Proceedings of the Federated Conference on
Computer Science and Information Systems pp. 47–53

ISBN 978-83-60810-22-4

Logical Inference in Query Answering Systems Based on Domain Ontologies

Juliusz L. Kulikowski
Nalecz Institute of Biocybernetics
and Biomedical Engineering PAS,
4, Ks. Trojdena Str,
02-109 Warsaw, Poland
Email:
juliusz.kulikowski@ibib.waw.pl

***Abstract*—This paper describes a proposal of using ontological models as a basis of Query Answering Systems design. It is assumed that the models are presented in the form of relations described on some classes of items (ontological concepts) specified by taxonomic trees. There are analyzed the sufficient and necessary conditions for getting the replies to the queries as solution of relational equations based on the data provided by ontological databases. Simple examples illustrate basic concepts of practical realization of the Query Answering Systems based on domain ontologies.**

***Index Terms*—query answering systems, domain ontologies, relations, relational equations,**

I. Introduction

DOMAIN ontology is a tool of formal representation of knowledge concerning an application area that in a decision problem should be taken into consideration. The application area knowledge can in general in many different forms be represented. Despite the traditional, descriptive form, rather unsuitable to computer implementation purposes, various types of knowledge can be presented by propositional logic terms [1] graphs (including their specific forms like trees [2], Petri nets [3], PERT networks [4], Bayesian networks [5], etc.), Horn clauses [6], semantic networks [7], Minsky frames [8], etc., less or more useful in a given decision problem. Generally speaking, a domain knowledge consists of verified data concerning the domain, its general nature, components, structure, properties of the components and satisfied by them relations. The above-mentioned formal tools to presentation of various aspects of the domain knowledge can be used. Otherwise speaking, they make possible construction of formal models of selected aspects of the application domain under consideration. The model should specify the concepts used to the application domain characterization and the existing among them physical, logical, organizational, etc. relationships. This leads to a domain ontology described by a quadruple [9]:

$$O = [C, R, A, Top] \qquad (1)$$

where: C – a non-empty set of concepts,
R – a set of relations among the concepts,
A – a set of axioms,
Top – a highest-level concept in C.

Among the relations a taxonomy of concepts headed by *Top* is mandatory, other relations are established according to the application problem needs.

This is illustrated by the following example.

Example 1.

A problem consists in calculation of a voltage drop on an electric resistor. This is well known that the solution is given by the Ohm law:

$$U = I \cdot r \qquad (2)$$

where U denotes the *voltage drop* [V] , I – *current intensity* [A], r – resistor *resistance* [Ω]. However, the problem can also be described by a domain ontology formalism. The domain ontology is ten given by (1) where:

C = {*electric current flow, physical entities, measurable parameters, resistor, electric current, electric tension, electric resistance r, current intensity I, voltage drop U*};

R = {a taxonomy T of concepts (see below), relationships between the concepts, formula (*2*)};

A = {*axioms concerning real functions*};

Top = *electric current flow*.

The taxonomy T of concepts can be presented in the form of a tree (Fig.1.):

electric current flow
- *physical entities*
  - *resistor*
  - *electric current*
  - *electric tension*
- *measurable parameters*
  - *electric resistance r*
  - *current intensity I*
  - *voltage drop U*

Fig. 1. A taxonomic tree of concepts constituting a domain ontology *electric current flow*.

The domain ontology should also contain a relation not following directly from the taxonomic tree, assigning *measurable parameters* to the *physical entities*. The relation D (*described by*) is given by a set of ordered pairs:

D = {[*resistor, electric resistance r*],
[*electric current, current intensity I*],
[*electric tension, voltage drop U*]}.

