Graph-based decision making for varying complexity multicriteria problems

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Abstract

In the modern world in various spheres of activity, the number of problems that need multi-criteria decision-making (MCDM) is constantly increasing. Researchers and experts offer a number of approaches to MCDM process in such tasks; in particular, most of them are based on expert methods. However, in practice, these methods require significant intellectual effort of experts and organizational and technical workload during the expert survey, and also usually take a long time. At the same time, it is not always possible for experts to use certain characteristics of alternatives, which also carries the risk of making decisions based on unfounded expert opinions. Therefore, such methods and tools should be clear and informative and at the same time easy to use to ensure the efficiency and effectiveness of their use.

We offer a graph-based approach to expert decision-making and information visualization processes that meets these requirements and can significantly improve the efficiency of decision-making in multi-criteria selection tasks.

Keywords: information technologies, MCDM, ontologies, expert voting, analytic hierarchy process, analytic network process, graphs, visualization.

1 Introduction

Solving multi-criteria decision-making (MCDM) tasks is largely related to expert intelligence in the field of alternatives. There are many expert methods, but most of them have a number of disadvantages. For

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example, the Delphi method is often proposed, but it produces a significant intellectual, organizational and technical burden on the organizers of the survey, causes a large number of iterations in the work of experts and usually requires considerable time to process questionnaires. One of the common methods for ranking alternatives according to certain criteria is the analytic hierarchy process (AHP) mentioned in many works, but it is also not without its drawbacks. Therefore, many experts and researchers offer different approaches to modifying the processes of using common expert methods to overcome existing shortcomings and increase the effectiveness of decisions.

Keep in mind that solving any complex multifactor problems is impossible without modeling and data analysis. Whatever methods are used to evaluate alternatives, in order to support expert decision-making in today's complex information space, it is necessary to ensure the collection, presentation, and analysis at various levels of a significant body of heterogeneous data. At the same time, it is emphasized that the processing of the necessary data is now difficult to imagine without the appropriate means of visualization of information.

Based on this, a set of methods and tools integrated to achieve this goal is needed to properly support expert decision-making. In this approach, we implement a support system that provides a visually interactive interpretation of the three main stages of decision-making – problem analysis, development of alternatives, and their comparison and selection – covering tasks of varying complexity. For each type of task, our system implements visual access to the model, in-depth analysis of generated solutions, and comparison of alternative solutions. Finally, we evaluate the usefulness and ease of use of our system in the field of security.

2 Literature survey and problem statement

In many cases, MCDM support model-driven computational methods. Providing intuitive access to these methods is crucial. Widely used tools to improve understanding of problems and, ultimately, to improve decisions include graphical and information visualization tools. Many studies in the social sciences confirm this conclusion [1]. Studies show that the data visualized in graphs require less cognitive effort in interpretation, contribute to the effectiveness of communication, clarity, speed, and understanding of complex concepts. Research also examines not only how visualizations convey complex information, but also how to use visualizations in the learning process, for example, in relation to data structures and algorithms [2].

Visualization began with the development of general recommended visualization systems in data analysis processes, which usually illustrated the design of a data set, but could not recommend target results. Therefore, researchers have begun to conduct research in the direction of approaches to visualization, focused on the task of analysis, with modeling of user needs [3, 4]. In fact, these were the first attempts to use visualization capabilities to decision support.

The use of visual representations provides the analyst with an effective method of sifting through a huge amount of information and making informed decisions on critical issues. The paper [5] investigates the impact of information complexity on situational awareness, measured as the density of the graph. The authors claim that the visual signal of the line thickness is an informational value associated with improving time savings and reducing the mental load on the analyst.

However, despite the prevalence of visualization in research and practice, results from different subject areas are rarely shared, although visualizations and their use may be based on general principles. The authors of [6] proposed an integrative model to provide inter-domain support, based on models of understanding visualization and the so-called dual decision-making process. An interactive visualization tool to support multi-criteria decision-making tasks based on the mental model of the user is proposed in [7]. In an environment where the analysis of "human-loop" data is required, covering not only many attributes of alternatives, but also contextual information (domestic policy, customer requirements, cost-effectiveness), the authors' approach allows users to intuitively explore different criteria and find solutions.

