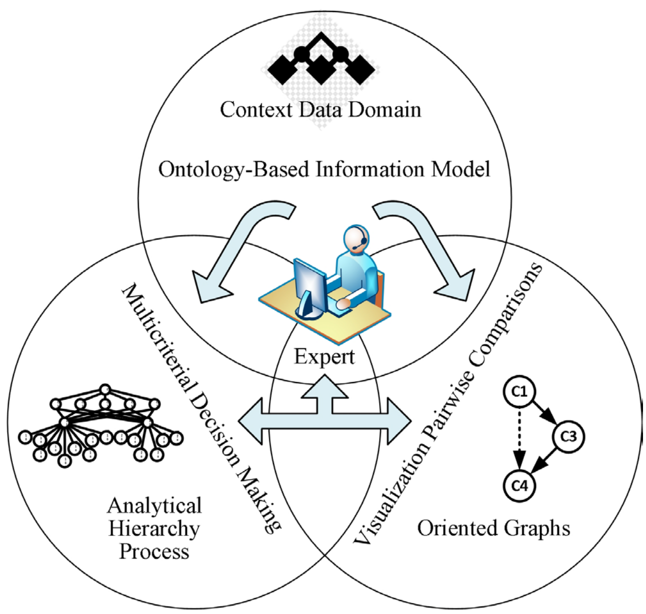

Fig. 3. The essence of an integration procedure

The contradictions in results of comparisons in the AHP are often caused by subjective views, lack of knowledge, and errors of experts, the impact exerted on experts by various factors and properties of assessed alternatives. To prevent the cases of the inconsistency of matrices, it is necessary in some way to "guide" experts in a certain direction in order to avoid extreme subjectivity. The constructed ontology of the DA, which should clearly define all the characteristics of the selection criteria, must be such a tool. The permanent appeal of experts to the ontological base is the basis for the substantiation of expert estimations. It is the ontological model that enables a group of experts to interact with each other in order to solve the problem, modify their views and, as a result, to form rationally their own considerations. At the same time, this base is a tool for conducting an audit of expert actions, if necessary.

5. Description of the process of solving multicriterial problems in the terminology of the proposed approach

To solve multicriterial problems using the expert method, the algorithm, and the corresponding software tool that supports the processes of evaluating alternatives and processing estimates by experts is proposed.

The first stage of problem-solving is preparatory, which implies the formation of the DA ontology. Usually, this stage is performed by experts in a domain, database keeping and data analysis.

The second stage involves structuring a problem as a hierarchy or a network based on the principle of identity and decomposition. A hierarchy is usually constructed from the top (targets – from the point of management), through intermediate levels (criteria and subcriteria, on which the following levels depend) to the lowest level (hierarchy leaves), which is a list of alternatives. Here, alternatives imply some domain objects that are evaluated with regard to achieving the goals, specified at the top of the hierarchy.

After the hierarchical reproduction of a problem at the third stage, a uniform set of tables is formed to fix the results of a pairwise comparison of alternatives by each criterion using ontological data. The structure of such tables is shown in Table 1.

In Table 1, $H_{n,m}(i,j)$ designates the numerical value of the i-th criterion, which corresponds to the value, chosen by the j-th expert when comparing the n-th alternative with other m alternatives, n, m=1, ..., N where N is the number of alternatives, j=1, ..., M, where M is the number of experts, who take part in the assessment. The number of experts is not limited. For pairwise comparison of all determined capabilities by one criterion, an expert must perform not more than $N(N-1)/2$ comparisons.

At the next stage, the issues of prioritizing the criteria and evaluating each of the alternatives based on criteria with the identification of most important of them are solved. Experts are offered to conduct comparisons of alternatives sequentially using the truncated scale of T. Saaty, containing not 9, but only 5 (without reverse magnitudes) options of naming an estimate in pairwise comparison (Table 2). This approach meets the requirements for simplifying the experts' activity without any essential disrupting the evaluation effectiveness.