So-presented domain ontology contains full information necessary to solve the above-formulated task. At a first glance it may see that the ontological description of the given application domain is too much complicated; this is because in practice, in a simplified reality description most of the ontology components by default are assumed. Nevertheless, solutions of a large class of simple physical, engineering, economical, management etc. tasks consciously or unconsciously on the corresponding domain ontologies are based. On thee other hand, domain ontologies presented by (1) in many other cases are insufficient. For example, description of an enterprise (a domain) should consist of components concerning its organizational structure, personal staff, administrative procedures, services, etc. The relationships between the staff members and the administrative procedures, the services and the organizational sections etc. play a substantial role in the enterprise functioning description, however, they do not follow directly from the domain ontology presented in the above-given form. This problem has also been remarked in [9] where an attempt to construct a taxonomy for the *blood* concept led to the necessity of *blood* characterization as a *fluid* and as a biological *tissue*. Each aspect of a composite real object like an enterprise, blood circulatory system, large educational project, etc. constitutes a specific sub-domain which by its proper ontology should be described. A formal description of such object should thus rather by several sub-domain ontologies than by a single, general domain ontology be presented. It also seems clear that a multi-aspect description of a composed object would be difficult when a single, unified taxonomic tree of concepts is used. E.g., in a domain representing a certain city, an entity *City Hall* of the corresponding taxonomic tree, as having several aspects, should be included into the sub-trees *Architectural monuments*, *Municipal offices*, *City communication sites*, etc. However, this destroys the structure of a single taxonomy tree where each concept by only one node should be represented. On the other hand, if the original concept *City Hall* is split into three separate concepts, say: $City\ Hall^1$, $City\ Hall^2$, $City\ Hall^3$ then it arises a problem, how in the taxonomic tree some pairs, triples, etc. of nodes should be to the same physical object assigned. Entering into consideration a concept of *multi-model domain ontologies* removes the above-mentioned difficulty. In such case, the domain ontology should also contain a set *Q* of higher-level relations (*super-relations*) among the relations constituting the ontological models. The concept of *ontological models* defined as sub-domain ontologies used to formal description of various aspects of a higher-level application domain has been introduced in [11]. The more general, multi-aspect domain ontology definition takes thus the form:

$$O = \{OM_1, OM_2, \ldots, OM_l;\ Q;\ A\} \qquad (3)$$

where:

OMi – ontological models of the sub- domains;

Q – a family of *super-relations* over the models;

A – an extended algebra of relations and super-relations.

This concept is convergent with a represented by other Authors [12], [13] general tendency to base domain ontologies on strong mathematical backgrounds. In the below-presented case mathematical set theory and extended relations algebra is used as a basic tool for domain ontologies formal description. Domain ontology given in the form (3) provides a basic information that makes possible reasoning about objects belonging to the given domain and relations among them not directly specified by the ontological models.

However, also this concept has some drawbacks caused by the dependencies between the component ontological models leading to a problem of effective logical reasoning based on the statements drawn from several different ontological models. The problem has been partially analyzed in a context of using domain ontologies to computer-aided image understanding [14]. In the present paper a problem of logical inference in computer query answering systems (QAS) based on domain ontologies is more largely presented. In particular, the concepts of *relational equations* and of *reversed relations* using to logical inference improvement is below presented. Basic concepts of the extended algebra of relations and super-relations have been presented in the papers [14]-[16] and here only roughly are described. The paper is organized as follows: In Sec. II selected basic concepts used in the paper are shortly presented. Sec. III presents the idea of the relationships among the ontological models description by super-relations. Sec IV contains a proposal of using reversed relations to improve the effectiveness of reasoning based on the statements drawn from the domain ontology. Conclusions are given in Sec. V.

II. Basic Concepts

A. Ontologies

Generally speaking, ontology is a philosophical concept while domain ontology in computer science is a notion related to a formal description of a selected, less or more complicated, part of reality. Domain ontology is also not a mathematical notion, but it in mathematical terms can be described. However, a certain duality of terms used in domain ontologies occurs and needs to be explained. In particular, concepts in ontological sense are equivalent to classes or to sets in a mathematical sense. A taxonomy of concepts T in ontology is represented by a rooted tree in the graph theory sense while the highest-level concept Top is the root of the tree. The leafs (lowest-level nodes) of a tree are in ontological sense interpreted as instances of the closest higher-level ontological concepts, usually representing some basic, individual objects of the described reality. Relations in the mathematical sense (see below) may denote not only simple set theory relations but also any algebraic or functional, discrete or continuous, deterministic or fuzzy relations. Entities described by ontological models are objects if considered in the application domain context while from ontological models point of view are instances satisfying the corresponding relations. The family Q of super-relations (see below) in (3) in ontological sense can be interpreted as a domain knowledge structure.

