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RESEARCH ARTICLE

Application for Creating and Analyzing Competency-Based Curricula Using an Ontological Approach

AIZHAN NAZYROVA[1,3], MAREK MILOSZ[2], ASSEL MUKANOVA[3], GULMIRA BEKMANOVA[1], DMITRII KUZIN[3], AND SHADI ALJAWARNEH[4]

[1]Faculty of Information Technologies, L. N. Gumilyov Eurasian National University, 010008 Astana, Kazakhstan
[2]Department of Computer Science, Lublin University of Technology, 20-618 Lublin, Poland
[3]Higher School of Information Technology and Engineering, Astana International University, 010000 Astana, Kazakhstan
[4]Department of Software Engineering, Jordan University of Science and Technology, Irbid 22110, Jordan

Corresponding author: Aizhan Nazyrova (aizhan_nazyrova@aiu.edu.kz)

ABSTRACT This article describes the development and implementation of cutting-edge software for creating, modifying, and analyzing curriculum plans based on a competency-based approach, structured in the form of ontologies. The authors continue a series of studies in the field of ontological modeling, focusing on the features of a hierarchical curriculum model with an unlimited level of competency nesting. The article details the mechanism for determining prerequisites for studying disciplines based on the analysis of interrelationships between competencies formed by various courses, as well as the model for assessing control tasks to determine the level of students' proficiency in the necessary competencies. The presented software solution includes functionality for integrating data into an ontological structure, editing, and analyzing the consistency of curriculum plans, with an emphasis on preliminary discipline requirements and assessment of educational outcomes. The developed interface simplifies the process of working with educational programs and supports their export in Ontology Web Language format, which facilitates easy integration and collaboration in the educational environment. The main scientific contribution of this work is the model developed for assessing control tasks to determine the level of mastery of necessary competencies and the creation of a comprehensive software product for managing competency-oriented curriculum plans through ontological modeling. The results obtained enhances the flexibility of designing and coordinating educational programs that meet modern educational and professional requirements.

INDEX TERMS Ontology, educational program, competency-based approach, prerequisites, semantic web.

I. INTRODUCTION

According to OECD (Organisation for Economic Co-operation and Development) research, future educational systems are described as global educational systems where decisions are made by the stakeholders of the educational process, including employers [1]. Such systems should be based on a dual approach to organizing the educational process, provided by the modern competency-based approach, where competency development occurs directly with employer participation. In such conditions, the development of special software for automated design of educational programs and verification of competencies formed at the stage of designing the educational program, based on the assessment of the learning trajectory, is relevant [2]. Currently, the ''competency-based approach'' is becoming increasingly popular in the development of educational programs in higher education systems in most countries of the world [3], [4], [5], [6], [7], [8], [9], [10], [11]. The advantages of this approach are numerous. Firstly, the competency-based approach prioritizes the end results of learning, rather than the educational process itself [12], [13]. Its goal is to ensure that students master certain competencies or skills that will prepare them for future activities [14]. Secondly, the

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competency-based approach sets priorities, paying special attention to practical skills that students can directly apply in real situations, ensuring that students actively develop the abilities necessary for success in their chosen fields. Thirdly, a notable strength of the competency-based approach, which sets priorities, is its ability to promote interdisciplinary learning [5], [16], [17], [18], [19].

The next important step in implementing the competency-based approach is the development of standardized, widely recognized competency models in various fields [20].

Standardization and unification in this context offer undeniable advantages. Firstly, standardization supports comparative analysis, allowing for the evaluation of different educational programs using a common competency framework [21], [22]. Secondly, standardized competency-based approaches facilitate the recognition of qualifications and academic achievements at an international level, encouraging global academic mobility and merit recognition [23], [24], [25], [26]. Thirdly, transparency is increased through standardization, simplifying the understanding and evaluation of educational offerings by stakeholders, including students, educational institutions, and employers. Fourthly, quality assurance in education can be based on standardized competency models, ensuring that technology, uses an ontology - a graph of arbitrary structure - as the primary data storage structure [27], [28], [29]. In the context of computer science and artificial intelligence, an ontology is a formalized interpretation of a set of concepts in a specific subject area and the relationships between them. The use of the ontological approach provides the following key advantages:

- The model offers the capability for unlimited expansion and enhancement, including integration with ontological models from other subject areas. This quality allows for the continuous improvement and augmentation of the competency model during its operation.

- There is also the possibility for the model to be jointly used and refined by various independent organizations and groups of experts. This is achieved through the use of namespaces, which allow for the development of the competency model in separate parts, corresponding to different knowledge areas. Over time, these components can supplement or replace each other, and may also achieve standard status at various levels.