Table 1

Structure of the table to compute pairwise comparisons

Chosen criterion	Alternatives				Geometric mean $Z_n(i,j)$	Normalized value $X_n(i,j)$
	$H_{n,1}(i,j)$	$H_{n,2}(i,j)$	...	$H_{n,5}(i,j)$		
Alternatives						
			...			
Total of estimates						1,00000
λmax						
CI						
RC						

Table 2

The truncated variant of the T. Saaty scale

Variants of the estimate name in pairwise comparison (qualitative values of a linguistic variable)	Numerical values
Much better/much more important/has an absolute advantage	9
Much better/much more important/has a significant advantage	7
Best/most important/has an advantage	5
A little better/a little more important/has an insignificant advantage	3
Equal	1

Numerical values of a_{ij} correspond to the results of qualitative (using a linguistic variable) pairwise comparisons made by experts. This results in a square table – a matrix form with the property of reverse symmetry, that is,

$$a_{ji} = 1/a_{ij},$$

where indices i and j belong to a row and a column, respectively.

Then these square inversely symmetrical matrices are "solved". The sense of such calculations is that they determine a method of quantitative determining the comparative importance of factors of an analyzed problem situation (sets of local priorities). The emphasis in the subsequent solution of the problem will be placed on the factors with the largest magnitudes of importance.

After that, $Z_n(i,j)$ – geometric mean of values $H_{n,m}(i,j)$ is computed in each row of the table and they are normalized, that is, bringing their values to the interval [0, 1] – each geometric mean is divided by the sum of all geometric mean. The geometric mean is used because it is known to give the most accurate result of averaging in determining the mean value of relative magnitudes. As a result of the elaboration of the table, we obtain $Xn(i,j)$ – the normalized values of the estimate by the j-th expert of all alternatives in comparison with the others against the i-th criterion.

The priority (weight) of criteria $P(i)$, i=1, ..., K, that differ for different problems is also determined by their pairwise comparison by experts with subsequent calculation of normalized values, the sum of which is equal to 1.

If it is considered expedient to take into consideration the competence (normalized weight) of experts $R(j)$, j=1, ..., M, it is also possible to do using a pairwise comparison of self-assessment questionnaires that experts themselves make up about their knowledge and experience.

As indicated above, an important part of the proposed procedure is helping experts to immediately maintain the transitivity of their judgments by visualization of comparisons on a directed graph. To do this, the expert's interface, in which the filling process is visualized in the form of such a graph synchronously with filling comparative tables, is implemented in the software tool. At the same time, there is transitivity control.

Successive filling the table and simultaneous construction of such a graph is carried out as follows. An expert qualitatively compares alternatives against a certain criterion and puts a quantitative estimate by the T. Saaty scale in the corresponding cell of the table. The reverse value of a quantitative estimate is automatically put into the table cell symmetrical to the main diagonal. At the same time, two vertices of the graph with the names of these alternatives are drawn.

At the same time, a cell in the table that is located at the intersection of these alternatives is colored. This indicates to an expert the need to put their "correct" comparison. Otherwise, a message that the transitivity of relations is violated will be obtained. When the vertex with a combined name of two or more vertices appears, it is automatically tracked if the corresponding rows in the table of paired comparisons have the same values.

If necessary, an expert may review some of his own previous judgments, preserving transitivity. As a result, taking into consideration the specified identification of vertices, we obtain an acyclic tournament, which is also called a transient tournament in graph theory. The evaluation option, which satisfies the conditions of transitivity, is sure to appear. This flows out of the possibility of a strictly linear arrangement of vertices in a transitive tournament in the accessibility order, since all its vertices have different input and output degrees of arcs.

Visualization on the graph helps an expert to achieve higher cardinal coordination. If the value of the RC is unsatisfactory after the comparison is completed, the arcs of the final graph will be loaded with the expert's estimates in the quantitative form. Such an opportunity approximates this program implementation to the level of an expert system. In particular, the program may offer an expert at each assessment step to make comparisons between such alternatives (graph vertices), which will result in the maximum number of transient closures.

6. Scheme of practical implementation of obtained decisions on the example of a typical problem of a military administration body

Consider the use of the proposed procedure on the example of solving the problem of capabilities rating as alternatives to conduct reconnaissance for the benefit of ground artillery. In the capabilities catalog of the armed forces, they belong to the functional group "Intelligence" – the capabilities of defense forces to collect, process, analyze, predict, and prove reconnaissance information. The ontology of the problem area of conducting reconnaissance for the benefit of ground artillery is shown in Fig. 4. To assess the capabilities by the standards, two criteria groups are proposed: compliance with a task (value) and the possibility of capabilities implementation.

