25. Shved A., Davydenko Y. The analysis of uncertainty measures with various types of evidence // 2016 IEEE First International Conference on Data Stream Mining & Processing (DSMP). 2016. doi: https://doi.org/10.1109/dsmp.2016.7583508
26. Jousselme A.-L., Maupin P. Distances in evidence theory: Comprehensive survey and generalizations // International Journal of Approximate Reasoning. 2012. Vol. 53, Issue 2. P. 118–145. doi: https://doi.org/10.1016/j.ijar.2011.07.006
27. Pavlovskaya O. O. Static methods of assessment of software // Vestnik Yuzhno-Ural'skogo gosudarstvennogo universiteta. Seriya: Komp'yuternye tekhnologii, upravlenie, radioelektronika. 2009. Issue 10. P. 35–37.
28. Orlov A. I., Savinov Yu. G., Bogdanov A. Yu. Experience of expert estimation of the conditional probabilities of a rare events during developing automated system for forecasting and prevention of aviation accidents // Izvestiya Samarskogo nauchnogo centra Rossiyskoy akademii nauk. 2012. Vol. 14, Issue 4 (2). P. 501–506.

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DEVELOPMENT OF METHODS FOR STRUCTURAL AND LOGICAL MODEL UNIFICATION OF METAKNOWLEDGE FOR ONTOLOGIES EVOLUTION MANAGING OF INTELLIGENT SYSTEMS

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Актуальність роботи обумовлена важливістю і необхідністю уніфікації побудови і використання інтелектуальних систем підтримки рішень для управління складними промисловими об'єктами та системами.

Метою роботи є обґрунтування єдиного підходу до управління базами знань різних конфігурацій і розробка уніфікованих математичних моделей операцій над елементами онтологій.

Запропоновано метод управління еволюцією онтологій професійних областей, заснований на уніфікації структурно-логічної моделі репрезентації метазнань.

Розроблено спосіб уніфікації структурно-логічної моделі еволюції інкорпорації онтологій. Розроблено формально-лінгвістичні моделі, доведено подібність форм репрезентації знань і еволюційне спадкування в рамках загальної інкорпорації онтологій. Для синтезу моделі інкорпорації еволюційного успадкування онтологій вирішені завдання розробки моделей еволюційного успадкування концептів, графів і онтологій рівнів БЗ. Модель забезпечує можливість для всіх рівнів БЗ єдиного підходу до інтерпретації структур взаємодії концептів.

Розроблено узагальнену модель сигнального графа рівнів структури БЗ. Модель включає в себе атомарний концепт, сигнал, потенціал вузла, активність вузла, поріг чутливості вузла до вхідного сигналу. Розроблено набір формальних моделей множини базових операцій на сигнальному графі БЗ, необхідних для інтерпретації та обчислення форм знань. Розроблено синтаксис метаправил і формально-лінгвістичний базис. Введено формалізми параметра маркування та функції маркування сигнального графа БЗ. Моделі маркування введені в загальну модель сигнального графа БЗ.

Досліджено можливості застосування розроблених моделей сигнального графа бази знань в різних професійних галузях. Показано, що запропоновані моделі метазнань не залежать від форм подання і формалізмів професійних онтологій. Це дозволяє використовувати єдиний механізм управління знаннями в будь-яких інтелектуальних системах підтримки рішень. Запропоновано спосіб ефективного динамічного управління структурою всіх рівнів БЗ і процесом логічного висновку в залежності від вхідних параметрів функціонування інтелектуальної системи

Ключові слова: інкорпорація онтологій, контекст моделі, маркування графа, метапродукція, репрезентація знань, сигнальний граф, система підтримки рішень

1. Introduction

At the present stage of development of automated control systems for large industrial facilities, aspects of management in crisis situations with a lack of time are of particular importance. These situations are usually called crisis due to the significant amount of damage that occurs in a very limited period of time. In this regard, the period of time for making management decisions should have at least the same order. However, the decision maker (DM) is unable to respond adequately to the situation at the required pace. There are two main reasons for this – extremely large amount of data that require an accurate assessment for a minimum time, and psychological pressure on the DM due to increased responsibility.

As an example of a complex production facility, we consider the electric power system (EPS), which is a large technical system of a cybernetic type. The parameters of the EPS components are functions of time and depend on control and random influencing factors. Therefore, the EPS control is iterative, adaptive in nature, accompanied by the collection and processing of large amounts of information.

The structure of the power system control needs to be considered at two levels – automatic control level, where emergency automation (EA) plays the main role, and automated control level, where the operating and dispatching personnel (ODP) are included in the control cycle as a decision maker (DM) [1]. In [2], personnel are considered as a structural unit of a multi-criteria control system.

At the stage of preliminary studies, extensive factual material, qualifying accidents at large technological facilities, including electric power systems is studied. In [3], the classification of accidents is carried out. The role of «human factor» in the development of accidents is investigated in [4]. In particular, according to the data provided by the National Power Company «Ukrenergo» [5], the number of failures at the power facilities of Ukraine on the basis of «wrong actions of operating personnel» increased by 25 % and is 6.7 % of total, on the basis of «wrong actions of management, maintenance personnel, services and laboratories» increased by 6.6 % and is 17.8 % of total, on the basis of «influence of unauthorized persons and organizations» increased by 52.5 % and is 6.8 % of total. In general, violations of technological processes as a result of incorrect actions of personnel («human factor») in the distribution according to classification criteria are 31.3 %.

We also give some examples of foreign incidents. The ocean coast of Rio de Janeiro, where 10 million people lived, was completely de-energized. Reason: the malfunction that was not timely and accurately identified by personnel. More than 10 million people in Mexico and the USA were left without electricity. Reason: the company's employee failed to organize work at the electrical substation. The center of Buenos Aires (Argentina), the presidential palace, the congress, the government were de-energized, 3 million people were affected. Reason: the personnel spent considerable time for finding out the details of the accident and coordinating actions. At the Saint Lawrence NPP, France, the launched 500 MW reactor exploded, about 50 kg of liquid nuclear fuel leaked. Reason: during the night shift, the operator incorrectly loaded the fuel channel.

The analysis performed allows us to conclude that the total number of failures and emergencies does not decrease, and damage is constantly increasing. Therefore, the problem of ensuring the reliability of the ODP, as an integral part of the ADCS of power systems is extremely urgent.

On the basis of the comparative analysis of existing scientific and technical solutions in the field of automation of emergency control (EC) systems, it can be concluded that it is necessary to develop intelligent decision support systems (DSS) and implement them as part of the ADCS of power systems.

Thus, there is the problem of automating the decision-making process in crisis situations, which should be solved by developing and implementing intelligent decision-support systems. The core of such systems are complexes of expert knowledge management with the help of metaknowledge (MK) [6]. As shown in [7], metaknowledge is responsible for meta-analysis and inference in the knowledge base.