B. Relations and super-relations

For description of a relation r between the elements of a finite family of sets $S_1, S_2,...,S_K$ they should be linearly ordered in a logical sense and then the family can be denoted by $[S_k]$, $k = 1,2,..., K$ or, shortly, by $[S_k]_1^K$. However, the logical order is not obviously identical to the physical one assuming that the a permutations transforming the logical order into the physical one (and vice versa) are defined. For the sake of simplicity, below, any logical order of a linearly ordered set will be assumed to be identical to the one of its presentation in the text. This is substantial for correct understanding of the operations of the extended algebra of relations.

A Cartesian product of a family of sets $[S_k]_1^K$ will be denoted by $\boldsymbol{C}$. If $|S_k|$ denotes a cardinal number of elements of S_k then $|\boldsymbol{C}| = |S_1|\cdot|S_2|\cdot \ldots \cdot|S_K|$. The relation is called *finite* if $|\boldsymbol{C}|$ is finite. Any subset

$$\rho \subseteq \boldsymbol{C} \tag{4}$$

is called a *relation* described on $[S_k]_1^K$. The number K is called a *length* of the relation while the maximum among the cardinal numbers $|S_1|, |S_2|,\ldots,|S_K|$ is called an *extent* of the relation. The relation is called an *empty relation* if it is an empty set; in such case it is denoted by $\boldsymbol{\theta}$. The relation ρ is called a *trivial relation* if $\rho \equiv \boldsymbol{C}$. For a given relation ρ any subset ρ', $\rho' \subseteq \rho$, is called a *sub-relation* of ρ while ρ is called an *over-relation* of ρ'. For a given relation ρ described on $[S_k]_1^K$ any *K-tuple* $\boldsymbol{s} = [s_1, s_2, \ldots ,s_K]$ belonging to ρ is called an *instance* of the relation. For a given sub-family of n sets $[S_p, S_q,...,S_t] \subseteq [S_k]_1^K$ (preserving its original logical order), and their Cartesian product denoted by $\boldsymbol{C}^*$, the corresponding elements of the instances $\boldsymbol{s}$ of ρ determine linearly ordered n-tuples ($n \leq K$) belonging to $\boldsymbol{C}^*$. The set ρ^* constitutes a relation called a *partial relation* of ρ created by its projection on $[S_p, S_q,...,S_t]$; in such case it is said that ρ is an *extension* of ρ^*.

In computer realization, due to the necessity of numerical data quantization, all relations are approximated by the finite ones. In a finite relation of finite length a coefficient:

$$d = \frac{|\rho|}{|C|} \tag{5}$$

is called a *density* of the relation.

Due to the fact that relations are described as subsets of Cartesian products the general set algebraic notions to the relations can be applied. In particular, if a countable linearly ordered family of sets F is taken into consideration and 2^F denotes a class of all its sub-families (including a null sub-family $\emptyset$ and 2^F itself) then it can be taken into consideration a family $\boldsymbol{\Omega}$ of all possible relations described on the linearly ordered sub-families of 2^F. In $\boldsymbol{\Omega}$ the ordinary set algebra can be interpreted as an *extended algebra of relations* described on the sub-families of 2^F [15]. The so-defined *extended algebra of relations* is a Boolean algebra with $\boldsymbol{\theta}$ as its null-element and $\boldsymbol{\Omega}$ as its unity element. The result of an algebraic operation (sum, intersection, difference) performed on any two relations ρ', ρ'' described, respectively, on the families of sets F', F'' is by a definition a relation described on $F' \cup F''$ (this is not so in a "traditional" algebra of relations defined on the families of all relations described on a fixed family of sets). The extended algebra of relations admits algebraic operations on finite algebraic compositions of other relations.

In a family $[S_k]_1^K$ of sets on which a relation is described some sets may be defined as relations described on lower-level sub-families of sets. This leads to the concept of *super-relations* as relations whose instances contain variables being instances of some lower-level relations. The structure of a super-relation may be presented by a multilevel bracket-expression, like e.g.:

$$\rho \subseteq S_1\times [S_2\times[S_3\times S_4]]\times S_5\times S_6$$

representing a three-level super-relation. It should be remarked that the above-given super-relation is not identical to $\rho^* \subseteq S_1\times S_2\times S_3\times S_4\times S_5\times S_6$, because a Cartesian product of sets is neither a symmetrical nor associative operation. Dates [*year, month, day*] or addresses [*country*, *city, street, house, flat*] are typical examples of compact variables used in super-relations. In algebraic operations performed on super-relations the contents of the pairs of corresponding (the same level) brackets should be considered as a compact (single) variables. Therefore, the extent of the above-presented relation is equal 4 (not 6).