In order to proceed to the evaluation using the AHP, we choose capabilities (Table 3) and evaluation criteria (Tables 4, 5) from the AD ontology.

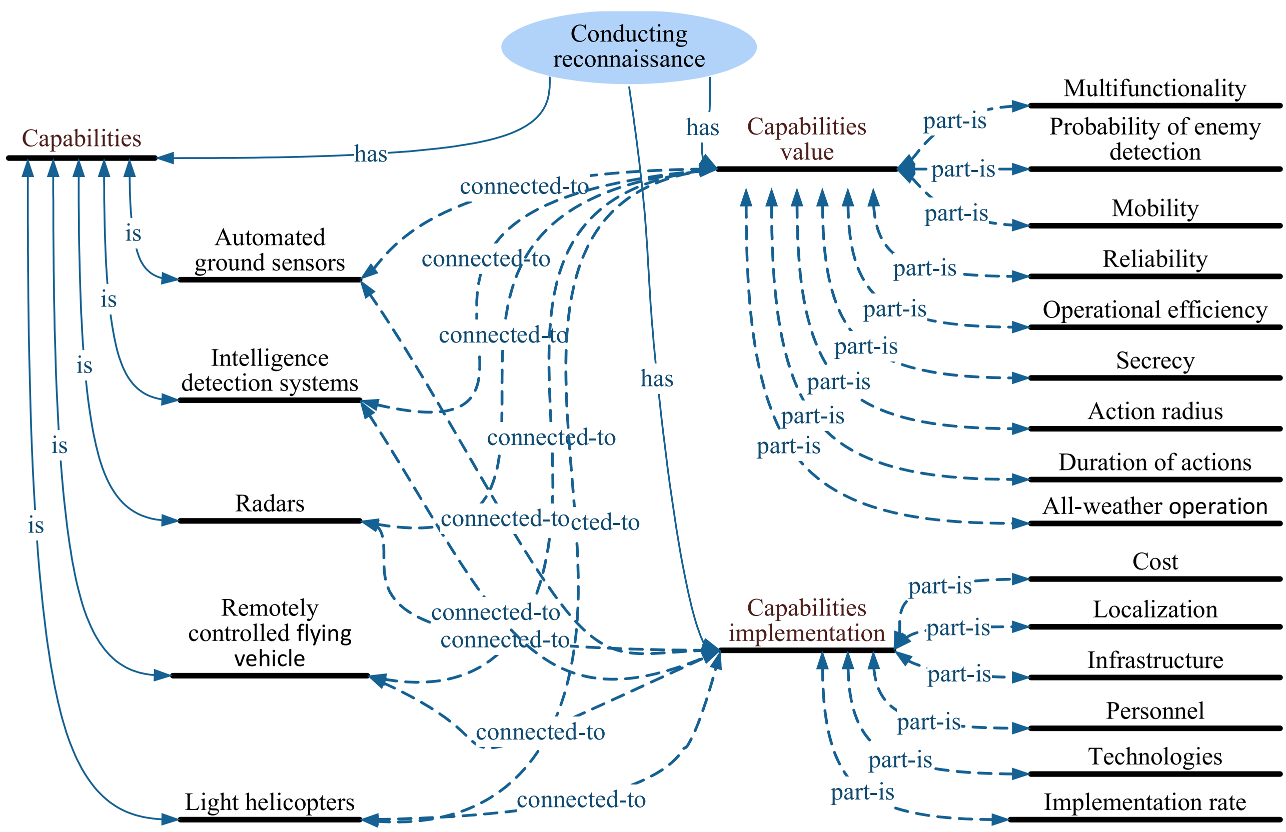

Fig. 4. Ontology of the problem area of conducting reconnaissance for the benefit of ground artillery

Table 3

Enumeration of capabilities (alternatives)

No. by order	Capability	Designation of capability
1	Automated ground sensors for surveillance, target detection and reconnaissance	*C*1
2	Close reconnaissance using improved intelligence system of target detection and recognition	*C*2
3	Radar for determining the location of fire means of reconnaissance, surveillance, target detection and technical reconnaissance	*C*3
4	Remotely controlled flying vehicle of medium height	*C*4
5	Light helicopter for general purposes	*C*5