2. Literature review and problem statement

In [8], the knowledge system for a narrow professional field is used, which makes it impossible to generalize the proposed approach. In [9], top-level metadata are used to build expert systems, but no unified method of constructing metarule structures for various professional fields is proposed. The paper [10] considers the problem of knowledge representation, but offers a table-oriented storage system with known limitations. In addition, no attention is paid to the management of knowledge systems. In [11], a general methodology for constructing expert systems is presented, but there is no specification of approaches to the implementation of the metaknowledge model. Methods of presenting information about processes under uncertainty are considered in [12], but this information is not updated in the form of metarules.

Thus, there is a methodological problem of constructing metarules that are invariant to the specifics of subject areas, *KB* structures, forms of knowledge representation, formal models used, and restrictions imposed.

Ontology formalism can be used as a unified form of metarules representation in the intelligent system. In the most general form, the ontology can be represented by the following formal specification:

$$O = < X, R, F >, \quad (1)$$

where X is the finite set of concepts (notions, terms) of the subject domain, represented by the ontology O; R is the finite set of relations between concepts (notions, terms) of a given subject area; F is the finite set of interpretation functions (axiomatization) defined on concepts and/or relations of ontology O.

In [13], a general characteristic of ontology is given, but the ways of implementing such a knowledge model within specific intelligent systems are not sufficiently shown. The work [14] generally describes the process of knowledge management in information systems, but does not provide tools for its program implementation. In [15], the ontology structure is considered, however, it applies to a relational database, which is a significant limitation. The paper [16] suggests a model of ontology patterns, however, the latter are difficult to apply in practical software implementations. Principles of unification are outlined in [17], but only the structure of the *KB* on facts is given as a base. The paper [18] is characterized by a detailed analysis of ontology, but is mainly a theoretical work without practical implementation. In [19], the complex problem of the knowledge representation methodology is formulated, but specific ways of its practical implementation are not indicated. The work [20] presents mathematical tools of the intelligence theory, but their practical application is extremely difficult. Methods and tasks of the intelligence theory are discussed in [21], but the work is difficult to use as a guide in practical software engineering. The work [22] proposes a predicate approach to knowledge formalization, which imposes certain restrictions on the internal software representation of the *KB*. A system approach to the unification and interpretation of the *KB* is made in the specification of the Common Warehouse Metamodel (CWM) standard [23]. However, in practice, many models of knowledge management in intelligent systems are used [24], which is a problem in the selection and adequate implementation within a specific task: KIF (Knowledge Interchange Format), lambda – notations, predicates, rules, relational algebra, logical-computing semantic networks (LCS networks), object-oriented representation forms, frames, deductive systems.

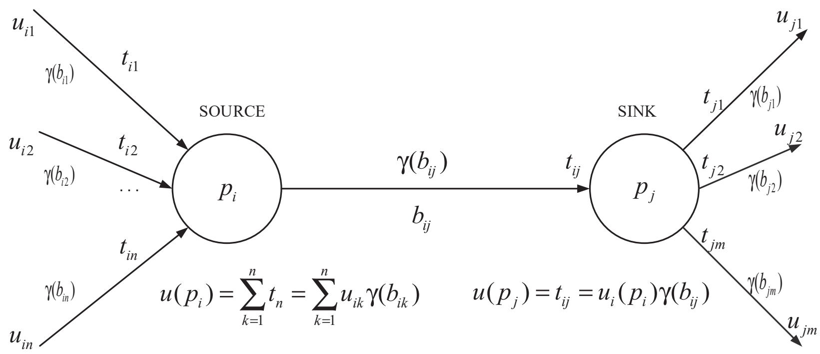

Fig. 1. Basic model of signal transmission in the elementary signal graph

The work [25] shows the specifics of the problems of mathematical modeling of knowledge systems in various fields: power engineering, medicine, process control, chemical synthesis, geological exploration, and others. At the same time, specific ways of knowledge unification are not indicated.

Summarizing the analysis performed, the problem of the lack of a unified model of theoretical representation and practical construction of metaknowledge models in intelligent systems is formulated. This does not allow for the mass production of cheap decision support systems.

3. The aim and objectives of the study

The aim of the study is to develop a universal formal-logical metaknowledge system for managing the evolutionary hierarchy of ontologies.

To achieve the aim, the following objectives were set:

– to develop mathematical models of procedures for the synthesis of knowledge structures of all levels;

– to develop a basic model of the elementary signal graph of the knowledge base;

– to justify and develop a model for labeling the signal graph of the knowledge base;

– to develop structural and functional models of metarules based on the model of the elementary signal graph.

4. Development of models of metarules based on the structure and labeling of the signal graph

4. 1. Development of mathematical models of procedures for the synthesis of knowledge structures of all levels

It follows from the stated principles that structural models of all levels of knowledge representation can be considered as signal (pulse) linear digraphs [26]. The latter model inference as a conducting system of logic chains [27]. From these positions, mathematical models of interpretation and computing of ontology hierarchies are developed. The paper proposes the following basic model of the signal graph of the *KB* (Fig. 1).

The formulas below describe labels of nodes p_i, p_j and edge b_{ij}, respectively.

$$\mu_i^p := < c_s(p_i), u(p_i), s_u(p_i), a(p_i) >,$$

$$\mu_j^p := < c_s(p_j), u(p_j), s_u(p_j), a(p_j) >,$$

$$\mu_i^b := b_i \to \gamma(b_i).$$

In the proposed interpretation, the node of the structure of knowledge representation of any level in terms of applying metarules to it means:

– for level 0 – atomic sentence;

– for level 1 – fact (as a connective of atomic sentences);

– for level 2 – semantic network cluster (as a connective of facts);

– for level 3 – production network (as a connective of semantic network clusters).

4. 2. Development of the basic model of the elementary signal graph of the knowledge base

Atomic concept c_s is a sentence assigned to the node of the signal graph and considered exclusively in the interpretation and computing of *KB*.

Signal t is a numerical concept characterizing the possibility of a causal relationship between the nodes of the signal graph. In this case, the signal can be considered as an implication, provided with a numerical characteristic of signal passage or propagation. In other words, if there is a signal in the graph edge, then a causal relationship between the nodes incident to this edge is active.

Node potential (node signal) $u \in \mathbb{R}$ is the number (generally valid) assigned to the node and associated with it in the current iteration of the system. At the next iteration, another number can be assigned or computed. The weight of the node does not carry a specific semantic load and is interpreted within the current problem. The numbers associated with the nodes can be interpreted as weights, potentials, connectors of the node. No fundamental restrictions on the node potentials are imposed. The activity level of the node (current potential of the node) is the accumulated potential (weight, signal) in the node at the time the node participates in the network interpretation process. The value of the node potential is defined as the sum of all input signals through the edges incident to the node. The assignment of signals to nodes is implemented by a labeling function or computed.