Although data visualization is crucial to help in decision-making, this tool places high demands on the volume, speed, and veracity of data. There is a need for qualified database experts. This is especially important in the case of processing unstructured data from mass sources, when decision-makers must be able to observe large graphs of visualization [8]. In response to these challenges, the article [9] discusses methods that make data visualization more efficient and effective by directly engaging users who specify their requirements for creating visualizations. In the article [10], the proposed prototype in the mode of comparison of alternatives displays a graph of parallel coordinates, which demonstrates the advantages of experts. To provide high-level summaries of large datasets "at a glance", heat maps are used, arranged in a grid as tabular histograms with a color mark.

Visualization issues are addressed to support sustainable decision-making in various areas, including administrative management, where in-depth analysis of societal issues and possible policy options is needed. An example of the inclusion of information visualization in the policy analysis process is provided by [11]. Paper [12] proposed a tool to support decision-making based on timeline and taxonomies visualization to manage the capabilities of the defense order portfolio.

In the current trend where information systems are becoming more intelligent, a variety of representations of formal models of context, including graphics, are used in decision-making processes. The aim of the article [13] is to propose a tree-like view of decision-making practices in a contextual graph based on the Contextual Graph formalism. At the same time, ontology-based models occupy a special place among context models. The analysis of the context of the business operation of employment using the context graph was carried out in [14]. For each business operation, its contextual ontology is determined, which reflects the contextual knowledge. Such ontology identifies situation-relevant entities, relationships, and rules. The ontological scheme consists of a hierarchical data structure, contains information about the properties, as well as the relationship between the concepts and objects of the subject area. It is important that the ontology supports decision-making through the possibility of program-interpreted computer representation of knowledge. As a result, it adds intelligence to relevant information technologies in various fields [15].

Most multi-criteria tasks can be represented by hierarchical systems. One of the common expert methods that is well suited for hierarchical data structures and offered in many works is analytic hierarchy process (AHP) [16]. At the same time, it should be noted that AHP does not lack certain shortcomings, in particular in terms of sensitivity to the clarity of the list of alternatives and limitations. It is also usually necessary to minimize the shortcoming associated with the relationship of consistency as an indicator of the quality of expert assessments. Due to this, the search for the method of multi-criteria analysis that is best suited to solve the problem is often extended either by modified AHP or other methods, as well as the use of ontologies [17, 18].

The main conclusion of the analysis is that such approaches allow finding acceptable solutions only if the state of the subject area is clearly defined, and the experts should be sufficiently qualified specialists. Many studies do not take into account the specifics of evaluating alternatives, due to the fact that expert groups usually include officials who find it difficult to navigate the evaluation methods. At the same time, building models based on the integration of concepts and objects in graphical form still remains a confusing problem in determining the priorities of information support of the decision-making process. All of this suggests that it is advisable to conduct research on further improvement of the typical expert decision-making process in multi-criteria problems of different levels of complexity [19, 20] based on the representation of models in the form of graphs and their visualization.

3 Research on the use of graphs to decision-making

3.1 Decision making and complexity of problems

Decision-making is a complex process that takes at least three consecutive steps: 1) to analyze the problem to be solved, 2) to develop alternative solutions and 3) to choose the best solution. Thus, the problem of decision-making can be formally defined by the scheme $\{X \to A, \Phi\} \to a^*$, where X is the set of data representing the problem area, $A = \{a\}$ is the set of alternatives (objects of choice), which can be discrete and continuous; Φ – the principle (function) of choice, according to which, using certain criteria, the advantage in the set of alternatives A is established; and a^* is the chosen alternative (or several), which is considered the “best”. There are usually three possible types of decision-making tasks:

1) the problem of optimal choice – if the sets X and A are unambiguously defined (fixed), and the principle of choice is formalized;

2) the problem of informal choice – if X and A are defined, but Φ cannot be formalized;

3) the general problem of decision-making – if X and A do not have defined boundaries (can be supplemented and modified), and Φ is informal.

Tasks of the second and third types are unstructured (poorly defined). Such problems are very difficult (and sometimes impossible) to describe in formal language to give the appearance of the optimal choice problem and they are usually solved by expert methods. In terms of complexity, such tasks can also be classified as simple, complex, and very complex. To reflect the differences between these levels of complexity, it is advisable to use the representation of X and A in the form of oriented graphs (see Fig. 1).