Table 4

Enumeration of criteria of capabilities value

Criteria of capabilities value (*K*1)	
Criterion	Designation
Multifunctionality	*K*101
Probability of enemy detection	*K*102
Mobility	*K*103
Reliability	*K*104
Operational efficiency	*K*105
Secrecy	*K*106
Action radius	*K*107
Duration of actions	*K*108
All-weather operation	*K*109

Table 5

List of criteria of the possibility of capabilities implementation

Criteria of implementation possibility (*K*2)	
Criterion	Designation
Cost	*K*201
Localization	*K*202
Availability of infrastructure	*K*203
Availability of trained personnel	*K*204
Availability of technologies	*K*205
Implementation rate	*K*206

We will construct a problem hierarchy based on the data of Tables 3–5 (Fig. 5). This hierarchy has two bushes of criteria, each of which has its own branches. We will consider criteria *K*1, *K*2 the level 1 criteria, and all the other – level 2 criteria.

Each capability should have attribute descriptions that characterize it in terms of each of these criteria (for example, for *C*5 criterion *K*107 is characterized by the value of 500 km). The availability of such descriptions for experts is ensured by the attributes of the ontological model of the AD.

First of all, using the ontological data for each taxonomy bush, a unified set of tables for fixing the results of pairwise comparison of capabilities against each criterion is formed. Then the experts are offered to conduct sequentially comparisons of capabilities using the truncated scale of T. Saaty.

A comparison of capabilities is made by selecting the qualitative values of a linguistic variable from the list, and corresponding quantitative values and their inverse magnitudes are automatically put into the table cells. Based on this information, all the others up to N^2 table cells (or elements a_{rq} of matrix $N\times N$) are also filled automatically, because according to the scale structure, this matrix is reverse-symmetric. That is, equalities $a_{rq}=1/a_{qr}$. are satisfied for all the elements of this matrix. If desired, an expert himself can also enter other numerical values from the interval [1–9] to the table cells.

The generalized form of this table with an example of results of pairwise comparison *C*1–*C*5 against one of the criteria is given in Table 6.

At the lower level of a hierarchy, each expert fills 15 tables of this kind – 9 for the first and 6 for the second bush.

Table 6

Example of a table for calculating the pairwise comparison of capabilities with filling against criterion *K*105 (operative efficiency)

Criterion *K*105	*C*1 $H_{n,1}(i,j)$	*C*2 $H_{n,2}(i,j)$	*C*3 $H_{n,3}(i,j)$	*C*4 $H_{n,4}(i,j)$	*C*5 $H_{n,5}(i,j)$	Geometric mean $Z_n(i,j)$	Normalized value $X_n(i,j)$
*C*1	1	9	3	7	9	4.42732	0.54189
*C*2	1/9	1	1/7	1/3	1	0.35052	0.0429
*C*3	1/3	7	1	5	5	2.25519	0.27603
*C*4	1/7	3	1/5	1	3	0.76214	0.09328
*C*5	1/9	1	1/5	1/3	1	0.37492	0.04589
Total of estimates						8.17009	1.00000
λmax	5.19862						
CI	0.04966						
RC	4.43 %						