C. Semantic interpretation

The relations described on the concepts of a domain ontology can usually be semantically interpreted. For example, if a domain ontology *Teaching plan* contains the concepts *Teacher*, *Subject, Group, Day, Time, Room* then the relation ρ' described on [*Teacher, Subject, Group*] can be semantically interpreted as "*teacher's obligations"* while ρ'' described on [*Group, Subject, Day, Time, Room*] as "*groups' time-schedule",* etc. Similarly, if there is given an instance of ρ':

$$\boldsymbol{s} = [Smith, physics\ I, A3]$$

where : *Smith* $\in$ *Teacher*, *physics I* $\in$ *Subject, A3* $\in$ *Group,* then a semantic interpretation of $\boldsymbol{s}$ may be:

"Smith is a teacher of physics I in the group A3".

The semantic interpretation of the relation instance can thus be given by an affirmative statement presented in any of stylistic forms admissible in a given natural language. Any given ontological model *OM* specifying its concepts and based on them relations defines thus a *semantic area* Σ as a set of semantic interpretations that can be assigned to the instances of any formally admissible instances of the relations. However, the semantic area may in general contain not only relations' instances corresponding to some real situations but also the ones that only theoretically are admissible, that are suggested, supposed, suspected, etc. In this sense, the semantic area does not describe the reality but rather a space of conceptual models in which a description of the actual reality is possible.

Let $\boldsymbol{s} = [s_1, s_2, \ldots, s_K]$ be an instance of the relation ρ described on $[S_k]_1^K$. We can replace a selected value s_k by x as a symbol of unknown variable and put:

$$[s_1, s_2, \ldots, s_{k-1}, x, s_{k+1} \ldots, s_K] \in \rho \qquad (6)$$

This expression is *true* only for certain $x \in S_k$. Therefore, (6) is a *relational equation* and any x making it *true* is its solution. The values $s_1, s_2, \ldots, s_{k-1}, s_{k+1}, \ldots, s_K$ can be considered as fixed *equation parameters*. The relational equation (6) can semantically be interpreted as a question: "*What is (are) an x such that for given $s_1, s_2, \ldots, s_{k-1}, s_{k+1}, \ldots, s_K$ the relation ρ is satisfied?"*. Similar questions can be formulated with respect to any other variable or subsets of variables.

Example 2

On the basis of the (above-mentioned) relation:

$$\rho' \subseteq Teacher \times Subject \times Group$$

and its instance $\boldsymbol{s}$ = [*Smith*, *physics I, A3*] the following relational equations can be formulated:

i. [*x, physics I, A3*] $\in \rho'$,
ii. [*Smith, y, A3*] $\in \rho'$,
iii. [*Smith, physics I, z*] $\in \rho'$.

In the equations two parameters are fixed (e.g. *physics I* and *A3* in eq. *i)*.Similarly, some multi-variable equations, like e.g.:

iv. [*x, physics I, z*] $\in \rho'$,

(containing a single parameter *physics I*) can be formulated. The following queries correspond to the above-given relational equations:

i. "*Who is the teacher of physics I in the group A3?";*
ii. *"What is the subject Mr Smith teaches the group A3?";*
iii. *"What is the group Mr Smith teaches physics I?"*;
iv. *"What group and by whom is taught physics I?"*;

(the queries, if necessary, can be stylistically reformulated). Therefore, a given relation ρ generates a set of *schemes of queries* that potentially on the basis of domain knowledge contained in the relation can be replied. A relational equation may represent a given query if the following conditions are satisfied:

a) Each item which in the query is asked for in the relational equation is represented by a variable;

b) each parameter of the query occurs and takes the same value as a parameter of the relational equation;

c) semantic interpretation of the relational equation is in accordance with this suggested by the query.