- The ability to expand the model and collaboratively refine it by various independent developers is extremely important. This is necessary because the main task is to create a model that will be shared and used by universities joining the community. Only in this case will a foundation be established for comparing educational programs and designing individual educational trajectories. This is a prerequisite for creating a technological platform for academic mobility [30], [31].

A simplified ontological model of a competency-oriented curriculum [26] is shown in Figure 1. This diagram illustrates the hierarchy of competencies, the semantic link between a course and competencies (Train), as well as the dependencies of competencies on each other (Require).

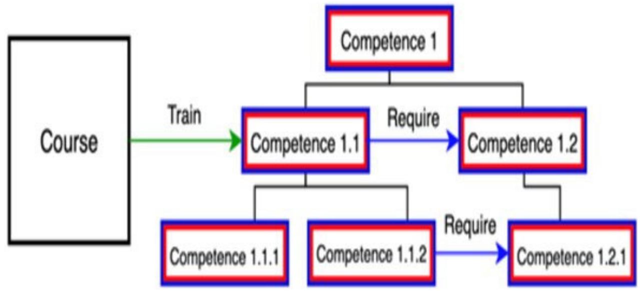

FIGURE 1. Simplified model of a competency-oriented curriculum [26].

The full graph of the ontological model of a competency-oriented curriculum [26] is presented in Figure 2. In addition to the competency model, it includes concepts describing periods of study – semesters and academic years, which are connected by corresponding relations that define their sequence and nesting.

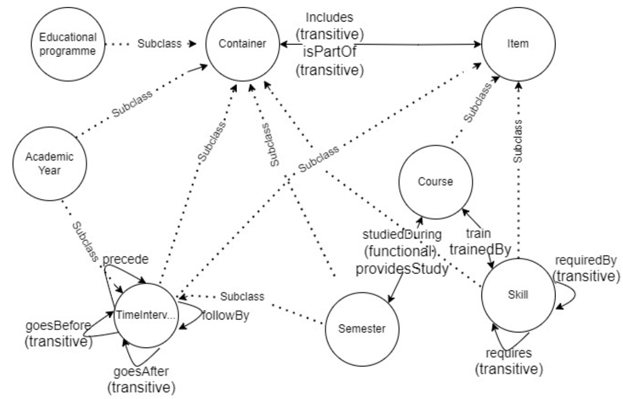

FIGURE 2. Ontology of the competency-oriented educational program [26].

II. RELEWANT WORKS REVIEW

To develop a competency-based curriculum model using an ontology approach, it is essential to consider the existing literature on ontology-based curriculum design and competency management.

Ontologies have proven their significance in various aspects of developing and optimizing educational programs, as illustrated in a wide range of studies. Abu-Salih and Alotaibi [32] highlight the importance of knowledge graphs for optimizing curricula, emphasizing the role of structured knowledge in the effectiveness of the educational process. Meanwhile, Weinhandl et al. [33] explore how digital design and characters can enrich learning in Austrian mathematics schools through visual and interactive elements. Underscore how ontologies facilitate the integration of educational modules and optimization of educational trajectories, respectively [34], [35], [36], [37].

Make an innovative contribution by presenting an ontology for analyzing and disseminating information about educational programs, focusing on its potential to facilitate academic mobility [30]. Emphasize the importance of personalized learning and the connection of education with the labor market, demonstrating how the ontological approach can contribute to structuring knowledge and competencies for creating comprehensive educational programs [38], [39], [40], [41], [42], [43].

The importance of integrating competencies into the structure of the curriculum using ontologies is emphasized, facilitating the development of effective educational trajectories [44]. Authors point out the benefits that corporate e-learning derives from using ontologies for competence management [45]. Research highlights the role of ontologies in managing the complexity of curricula and their adaptation to changing requirements, while demonstrates the versatility of ontologies in various fields of education [46]. Work sheds light on the use of ontologies in competency assessment, highlighting their ability to meet educational needs [47].

