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DEVELOPMENT OF ONTOLOGY-BASED INTELLIGENT DATA RETRIEVAL METHODOLOGY

Summary of the Doctoral Thesis

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DOCTORAL THESIS
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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to a scientific degree.

Henrihs Gorskis ………………………. (signature)

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The doctoral thesis has been written in Latvian. It consists of an introduction; 4 chapters; result analysis and Conclusions; 4 appendices; 13 tables; 35 figures; the total number of pages is 181. The Bibliography contains 121 titles.

TABLE OF CONTENTS

GENERAL CHARACTERISTICS OF THE WORK

Problem domain

Owing to the latest advancements in information technology, it is possible to store and process large amounts of information. Almost every sector needs to keep track of events and objects, as well as collect and analyze different types of information. Storage of information is fundamental for further analysis and information processing. Any size organization or company, in time, is confronted with data access issues [106]. The more data collected in the database, the more difficult it is to retrieve the necessary information. During the life of the project, the internal structure of the database changes. This phenomenon can be observed, in particular, in scientific studies where it is not known at the beginning of the study how the future will develop or change the project and how the data will be analyzed in the future. Even if the designed data structure is adequate for the information, the problem with storing large volumes of heterogeneous data may still arise. In any case, it becomes necessary to access data in a way that makes it easy to work with. One of the technologies that has arisen precisely because of this need is ontology. This work examines the use of ontologies for simplifying data retrieval.

Topicality

A methodology has been developed for the development of an ontology-based data retrieval system. Although there are other approaches and systems that promise to introduce similar functionality, existing systems offer the transformation of a classic database into semantic networks or other structures that are largely different from those used by current systems. Existing ontology approaches handle all data at the same time, which greatly slows down the performance in case of a large amount of data. Some of the existing systems use only part of what the ontology offers (see Chapter 2). These systems only offer classes and create a hierarchy of classes. Typically, these types of systems skip the development of complex classes (classes with restrictions) that have properties and limitations. When using such systems, there is a problem, because it is precisely in the complex classes that a large part of knowledge is stored, which allows the classification of individuals by attributes.

Problem statement

There are situations where an existing data processing system uses a separate data storage system (database) that contains complex structured information consisting of many heterogeneous records. The data can be found in several tables, with no clear links between the tables, and without any restrictions. The tables are large and complex; they contain many columns. There are no rules for how columns are filled or left empty.

Retrieving data from such a system is a complex and time-consuming process, which can only be performed by an experienced database expert. Retrieving the correct and necessary data requires in-depth knowledge of the structure of the database, which is not simply transferable to all data users.

Therefore, the task is to describe the expert's knowledge along with knowledge from other sources in the shared knowledge model. The purpose of creating such a model is to construct a system that clearly defines the terms for describing and reflecting the content of the database. These terms must be based on the terms used in the domain. It is important that such a model is not a database model, but a domain model with domain terminology, which links the database and data retrieval rules, so that a domain expert can use it. Ontologies provide an opportunity to supplement existing database schema information with domain descriptions and classes.

In the approbation of this work, a fragment of a medical research database is explored with the aim of applying the developed methodology for the implementation of an ontology-based data retrieval system. The methodology developed by the system would allow connecting and retrieving data from this database in a simplified manner using the terminology of the staff employed in the study. This must be achieved by providing the necessary knowledge about the domain and the database in the ontology.

Research aim and tasks

The **aim** of the Doctoral Thesis is to develop a methodology for realizing ontology-based data retrieval, which is aimed at the simplification of usability and is intended as a supplement to an existing relational database. To accomplish this goal, it is necessary to perform the following **tasks.**

- To explore ontology and ontology-based data retrieval technologies to gain insight into the potential of these technologies.
- To explore and compare existing data retrieval-focused intellectual technologies and software and their design approaches to identify possible gaps and set requirements for methodology.
- To develop methods and approaches that allow the implementation of all the operations needed to retrieve data in an ontology-based manner.
- To develop a methodology that describes methods, approaches and guidelines for ontology-based data retrieval.
- To create an ontology-based data retrieval system prototype in accordance with the developed methodology, with the purpose of approbating the prototype and methodology.

The methodology for developing an intellectual data retrieval system is designed to describe the approach and set of methods by which it is possible to implement an ontology-based data retrieval system as an extension to an existing relational database.

Research object and field

The object of the research is a methodology for the creation of an ontology-based intelligent data retrieval system. The field of the research is ontology, ontology creation methods, the use of ontologies in the task of retrieving data, the possibilities of describing knowledge with ontology.

Research hypotheses

During the development of the Doctoral Thesis, three hypotheses were put forward for testing related to the research and analysis of ontology-based technology and data retrieval approaches.

1. Ontology capabilities are sufficient for linking ontologies and databases, defining a subset of data, validating data, and discovering additional knowledge about classes and individuals, without additional technologies.
2. Defining database concepts within a domain ontology is sufficient information for the process, which dynamically generates SQL queries to populate the ontology with individuals.
3. The system developed by the methodology provides an interactive semantic layer to the extent that the user is capable of the creation of *ad hoc* data requests using familiar terms without having to deal directly with the database technologies.

Research methodology

The Doctoral Thesis uses methods for creating ontology and several ontology learning approaches, which are automatic methods for creating ontology [37], [41], [44], merging and mapping methods, methods for database processing [37], data analysis methods [37], database "health" testing methods [37], implementation of ontology reasoning [39], [42]. The method used in this Doctoral Thesis to define and extend the developed ontology (see Chapter 4), is described in the Ontology 101 document, which is a fundamental material on ontology creation [87].

Scientific novelty

A methodology has been developed that describes the process of developing an ontology-based data retrieval system. It describes the process of developing a data retrieval system that implements abstraction of the database and simplifies the description of the required data. Several new approaches have been developed in the process of developing the methodology that are needed to implement such a system.

1. A new ontology and database linking approach has been developed. In this approach, ontologies use concepts to describe database objects, which serve as connecting points between the ontology domain concepts and information from the database.

2. A new ontology learning approach has been developed. The purpose of this approach is to create ontologies that use connecting elements. As a result of using this ontology learning approach, a domain ontology is created that uses database concepts as connecting points. Using this approach, an interconnected ontology is obtained, which can serve as a knowledge base for the data retrieval system.
3. An assessment approach for interconnected ontology has been developed. Using this evaluation approach, one can determine to what extent the ontology domain concepts are related to the elements of the database, as well as discover domain concepts without mappings to the database.
4. An approach to distinguish the concepts of the database and domain concepts has been developed. For the developed system to be able to take into account the diversity of concepts, to differentiate between the concepts and to use the correct concepts for creating a SQL query, it is necessary to identify the database concepts. For this purpose, the methodology proposes an approach that uses the concept identifier prefix parts to indicate the types of concepts.
5. A SQL query creation approach has been developed that uses queries related to the query description to discover the database concepts involved in the query. By using the ontology information and reasoning functions, queries are created for the retrieval of databases.
6. A user interface has been developed that allows the user to select domain ontology concepts to describe the data to be searched. The user, by choosing familiar terms, creates a conceptual description that is interpretable in the ontology. The ontology updates the description and the system transforms them into a SQL query.