The conditions *a), b)* can be formally proven. However, the condition *c)* is not easy to be proven if the semantic accordance is not by default assumed and no relations' entries suggest their semantic meaning. Moreover, some queries can not be replied on the basis of a given relation if it does not admit formulation of a relational equation satisfying the above-given conditions. E.g., a query:

"What day Mr Smith teaches the group A3 physics I?"

can not be replied on the basis of ρ' which does not contain a variable *Day* being an item of the query. However, such queries can be replied if the ontological model contains additional relations satisfying the necessary conditions. For example, suppose that from the above-mentioned relation ρ'' the following instances can be drawn:

s' = [*A3 Mathematics II,Tuesday,11^{00}-11^{45}, 120*],

s" = [*A3, Mathematics II, Wednesday, 12^{00}-12^{45}, 122*],

s''' = [*A3, Physics I, Friday,11^{00}-11^{45}, 122*].

Then, we can take into consideration an extended intersection of the relations $\tau = \rho' \cap \rho''$ and on the basis of the above-given instances the following instances will be obtained:

$\boldsymbol{t}$ = [*Smith, physics I, A3, Friday,11^{00}-11^{45}, 122*].

One can try to express the above-given query in the form of a set of relational equations:

$$[Smith, physics\ I, A3, x, *, *] \in \tau$$

where * denotes any value of the parameters *Time* and *Room* which in the question have not been specified. Therefore, the relation τ can be reduced by taking into consideration a partial relation τ^* defined as a projection of τ on [*Teacher, Subject, Group, Day*]. This leads to the relational equation

$$[Smith, physics\ I, A3, x] \in \tau^*$$

whose solution is *Friday*.

III. Logical Inference Based on a Domain Ontology

It has been shown that a domain ontology provides domain knowledge presented in the form of concepts and based on them relations and also it determines the set of admissible structures of queries about the given application domain that can be logically answered. In the case of a single ontological model the set of admissible questions is the larger the larger is the number of relations and are their lengths.

The *sufficient* conditions for answering by a QAS a query concerning the given application domain are:

1) Existence of a corresponding domain ontology;

2) Expression of the query in the terms semantically equivalent to some concepts of the given ontology;

3) Presentation of the query by a semantically equivalent form of a relational equation based on a non-empty relation belonging to an ontological model and satisfying the conditions *a), b), c)* (formulated in Sec. II).

Let us remark that if ρ is a relation in the given ontological model then any its sub-relation as well as any partial relation can also be considered as a relation of this ontological model. Hence, the sufficient condition 3) means that a relational equation can be based on a relation directly belonging to the ontological model or on any its sub-relation or partial relation. And still, the situations in which the above-described sufficient conditions are fully satisfied are rather exceptional. In a more general case, a relation that directly can be used to presentation of a given query in the form of a relational equation can not be found. In such case it is necessary to look for the suitable *algebraic combinations* of the relations satisfying the below-formulated *necessary* conditions:

a) the algebraic combination of relations contains as its entries the variables and parameters of the query;

b) the algebraic combination of relations is not empty by definition;

c) the algebraic combination of relations admits semantic interpretation being in accordance with this suggested by the query.

Like in Sec. II, the conditions a) , b) can be formally proven by the below-described procedure while c) is assumed to be satisfied in the below-considered cases.

Let $\rho^1, \rho^2, \ldots, \rho^M$ be all relations that in a given ontology have been described. Each relation ρ^m, $m = 1,2,\ldots,M$, is described on a sub-family of sets (ontological concepts) S^m.

The sum

$$S = S^1 \cup S^2 \cup \ldots \cup S^M \tag{7}$$

contains all concepts on which the relations are based.

A general structure of the domain ontology then can be described by a *hyper-graph* [17] H whose nodes are given by S and the subfamilies S^m, $m = 1,2,\ldots,M$, represent its hyper-edges. Two hyper-edges are *adjacent* if their intersection $S^\mu \cap S^\nu$ is non-empty.

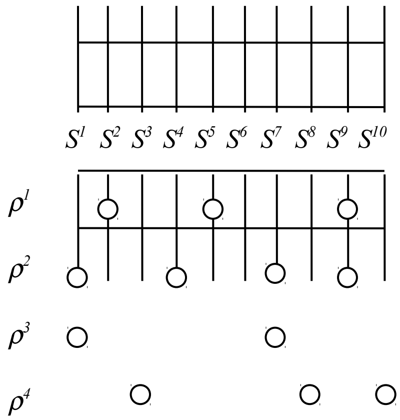

Fig. 2. A hyper-graph consisting of 10 nodes and 4 hyper-edges.