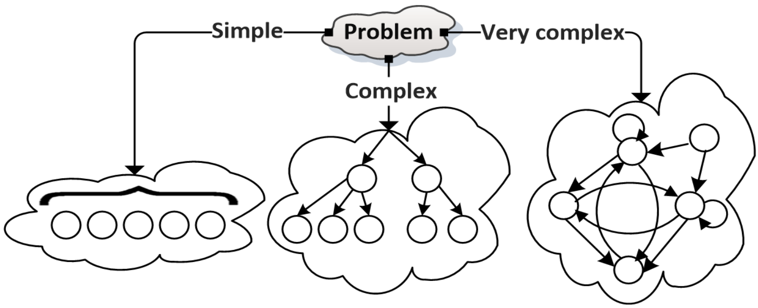

Figure 1. Classification of unstructured problems in terms of complexity

Simple problems can be represented by a linear scheme of alternatives, which in the process of finding a solution are ranked in order of preference over each other. For complex problems that differ in a large number of criteria and characteristics, the search for a solution according to the previous scheme does not give good results.

Usually, such problems are represented by a hierarchical scheme of "criteria – alternative" and require the use of certain algorithms for pairwise comparisons of alternatives according to these criteria. Then, the appropriate calculations are performed on the basis of scalar convolutions of the obtained estimates, taking into account the weights of the criteria.

A hierarchical structure is no longer enough to solve more complex problems. First, for adequate modeling, it is necessary to take into account more parameters of subject areas – objects, factors, requirements, conditions, characteristics, properties, criteria, etc. Second, these parameters can affect each other, and it is important to consider the degree of influence. In this case, it is advisable to use network structures in which the elements of the upper levels may depend on the elements of the lower levels, as well as elements of one level may depend on each other. The network structure allows you to more accurately reflect the relationship in such a subject area. In this case, the elements of the network can be not only simple elements, but also complex elements (components), which in turn consist of a group of homogeneous simple elements. This makes it possible to include in the review almost any knowledge and judgments that may influence the decision.

As the complexity of the problem $\{X \to A, \Phi\} \to a^*$, we can take the number of connections (relationships) between the elements of the structure of its model. Denote by $C^{(L)}(X_1, A)$ the complexity of the linear structure, $C^{(I)}(X_2, A)$ – the complexity of the hierarchical structure, and $C^{(N)}(X_3, A)$ – the complexity of the network structure. Then, applying graph theory, these entities can be defined by the following expressions:

$$C^{(L)}(X_1, A) = 0;$$

$$C^{(I)}(X_2, A) = N - 1,$$

where N is the number of vertices in the corresponding oriented tree of criteria; $N - 1$ is the number of edges in this tree;

$$N \leq C^{(N)}(X_3, A) \leq N^2,$$

where N is the number of vertices in the network of components; $N^2 = 2N(N-1)/2 + N$ – the maximum possible number of arcs and loops in such a network (i.e., in a complete Berge graph – oriented graph without multiple loops and multiple arcs of one direction).

As you can see, the complexity of the network model increases very quickly as new connections are added between its elements. This must be taken into account when building a model for solving a multi-criteria problem.

The procedure of expert formation and evaluation of alternatives is based on the principle of individual and collective work of experts when forming a group of experts, and they can choose from different alternatives using their informal Φ_i. That is, the choice usually depends on the personal preferences of the expert. Thus, overcoming the problem of complexity of tasks also has a negative impact on the subjective vision of experts, which often leads to the preparation of unreasonable decisions.

One of the approaches to solve this problem is a comprehensive information representation of the subject area using a conceptual scheme in the form of ontology, consisting of a hierarchical data structure, containing information about the properties and relationships between concepts and objects of the subject area. As you know, in the general case, computer ontology is formally represented by an ordered trio $O = \langle X, R, F \rangle$, where X is the set of concepts (concepts, terms) of the subject area, R is the set of relations and properties between them, F is the interpretation function (definitions) X and/or R. Finally, as mentioned above, one of the popular tools to improve understanding of the problem and, ultimately, to make effective decisions is to visualize information. Thus, for unstructured tasks, the cognitive decision-making process on an information basis can be presented in Fig. 2.

That is, the choice usually depends on the personal preferences of the expert. At the stage of problem analysis, the collected data is studied and on their basis the initial list of alternatives – “long list” (LL), usually with a linear structure – is determined. At the stage of developing alternatives, it is necessary to select a short list (usually no more than five) – ”short list” (SL). It is believed that human thinking is better suited to assessing preferences on multiple objects than on multiple sets of characteristics. But the advantage of the first approach is only when evaluating fairly simple objects.