Practical significance

The developed system helps to get data from a complex database by offering domain terminology instead of complex queries. The prototype of the medical data retrieval system IRDIS, developed in the Thesis, allows access to data from medical research personnel who do not have the technical knowledge of the database. The system allows them to retrieve the necessary information in a complete and convenient way. Using the system interface, users can describe the search information in understandable medical and research-related terminology, which have implicit definitions and data descriptions. The system possesses functionality in which it replaces these terms and describes the structure with the data acquisition query. The resulting data are structured to meet user requirements. This allows the staff to obtain the information they need conveniently and directly from the database. Before the introduction of this tool, each time it was necessary to retrieve a subset of previously unplanned data, the staff had to turn to the database specialists. It took extra time, experts' efforts, and introduced the mistakes that might have arisen from such mediation. The developed tool facilitates the work of an expert and enables users to work quickly, comfortably and in an iterative manner directly with the content of the database.

Based on work-tested and developed approaches, data retrieval software for medical research was implemented. The developed system was introduced in a medical study, which uses it to retrieve the necessary data from the database.

A system was developed, using the ontology concepts associated with the research activity, to connect to the database and retrieve information that is needed for the medical staff. An employee can find and select the concepts necessary for him. The concept corresponds to what the user has put forward as desired.

Approbation

The results and achievements obtained during the development of the Doctoral Thesis have been reported at 11 international scientific conferences.

1. Riga Technical University 58th International Scientific Conference 13.10.2017. (*Gorskis H. Database Object Concepts for Ontology Based Data Access*).
2. 11th International Scientific and Practical Conference. 15–17 June, 2017, Rezekne Academy of Technologies, Rezekne, Latvia (*Gorskis, H., Aleksejeva, L., Polaka, I. Ontology-Based System Development for Medical Database Access*).
3. Riga Technical University 57th International Scientific Conference 18.10.2016. (*Gorskis H., Using ontology reasoning in data queries*).
4. 12th International Conference on Application of Fuzzy Systems and Soft Computing, ICAFS 2016, Vienna, Austria, 29–30 August, 2016 (*Gorskis H., Aleksejeva, L., Polaka, I. Database analysis for ontology learning*).
5. 22rd International Conference on Soft Computing Mendel 2016, 8-10 June, 2016, Brno, Czech Republic (*Gorskis, H., Borisov, A., Aleksejeva, L. Genetic algorithm based random selection-rule creation for ontology building*).
6. Research and Technology – Step into the Future TTI Research and Academic Conference, 22 April, 2016, Riga, Latvia (*Gorskis, H. Location Based Reminder System with Reusable Ontology*).
7. Riga Technical University 56th International Scientific Conference 16.10.2015. (*Gorskis, H., Borisovs, A. Automated Ontology Building using Classification Trees*).
8. 10th International Scientific and Practical Conference: Environment. Technology. Resources, 18–20 June, 2015, Rezekne Higher Education Institution, Rezekne, Latvia (*Gorskis, H., Borisovs, A. Storing an OWL 2 Ontology in a Relational Database Structure*).

9. 6th International Conference on Knowledge Engineering and Ontology Development, KEOD 2014, 21–24 October, Rome, Italy (*Gorskis, H., Borisov, A. Location based Reminder System with Reusable Ontology*).
10. Riga Technical University 55th International Scientific Conference 17.10.2014. (*Gorskis, H., Borisov, A. An ontological basis for a reminder system*).
11. Riga Technical University 54th International Scientific Conference 16.10.2013. (*Gorskis, H., Borisovs, A. Reusable components in knowledge-based systems*).

Research results have been presented in the following scientific articles.

1. Gorskis, H. Aleksejeva, L., Poļaka, I. Database Concepts in a Domain Ontology. *Information Technology and Management Science*, 2017, Vol. 20, pp. 69–73. ISSN 2255-9086. Indexed in: EBSCO, Google Scholar, Ulrich's International Periodicals Directory.

2. Gorskis, H., Aleksejeva, L., Poļaka, I. Ontology-Based System Development for Medical Database Access. In: *Environment. Technology. Resources : Proceedings of the 11th International Scientific and Practical Conference. Vol. 2*, Latvia, Rezekne, 15–17 June, 2017. Rezekne: Rezekne Academy of Technologies, 2017, pp.24–29. ISSN 1691-5402. Indexed in: **Scopus**.

3. Kiršners, A., Paršutins, S., Gorskis, H. Entropy-Based Classifier Enhancement to Handle Imbalanced Class Problem. *Procedia Computer Science*, 2017, Vol. 104, pp.586–591. ISSN 1877-0509. Indexed in: **Scopus**.

4. Gorskis, H. Improved database schema development for OWL2. *Information Technology and Management Science*, 2016, Vol. 19, pp. 85–91. ISSN 2255-9094 Indexed in: EBSCO, Google Scholar, Ulrich's International Periodicals Directory.

5. Gorskis, H., Aleksejeva, L., Poļaka, I. Database Analysis for Ontology Learning. *Procedia Computer Science*, 2016, Vol. 102, pp.113–120. ISSN 1877-0509. Indexed in: **Scopus** and ISI Web of Knowledge.

6. Gorskis, H., Borisovs, A., Aleksejeva, L. Genetic Algorithm Based Random Selection-Rule Creation for Ontology Building. In: *Recent Advances in Soft Computing: Proceedings of the 22nd International Conference on Soft Computing (MENDEL 2016). Advances in Intelligent Systems and Computing. Vol. 576*, Czech Republic, Brno, 8–10 June, 2016. Cham: Springer International Publishing AG, 2017, pp. 34–45. ISBN 978-3-319-58087-6. Indexed in: **Scopus**, ISI Web of Knowledge.

7. Gorskis, H., Borisovs, A. Ontology Building Using Classification Rules and Discovered Concepts. *Information Technology and Management Science*.

Vol. 8, 2015, pp. 37–41. ISSN 2255-9086. e-ISSN 2255-9094. Available from: doi:10.1515/itms-2015-0006. Indexed in: Baidu Scholar, Cabell's Directory, Celdes, CNKI Scholar, CNPIEC, EBSCO, Google Scholar, Ulrich's International Periodicals Directory, VINITI and others.