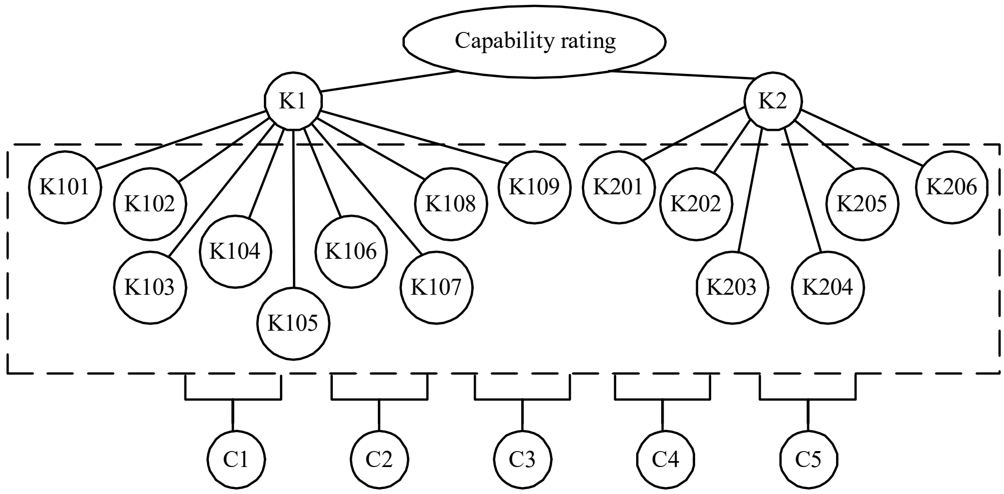

Fig. 5. The hierarchy of criteria for determining the capability rating

Next, $Z_n(i, j)$ is computed for each row of Table 6 and their normalization is carried out. As a result of processing the table, we obtain normalized values of estimates by the j-th expert of all Cn in comparison with other capabilities against the i-th criterion.

Using a scalar convolution that takes into consideration the weight coefficients of the criteria and, if necessary, the weight coefficients of experts, we obtain estimates $X_{n(1)}$, generalized by all criteria of bush 1, for each Cn:

$$X_{n(1)} = \sum_{i=1}^{|K1|}\left(\sum_{j=1}^{M} X(i,j)R(j)\right)P(i), \tag{1}$$

where $|K1|$ is the number of criteria in bush 1. $X_{n(2)}$ is calculated similarly for bush 2. After this, the composition of the criteria is carried out by the convolution of estimates for each bush, taking into account weight coefficients of the first level criteria.

$$X_n = X_{n(1)}P_{n(1)} + X_{n(2)}P_{n(2)}, \tag{2}$$

where $P_{n(1)}$ and $P_{n(2)}$ are, respectively, the weight of first-level criteria (correspondence to the task and implementation possibility). This will result in obtaining the enumeration of estimates X_n, based on which the decision on choosing capability Cn, which is the most suitable to accomplish the task, is made. In case a hierarchy of criteria has a multi-level structure, the estimates of various levels are generalized bottom-up by the nested convolution method.

An example of the steps of expert's comparisons, leading to the final transitive tournament, which corresponds to Table 6 is shown in (3) and in Fig. 6.

$$1.C2 \sim C5$$
$$\left\{\begin{matrix}\left.\begin{matrix}2.C1 \succ C3\\3.C3 \succ C4\end{matrix}\right\} \Rightarrow C1 \succ C4\\4.C4 \succ C2\end{matrix}\right\} \Rightarrow \begin{pmatrix}C1 \succ C2\\C3 \succ C2\end{pmatrix}. \tag{3}$$

From this example, it is evident that the software tool automatically detects three transitive closures, prompts it to an expert, and thus simplifies his activity. If an expert chooses this path, the number of steps of comparison selection may be much smaller than the above-mentioned $N(N-1)/2$ (there are only 4 steps in this example).

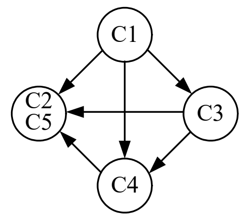

Fig. 6. Transitive tournament for example 6

The corresponding fragment of the interface of program implementation of the algorithm is shown in Fig. 7.

As noted above, visualization on the graph helps an expert to achieve more cardinal coordination. For example, a subgraph for three capabilities after a transitive closure will look as shown in Fig. 8, *a*. Then, in order to improve cardinal coordination, the program will offer an expert to adjust his opinion, for example, as shown in Fig. 8, *b*.