Node activity $a=(0|1)$ is a binary sign characterizing the participation of the node in network interpretation. If the node is not active ($a=0$), it is not interpreted in any way by the inference unit (engine) (IU), does not participate in inference, and the content of such a node is not considered.

The threshold of node's sensitivity to the input signal in general $s_u = f(t_m)$ is a measure of the node's ability to pass the input signal to subsequent edges incident to it, where t_m is the signal threshold level. The type of function $f(t_m)$ is determined by the specifics of the problem and goals of modeling. In the simplest case, a threshold function or sigmoid function can be used. When the sensitivity threshold s_u is exceeded, the node p_i is activated, and the signal of a given value $t(p_i)$ is detected in it. Signals smaller than s_u are not perceived by the node:

$$a(p_i)=\begin{cases}0\,|\,t(p_i)\le s_u(p_i),\\ 1\,|\,t(p_i)>s_u(p_i),\end{cases} \quad (2)$$

$$u(p_i)=\begin{cases}0\,|\,t(p_i)\le s_u(p_i),\\ u(p_i)\,|\,t(p_i)>s_u(p_i).\end{cases} \quad (3)$$

4. 3. Development of the model for labeling the signal graph of the knowledge base

We introduce the function of labeling the i-th node of the signal graph of the knowledge base. Determine the labeling parameter through the tuple:

$$m_\mu=<c_s, u, s_u, a>. \quad (4)$$

Then labeling for an arbitrary i-th node is defined as follows.

$$\mu_i^p : p_i \to m_\mu(p_i)=<c_s(p_i),u(p_i),s_u(p_i),a(p_i)>,$$

$$\mu_i^p \in M^p,$$

$$p_i \in P(G_s),$$

$$M^p:\ P(G_s)\to m_\mu(P),$$

$$u(p_i),s_u(p_i)\in\mathbb{R}, \quad (5)$$

where μ_i^p is the function of labeling the i-th node p_i by the parameter $c(p_i)$; M^p is general labeling of cluster nodes (or the entire network) in relation to which the metaknowledge model is used; $P(G_s)$ is the set of cluster nodes (or the entire network) in relation to which the metaknowledge model is used; $\mathbb{R}$ is the set of real numbers.

The edge b_{jk} between nodes j and k of the knowledge representation structure of any level, in terms of applying metarules to it, means the directional relation (connection, arc) between these nodes in the knowledge base signal graph. Each edge has input and output potentials (signals). Moreover, if the edge is directed from node j to node k, then node j, having potential u_j, will be source, and node k, having potential u_k, will be sink. Using the previously adopted notations, the edge of the *KB* graph will be presented as follows:

$$I : b_{jk}\to(p_j,p_k),$$

$$b_{jk}\in A(G_s),$$

$$p_j,p_k\in P(G_s),$$

where b_{jk} is the edge of the network graph of the *KB* level; I is the incidence function; $A(G_s)$ is the set of all edges of the graph G_s of the network of the *KB* level; p_j, p_k are the nodes, incident to the edge b_{jk}.

Conductance (transmission) of the edge $\gamma(b)$ is a number (generally valid) associated with the edge. Assigning numbers to edges is made by labeling. The numbers associated with edges can be considered weights, conductances, lengths, edge values, etc. No restrictions on these numbers are imposed. In this work, we suppose that the numbers labeling the edges are conductances of these edges.

We introduce the labeling function of the i-th edge as follows:

$$\mu_i^b : b_i\to\gamma(b_i),$$

$$\mu_i^b\in M^B,$$

$$M^B:\ A(G_s)\to\mathbb{R},$$

$$b_i\in A(G_s),$$

$$\gamma(b_i)\in\mathbb{R}, \quad (6)$$

where μ_i^b is the labeling function of the i-th edge b_i by the number t_i; M^B is general labeling of cluster edges (or the entire network) in relation to which the metaknowledge model is used; $A(G_s)$ is the set of directed edges of the cluster graph (or the entire network) in relation to which the metaknowledge model is used; $\mathbb{R}$ is the set of real numbers.

Now the proposed generalized model of the *KB* structure level graph can be described by the following tuple:

$$G_s=(P(G_s),A(G_s),M_\Sigma),$$

$$M_\Sigma=<M^P,M^B>. \quad (7)$$

4. 4. Development of structural and functional models of metarules based on the model of the elementary signal graph

We introduce a subset of the basic operations on the *KB* graph – G_s, needed to interpret and compute *KB* levels:

$$O_{KB}(G_s)\subset O(G),$$

where $O_{KB}(G_s)=\{O_{KBi}\}$ is the subset of operations in relation to the knowledge base such that: O_{KB1} := addition of a new concept in the *KB*; O_{KB2} := removal of the concept from the *KB*; O_{KB3} := addition of a new connection to the *KB*; O_{KB4} := removal of the connection from the *KB*; O_{KB5} := accession of the new fragment to the *KB*-*KB′*; O_{KB6} := detachment of the fragment from the *KB*-*KB′*; $O(G)$ is the entire set of operations implemented on graphs.

Then we formally define.

For O_{KB1}:

$$G_s(P(G_s),A(G_s))+p_s,\quad p_s\notin P(G_s),$$

$$G_s(P(G_s),A(G_s))+p_s=G_s'(P(G_s'),A(G_s')),$$

$$P(G_s')=P(G_s)\cup\{p_s\},$$

$$A(G_s')=A(G_s),$$

$$\mu_i^p : p_{si}\to m_\mu(s_i,0,0,0). \quad (8)$$

For O_{KB2}:

$$G_s(P(G_s),A(G_s))-p_s,\quad p_s\in P(G_s),$$

$$G_s(P(G_s),A(G_s))-p_s=G_s'(P(G_s'),A(G_s')),$$

$$P(G_s')=P(G_s)\setminus\{p_s\},$$

$$A(G_s')=A(G_s)\setminus\{b=\{p_{s1},p_{s2}\}\,|\,b\in A(G_s),p_{s1}=p_s\vee p_{s2}=p_s\},$$

$$\mu_i^p : p_{si}\to m_\mu(0,0,0,0). \quad (9)$$

For O_{KB3}:

$$G_s(P(G_s),A(G_s))+b,\quad b\notin A(G_s),$$
$$G_s(P(G_s),A(G_s))+b=G_s'(P(G_s'),A(G_s')),$$
$$A(G_s')=A(G_s)\bigcup\{b\},$$
$$b=\{p_{s1},p_{s2}\}\,|\,b\in A(G_s');\,p_{s1},p_{s2}\in P(G_s),$$
$$P(G_s')=P(G_s),$$
$$\mu_i^b:b_i\to\gamma(b_i). \tag{10}$$