8. Gorskis, H., Borisovs, A. Storing an OWL 2 Ontology in a Relational Database Structure. In: *Environment. Technology. Resources: Proceedings of the 10th International Scientific and Practical Conference*, Latvia, Rezekne, 18–20 June, 2015. Rezekne: Rezeknes Augstskola, 2015, pp. 71–75. ISBN 978-9984-44-173-3. Indexed in: **Scopus**.
9. Gorskis, H., Borisovs, A. Location Based Reminder System with Reusable Ontology. In: *KEOD 2014: Proceedings of the International Conference on Knowledge Engineering and Ontology Development*, Italy, Rome, 21–24 October, 2014. [S.l.]: SciTePress, 2014, pp. 161–167. ISBN 978-989-758-049-9. Indexed in: **Scopus**, Engineering Village, dblp, Inspec, Web of Knowledge.
10. Gorskis, H., Borisovs, A. Knowledge-based System Design Based on Generic Method Conception. *Information Technology and Management Science*. Vol. 17, 2014, pp.55–60. ISSN 2255-9086. Indexed in: Cabell's Directory, Celdes, CNKI Scholar, CNPIEC, EBSCO, Google Scholar, Ulrich's International Periodicals Directory, VINITI.
11. Gorskis, H., Borisovs, A. Reusable Components in Knowledge-based Configuration Design Systems. *Information Technology and Management Science*. Vol. 16, 2013, pp. 66–72. ISSN 22559086. Indexed in: EBSCO, ProQuest, Cabell's Directory, Celdes, CNKI Scholar, CNPIEC, Google Scholar.
12. Gorskis, H., Čižovs, J. Ontology Building Using Data Mining Techniques. *Information Technology and Management Science*. Vol. 15, 2012, pp. 183–188. ISSN 2255-9086. Indexed in: EBSCO, ProQuest, Versita, VINITI.

The results of the dissertation research have been developed in relation to the following projects:

- "Smart Phone for Disease. Detection from Exhaled Breath". European Comission, Research Programme, DG Research & Innovation – HORIZON 2020 (since 10.2015.);
- "Development of risk stratification method for gastric cancer and pre-cancerous conditions using biomarkers". LU project 2014/0035/2DP/2.1.1.1.0/14/APIA/ VIAA/102 (09.2014.– 09.2015.).

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Structure and content of the Thesis

The **first chapter** examines basic technologies that directly affect the capability and functionality of ontologies. It provides an insight into the essence of ontology; discusses what other technologies affect it, what its history is and what features it offers for describing knowledge and information.

The **second chapter** looks at the state of ontology-based data retrieval. It summarizes what is being done and which methods are available to implement the ontology-based retrieval of data with existing approaches. The second chapter also examines and compares existing software applications that implement ontology-based data retrieval.

The **third chapter** is devoted to the development of methodology for the realization of an ontology-based data retrieval system. It describes the modifications of existing methods that are used in methodology, as well as the missing steps for which there is no ready-made solution and their implementation approaches. The chapter describes all the structure and operational steps of the methodology.

The **fourth chapter** outlines the implementation of a prototype of the intellectual data retrieval system (IRDIS), which has been developed following the developed methodology.

The **results and conclusions** section describes the insights obtained during the execution of the work, and lists the achieved results and interpretations.

SUMMARY OF THESIS CHAPTERS

1. TECHNOLOGY RELATED TO ONTOLOGY-BASED DATA RETRIEVAL

This chapter describes the technologies that serve as the basis of ontologies: ontologies themselves and ontology use in data retrieval task. An overview of these technologies provides an insight into the possibilities and uses of ontology. Ontologies relied on the semantic technologies that existed before them. Semantic technologies are technologies that handle information that is provided in a free and unstructured way, using concepts. Semantic technologies are based on semantic networks that describe information using nodes and links.

Fundamental technologies for ontologies

Semantic technologies are diverse and have many realizations. There are different types of semantic networks that provide knowledge descriptions using nodes. One of the types of semantic networks is concept maps (CM), which are used to represent semi-formal semantic knowledge [50]. The Resource Description Framework (RDF) is a technology that is designed to standardize resource description [92]. Typically, when it comes to describing information, data structures are created. This structure is a way a model of the data that affects the information collection process. In cases where all possible information is unknown or very diverse, it is difficult to build a strictly structured model. One of the possible approaches to solving the problem of unstructured data is to use semantic networks together with RDF. Semantic networks allow the description of information in a less restrictive way. Any inbound information can be viewed as a central node representing an information item (object) and a list of links that connect this node with data or other objects. Semantic networks of this type can be described by naming related objects (or objects and data units) and the link that connects them. Within the framework of the description of resources, this is referred to as an expression consisting of triples. A triple is the formations of a subject, a predicate, and an object where

- the subject is the element on which the statement is made;
- the predicate is a connection, link or property that indicates a relationship or a type of property;
- the object is the part of the triple, which passively participates in the statement and is connected to the subject through the predicate.

Simple RDF is not sufficiently complex for the conceptual description of domain information, since all information is homogeneous, and RDF is not sufficiently capable of describing all ideas. RDF solved the problem of the diversity of information. The lack of a rigorous structure made it possible to describe any kind of information. This, however, led to the fact that this type of network could grow disproportionately large and obtain an exponentially large number of links. A network that is formed from resources, referring each other, with many nodes becomes inimitable opaque. In addition, all resources are the same. These are simple property collections. There was a need for classes or ways to divide them to simplify the selection of the required resources. RDF scheme [93] was created to complement RDF with greater ability to describe the information.

RDF scheme is an RDF extension [56] to extend the RDF's ability to describe the data on a meta-level. The RDF scheme introduced concepts such as class and property. Ontology uses the level of classes created in the RDF scheme and complements it with a certain type of reasoning [1] and some other class-level elements. It is important to understand that ontology is not a substitute for the implementation of the class level defined in the RDF framework. It is a very specific extension. Introduction of the class level in RDF data allowed distinguishing between different types of properties. This made it possible to describe classes and class properties. However, this approach does not have a strict mechanism for classification with the RDF scheme alone and there is no unified approach to what a class is and what resources may or may not belong to classes.

Ontology in Information Technology

Ontology is a way to describe knowledge, which permits the definition of classes and class relationships, in a way that it makes classification and inheritance possible. Classification is performed by looking at the set of properties of an information unit. In an ontology, such a unit is called an individual. Each individual has a set of properties that can be classified. It is also possible to deduce the default properties by class relation. In information technology, the ontology is a specially structured knowledge base, which defines all concepts that are considered important in a domain. The concept describes classes, data types, and links to various types of attributes. Several authors offer their formal ontology definitions [31], [87], [107]. Based on these definitions, in the Thesis, ontology is formally defined as a set of these elements (see Expression (1)).

$$O = \{C, R^D, R^I, D, H^C, H^{R^D}, H^{R^I}, H^D, I_C, I_R, A\} \quad (1)$$

where
C class set;
D data type set;
R^D data set of properties;
R^I object property set;
H^C class hierarchy;
H^D data type hierarchy;
H^{R^D} data property hierarchy;
H^{R^I} object property hierarchy;
I_C class instances – individuals;
I_R property instances;
A individual axioms.

Ontologies are formed from several classes C, data types D, data properties R^D, object properties R^I and individual I_C types. These types of concepts are used in the ontology to create a domain definition. Each concept type has its own hierarchy (H^C,

H^D, etc.), after which conceptual relationships are established. With Axiom, all assertions about domain concepts that describe the content of the model are made.

Ontology differs from other semantic technologies and class models in that it describes the criteria for the existence of concepts (similar to the philosophical ontology). This unique approach has an impact on the definition of classes and reasoning mechanisms. Often, the philosophical part is ignored, leading to misunderstandings and disagreements about how ontologies are created and used. Sometimes ontologies are mistaken for simple class models. Ontologies are mistakenly treated as an object-oriented class modelling approach. Ontologies are not intended to define object templates. It is possible on the ontology to point to the class properties that are characteristic of all its individuals, but it refers only to existentially important properties, not to all possible common properties. Ontology classes are only associated with properties if these properties are existentially important.