The use of ontologies promotes the formation of a common understanding in the field of education and improves the development of competency-based curricula [48]. Underscore the importance of integrating ontologies with software tools to enhance competence management [49], [50]. Research reveals the significance of reliable ontological models for defining and managing competencies, and presents the potential of Semantic Web architecture for competency management [51]. The efficacy of ontological models in synchronizing educational content with labor market needs and improving the accessibility of educational resources is well-documented in studies [52]. Concurrently, research indicated by references underscores the critical role of ontologies in the assessment of educational outcomes and the cultivation of key competencies [53]. Ontologies demonstrate their effectiveness as a tool for defining, representing, and annotating competencies, as well as aggregating educational content, as confirmed by research [54]. They facilitate the integration of competencies into curricula and promote the development of a collective, competency-oriented mindset [55]. Furthermore, ontologies improve the coordination and optimization of educational trajectories, adapting them to individual needs and goals of learners, as expressed in the ability to automatically annotate educational content and create competency-oriented web services [56]. They also enhance competence management through the automation of profiling, matching, and planning processes, considering current educational trends [57], and play a key role in structuring the assessment of educational outcomes and preparing curricula [58]. The application of ontologies for automatic generation of assessment questions offers teachers innovative support for improving the quality and efficiency of assessing educational achievements [59]. It also describes a method for automatic ontology creation using Massachusetts Institute of Technology OpenCourseWare computer science course materials as a data source [60]. A prototype inter-institutional information system for translating student credits in Hong Kong was developed, aimed at improving transparency and simplifying the process between educational institutions [61], using methods of text processing, analysis, ranking according to Bloom's taxonomy, and competency clustering, achieving an accuracy of 77% [62]. The paper discusses the development of a cross-institutional (CIS) credit transfer information system for community college transfer students in Asia, detailing a prototype that enhances the transparency and sustainability of credit transfer information through a four-phase life cycle model, covering user needs assessment, prototype development, and expert reviews, while also addressing challenges faced during the process [63]. It described the creation of an Natural Language Processing system for matching courses between computer science programs at various educational institutions [64].

In summary, the synthesis of the referenced literature underscores the significance of ontology-based approaches in developing a competency-based curriculum model. Ontologies offer a robust foundation for modeling competencies, curriculum knowledge, and learning resources, providing a structured framework for designing and implementing competency-driven educational programs.

Overall, authors underscore the importance of utilizing software tools that support ontology-based competency management systems. These tools should enable effective ontology design, competency question-driven ontology authoring, and the development of competency-based systems.

In conclusion, the use of ontology-based approaches in competency-based curriculum development is well-supported by research, demonstrating their effectiveness in representing competencies, guiding learning paths, and supporting competency management, as well as in facilitating the creation of competency-based curriculum and the assessment of learning outcomes.

III. RESEARCH QUESTIONS

The considerations presented in the Introduction, along with the results of the literature and related works review, have led to the formulation of the following research questions:

Q1. Is it possible to create applied software that provides tools for working with the ontological model of a competency-oriented curriculum?

Q2. Is it feasible to dynamically implement logical reasoning procedures for analyzing the consistency of a competency-oriented curriculum?

Q3. Are there effective options for constructing a user interface to display the structure and results of consistency analysis for a competency-oriented curriculum represented in the form of an ontological model?

Q4. How can the software processing of the competency tree of a curriculum be organized, taking into account an unlimited number of hierarchical levels within it?

IV. MATHEMATICAL MODEL FOR ESTIMATION OF THE LEVEL OF PROFESSIONAL COMPETENCIES OF STUDENTS

Competencies are a set of knowledge, abilities, and skills of a learner, which are necessary for the effective performance of professional duties in the specialty and achieving high results.

The hierarchy of competencies in an educational program can be described as follows:

$$E_i = \cup_k M_{i_k}, \quad (1)$$
$$M_k = \cup_l D_{k_l}, \quad (2)$$
$$D_l = \cup_m S_{l_m}, \quad (3)$$

where: $\cup$ - union operator, E_i- competencies at the i level of the educational program, M_k- competencies at the k module level, D_l- competencies at the discipline level and S_m- competencies at the m section level.

Various assessment methods are used to determine the level of competence mastery: tests, written assignments, and oral questioning of students. Each task should encompass one or more competencies of the section/discipline:

$$Q_p = \cup_t S_{p_t} \quad (4)$$

i.e., a student's response to a question/assignment/test Q_p is positively assessed if it demonstrates mastery of the set of competencies $\{S_{p_t}\}_t$ from discipline D_l.

The difficulty of each task can be determined as follows by using (4):

$$complexity\left(Q_p\right) = \frac{n\left(\{S_{p_t}\}_t\right)}{n\left(\{S_{l_m}\}_m\right)} \quad (5)$$

where: $n(\cdot)$ signifies the number of elements in a finite sequence and $\{S_{p_t}\}_t \subset \{S_{l_m}\}_m$ using formulas (1) - (3).

To assess competencies, it is necessary to create tasks that effectively determine the degree of mastery of the skills of the discipline/module/program. The formulation of tasks and their objectivity and effectiveness are important tasks in determining the level of knowledge and competencies. The level of difficulty of test tasks can be determined using various techniques, and this paper also proposes to use approach (5). Therefore, let's consider a mathematical model that describes the evaluation of tasks in any format: test, written work, colloquium, or exam.

For further research, let us first introduce a series of concepts. Let us call the benchmark set of tasks:

$$\{Q^*_{l_i}\}_i \quad (6)$$

for an objective assessment of the competencies of discipline D_l. Let's assume that when developing tasks, the developer followed a strategy/policy $\pi\left(\cdot|D_l\right)$.