For O_{KB4}:

$$G_s(P(G_s),A(G_s))-b,\quad b\in A(G_s),$$
$$G_s(P(G_s),A(G_s))-b=G_s'(P(G_s'),A(G_s')),$$
$$P(G_s')=P(G_s),$$
$$A(G_s')=A(G_s)\setminus\{b\},$$
$$\mu_i^b:b_i\to 0. \tag{11}$$

For O_{KB5}:

$$G_s(P(G_s),A(G_s),M_\Sigma(G_s))+G_s'(P(G_s'),A(G_s'),M_\Sigma(G_s')),$$
$$P(G_s)\bigcap P(G_s')=\varnothing,A(G_s)\bigcap A(G_s')=\varnothing,$$
$$G_s(P(G_s),A(G_s),M_\Sigma(G_s))\bigcup G_s'(P(G_s'),A(G_s'),M_\Sigma(G_s'))=$$
$$=G_s''(P(G_s''),A(G_s''),M_\Sigma(G_s'')),$$
$$P(G_s'')=P(G_s)\bigcup P(G_s'),A(G_s'')=A(G_s)\bigcup A(G_s'),$$
$$M_\Sigma(G_s'')=M_\Sigma(G_s)\bigcup M_\Sigma(G_s'),$$
$$\forall p_i\,|\,p_i\in P(G_s')(\mu_i^p:p_{si}\to m_\mu(s_i,0,0,0)),$$
$$\forall b_i\,|\,b_i\in A(G_s')(\mu_i^b:b_i\to\gamma(b_i)),$$
$$\forall b_i\,|\,b_i=[p_{s1},p_{s2}]\wedge(p_{s1}\in A(G_s)\wedge p_{s2}\in A(G_s'))\vee$$
$$\vee(p_{s1}\in A(G_s')\wedge p_{s2}\in A(G_s)))(\mu_i^b:b_i\to\gamma(b_i)). \tag{12}$$

For O_{KB6}:

$$G_s(P(G_s),A(G_s))-G_s'(P(G_s'),A(G_s')),$$
$$P(G_s')\subseteq P(G_s),A(G_s')\subseteq A(G_s),$$
$$G_s(P(G_s),A(G_s))\setminus G_s'(P(G_s'),A(G_s'))=$$
$$=G_s''(P(G_s''),A(G_s'')),$$
$$P(G_s'')=P(G_s)\setminus P(G_s'),$$
$$A(G_s'')=\{[p_{s1},p_{s2}]\,|\,p_{s1},p_{s2}\in A(G_s)\setminus A(G_s')\wedge$$
$$\wedge[p_{s1},p_{s2}]\in A(G_s)\wedge[p_{s1},p_{s2}]\notin A(G_s')\}, \tag{13}$$
$$\forall p_i\,|\,p_i\in P(G_s')(\mu_i^p:p_{si}\to m_\mu(0,0,0,0)),$$
$$\forall b_i\,|\,b_i\in A(G_s')(\mu_i^b:b_i\to 0),$$
$$\forall b_i\,|\,b_i=[p_{s1},p_{s2}]\wedge(p_{s1}\in A(G_s)\wedge p_{s2}\in A(G_s'))\vee$$
$$\vee(p_{s1}\in A(G_s')\wedge p_{s2}\in A(G_s)))(\mu_i^b:b_i\to 0).$$

Naturally, when adding a new concept, there is a probability of its repetition (duplication). For this purpose, the procedures of «normalizing» the knowledge base and getting rid of redundancy should be used. In this case, a formal set-theoretic interpretation, characterizing the fact of addition of a new concept is given. Therefore, the additional formal constraints associated with the occurrence of redundancy were omitted.

The developed control models of the *KB* structure, based on the apparatus of graphs, allow us to formalize the language of the level of metarules and describe its ontology. When developing a formal language of metarules, it was necessary to choose a formal-theoretical apparatus that would be suitable for representing all forms of knowledge. As such, the graph model was chosen as the most fundamental one. In addition, the task was to integrate the representation of metarules into the general hierarchy of knowledge representation. Therefore, metaknowledge is also represented by graph models and does not require a separate theoretical mechanism for representation. Thus, all levels of knowledge are represented and described by the same mathematical model of graph representation. The proposed approach allows us to avoid introducing additional formal or instrumental metarule management mechanisms, which are expensive, computer-intensive and time-consuming.

At the same time, it is necessary to consider the following features:

– metarules perform structuring of the *KB*, which determines the mechanism of its implementation (computing);

– metarules have access to all *KB* levels below;

– metarules receive input data (signals) from the «outside world». The structure of the input data may differ from the internal representation of the *KB*;

– metarules act as an interface between the intelligent system and the IU;

– metarules may not form network structures, since the logic of use is determined by the operation of the intelligent system, and not by the logic of the *KB*.

Metarule *MR* will be represented by the following relation:

$$MR:\underset{i=1}{\overset{n}{Lop}}\,S_{MRi}\to O_{KBj}, \tag{14}$$

where *Lop* is logical operation, AND ($\wedge$) or OR ($\vee$) connective, related to metarule states. NOT ($\neg$) operation is used when $n=1$ and usually implemented in the antecedent of the metarule; S_{MRi} is the current metarule condition; O_{KBj} is one of the operations of labeling or structuring the *KB* (given in formulas (8)–(13)), $O_{KBj}\in O_{KB}$; $\to$ is the implication operation, here – application of the operation O_{KBj}.

It is necessary to specify that the logical operations (connectives) implemented in metarules in relation to *KB* clusters consider the sign of activity (actualization) of these clusters. Metarule understands activation or actualization of the cluster or its element as the labeling condition $a=1$.

The graphic illustration of the proposed metarule model is shown in Fig. 2, which shows that the metarule can be applied to all levels of the knowledge representation system.

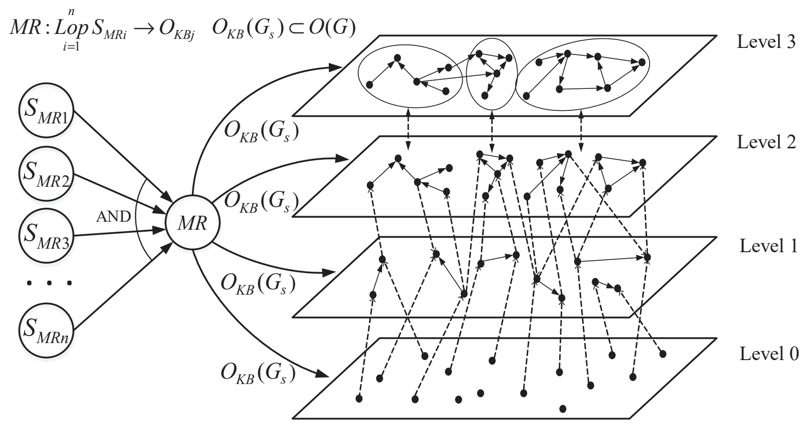

Fig. 2. Model of metarule application in relation to ontology evolution

Assuming that the base of metarules is normalized, the properties of the production level *MR* should be as follows:

$$N_{MR}=S_{MR}^{c_1}\bigcup S_{MR}^{c_2}\bigcup ...\bigcup S_{MR}^{c_m}\bigcup$$
$$\bigcup O_{KB}^{c_1}(G_S)\bigcup O_{KB}^{c_2}(G_S)\bigcup ...\bigcup O_{KB}^{c_n}(G_S)=$$
$$=\bigcup_{i=1}^{m}S_{MR}^{c_i}\cup\bigcup_{i=1}^{n}O_{KB}^{c_i}(G_S), \qquad (18)$$

$$S_{MR}^{c_1}\bigcap S_{MR}^{c_2}\bigcap ...\bigcap S_{MR}^{c_m}=\bigcap_{i=1}^{m}S_{MR}^{c_i}=\varnothing, \qquad (19)$$

$$O_{KB}^{c_i}(G_S)\bigcap O_{KB}^{c_2}(G_S)\bigcap ...\bigcap O_{KB}^{c_n}(G_S)=$$
$$=\bigcap_{i=1}^{n}O_{KB}^{c_i}(G_S)=\varnothing. \qquad (20)$$

Generally, metarules can be of AND and OR types. Moreover, their structure is described in the same way. They are run in accordance with the rules of conjunction or disjunction. During unification, OR type rules can be divided into AND type rules by the number of entries. Thus, only conjunctive forms of metarules can be used. As noted earlier (and in accordance with the definition of metaknowledge), the metarule implements the control mechanism in relation to *KB* levels. Arcs show the directions of influence and implementation of the control functions by the metarule in relation to the *KB* hierarchy levels. The input elements of the metarule $\{S_{MRi}\}$ represent the signal data from the DSS software environment (IU, user). The figure on the right shows the hierarchy (evolution) of ontologies and formal models.

Implication in the metarule occurs on the basis of actualization of the antecedent – $\mathop{\wedge}\limits_{i=1}^{n}S_{MRi}$ or $\mathop{\vee}\limits_{i=1}^{n}S_{MRi}$. In the case of validity of the combined condition, the consequent is implemented as actions in relation to the signal graphs of the *KB* hierarchy levels.

Let's set a metarule tuple similarly, but specifying the features of its functioning:

$$MR=<S_{MR}, L, A\rightarrow B, Q>, \qquad (15)$$

where S_{MR} is the class of signaled states of the *KB*, DSS, environment, for which the MR metarule is applicable; *L* is the metarule trigger condition; $A\rightarrow B$ is the core (structure) of the metarule; *Q* is the informal production substantiation.

We formalize the metarule core, considering its specifics.

The terminal alphabet of metaproduction is the set:

$$\Sigma=A_t=\{\varepsilon\}\bigcup S_{MR}\bigcup O_{KB}(G_S), \qquad (16)$$

where S_{MR} are identifiers of signaled states in accordance with (15); $O_{KB}(G_S)$ are identifiers of operations on *KB*.

The synthesis of a formal metarule model is described as a procedure of logical combination of signaled state S_{MRi} of the complex (KB-IU-DSS-environment) and operations from the set $O_{KB}(G_S)$, meeting the following condition:

$$\exists\left(\mathop{\vee}\limits_{i=1}^{n}S_{MRi},\mathop{\wedge}\limits_{i=1}^{n}S_{MRi}\mid S_{MRi}\in S_{MR}\right)\exists$$
$$\exists\left(O_{KBi}(G_S)\mid O_{KBi}(G_S)\in O_{KB}(G_S)\right)$$
$$\left(\left(\mathop{\vee}\limits_{i=1}^{n}S_{MRi}\right)\vee\left(\mathop{\wedge}\limits_{i=1}^{n}S_{MRi}\right)\rightarrow O_{KBi}(G_S)\right). \qquad (17)$$

The term «normalization» is used in the field of relational databases, but in a more general sense. It is assumed that the process of «normalization» in relation to the knowledge base consists primarily in removing redundancy and inconsistency of the *KB*. In addition, mechanisms to reduce the *KB* volume are proposed.

The integrity of the metarule base can be ensured by the same principles as the integrity of the *KB*, by introducing a system of constraints on the *KB* elements.

The issues of preserving the previously defined connections between individual concepts, as well as the issues of preserving other attributes of the *KB*, are provided by common means of *KB* support. Different levels of knowledge management are different levels of interpretation of the same basic elements – concepts and relations between them. The knowledge base is built only of these elements. Therefore, when moving to higher levels, elements of the basic level of concepts are always used.

We introduce the syntax of the metarule base:

<metarule base> ::=<metarule>[<metarule>];

<metarule> ::=

<type> <condition_id>[<condition_id>]

<operation_id>;

<type> ::= AND | OR;

<condition_id> ::=<situation_code>;

<operation_id> ::=<operation_code>.

Here, the terms <situation_code> and <operation_code> are obtained from the identifiers <condition_id> and <operation_id> after compiling the *KB*.

Represent the formal language of the model of metarules of ontology hierarchy as follows:

$$L(G)_{MR}=<\Sigma_{MR},N_{MR},P_{MR},S_{MR}>, \qquad (21)$$

where *G* is the formal grammar of the metarule set; Σ_{MR} is the main terminal alphabet of the metarule set; N_{MR} is the auxiliary non-terminal alphabet of the metarule set; P_{MR} are rules of substitution (production) of the formal network grammar: $\exists a,\exists b,(a,b)\in P_{MR}:a\rightarrow b$; S_{MR} is the starting non-terminal symbol of grammar *G*, where $N_{MR}\bigcap\Sigma_{MR}=\varnothing$ and $P_{MR}\subset((N_{MR}\cup\Sigma_{MR})^{+}\times(N_{MR}\cup\Sigma_{MR})^{*})$.