Ontology-based data retrieval concept

Ontology-based data retrieval is a combination of the above technologies and approaches aimed at retrieving data from an ontology or other data source by using ontology. The purpose of retrieving ontology-based data is to enable the use of knowledge and reasoning inherent in ontology to describe the desired data. After the description is created, the knowledge stored on the ontology is used and the selection of data is carried out together with the reasoning procedures. This process retrieves data from the data source. Ontology-based data retrieval originates from the use of ontology queries to retrieve ontology information [72]. With the SPARQL query language, it is possible to retrieve nodes and link information from RDF and ontology descriptions [105]. Ontology-based data retrieval was based on the use of this query language to combine a data source with an ontology description. This will ensure that information is retrieved not only from ontology but also from the data from a data source using ontology. The purpose of such functionality is to retrieve not only the desired information from the data source, but also to supplement it with the known domain classifications.

2. ONTOLOGY-BASED DATA RETRIEVAL METHODS

This chapter provides a deeper look at the ontology-based data retrieval process and approaches to its implementation. It explores the elements of the ontology-based data retrieval process, which technologies are associated with this process, and which principles are used in their implementation. Several systems that rely on the retrieval of ontology-based data in a variety of ways are considered; it also explores how existing systems implement this process.

Ontology-based data retrieval systems

To understand how the existing systems have been developed and what methodologies they are designed for, it is necessary to look at their functionality and technologies used. Systems that use ontologies for the realization of intellectual data retrieval are considered. In most of the existing systems, the SPARQL query language is used. It can be used directly, graphically, as a basis for another solution, or as an access point that must be accessed with another tool to retrieve the desired data. The solutions offered at the University of Latvia [6], [7], [8], [9], [95], the Ontop [18] project for the Free University of Bozen-Bolzano, the large data project Optique [67] supported by the European Commission, as well as some separate articles on various studies in ontology-based data retrieval, are examined. As a result of this review, these tools have been compared by the following criteria: simplicity of implementation, query technology, suitability for semantic layer functions, model independence and performance dynamics. The comparison is shown in Table 1.

Table 1

Comparison of Tools and Approaches

Tool / approach	Simplicity of implementation	Query involved technology	Semantic layer	Data and model relevance	Dynamic performance
Ontop	Easy	SPARQL	Weak abstraction	Independent	Yes
	+	–	–	+	+
Optique	Average	Visual tool, SPARQL	Weak abstraction	Independent	Yes
	±	±	–	+	+
Star ontology and QL	Average	Fast query language	Partial abstraction	Strongly connected	Yes
	±	±	±	±	+
RDF store	Difficult	SPARQL	No abstraction	United	No
	–	–	––	–	–
Ontology DB	Difficult	SQL	No abstraction	United	No
	–	––	––	–	–
Methodology system	Easy	Concepts	Good abstraction	Independent	Yes
	+	+	+	+	+

Ontop and Optique create virtual RDF descriptions from a database using a mapping document that links database queries with ontology concepts. Data retrieval is performed with SPARQL queries. In the Optique case, there is a visual tool that helps create a SPARQL query. Execution takes place dynamically, the model exists separately from the data, but the semantic layer is not fully realized due to the complexity of the query. The star ontology developed by LU, combined with the fast query language, uses the description of the database as an ontology. Using a special query language that is similar to SQL with some additions and Latvian syntax, a tool is proposed that selects the data stored in the memory from the database. Tools that use ontology to store data or a database to store ontologies and data combinations are not able to work in an independent manner. Data retrieval is performed using SPARQL or SQL. The systems user will not know SPARQL and will not be able to create a suitable query. Consequently, the methodology asserts that the task must be based on ontology capabilities. Although SPARQL queries can retrieve ontology elements, the query itself is not a concept and is not directly related to ontology.

The system established by the methodology must overcome these gaps and offer a solution that implements the data in a separate model, which is available to users in an understandable way, for dynamic data retrieval.

Database and ontology linking approaches

There are several approaches that implement data linking between ontologies and databases, and these approaches are differently implemented. The most commonly used typing approaches are as follows.

- Using a separate mapping document [2], [18], [96], [103]. This approach creates a separate document that describes how the ontology concepts are related to the data source. Such a document is created using technologies that are not directly related to ontologies. Typically, such a document consists of a list of related concepts combined with a database query.
- Ontology annotation [17], [23]. In this approach, the ontology document is expanded with annotation elements that describe how to get class individuals. The advantage of this approach is that the ontology developer can immediately see the query on the element. The downside of this approach is that the developer needs to look at each element individually to find all the annotations associated with the database.
- Database ontology approach [22], [94]. In this approach, the entire ontology is created from the database schema [115], [116]. This kind of ontology is often the result of automated ontology creation [34], [36, [43]. The ontology becomes a description of the database using ontology semantics [89]. The advantage of this approach is that the ontology itself is closely linked to the database [82] and the ontology developer does not need to take care of the database mapping as a separate element of the ontology. The disadvantage is excessive focus on the database and a weak domain description.
- Only ontology [102]. Instead of linking the database and ontology, only ontologies are used, which in addition to the model contains completely all the

data from the database. In this way, it is not necessary to connect to the database and all operations are performed only within the ontology framework. This approach is only possible in the case of a small amount of data, since ontology processing technologies are not optimized for large amounts of data for processing.

- Ontology Database [3], [4], [28], [57]. Similar to the previous approach, ontology and data are combined together, with the difference that the ontology is implemented and maintained in a database [120].

Ontology creation methods

The purpose of the ontology is to describe different levels of expertise, domain, task, application, or data. As ontologies gain popularity, ontologies that already describe a specific area of the problem are likely to exist, but in most cases, it is necessary to create a new knowledge description, when a fitting ontology has not yet been created. Since ontologies can be different, there are various ways to create them. It is possible to create different, often incompatible, ontologies for the same domain. Not all ontologies can be guaranteed to be useful to the task. The process of creating an ontology is predominantly manual. This process is interactive because it is necessary to validate whether the created ontology meets the requirements [101]. There is no one correct way to create ontologies, there are always alternatives that are acceptable depending on the situation [87]. There are also several attempts to partially automate the creation of an ontology using existing formal materials [41], [44], [45], [66]. Some of these techniques were influenced by the methodology developed in the work, the process of creating ontology.

3. ONTOLOGY-BASED DATA RETRIEVAL METHODOLOGY DEVELOPMENT

Based on the research of all approaches and solutions related to ontology and ontology-based data retrieval, a new ontology-based data retrieval system has been developed. The establishment of such a methodology is based on the fact that all such existing systems have shortcomings. Systems that implement ontology capabilities are not easy to use because they are too focused on resource descriptions and query languages. Easy-to-use systems do not use all ontology capabilities or distance themselves from ontologies, creating systems that are only inspired by ontologies, but do not use their full potential [6]. The developed methodology is intended for:

- the creation of OBDI systems that are fully based on ontologies;
- ensuring that all functions related to data retrieval are mainly realized using ontology;
- creating an easy-to-use system.