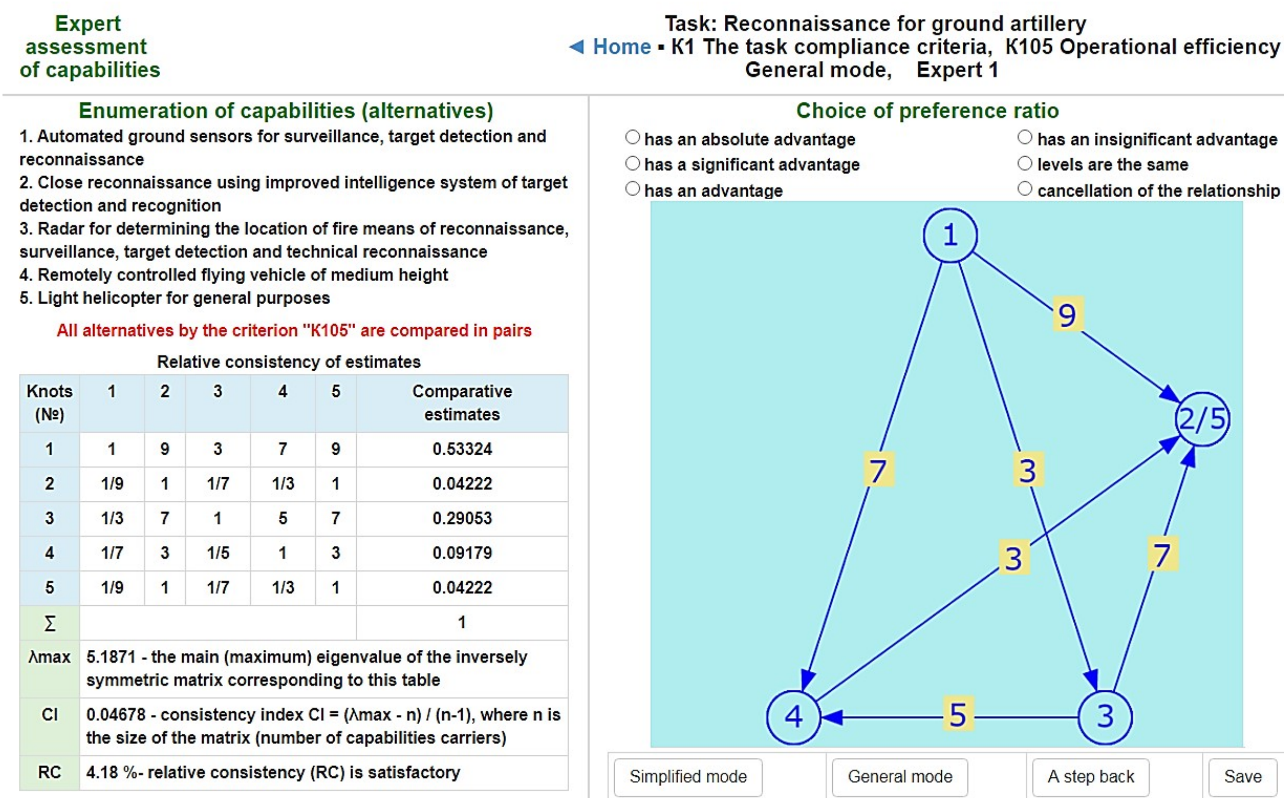

Fig. 7. A fragment of the interface of the program implementation of the algorithm in the procedure

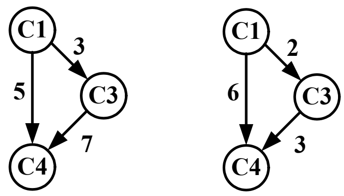

Fig. 8. Illustration of achievement of higher cardinal coordination: *a* – sub-graph for three capabilities after transitive closure; *b* – program tip of adjustment to improve cardinal coordination

Thus, these properties ensure operative efficiency, versatility, and simplicity of technical implementation of the procedure of decision-making support. The friendly software interface reduces subjectivism and generally creates conditions for keeping to the impartiality and justice principles.

7. Discussion of results of studying the application of the integration procedure in the operational environment of expert activity

Based on the foregoing, it can be noted that the obtained results of using the proposed procedure are explained by the integration of the AHP, ontological model of data, and the means of visualization of the process of alternatives comparison in a single complex. The features of the procedure and the obtained results in comparison with the existing ones include gaining such advantages. First of all, expert activity is considerably simplified at the expense of visualization of the evaluation process and maintenance of the transitive coordination of experts' judgments. It also contributes to an increase in cardinal coordination, eliminates dependence on measurement units. Besides, it becomes possible to apply the same technology of experts' activity at different stages of this process:

1) to determine the priority (weight) of criteria;
2) competence (weight) of experts;
3) own estimation of capabilities carriers.

At the same time, the proposed approach uses the psychological ability of any person to compare, especially in the presence of visual images. In this case, it involves the ability of a person not only to point out the preferred object but also to assess the preference degree. This property of the procedure ensures operative efficiency, versatility, and simplicity of technical implementation of the procedure of decision-making support. And a user-friendly interface decreases subjectivism and generally creates conditions to observe the impartiality and justice principles.