Now we define the formal grammar rules P_{MR} for the metarule set language $L(G)_{MR}$:

$$S_{MR}\rightarrow MR^{C_i},$$

$$MR^{C_i}\rightarrow <and>S_{MR}^{C_i}O_{KB}^{C_i},$$

$$MR^{C_i} \to <or> S_{MR}^{C_i} O_{KB}^{C_i},$$

$$MR^{C_i} \to <and> S_{MR}^{C_i} \,|[S_{MR}^{C_i}] O_{KB}^{C_i},$$

$$MR^{C_i} \to <or> S_{MR}^{C_i} \,|[S_{MR}^{C_i}] O_{KB}^{C_i}.$$

Develop a structural-linguistic ontology model for the *KB* level of metarules – KB_{MR}:

$$O_{KB}^{MR} = < X^{MR}, R^{MR}, F^{MR} >. \quad (22)$$

The ontology concepts of metarules are contextual metarule clusters consisting of subsets of situations and operations. Then for all clusters of all contexts we have:

$$X^{MR} = N_{MR} = \{\{S_{MRk}^{c_i} \,|\, k = 1, n_s\} \,|\, i = 1, n_C\} \cup \cup \{\{O_{KBk}^{c_i} \,|\, k = 1, n_O\} \,|\, i = 1, n_C\} = = \bigcup_{i=1}^{n_C} \left\{ \bigcup_{i=1}^{n_S} S_{MRk}^{c_i} \cup \bigcup_{k=1}^{n_O} O_{KBk}^{c_i} \right\}. \quad (23)$$

However, operations $O_{KBk}^{c_i}$ are implemented in relation to the structural elements of the *KB*, which is a signal graph. Therefore, the result of the operation will depend on the structure and labeling of the graph immediately before the operation and it should be considered as a function of the current state of the *KB* graph:

$$O_{KBk}^{c_i} = F_k^{c_i}(P(G_s), A(G_s), M_\Sigma). \quad (24)$$

Then

$$X^{MR} = \bigcup_{i=1}^{n_C} \left\{ \bigcup_{i=1}^{n_S} S_{MRk}^{c_i} \cup \bigcup_{k=1}^{n_O} F_k^{c_i}(P(G_s), A(G_s), M_\Sigma) \right\}. \quad (25)$$

From (24) it also follows that the result of the operation will be a new *KB* structure, and, therefore, at the next iteration a different structure of metarules should be used. Thus, the structure of the relations of the applied metarules $R(MR)$ depends on the structure (state) of *KB* levels. In other words, for two *KB* states (*KB′* and *KB″*), it is fair to write

$$O_{KBk}^{c_i} : KB' \to KB'',$$

$$R(MR') : f(R(KB')),$$

$$R(MR'') : f(R(KB'')),$$

$$R(MR) = F(R(KB)). \quad (26)$$

To determine the set of interpretation functions F^{MR}, it is necessary to consider that operations $O_{KB}^{C_i}$ in relation to the levels of ontology incorporation correspond to the evolutionary hierarchy of knowledge forms, and, therefore, are hierarchically nested. Therefore, complex operations can be considered as a superposition of simpler ones. Consequently, high-level metarules can be interpreted through elementary sets.

Let O_{KBj} be a superposition:

$$O_{KBj} = O_{KB1} \circ O_{KB2} \ldots \circ O_{KBn}.$$

Then

$$MR : \underset{i=1}{\overset{n}{Lop}} S_{MRi} \to O_{KBj},$$

$$MR : \underset{i=1}{\overset{n}{Lop}} S_{MRi} \to (O_{KB1} \circ O_{KB2} \ldots \circ O_{KBn}),$$

$$MR_n : \underset{i=1}{\overset{n}{Lop}} S_{MRi} \to O_{KBn}, \ \ldots \ MR_2 : \underset{i=1}{\overset{n}{Lop}} S_{MRi} \to O_{KB2},$$

$$MR_1 : \underset{i=1}{\overset{n}{Lop}} S_{MRi} \to O_{KB1},$$

and, therefore,

$$MR_j = MR_n \circ MR_{n-1} \circ \ldots \circ MR_2 \circ MR_1. \quad (27)$$

Consequently, the interpretation function f_j for the metarule MR_j in general can be represented as:

$$f_j^{MR} : Op(MR_n \circ MR_{n-1} \circ \ldots \circ MR_2 \circ MR_1, I_j) \to \to (MR_j, I_j) \,|\, f_j^{MR} \in F^{MR}, \quad (28)$$

where *Op* is the operation of aggregation (superposition) of metarules; I_j is the index of the applicability context of metarules.

On the basis of the developed structural-set models, the formal model of the unified ontology of metarules for the level of knowledge evolution of «Metaontology» type is obtained.

$$O^{MR} = < \bigcup_{i=1}^{n_C} \left\{ \bigcup_{i=1}^{n_S} S_{MRk}^{c_i} \cup \bigcup_{k=1}^{n_O} F_k^{c_i}(P(G_s), A(G_s), M_\Sigma) \right\}, F(R(KB)), F^{MR} >. \quad (29)$$

4. 5. Experimental confirmation of research results

For experimental confirmation of research results, a test *KB* and a metarule base for managing knowledge levels were built. After the formation of the concept thesaurus and translation into minimum length codes, fact codes and metarule codes were formed. On this basis, operations on the structure of facts are implemented by labeling their signal graphs. Analysis of practical results showed that labeling is an effective means of *KB* modification. For example, the formation of a new fact on the basis of the thesaurus requires labeling of only two new connections – recording two numerical codes of the signal graph arcs in the *KB*. The detailed practical example of using metarules is given below.

Let us give an example of practical use of the developed mathematical models for the representation of metarules and the model of professional ontology O^{MR} – knowledge base (KB^{MR}) (Fig. 3).

We introduce sets of atomic sentences related to the same context c^0:=«7.2 Elimination of technological violations in case of de-energization of busbars 150–330–750 kV.».

$s_1^{c_0}$ – «DS-8 manual», $s_2^{c_0}$ – «p. 7.2.1», $s_3^{c_0}$ – «Voltage is supplied on BB after inspection, identification and separation of the damaged connection or BB element and removal of people from the SG».

S_{MR1}:=<Add a new fact to the *KB*>.

S_{MR2}:=$<s_1^{c_0}><s_2^{c_0}><s_3^{c_0}>$.

O_{KB1} :=<Add a new fact to the level 2 semantic network $<s_1^{c_0}><s_2^{c_0}><s_3^{c_0}>$ and connect it to the context>

O_{KB2} :=<Add atomic semantic units – $<s_1^{c_0}>, <s_2^{c_0}>, <s_3^{c_0}>$ to the thesaurus (layer 0)>

O_{KB3} :=<Add the node $<s_1^{c_0}>$ to the level 1 structure; Add the node $<s_3^{c_0}>$ to the level 1 structure; Add the relation $<s_2^{c_0}>$ between the nodes $<s_1^{c_0}>$ and $<s_3^{c_0}>$>

O_{KB4} :=<Add the subgraph $<s_1^{c_0}><s_2^{c_0}><s_3^{c_0}>$ to the level 2 graph. Establish connection with the context network C^0>