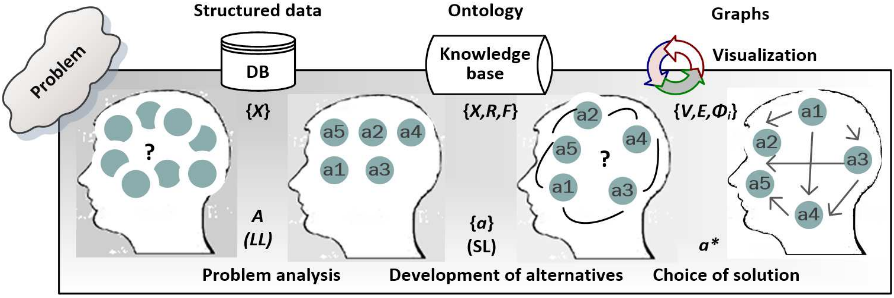

Figure 2. Cognitive decision-making process on information basis

For complex experts, it is easier to determine which of the alternatives is better, given its individual properties (characteristics) – of course, provided they exist. The information space, which should provide experts with comprehensive and clear support of their activities on an objective basis, is formed by the ontological system of the knowledge base. The properties of ontology objects can be used by experts as criteria against which experts can choose alternatives from a variety of possible alternatives.

For complex problems (with a hierarchical structure), the evaluation and selection of the best alternative to SL is based on the principle of direct dominance (greater influence, greater advantage, greater probability), according to which structural elements are compared in pairs (usually on a qualitative scale of linguistic variable). After completing this step, it is necessary to return to the evaluation and comparison of alternatives in general – that is, to perform a composition of criteria. This allows you to find the best of the alternatives or rank them. The ontology of the subject area should clearly define all the characteristics of the criteria, prevent inconsistencies in the selection results due to subjective views, lack of knowledge and errors of experts, and the influence of various factors on them. But such informational support for solving selection problems is not always enough. For example, when using AHP, the number of spreadsheets, which depends on the number of alternatives, characteristics, and experts, is usually quite significant. This is especially true for recalculations in the event of significant inconsistencies. In addition, the AHP does not check transitive consistency. In order to prevent matrix inconsistencies, it is necessary to “direct” experts in a certain direction in order to avoid extreme subjectivism.

As such a tool, it is proposed to visualize the process of pairwise comparisons in the form of an oriented graph (V, E) with synchronous control of transitivity. The vertices V of the indicated graph correspond to the alternatives, and the edges E with the arrow indicate the advantages of the alternatives. For example, an arc (a_r, a_q) will go from vertex a_r to vertex a_q if $(a_r \succ a_q)$, where the symbol $\succ$ means general superiority. To improve understanding, if necessary, the arcs are loaded with numerical values that correspond to the expert qualitative values of the degree of superiority of one alternative over another according to a certain criterion. Based on their non-formalized Φ_i, the expert can adjust the directions and loads of the edges. Because all selected alternatives are compared in pairs, all vertices will be connected by arcs at the end of the procedure. The resulting graph will be a complete oriented graph, which in graph theory is called a tournament. An evaluation option that satisfies the conditions of transitivity is a must. This stems from the possibility of strict linear ordering vertices of the transitive tournament in the order of their reachability, as all its vertices have different input and output degrees of arcs.

3.2 Complexity of problems and methods of decision making

Practice shows that the most common way of collective decision-making in expert groups is voting. Voting procedures, even if they seem simple, are complex and sophisticated ways of deciding on the basis of conciliation of interests. Finding such a decision is facilitated by the correct choice of the voting procedure, which is characterized by the following stages: a) each participant in the procedure forms his/her opinion on alternatives and reflects it in accordance with the instructions; b) in accordance with one or another formal procedure for processing this information, a collective decision is determined.

There are numerous voting procedures. Given the above requirement of simplification for experts of the process of forming and evaluating alternatives and choosing the most acceptable one, when these alternatives are fairly simple objects for the basic method, the technique of approval voting (with modification) is proposed. Each expert can both submit his/her proposal for inclusion/exclusion in a variety of alternatives, and participate in the process of improving the proposals of other experts. The main thing is that the expert has the right to support not only one, but also several alternatives, which allow experts to make decisions being closer to consensus than other methods.