Example of a hyper-graph is shown in Fig. 2. It consists of 10 nodes ($S^1,\ldots, S^{10}$) and 4 hyper-edges ($\rho^1,\ldots,\rho^4$) denoted by circles in the corresponding rows. In the context of ontology's structure interpretation, each hyper-edge represents a relation described on the sets (ontological concepts) represented by the nodes. So, for example, ρ^1 is a relation described on the sets S^2, S^5 and S^9. The pairs of hyper-edges (ρ^1, ρ^2) and (ρ^2, ρ^3) are adjacent while (ρ^1, ρ^3) is not. Similarly, ρ^4 is not adjacent to any other hyper-edge. A subset of hyper-edges such that any pair of them can be connected by a sequence of pair-wise adjacent hyper-edges of the subset is called a *weak component* of the hyper-graph. The hyper-graph in Fig. 2 consists thus of two weak components: (ρ^1, ρ^2, ρ^3) and (ρ^4).

Let us denote by Q a family of concepts that are used as unknown data or fixed parameters of a query ordered to the QAS. For proving the necessary conditions a)-b) for replying the query on the basis of a domain ontology whose structure is described by the hyper-graph H it is necessary:

1. to select in H the minimum sub-family of nodes such that $Q \subseteq \{S^j\}^*$;
2. to find in H all minimal subsets R^h of hyper-edges such that the sum Γ^h of nodes belonging to R^h satisfies the condition:

$$Q \subseteq \Gamma^h \subseteq \{S^j\}^*; \tag{8}$$

3. taking into account that each hyper-edge in R^h represents a relation of the domain ontology described by H, construct an extended intersection of all represented by R^h relations;
4. if $Q \subset \Gamma^h$ then replace the intersections by partial relations defined as projections of the intersections on Q, denote such relations by r^α;
5. from any relation r^α select its instances whose components corresponding to the query parameters take values equal to those of the query, collect all such instances as a sub-relation of r^α, $\chi^\alpha \subseteq r^\alpha$;

6. each χ^α being not an empty relation can be used as a basis for a relational equation representing the given query;

7. solution of the relational equation based on χ^α is given as its projection on the set (node of H) belonging to Q and denoting the unknown data of the query.

The above-described procedure may provide more than one solution of the problem presented by the query. This may happen not only because χ^α may contain several instances satisfying the condition 7 but also because in the step 2 more than one subset R^h can be found. In such case elimination of formal solutions not satisfying the necessary semantic condition c) is possible and recommended.

Example 3

Let us assume that a query has a form:

"What is the value of S^2 assuming that the values of S^4 and S^7 are given?"

Let the corresponding domain ontology is represented by the hyper-graph H shown in Fig. 2. For replying the question the set $Q = \{S^2, S^4, S^7\}$ will be taken into consideration. No hyper-edge of H directly covers Q. However, it is covered by the sub-set of hyper-edges $R = \{\rho^1, \rho^2\}$ for which we obtain

$$\Gamma = \{S^1, S^2, S^4, S^5, S^7, S^9\} \supset Q.$$

It will be thus taken into consideration an extended intersection of the relations:

$$r = \rho^1 \sqcap \rho^2$$

described on the family of sets Γ. However, this relation is redundant and for replying the query it is sufficient to take into account its projection χ on the sub-family Q. Then the steps 6 and 7 should be performed by taking into account the instances of χ.

In the above-described procedure of query answering the following basic steps can be discriminated:

i. reformulation of the query for its formal processing;

ii. proving formal possibility to reply the query on the basis of the given domain ontology (steps 1, 2);

iii. finding formal solutions of the query problem (steps 3 – 7).

Therefore, a block-scheme of a QAS based on a domain ontology can be presented as shown in Fig. 3.

IV. CONCLUSIONS

A practical role of QAS in numerous application areas is permanently increasing. However, it arises the problem of application domain knowledge representation in a form suitable to computer processing. The proposal of using for this purpose ontological models based on the extended algebra of relations seems to be one of several possible ones. It seems to be relatively easy to be realized by computer system assuming that the ontological models for the application domains being of interest are designed and available. However, this approach needs practical solution of several technical problems among which proving semantic accordance between the queries expressed in natural language with the ontological models and effective searching of relations' instances in ontological databases should be mentioned as the most important ones.