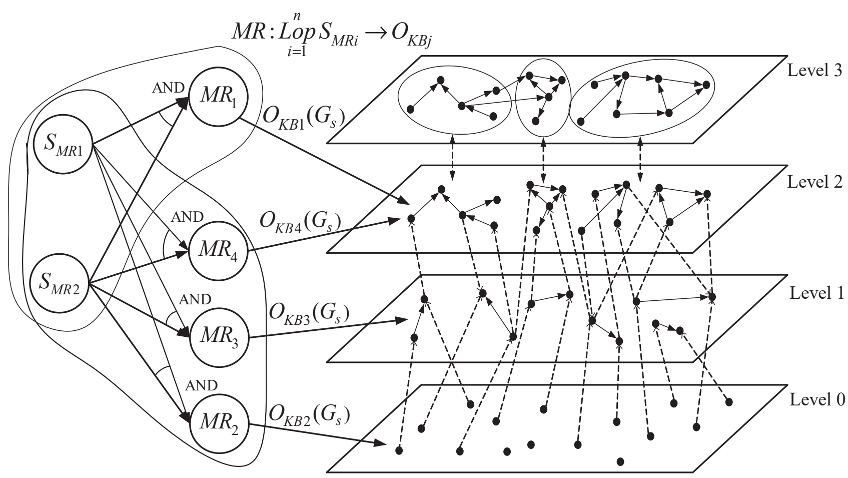

Fig. 3. Example of the interpretation scheme in metarule ontology

Metarules have the following form:

$$MR_1^{C_0} := <and> S^{C_0}_{MR1} S^{C_0}_{MR2} O^{C_0}_{KB1};$$

$$MR_2^{C_0} := <and> S^{C_0}_{MR1} S^{C_0}_{MR2} O^{C_0}_{KB2};$$

$$MR_3^{C_0} := <and> S^{C_0}_{MR1} S^{C_0}_{MR2} O^{C_0}_{KB3};$$

$$MR_4^{C_0} := <and> S^{C_0}_{MR1} S^{C_0}_{MR2} O^{C_0}_{KB4}.$$

We show the practical implementation of one of the metarules of the reduced system – $MR_1^{C_0} := <and> S^{C_0}_{MR1} S^{C_0}_{MR2} O^{C_0}_{KB1}$.

AND
<Emergency response instructions>
<Add a new fact to the *KB*>
<<DS-8 manual> <p. 7.2.1> <Voltage is supplied on BB after inspection, identification and separation of the damaged connection or BB element and removal of people from the SG>>
<Add a new fact to the level 2 semantic network and connect it to the context>

Or (with examples of codes) after translation:

AND<027B><002C><01A3 00D8 10F5><0004>,

where 027B is the context code; 002C is the metarule code; 01A3 00D8 10F5 are the codes of fact concepts; 0004 is the code of the operation of adding a fact to the *KB*.

As a result, the codes of fact concepts <01A3 00D8 10F5> will be recorded in the *KB*, connected to each other in the node adjacency matrix and with the corresponding context. Further, the fact becomes suitable for work.

Now the interpretation function for the metarule level will be:

$$f_1^{MR}: Op(\{(MR_2^{C_0}, c^0), (MR_3^{C_0}, c^0), (MR_4^{C_0}, c^0)\}) \to$$
$$\to (MR_1^{C_0}, c^0).$$

Thus, the structural-linguistic model of the unified professional ontology of the metarules level is theoretically substantiated and practically constructed.

5. Discussion of the results of research of management of evolutionary incorporation of knowledge levels using metarules

The obtained results of structural and logical modeling of knowledge levels as signal graphs and their labeling adequately model the processes of dynamic synthesis of knowledge structures and allow building metarule models for effective *KB* management.

It should be noted that the mechanism of metarules does not depend on the level of knowledge incorporation and can be dynamically implemented in relation to any of them.

The features of the proposed method and the results obtained in comparison with the existing ones are that the developed models of the *KB* and metarules are invariant to professional fields, which makes the proposed mechanisms of metarules universal. The proposed mathematical apparatus, combining the formalism of the signal graph and the function of its labeling, is an effective means of knowledge representation and a promising tool for mass production of decision support systems.

The problem of efficiency and speed of the *KB* has two components. The first is *KB* preparation, including formation of metarules and knowledge processing. The second is the time of entering the source data.

Preparation (filling, verification) of the knowledge base is made in the preparatory period out of the process of direct operation. When new conclusions (knowledge) appear, their introduction into the *KB* takes minimum time with the user's consent (or rejection).

Entering source data identifying the task is a really big problem. It is solved by a combination of two approaches. Firstly, all known parameters of situations are introduced into the *KB* in advance at the preparation stage. Therefore, in the process of work, the situation is identified in relation to the accumulated models. Secondly, introduction of initial data should be read to the maximum extent from the control object sensors. In this case (in the limit), the DSS goes to the automatic system mode. However, part of the data is entered manually, and the operator makes intermediate decisions in the process of dialogue with the system. In this case, the latter is automated and aimed at automating the management and decision-making process.

The proposed models for labeling graph vertices and edges, as well as signal propagation for modeling the process of inference, have the advantage of allowing the dynamic formation of clusters of intelligent networks. Such networks can be viewed as fact sets, semantic networks, or production networks. As particular cases, reference books, relational databases or subsets of artificial neural networks can be formed of signal graphs.

As a limitation of the proposed models, we can consider a strongly connected *KB* graph and a long time of traversal. However, this restriction can be compensated for by clustering a large *KB* on the basis of the task context.

The disadvantages of the study include the following circumstances. In terms of compliance of the developed models of the signal graph to physical models, further specification of formal representation of signal propagation between nodes with different atomic concept potentials is required. It is proposed to adjust the direction of signal propagation in the network by the potential difference of the signal graph vertices. However, this raises the problem of signal backpropagation, which may contradict the logical reasoning model. This problem is the subject of further theoretical studies and practical testing. It can be solved by introducing additional restrictions on the directions of the signal graph arcs into formal-logical models, for example, in the form of a ban on negative weights of arcs.

The main directions of research development are to improve and increase the rigor of the mathematical apparatus to ensure its compatibility with related disciplines of information technology.

6. Conclusions

1. Mathematical models of procedures for the synthesis of knowledge structures of all levels are developed. It is shown that mathematical models of procedures are based on a minimum set of standard actions in relation to the graph structure of knowledge levels. Subtasks of developing models of evolutionary inheritance of concepts, graphs and ontologies of *KB* levels are solved. For these subtasks, formal linguistic models are developed, the similarity of forms of knowledge representation and evolutionary inheritance within the general ontology incorporation are proved.

2. The basic model of the elementary signal graph of the knowledge base is developed. Formalisms of the labeling parameter and the labeling function of the elementary signal graph of the *KB* are introduced. The rule of signal propagation based on the potentials of nodes, which are set by the labeling function and can dynamically change during signal passage, is substantiated.

3. The model of labeling the signal graph of the knowledge base is substantiated and developed. The developed model includes labeling of graph nodes and edges, by giving them labeling parameters – concept value, node potential, node sensitivity threshold, node activity sign, edge conductance (transmission). Formal definitions of the specified labeling parameters are given. Formal definitions are expressed by labeling functions reflecting a particular graph node or edge in a set of their labeling parameters.

4. Structural and functional models of metarules based on the model of the elementary signal graph are developed. On the basis of the developed model, the basic model of the flow of inference between ontology concepts in the elementary column of the *KB* is proposed, which made it possible to form a set of formal models of a set of basic operations on the signal graph of the *KB* necessary for interpretation and computing of knowledge forms.