This chapter describes a developed methodology that seeks to summarize approaches and methods that enable the implementation of ontology-based data retrieval systems.

Methodological requirements for the system

The task of the methodology is to offer a set of processes and methods that enable the implementation of an ontology-based data retrieval system that complements the existing relational database with user-friendly functionality for data retrieval. The shortcomings and weaknesses found in the second chapter have been identified (see Table 1). Based on the developed methodology, requirements to the system have been established to address the identified deficiencies. The system requirements address the following aspects of the system:

- implementation requirements;
- technology involved in query;
- semantic layer support;
- data and model interconnection;
- query execution dynamics.

Implementation requirements should be as minimal as possible. These are related to the necessary changes in existing systems or databases. After the stated purpose of work and the analysis of existing systems, a system to be developed must be a complement to an existing solution. The system being developed must be able to connect and use the existing relational database without the need for changes in the structure or content. It is also argued that the system being developed does not have to implement a substitute for an existing database. The developed system does not implement a data storage alternative.

Fundamentals and stages of methodology

The approaches and stages of the developed methodology are shown in Fig. 1. The ontology-based data retrieval system consists of three large parts.

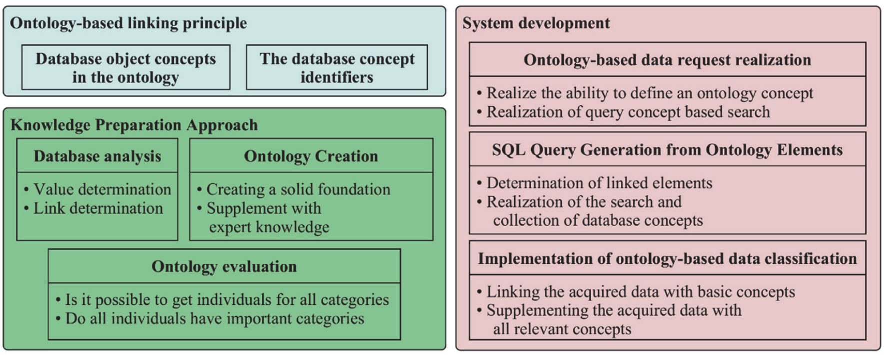

Fig. 1. Methodological approaches and stages.

The core of the methodology is the principle of the ontology-based mapping. The proposed way to map ontology concepts and database objects influences the way in which all other activities need to be implemented. The methodology is divided into two major stages related to the development of the system. The knowledge preparation stage describes the activities and approaches that are related to the creation of a connected ontology. This is an ontology that will be the central knowledge base of the developed system.

The System properties stage describes the steps, techniques, and approaches that should be applied and implemented in the system. This chapter describes all stages, approaches and principles of the methodology. The steps are shown in Fig. 2. These stages are divided into specific activities that must be performed at each stage. The approaches include the type of mapping between the ontology and the database, and the type of identification of the mapping elements. The methodology consists of two stages:

- creation of a knowledge base, and
- system creation.

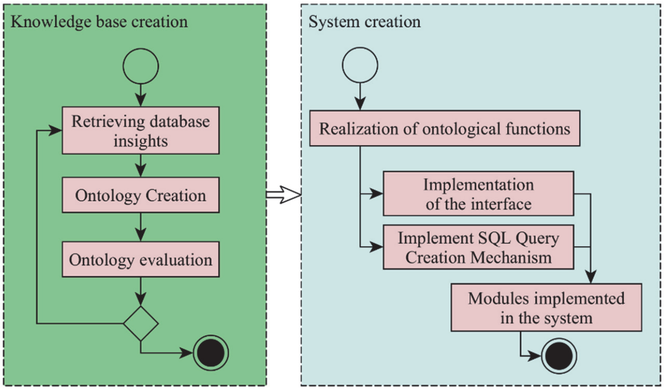

Fig. 2. The process of operations according to the methodology.

Implementation of ontology and database linking

The developed methodology is based on the approach used to map between the database and ontology. It affects the knowledge base and system development steps. Three types of interconnected ontology concepts are used in this mapping approach. These are tables (or views), columns, and relational concepts:

- the concept of a table is a class. This class indicates a database table or view, because the views are processed in exactly the same way as tables;
- columns are data properties. Data properties are directly attributed to table columns. This is due to the fact that the data properties refer to an individual's data, but the table column contains a record's data;

- relations are described by object properties. Object properties point to the relationship between individuals. It is possible to describe the relations between database tables using the object properties.

In addition to these three major types of database concepts, there are additional concepts that are also related to the database. Since the reflection of the database table in ontology is a class concept, the individual of such a class must have a database entry. This means that the reflection of the database entry on ontology is an individual. Since the data retrieval task must separate the data and model, individuals that are not used to define the class are not added to the ontology.

In order to implement the developed ontology and database linking approach, it is necessary to distinguish and identify database and domain concepts. This is necessary in those cases where it is needed to define a domain concept with the same name that has already been used to identify a database concept. For this purpose, an approach was developed that uses a variety of prefixes for domain and database identifiers. By using different prefixes, it is possible to distinguish between database concepts and domain concepts and use multiple objects with the same basic name.

The creation of the knowledge base

Creating the knowledge base is a stage of the methodology that creates a database-mapped ontology that will serve as a knowledge base for the system. According to the methodology, the ontology must contain elements that refer to the elements of the database. To create a suitable ontology, the database must be explored to gain the necessary insights on the elements that need to be described in the ontology. During the database analysis, important elements (tables and columns) are identified, and lists of values (specific values in columns) and links between tables are searched. This information may be available from the description of the database or found during the analysis. The transfer of tables, columns, and values to related ontologies is mostly manual work for an expert. The analysis helps to identify the elements that are needed to look at the expert in decision making. Enumerated values are found using the following algorithm:

```
1. Select count(F) from T where not F is null and not F = ''
2. If count < min then not enum
3. Select count(distinct F) where not F is null and not F =
''
4. if distinct count < sqrt(count) then is enum
```

where F is the column under consideration, and T is the table under consideration. Finding all the unique (not empty) column values and comparing them with the number of all records exposes potential enumerators.

The table relations are detected by checking whether all column values are found in the column of another table's key column.

After analyzing the database and noting objects and values, a basis of the linked ontology is created. This foundation is complemented by domain concepts derived from the viewing of the problem domain.

The ontology creation process ended with evaluation. The ontology created is evaluated by checking whether all the database concepts are used in the definitions of domain concepts.

System building phase

The system development stage is the part of the methodology, which describes the techniques, principles and actions that need to be applied to implement the system.

Since the developed methodology involves a completely new approach to creating a data query, it is necessary to develop an appropriate interface. According to the methodology, the system to be developed must fulfill all data retrieval tasks using the ontology as the basis and the ontology-based reasoning abilities.

To implement an interface that does not use query language to be handled separately from ontology, an approach is introduced that uses the query concept instead of the query. Query concept is a special class concept, representing the desired individuals or set of information.

The created concept describes the set of individuals that possess the specified properties of the user. By executing the ontology-based reasoning process, it is possible to identify all the database concepts related to the query concept and to create a data query.