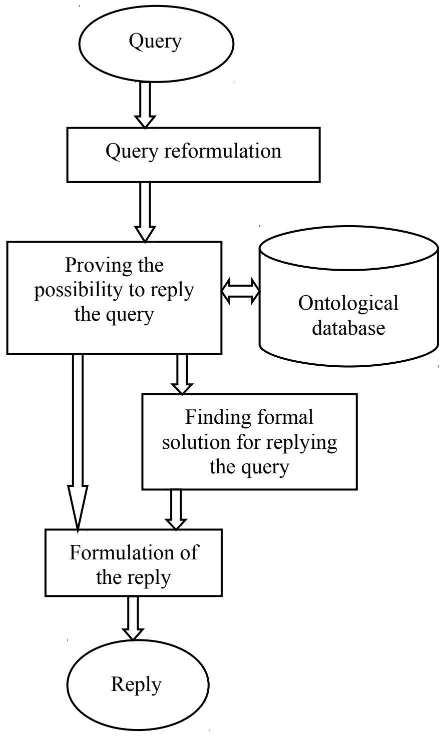

Fig. 3. Block-scheme of a Query-Answering System based on domain ontology.

REFERENCES

[1] S. Russel, P. Norvig. Artificial Intelligence. A Modern Approach. Prentice Hall, 2003.

[2] R. J. Wilson. "Introduction to Graph Theory". Longman Group Ltd., London, 1979.

[3] J. L. Peterson. "Petri Net Theory and the Modeling of Systems". Prentice-Hall, Inc., Englewood Cliffs, 1981.

[4] D. T. Phillips, A. Garcia-Diaz. "Fundamentals of Network Analysis". Prentice-Hall, Inc., Englewood Cliffs, 1981.

[5] J. Pearl. "Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference". Morgan Kaufmann, San Mateo, 1988.

[6] R. Kowalski. "Logic for Problem Solving". North-Holland, New York, 1979.

[7] R. C. Schank. "Conceptual Information Processing". North Holland Publishing Co., Amsterdam, 1975.

[8] M. A. Minsky. "Frameworks for Representing Knowledge in the Psychology of Computer Vision". Mc Graw Hill, New York, 1975

[9] M. Fernandez-Lopez, A. Gomez-Perez, "Overview and Analysis of Methodologies of Building Ontologies". The Knowledge Eng. Rev., vol. 17, no 2, 2002, pp. 129-156.

[10] O. Bodenreier, A. Burgun. "*Biomedical Ontologies*". In: H. Chen, S. S. Fuller, C. Friedman, W. Hersh (Eds.), Medical Informatics. Knowledge Management and Data Mining in Biomedicine. ISIS 8, Springer, USA, 2005, Chapt. 8, pp. 211-236.

[11] J. L. Kulikowski. "The Role of Ontological Models in Pattern Recognition". In: M. Kurzynski *et al.* (Eds.), *Computer Recognition Systems. Proc. of the 4th Int. Conf. on Computer Recognition Systems CORES'05.* AiSC , Springer, Berlin, 2005, pp. 43-52.

[12] A. Abddoullayev. "Reality, Universal Ontology, and Knowledge Systems. Toward the Intelligent World. IGI Publishing, Hershey, 2008.

[13] A. Zilli, E. Damiani, P. Ceravolo, A. Corallo, G. Elia (Eds.). „Semantic Knowledge Management. An Ontology-Based Framework". IGI Global, Information Science Reference, Hershey, 2009.

[14] J. L. Kulikowski, "Ontological Models as Tools for Image Content Understanding". In: *Computer Vision and Graphics. Int. Conf.*

ICCVG 2010, *Warszawa*, *Proc. Part 1*, LNCS 6374, Springer,. Berlin, 2010, pp.43-58.

[15] J. L. Kulikowski. "Relational approach to structural analysis of images". Machine Graphics and Vision, vol. 1, nos ½, 1992, pp. 299-309.

[16] J. L. Kulikowski "Description of irregular composite objects by hyper-relations". In: K. Wojciechowski, B. Smolka, H. Palus, R. S. Kozera, W. Skarbek, L. Noakes (Eds.), Computer Vision and Graphics. Int. Conference ICCVG 2004, Warsaw. CIV 32, Springer, Dordrecht, 2006, pp. 141-146.

[17] C. Berge. "Graphs and Hypergraphs". North-Holland, Amsterdam, 1973.