But by voting, it is possible to achieve acceptable results only in the case of simple tasks. More complex multi-criteria tasks are usually represented by a hierarchical system. At its lower level, alternatives are evaluated using a vector of criteria formed by the decomposition of properties. At the upper level, with the help of the composition mechanism, the assessment as a whole is formed. One method that is well suited for hierarchical data structures is AHP. In AHP, 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 top, depends on one or more elements above.

For even more complex problems from these classes, when indirect dominance is used to determine the relationship between their elements (alternatives, criteria, characteristics, factors, conditions, scenarios, etc.) network models are needed. To build such models, it is advisable to use the analytic network process (ANP), which is a development of AHP [21]. The ANP involves the construction of an oriented graph without multiple loops and multiple arcs of one direction (Berge graph) and a super-matrix of influences between simple elements and components of the graph. In a super-matrix (block matrix) formed on the basis of a graph, each block is a matrix of pairwise comparisons Mij, which determines the influence of the elements of the i-th component on the elements of the j-th component. After formation of all necessary matrices with application of the corresponding matrix transformations, the algorithm of their calculations is realized to obtain the generalized numerical values. Based on them, the ranking of alternatives is carried out. Finally, visualizing the process of pairwise comparisons of alternatives in the form of an oriented graph is an additional means of improving the consistency of expert judgments. Thus, the decision-making process, in general, takes place according to the algorithm shown in Fig. 3.

It is not uncommon for a problem, originally defined as simple, to be not quite as it seemed in the simulation process. Therefore, the algorithm provides transitions from one level to another and cyclic return in case of unsatisfactory results.

4 The decision-making process on the example of a typical multi-criteria problem

Let's consider the application of the proposed approach on the example of solving the problem of rating alternatives for extinguishing forest fires (FF), which are the most common dangerous event. This is a typical multi-criteria task facing the organizational unit of the Civil Defense Force whose goal is to determine the composition of means and resources that will have the necessary capabilities to perform tasks, taking into account the importance of tasks and other criteria.

The modern way of extinguishing FF is to involve aviation. The aircraft flight modes during the discharge of fire-extinguishing liquid depend on many factors: the distance from the aerodromes of the permanent base of the aircraft, fire characteristics and level of smoke, the length of the section on the combustion front, and others. Forest fires are accompanied by high combustion temperatures, intense air turbulence and smoke.

Thus, to calculate the forces and means of FF liquidation, the fire extinguishing manager must operate with the values of many data. The formation of the database should take place in advance on the basis of experience and knowledge of experts, taking into account possible situations. An important factor in the presentation of such knowledge is the ontological descriptions of the set of concepts, objects, connections and processes due to the characteristics of this area, which are usually formed using graph models.