Creating a SQL query is based on the exploration of a query concept. A query concept is selected within an ontology. The query concept hierarchy is searched to find concepts related to the database. These can be both the concepts of database table classes and the characteristics of database column data that are used in the definitions of complex concepts; they can also be properties of objects that refer to table relationships. All the database concepts found will affect the created SQL query.

All the described parts and processes need to be combined into a common system. For this purpose, a module is implemented for each part of the system. All modules are capable of operating independently, referring to a common ontology and retrieving the necessary knowledge.

4. DEVELOPMENT OF INTELLECTUAL RESPONDENT DATA CALCULATION SYSTEM

Based on the developed methodology (see Chapter 3), an intellectual retrieval system for medicine research data IRDIS has been developed [38]. The purpose of this system is to offer medical personnel (data users) the opportunity to obtain data on treated persons (hereinafter referred to as respondents), acting as an intermediary with the existing database of respondents. The intellectual abilities of this system (reasoning, knowledge management) ensure the use of ontology as described. This chapter describes the development process and develops the implementation of system prototypes as well as the results of the approbation of the system.

Preparing knowledge base

The Thesis deals with a database that stores medical data on respondents. This database has 60 tables. Some of these tables contain metadata and technical information for which the user does not need access. From these tables, seven most important tables (see Fig. 3) have been selected and identified for description in the ontology of the prototype. The decision on the tables to be used is accepted by the database expert.

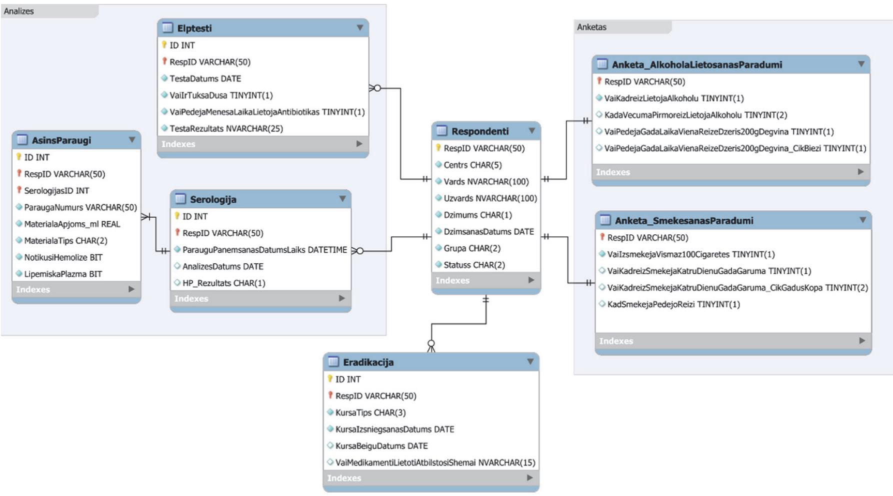

Fig. 3. Structure of the database fragment.

Based on the selected tables, a database analysis has been carried out, which has led to the discovery of all useful values and relationships between the tables. From this information the basis of the ontology is formed. After extending the base with domain concepts, a linked ontology for the system is obtained, which serves as the systems knowledge base. The class level of the created ontology is depicted in Fig. 4.

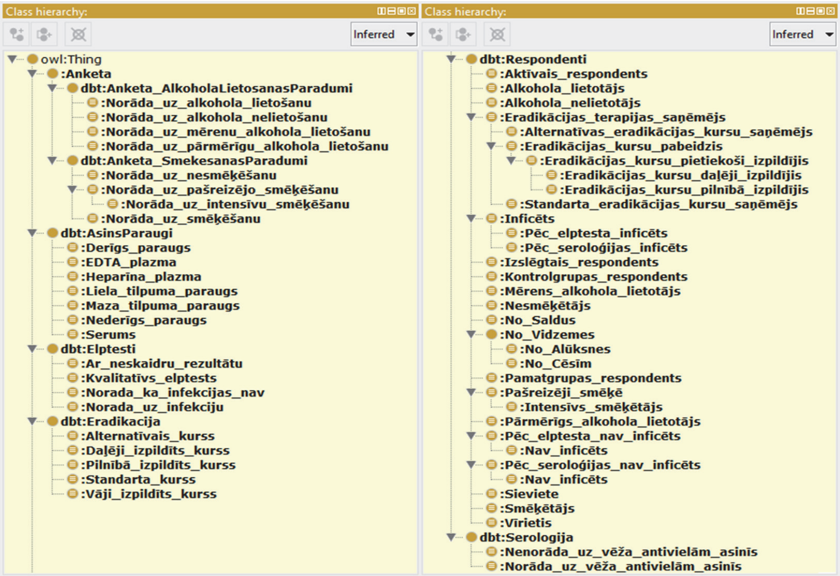

Fig. 4. IRDIS ontology.

Realization of ontology functions

The core of the created system is the ontology and its reasoning mechanisms. Although it is possible to implement ontology management mechanisms using existing ontology software libraries [58], the ontology implementation of the created system, has been redesigned to simplify the search for the concepts needed to create a SQL query. The ontology management functions, as well as the prototype itself, are created in Java language. The Ontology Management module consists of 53 Java classes that provide all the basic functions of ontology, and another 2 classes that provide OWL / XML document retrieval.

All ontological resources are divided according to one of the five types of elements and is stored and processed in the corresponding element type module. These are modules for classes, object properties, data properties, annotation properties and data types. The class module processes all knowledge associated with class concepts, their definitions, and the class hierarchy. The Data Properties module does the same, but contains only the data properties concepts. The Object Properties module manages the concepts and hierarchy of object properties. The data type module manages the types of data defined ontology, as well as the concept of standard data types and the hierarchy of these concepts. The Annotation Properties module manages the properties and their hierarchy of annotations.

Each element of the ontology module manages unique elements of ontology concepts. All the elements that are to be processed in the ontology (see Table 2) are divided into elements by function and category.

Table 2

Types of Concepts

			Class	Datatype	Object property	Data property	Annotation property
T-box element function		Named element	Named class	Named datatype	Named object property	Named data property	Named annotation property
		Element complement	Class complement	Datatype complement	Object property complement	Data property complement	Annotation property complement
		Value element	Individual class	Value datatype			
	Group elements	Conjunction	Class conjunction	Datatype conjunction			
		Disjunction	Class disjunction	Datatype disjunction			
		Other group			Object property chain		
	Other elements		Cardinality class	Datatype restriction	Inverse object property		
			Key class	Language type			

Ontology reasoning mechanisms are partly realized in the hierarchy of elements (it is possible to draw several conclusions from the addition of a new element to the hierarchy) and partly in the reasoning module in which the existing knowledge is replenished in an iterative manner by looking for certain situations corresponding to the rules described in the reasoning module.

Prototype interface

The interface for the system developed for the Thesis has been created as a visual tool in which the concept to be defined is a set of classes. By choosing from a list of related classes, the user extends the set of classes to be created and forms a class conjugation. An interface implementation is illustrated in Fig. 5. It shows that the query concept is defined as a group of other classes (conjunction or disjunction).

Each panel (blue) represents a separate concept. The largest box, containing everything, is the defined query class. In this case, the query concept is based on the class "From the table 'Respondents' ", which is the label for the database concept that indicates the database table "Respondents".