It should be noted that this research is characterized by a significant limitation. The validity and objectivity of a decision are largely determined by the correctness and adequacy of an ontological model of a domain area. That is why we are talking about the need for comprehensive data on the DA, terminology dictionaries, and technical reference books in the electronic form, from which it is possible to construct an ontological base. However, there is also a need to involve a qualified specialist in the Data Scientist, aware of the peculiarities of the DA, and capable to build ontological descriptions. Nonetheless, even in the absence of modern information means, the proposed procedure can provide essential advantages.

A significantly narrowed representation of a defense planning problem can be mentioned as a drawback of this research. That is why, in the long term, the positive effect of using the potential of this procedure in defense planning practice can be related to the expansion of the ontological model for military tasks (by the classes of strategic deployment, operations, combat actions, battles, blows), possible threat scenarios and their probable negative effects, other components of force planning. However, it is possible to face the difficulties of the organizational and experimental nature, taking into consideration the specifics of the Defense Department.

The universality of the approach creates conditions for the development of this research in the direction of its application in various fields of activity, especially in force agencies. The procedure can be used as an alternative or verifying to assess capabilities by other methods, such as the Delphi method. The proposed procedure actually represents one of the innovative tools to achieve strategic goals and accomplish the basic tasks of the defense reform, which is relevant in modern conditions.

8. Conclusions

1. The analysis of the features of the ontological model, which describes the domain area of control, and the method of hierarchy analysis, which shows the possibility of applying a combination of these methods in the problems of multicriteria choice, was carried out. This conclusion relies on the hierarchy properties inherent in both specified components. The involvement of the graph theory elements significantly strengthens the given opportunity, which generally forms an integration environment of experts' activities. This primarily enhances the visibility of the domain area representation and decreases the requirements to the experts' knowledge volume.

2. The description of the process of solving a multicriterial problem of capabilities evaluation in the terminology of integration procedure was proposed. The peculiarity of this description is a clear algorithmizing of the process of expert evaluation and the concretization of experts' actions. Consequently, the presented steps in the corresponding algorithm reduce the number of steps of the choice of pairwise comparisons of alternatives by 2–3 times when applying the hierarchy analysis method.

This possibility approximates the program implementation of the procedure to the level of an expert system. In particular, the program may offer an expert at each evaluation step to make a comparison of such alternatives (graph vertices), which will result in the maximum number of transient closures.

3. The obtained description of the process of solving a multicriterial problem using the integration procedure is implemented in the corresponding software tools. Using the example of solving the typical problem in the structures of the military administration bodies, it was shown that the toolset makes it possible to simplify significantly the technology of implementation of the procedure of decision-making support. Features of the interface decrease subjectivism and create conditions for the observance of the impartiality and justice principles. In general, this makes it possible to unify the work of experts and provide it with operative efficiency.