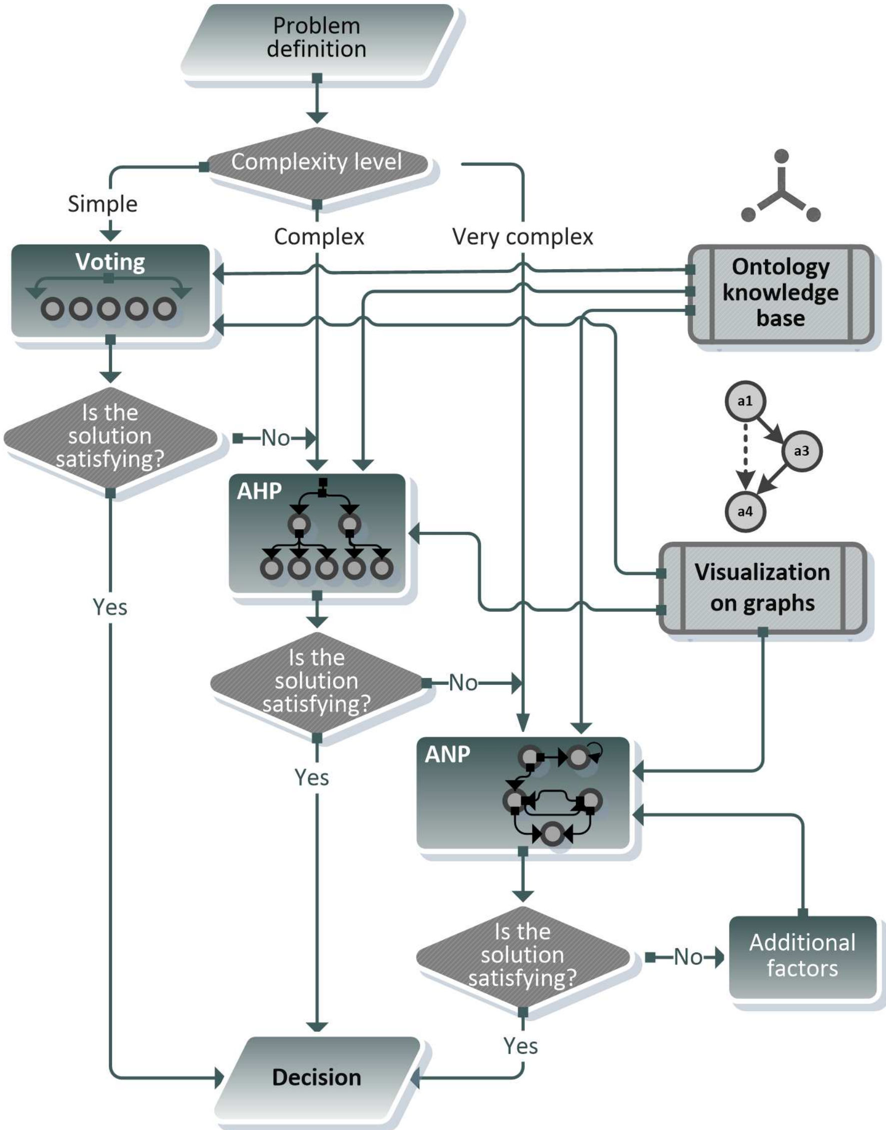

Figure 3. Algorithm of the decision-making process

Clarity of actions on FF liquidation is achieved by development and delivery to extinguishing participants of the aircraft flight schedule. The source information for the schedule compilation should be the values from the database and knowledge base. Based on these data, it is possible to make a significant number of options for aviation tasks (alternatives), among which you need to choose the best for flight schedule preparation.

Thus, according to the developed variants of tasks, five alternatives (C1 – C5) have been proposed for consideration, which can be used for the flight schedule. To move to the evaluation, the necessary characteristics are selected from ontologies of the knowledge base (see Fig. 4).

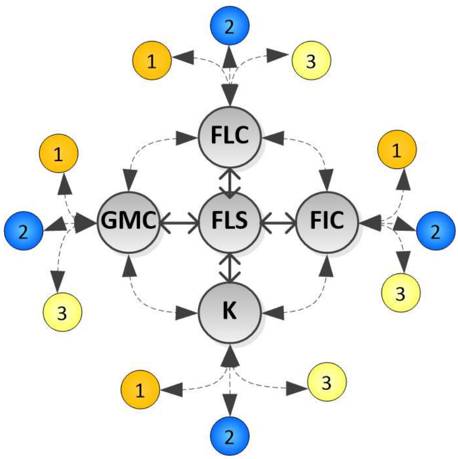

Figure 4. Top level graph of ontologies (FLS – flight schedule; FLC – flight characteristics; FIC – fire characteristics; GMC – characteristics of ground means; K – criteria; 1,2,3, and so on – groups of characteristics)

Initially, all experts vote, using a built ontology graph, which helps them to evaluate the alternatives. An example of display for one of the voting variants for one expert is shown in Fig. 5.

Virtually every voting procedure can lead to the choice of more

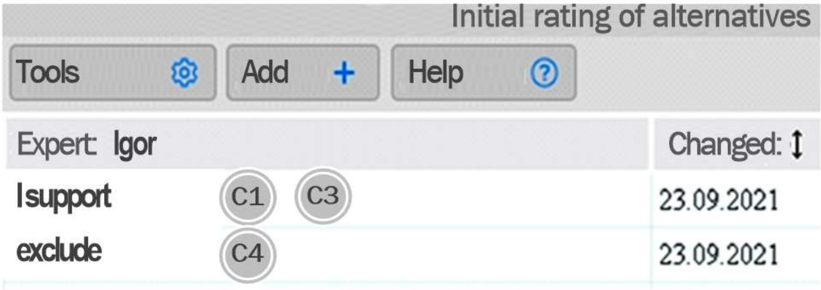

Figure 5. Evaluation results by voting procedure

than one alternative or not even being able to identify any alternative. According to the approach under consideration, it is proposed to clarify the decision by transferring the problem to a higher level of complexity and applying a hierarchical method of evaluation.