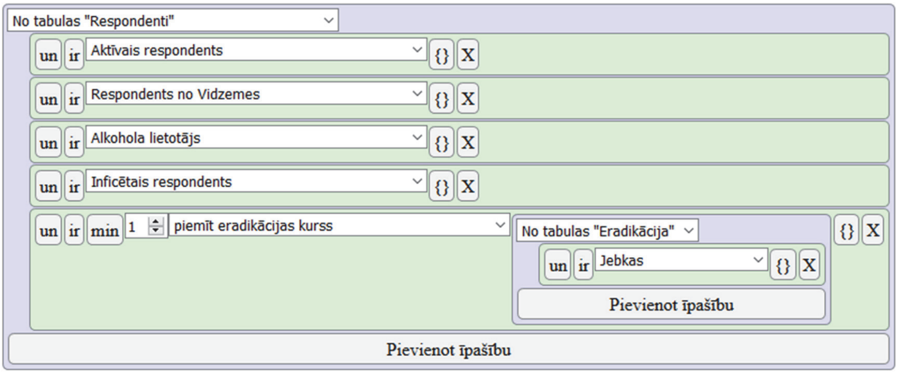

Fig. 5. Query concept creation interface window.

This basic concept is needed to restrict the users' concepts from the menus. Subsequently, classes follow the conjugation of the query concept. It is evident that this is a conjuncture, because all rows begin with the word "and". By clicking on this keyword, the conjunction is converted to disjunction and all lines are started with "or". Each row can specify a class concept that is an element of this group (conjuncture or disjunction).

Data retrieval and processing

The query element created in the interface is added to the ontology. After completing the reasoning functions, it is supplemented with all deducible relationships with other elements. By locating all the elements in the ontology, all the mappings to the database are discovered. An example of this process is shown in Fig. 6. The concept of the query is defined, which after its definition is linked to several existing classes. When searching for the concept transcripts, they look for those classes that are defined as database mapping points or use mapped elements in their definitions.

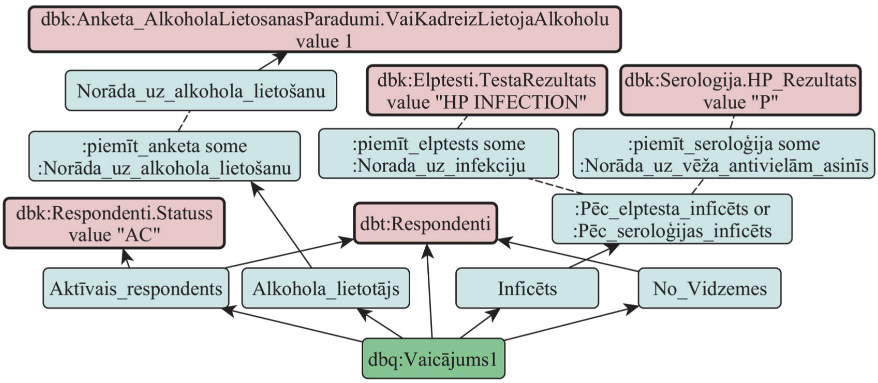

Fig. 6. Topic concept for query concept.

Summarizing the related mapping points, the SQL generator creates and executes a query to the database. The query result is added to the ontology. Each database entry represents an individual. When processing each resulting entry, a new individual is created that has a programmatically assigned name. This individual has data properties that coincide with the column name. By completing the ontological reasoning process in this step, all individuals and class relations are inferred. By selecting all created individuals who are classified as belonging to the query class, they and all their intrinsic properties are returned as the result of the query.

Structure of the system

All the developed modules together form the system (see Fig. 7). The center of the system is an ontology management module that corresponds to the storage and use of knowledge.

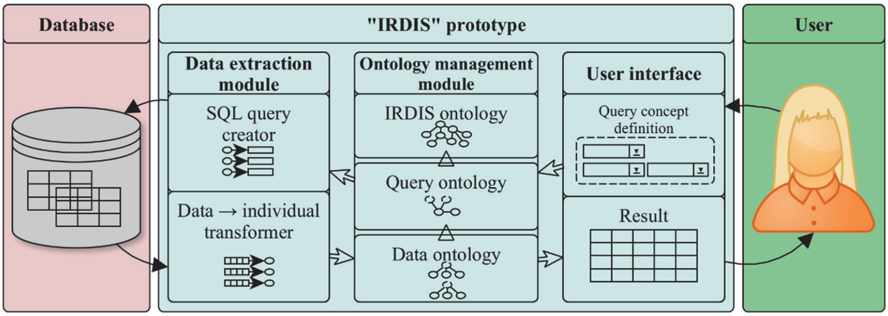

Fig. 7. Structure of the system.

All other parts of the system use the central ontology to carry out their functions. The user interface uses the ontology to offer the concepts to be used for query description. The data retrieval module, which creates SQL queries and loads data into the ontology, uses the ontology to create a SQL query that matches the query concept. The Ontology module itself is a multi-layer ontology. Each layer extends the previous ontology layer. In the beginning, the ontology module only contains the ontology of the system (IRDIS). Creating of a query concept creates a temporary query ontology layer that contains an ontology that refers to the basic ontology, but also contains the query concept. Data is loaded into a data ontology that itself contains only data individuals and refers to the previously created ontologies. When the user finishes working, the created ontology layers are removed, maintaining only the fixed base ontology.

Determining the suitability of the developed system

To investigate and determine the suitability of the developed intellectual data retrieval system IRDIS, two experimental series are defined.

The first set of experiments is to determine the correctness of the developed prototype. In this series of experiments, it is verified that the knowledge described in the developed ontology is sufficient and suitable for validating and selecting data. In this series of experiments, several concept descriptions are created to test the datasets that have been deduced and retrieved. The execution of the experiments showed that the ontology functionality had been developed, and the system as a whole was capable of constructing suitable SQL queries for the described concepts. Successful queries for complement concepts were created, and empty classes were found.

The purpose of the second series of experiments is to check that the created system serves as a suitable semantic layer in the data retrieval task. In this series, users create concept descriptions based on a predetermined task. Query relevance is determined by comparing the system output with the result obtained by the expert's query. Each experiment consists of three parts.

1. The user sets up an experiment task statement. In the form of a free description, a task is created for retrieving the subset of the data. It describes what information you need to retrieve from the database.
2. The user creates a concept of the search query according to the task statement. Using the developed prototype interface, the user creates a conceptual description of the search data. The system executes data retrieval.
3. The database expert creates a SQL query and retrieves the data for comparison with the system result.

The concept definition that has been created for a complex data description is presented in Fig. 8. The screenshot shows the user interface of the prototype developed for this work, which allows to define concepts by using terms from the ontology.