References

1. Ustymenko, O. V., Bilyk, V. I. (2018). Planning for the development of the capabilities of the Ukrainian defense forces to counter the threats during the hybrid war. Visnyk NADU pry Prezydentovi Ukrainy (Seriya "Derzhavne upravlinnia"), 2, 48–52. Available at: http://visnyk.academy.gov.ua/pages/dop/79/files/26ce167b-d55b-468e-bc9f-c6ec018615af.pdf
2. Rusnak, I. S.. Petrenko, A. H., Yakovenko, A. V., Romaniuk, I. M., Kokhno, V. D. (2017). Oboronne planuvannia na osnovi spromozhnostei: osoblyvosti ta perspektyvy vprovadzhennia. Nauka i oborona, 2, 3–10.
3. De Spiegeleire, S. (2011). Ten Trends in Capability Planning for Defence and Security. The RUSI Journal, 156 (5), 20–28. doi: https://doi.org/10.1080/03071847.2011.626270
4. Davis, P. K. (2002). Analytic Architecture for CapabilitiesBased Planning, Mission-System Analysis and Transformation. National Defense Research Institute, Santa Monica, USA.
5. Ivashchenko, A., Pavlikovsky, A., Sivoha, I. (2017). Conception of the defensive planning on the basis of development of possibilities: problems of introduction. Research papers collection of the Center of military and strategic studies, 1 (59), 53–58. doi: https://doi.org/10.33099/2304-2745/2017-1-59/53-58
6. Saaty, T. L. (2013). On the Measurement of Intangibles. A Principal Eigenvector Approach to Relative Measurement Derived from Paired Comparisons. Notices of the American Mathematical Society, 60 (02), 192. doi: https://doi.org/10.1090/noti944
7. Palagin, A. V., Petrenko, N. G. (2007). K voprosu sistemno-ontologicheskoy integratsii znaniy predmetnoy oblasti. Matematicheskie mashiny i sistemy, 3-4, 63–75.
8. Nesterenko, O., Trofymchuk, O. (2019). Patterns in forming the ontology-based environment of information-analytical activity in administrative management. Eastern-European Journal of Enterprise Technologies, 5 (2 (101)), 33–42. doi: https://doi.org/10.15587/1729-4061.2019.180107
9. Vlahavas, L., Bassitiades, N., Sakellariou, I., Molina, M., Ossowski, S., Futo, I. et. al. (2002). ExperNet: an intelligent multiagent system for WAN management. IEEE Intelligent Systems, 17 (1), 62–72. doi: https://doi.org/10.1109/5254.988459
10. Niaraki, A. S., Kim, K. (2009). Ontology based personalized route planning system using a multi-criteria decision making approach. Expert Systems with Applications, 36 (2), 2250–2259. doi: https://doi.org/10.1016/j.eswa.2007.12.053
11. Xu, F., Liu, X., Chen, W., Zhou, C., Cao, B. (2018). An Ontology and AHP Based Quality Evaluation Approach for Reuse Parts of End-of-Life Construction Machinery. Mathematical Problems in Engineering, 2018, 1–12. doi: https://doi.org/10.1155/2018/3481030
12. El-Dsouky, A. I., Ali, H. A., Rashed, R. S. (2018). Ranking Documents Based on the Semantic Relations Using Analytical Hierarchy Process. Information Retrieval and Management, 1841–1859. doi: https://doi.org/10.4018/978-1-5225-5191-1.ch084
13. Groza, A., Dragoste, I., Sincai, I., Jimborean, I., Moraru, V. (2014). An Ontology Selection and Ranking System Based on the Analytic Hierarchy Process. 2014 16th International Symposium on Symbolic and Numeric Algorithms for Scientific Computing. doi: https://doi.org/10.1109/synasc.2014.47
14. Wasielewska, K., Ganzha, M., Paprzycki, M., Bădică, C., Ivanovic, M., Lirkov, I. (2014). Multicriteria analysis of ontologically represented information. AIP Conference Proceedings. doi: https://doi.org/10.1063/1.4902284
15. Liao, Y. X., Rocha Loures, E., Canciglieri, O., Panetto, H. (2014). A Novel Approach for Ontological Representation of Analytic Hierarchy Process. Advanced Materials Research, 988, 675–682. doi: https://doi.org/10.4028/www.scientific.net/amr.988.675
16. Lai, C.-M. (2019). Integrating simplified swarm optimization with AHP for solving capacitated military logistic depot location problem. Applied Soft Computing, 78, 1–12. doi: https://doi.org/10.1016/j.asoc.2019.02.016
17. Kovac, M., Stojkovic, D., Mitic, V. (2013). Capability based defence development planning - optimal option selection for capability development. XI Balkan Conference on Operational Recarch (BALCOR-2013), Conference Paper, 551–558. Available at: https://www.researchgate.net/publication/287999099
18. DeStefano, R. J., Tao, L., Gai, K. (2016). Improving Data Governance in Large Organizations through Ontology and Linked Data. 2016 IEEE 3rd International Conference on Cyber Security and Cloud Computing (CSCloud). doi: https://doi.org/10.1109/cscloud.2016.47
19. Rabaey, M., Van Damme, C., Vandenborre, K., Vandijck, E. (2007). Ontology Negotiation in an Intelligent Agents Dynamic System for Military Resources and Capabilities Planning. IRMA International Conference. Available at: https://www.researchgate.net/publication/305490801_Ontology_Negotiation_in_an_Intelligent_Agents_Dynamic_System_for_Military_Resources_and_Capabilities_Planning
20. Nesterenko, O. V. (2019). Ontologically-driven information systems in the administrative management. Mathematical modeling in economy, 15 (2), 57–68. Available at: https://www.mmejournal.in.ua/index.php/mmejournal/article/view/66/66