Using ontological data, a hierarchy of the problem is built. This hierarchy for our model example has three bushes (root subtrees) of criteria, each of which has its own branches. For example, three groups of criteria can be defined: K1 – compliance with the task; K2 – risks in task performing; K3 – cost of flights. The first group includes such criteria as versatility, probability of detection, mobility, reliability, efficiency, range, duration of action, etc. The second group includes the dependence on fire intensity, dependence on wind force, etc. The third group includes the estimated costs of using different aircraft depending on their types, bases, etc. The values of these criteria (characteristics) are presented in databases. The hierarchy for this example is shown in Fig. 6.

According to the AHP algorithm, a unified set of tables is formed for experts to record the results of pairwise comparison of alternatives for each criterion. As a result of processing of tables the standardized values of estimations by all experts of all alternatives in comparison with others on each criterion are determined. After that, they are folded. According to the proposed approach, instead of filling in the tables, the expert compares any pair of alternatives using a special graphical interface, which displays the vertices of the graph with the names of the alternatives.

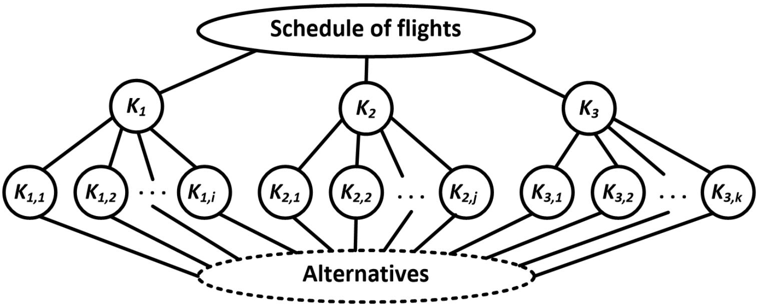

Figure 6. Hierarchy of the task

In this case, tables with the corresponding quantitative estimates (degrees of preference) are formed automatically. If necessary, the expert can review some of his/her own preliminary judgments in order to improve their consistency by editing the graph with preservation of transitivity. An example of the comparison steps ($S1 - S4$) of one of the experts leading to the final transitional tournament is given in Eq. (1), and the visualization of the tournament is shown in Fig. 7.

$$\begin{aligned} S1.C2 &\sim C5.\{\{S2.C1 \succ C3.S3.C3 \succ C4.\} \Longrightarrow \\ &\Longrightarrow (C1 \succ C4).S4.C4 \succ C2\} \Longrightarrow \\ &\Longrightarrow (C1 \succ C2, C3 \succ C2). \end{aligned} \tag{1}$$

In emergencies, alternatives often need to take into account the various elements and entities and the relationships between them. It is often not possible to describe all the necessary relationships in a hierarchical structure. In this case, it is proposed to use a network model based on ANP.

An example of such a more complex task can be the case where the interaction of fire crews with ground rescue units is taken into account in firefighting. To do this, in addition to the general situation, it is

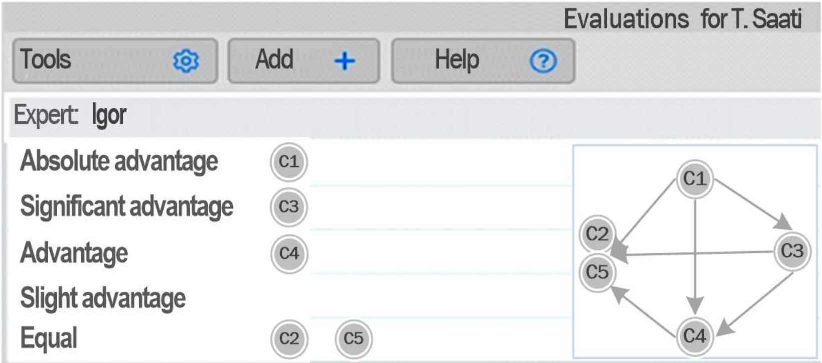

Figure 7. Preliminary visualization of AHP tournament for one of the experts

necessary to take into account various factors and their mutual influences to ensure ground methods of firefighting and security of forces and means. Therefore, when building network models, much attention should be paid to the development of network structure, which should provide the ability to have simple elements (individual entities) and complex elements (components), which in turn consist of simple elements, as their vertices (nodes). Both external dependencies between components and internal dependencies between elements within one component must be taken into account. For example, the ability to maintain the wetness of the local area band by ground units (L1) can significantly reduce the requirement to maintain the wetness only by aircraft, and the involvement of special ground equipment (L2) can affect the number of flights and, consequently, the cost of the operation.