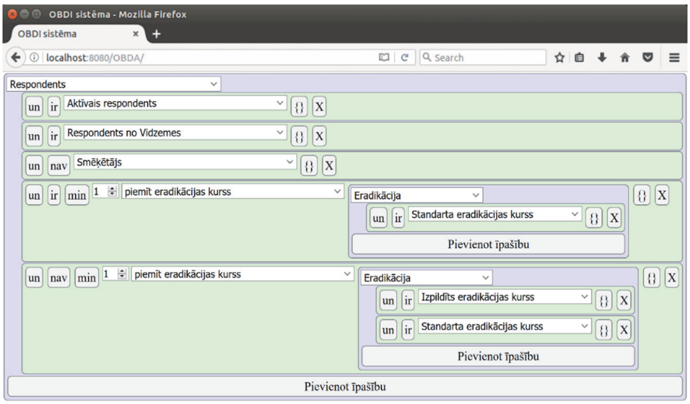

Fig. 8. Definition of query concept

The displayed concept description defines all active respondents from Vidzeme who are non-smokers and who have incomplete eradication therapies. The description of these concepts matches and yields the same result for comparison purposes with an SQL quiz created by an expert. Corresponding SQL Query is as follows:

```
select * from Respondenti, Anketa_SmekesanasParadumi, Eradikacija
where
Respondenti.Statuss = 'AC' and
(Respondenti.Centrs = 'LV101' or Respondenti.Centrs = 'LV102') and
Anketa_SmekesanasParadumi.RespID = Respondenti.RespID and
Anketa_SmekesanasParadumi.VaiIzsmekejaVismaz100Cigaretes = 0 and
Eradikacija.RespID = Respondenti.RespID and
Eradikacija.KursaTips = 'STD' and
Eradikacija.VaiMedikamentiLietotiAtbilstosiShemai is null;
```

The series of experiments showed that the developed system can realize data retrieval by transforming the conceptual description of the SQL query and retrieving the same data as the expert retrieves. The number of records retrieved in experiments is shown in Table 3. This table shows the result of the queries made by the system and expert in Experiment 4. Because of the ontology specific reasoning, the result of the system differs from that of the expert's due to the incomplete description of the concept sought by the user. After the concept was perfected, the results were similar.

Table 3

Number of Entries Retrieved During Experiments

	Experiment			
	1	2	3	4
System	3521	702	673	0 / 434
Expert	3521	702	673	434

This chapter discussed the use of the established methodology by creating an intelligent respondent data retrieval system. The developed approach to database analysis has been implemented and applied with the aim of obtaining insights into the data, using the result as a source of information for the development of ontology. Actions were reviewed and executed with the aim of obtaining information about the contents of the database, which makes it possible to create data-based concepts. The established system has been approbated by several experiments, which showed its compliance with the set task.

RESULTS AND CONCLUSIONS

The Thesis has explored the possibilities of using ontology to access a database and retrieve data from it. Related technologies and existing solutions have been studied. As a result of this analysis, a methodology has been developed that describes the approaches and methods for developing ontology-based intelligence retrieval systems. Such systems are focused on improved usability by providing a semantic layer for data retrieval tasks. The methodology offers an approach to the creation of a linked ontology that is mapped to the existing relational database. To create the linked ontology needed for the system the methodology describes the database analysis approaches. The use of this approach results in an ontology that contains mapping elements.

By realizing the ontology's reasoning for data elements that are included in the ontology described in the methodology, it is possible to use knowledge about the structure of the linked database. In this way, knowledge of the domain and the knowledge of the data are complementary. Knowledge of data and the structure of the database helps to focus on domain knowledge and describe only what is retrieved from the database. Domain knowledge complements database data with affiliation with conceptual domain classes.

This approach facilitates the technical part of the ontology-based data retrieval task. In order to make intellectual data retrieval more accessible to the end user, the methodology offers an approach to the creation of a user interface. One of the possibilities of ontology is its ability to promote communication and mutual understanding. However, if these opportunities are concealed behind complex technologies that mitigate them, usability and awareness are lost. For ontology-based data retrieval to be used also by those who are not ontology experts, the methodology offers access to the semantic layer. The semantic layer is provided by implementing an interface to the user that offers domain concepts. Using domain concepts, the user defines a new concept that has certain properties. The user is able to describe the desired data class using familiar terminology, without knowledge of data-storage technologies and data structures.

The following results have been achieved during the development and study of the work.

- The technologies related to the ontology and ontology-based data retrieval have been studied. This analysis gave an insight into the possibilities of ontology, its reasoning functions and applications. This allowed the creation of missing approaches to ontology-based interconnection, the identification of database concepts, and ontology-based SQL queries. Based on the OWL 2 language analysis, a Java software library is developed that implements ontology management and reasoning functions.
- Existing intellectual data retrieval software and their construction approaches have been researched and compared. The result of this analysis is a comparison of existing tools and a summary of identified shortcomings. On this basis, there have been developed methodological requirements for the system to be

developed. There are gaps in the link between databases and ontology and the use of systems that directly affected the foundations of the methodology.

- Methods and approaches have been developed that allow the realization of intelligent data retrieval in an ontology-based way. An ontology-based database and ontology linking, a way to create SQL queries from linking concepts, and an ontology-type database classification entry is developed.
- Based on the intermediate results, the main result of the thesis has been achieved – the development of a methodology for realizing data retrieval based on ontology. A methodology has been developed that summarizes database analysis methods, methods for creating ontologies, methods for the implementation of the system, and approaches to linking concepts to database objects.
- For the purpose of methodological approbation, a prototype of an Intelligent Reporter Data Retrieval System (IRDIS) has been developed, based on the developed methodology. In the prototype approbation, it showed all the properties described in the methodology by retrieving data from a linked relational database from technologies in abstract form.

During the development and research of the Doctoral Thesis, the following main conclusions have been made on the basis of the results and achievements obtained.

- The developed prototype has shown that the ontology capabilities are sufficient to implement database linking, defining a subset of data, validating data and discovering additional knowledge about classes and individuals, without additional technologies. The developed prototype does not apply ontology-compliant technologies (typing document or SPARQL query interpreter). All functions are realized only with an ontology that confirms the first hypothesis.
- The developed prototype system creates SQL queries to retrieve the necessary data using ontology-based knowledge of database tables, columns, relationships, and values. In the developed prototype, it is possible to use the ontology reasoning and concept hierarchy crawling to retrieve sufficient information to create a SQL query. This confirms the second hypothesis.
- The IRDIS prototype users did not have to deal with database terms or technologies when creating an ad hoc data request. The interface offered in the prototype gives the user the ability to define the desired data class using only the domain terminology. The user does not need to know database technology, database structure, or specific value used. The user also does not need to know

the semantic technology and does not need to be able to create SPARQL queries. Consequently, the third hypothesis will be confirmed.

- Using the concept of a query and the reason for ontology, it is possible to perform data validation without accessing the database. The described ontology model, combined with the ontology's reasoning capabilities, is capable of identifying non-executable data queries at model level without the need to refer to the database. Erroneous querying at the system level allows to minimize database loading.

The developed methodology describes the implementation of an ontology-based data retrieval system with the aim of supplementing existing relational databases with semantic information, intellect (in the form of ontological knowledge), and providing a semantic layer between used and database technologies. Future research can be a visit to the ontology capability to work directly with databases. This would streamline knowledge management and reasoning processes in relation to the approaches of relational databases for storing data, and eliminating the complexities of ontology implementation moments.

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