References

1. Bartolomey P. I., Tashchilin V. A. Informacionnoe obespechenie zadach elektroenergetiki: ucheb. pos. Ekaterinburg, 2015. 108 p.
2. Morkun V., Tron V. Ore preparation multi-criteria energy-efficient automated control with considering the ecological and economic factors // Metallurgical and Mining Industry. 2014. Issue 5. P. 4–7. URL: http://www.metaljournal.com.ua/assets/Journal/1-MorkunTron.pdf
3. Besanger Y., Eremia M., Voropai N. Major Grid Blackouts: Analysis, Classification, and Prevention // Handbook of Electrical Power System Dynamics. 2013. P. 789–863. doi: https://doi.org/10.1002/9781118516072.ch13
4. Smolovik S. V. Rol' «chelovecheskogo faktora» v razvitii krupnyh sistemnyh avariy // ELEKTROENERGETIKA. 2008. Vol. 1, Issue 1. P. 16–19.
5. Avariynist na obiektakh elektroenerhetyky Ukrainy u 2005 rotsi. Haluzevyi informatsiynyi dokument // Obiednannia enerhetychnykh pidpryiemstv «Haluzevyi rezervno-investytsiynyi fond rozvytku enerhetyky». Kyiv: Vydavnytstvo «Enerhiya», 2005. 102 p.
6. Kalibataitė G. The Importance of Meta-Knowledge for Business and Information Management // Social Technologies. 2011. Vol. 1, Issue 1. P. 163–178.
7. Nasrollahi S. N., Mokhtari H., Seyedein M. Meta-analysis: An Approach to Synthesizing and Evaluating Research on Knowledge and Information Science // Iranian Journal of Information Processing & Management. 2011. Vol. 29, Issue 2. P. 293–316.
8. Morkun V., Tcvirkun S. Investigation of methods of fuzzy clustering for determining ore types // Metallurgical and Mining Industry. 2014. Issue 5. P. 12–15. URL: http://www.metaljournal.com.ua/assets/Journal/3-MorkunTs.pdf
9. Open Data as a key factor for developing expert systems: a perspective from Spain / Rodriguez-Rojas L. A., Cueva-Lovelle J. M., Tarazona-Bermudez G. M., Montenegro-Marin C. E. // International Journal of Interactive Multimedia and Artificial Intelligence. 2013. Vol. 2, Issue 2. P. 51. doi: https://doi.org/10.9781/ijimai.2013.226
10. Ligeza A. Knowledge Representation and Inference for Analysis and Design of Database and Tabular Rule-Based Systems // Computer Science. 2001. Vol. 3, Issue 1. P. 13–60.
11. Miah S. J., Genemo H. A Design Science Research Methodology for Expert Systems Development // Australasian Journal of Information Systems. 2016. Vol. 20. doi: https://doi.org/10.3127/ajis.v20i0.1329
12. Morkun V., Morkun N., Tron V. Formalization and frequency analysis of robust control of ore beneficiation technological processes under parametric uncertainty // Metallurgical and Mining Industry. 2015. Issue 5. P. 7–11. URL: http://www.metaljournal.com.ua/assets/MMI_2014_6/MMI_2015_5/001-Morkun.pdf
13. Kuznecov O. P., Suhoverov V. S., Shipilina L. B. Ontologiya kak sistematizaciya nauchnyh znaniy: struktura, semantika, zadachi // Trudy konferencii «Tekhnicheskie i programmnye sredstva sistem upravleniya, kontrolya i izmereniya». Moscow: IPU RAN, 2010. P. 762–773.
14. The impact of knowledge management processes on information systems: A systematic review / Al-Emran M., Mezhuyev V., Kamaludin A., Shaalan K. // International Journal of Information Management. 2018. Vol. 43. P. 173–187. doi: https://doi.org/10.1016/j.ijinfomgt.2018.08.001

15. Sedighi S. M., Javidan R. Semantic query in a relational database using a local ontology construction // South African Journal of Science. 2012. Vol. 108, Issue 11/12. doi: https://doi.org/10.4102/sajs.v108i11/12.1107
16. From reference ontologies to ontology patterns and back / Ruy F. B., Guizzardi G., Falbo R. A., Reginato C. C., Santos V. A. // Data & Knowledge Engineering. 2017. Vol. 109. P. 41–69. doi: https://doi.org/10.1016/j.datak.2017.03.004
17. Duer S., Wrzesień P., Duer R. Creating of structure of facts for the knowledge base of an expert system for wind power plant's equipment diagnosis // E3S Web of Conferences. 2017. Vol. 19. P. 01038. doi: https://doi.org/10.1051/e3sconf/20171901038
18. Xamena E., Brignole N. B., Maguitman A. G. A Structural Analysis of topic ontologies // Information Sciences. 2017. Vol. 421. P. 15–29. doi: https://doi.org/10.1016/j.ins.2017.08.081
19. Gadomski A. M. From Know-how to How-to- Know: An Approach to Knowledge Ordering for Specification of Complex Problems (TOGA methodology) // Presented at the International Symposium on Computational Intelligence. Milan, 1989.
20. Shabanov-Kushnarenko Yu. P. Teoriya intellekta. Matematicheskie sredstva. Kharkiv, 1984. 144 p.
21. Dudar' Z. V., Kalinichenko O. V., Shabanov-Kushnarenko S. Yu. About a method and problems of the theory of intellect. I // Radioelektronika i informatika. 2000. Issue 2. P. 112–122.
22. Shabanov-Kushnarenko S. Yu., Kudhair Abed Tamer, Leschynskaya I. A. The predicative approach to non-obvious knowledge formalization // Systemy obrobky informatsiyi. 2013. Issue 9. P. 113–116.
23. Bashmakov A. I., Bashmakov I. A. Intellektual'nye informacionnye tekhnologii: ucheb. pos. Moscow, 2005. 304 p.
24. Genesereth M. R., Fikes R. E. Knowledge Interchange Format. Reference Manual. Computer Science Department, Stanford University Stanford, California, 1992. 68 p.
25. Yalovec A. L. Predstavlenie i obrabotka znaniy s tochki zreniya matematicheskogo modelirovaniya problemy i resheniya. Kyiv: Naukova dumka, 2011. 339 p.
26. Emergence and complex systems: The contribution of dynamic graph theory / Gignoux J., Chérel G., Davies I. D., Flint S. R., Lateltin E. // Ecological Complexity. 2017. Vol. 31. P. 34–49. doi: https://doi.org/10.1016/j.ecocom.2017.02.006
27. Wiener G. On constructions of hypotraceable graphs // Electronic Notes in Discrete Mathematics. 2016. Vol. 54. P. 127–132. doi: https://doi.org/10.1016/j.endm.2016.09.023