It is advisable to build network models by expanding the already built hierarchical models. With this in mind, the network structure for modeling the interaction of fire crews with ground rescue units is shown in Fig. 8.

An example of the resulting graph of comparisons of one of the experts on one of the criteria is shown in Fig. 9.

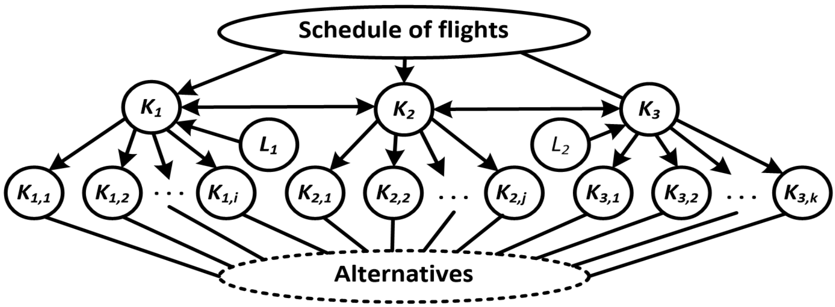

Figure 8. Network structure of the task

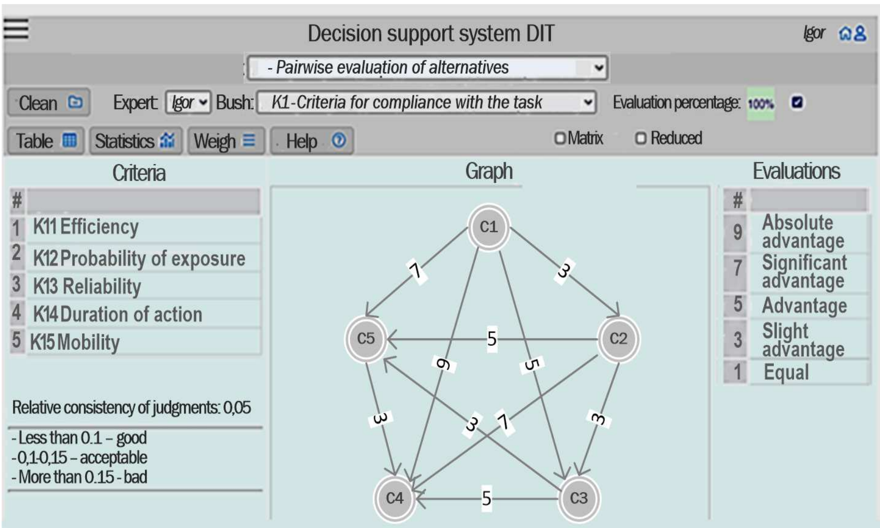

Figure 9. An example of the resulting graph of comparative evaluations for AHP/ANP according to one of criteria of one of experts

5 Conclusions and future work

The proposed approach represents one of the innovative tools for achieving goals and objectives in decision making, which is always relevant. The results of the study are related to the use of graphs as an integrated means of combining into a single set of ontological data models, means of visualizing alternative comparison processes and known methods of multi-criteria analysis. Features of the proposed technique and the results obtained in comparison with existing ones have several advantages. First of all, the proposed approach uses the psychological ability of any person to effectively compare in the presence of visual images. By visualizing on graphs all stages of the process of evaluating and supporting the opinions of experts, expert activity is significantly simplified. In particular, it helps to increase transitive and cardinal coherence. The graphical interface reduces subjectivity and generally creates the conditions for impartiality and fairness. This feature ensures the efficiency, versatility, and simplicity of technical implementation of the decision support procedure.

It should be noted that this study has certain limitations. First of all, they are related to the possibility of building a correct and adequate ontological model of the subject area, which largely depends on the validity and objectivity of the decision. It is necessary to have comprehensive data on the subject area, terminological dictionaries and technical reference books in the electronic presentation, from which it is possible to build an ontological base. At the same time, there is a need to involve qualified specialists in the field of Data Scientist. This is especially true for ANP. In practice, these conditions may not always be met. Usually, when collecting additional data, in particular of a special nature, you may encounter organizational difficulties.

Further directions of this study can be directed on more detailed extension the presented solution of the problem based on the network model. The positive effect of using the potential of this approach may be related to the improvement of the ontological model of the subject area. Given the universality of the approach, the development of this study may consist in its application in various fields.

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