Given that the determinacy of the policy cannot be pre-asserted due to the stochastic nature inherent in any human action, we can consider the policy as a distribution function of a certain random variable. Let us assume that there is a certain benchmark policy:

$$\pi^*\left(\cdot|D_l\right) \quad (7)$$

using which the tasks (6) were implemented.

Consider the strategy (7), followed by the developer, as the benchmark based on expert assessment. The problem is to define another set of control tasks to test knowledge and assess the competencies of students, while maintaining the completeness and effectiveness of the benchmark examples with the benchmark policy. These tasks may be in a different format than the benchmark ones.

Completeness is not difficult to determine; the primary necessary condition is the content of the tasks that assess all the competencies of the given discipline.

Let's consider a new policy/strategy $\pi'\left(\cdot|D_l\right)$ and a list of control tasks $\{Q'_{l_i}\}_i$. To make comparisons let us consider KL-divergence (Kullback–Leibler divergence) [65] between two distributions:

$$D_{KL}\left(\pi'||\pi^*\right) = \sum_i \pi'_i log\frac{\pi'_i}{\pi^*_i} \quad (8)$$

it is needed to determine how close the distributions of students' answers are regarding the competencies necessary for mastering the discipline.

Here, probabilities denote the distribution of responses according to competencies. Based on the value obtained from formula (8), one can judge the potential inclusion of this set of tasks for assessing students' mastery of the discipline. Based on the obtained results, the final grade can be assigned.

This approach ensures that the evaluation not only measures how well students have learned specific content but also how effectively they can apply their competencies in different contexts. By using KL-divergence, educators can quantify the alignment between the intended outcomes of the educational program and the actual outcomes demonstrated by the students, leading to a more tailored and effective educational experience.

V. DEVELOPMENT OF A COMPETENCY-BASED CURRICULUM ANALYSIS APPLICATION

The architecture of the developed application for working with competency-based curricula is shown in Figure 3. The competency model, as well as the curriculum itself, are implemented in the form of an ontology, the development and maintenance of which is carried out using the Protégé ontology editor. Then the prepared ontology in OWL (Ontology Web Language) format is loaded into the main application. The main application performs the functions of visualizing the curriculum and competency tree, viewing the properties of training courses from the point of view of the competency-based approach, and analyzing the consistency of the curriculum.

The main application is a cross-platform Python application written using the PyQT and OWLReady2 libraries. The choice of the Python programming language for implementing the system is due to the fact that the largest number of application libraries, including those listed above, were created for Python, as a modern, multi-purpose and rapidly developing language. PyQT is a popular library for creating visual interfaces for desktop applications [66]. OWLReady2 is a library for working with ontological models represented in the OWL.

Upon loading the application, the following actions are performed:

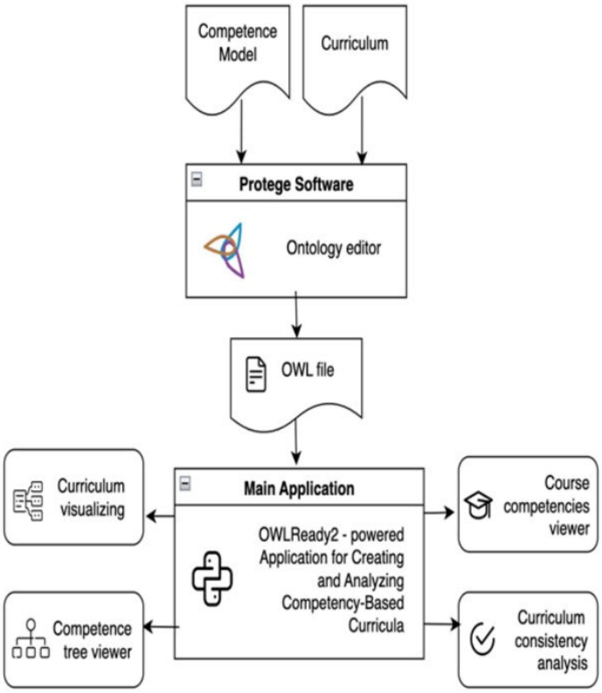

FIGURE 3. The architecture of the developed application.

1) Initialization of the user application.

2) Binding control activation events to handler functions.

3) Loading the ontology from a file into an OntologyClass object.

4) Extraction of all individuals of the class "semester" from the ontology using the methods of the OntologyClass (Figure 4, line 315).

5) Processing the list of semesters in a loop and forming top-level expandable items in the curriculum (Figure 4, line 317).

6) Retrieving all courses for the current semester in a loop using a SPARQL query (Figure 4, lines 318 – 327).

7) Adding courses to the curriculum (Figure 4, line 329).

```
315 for semester in self.onto.Semester.instances():
316     print(semester.label[0])
317     parent = QStandardItem(semester.label[0])
318     courses = list(default_world.sparql("""
319    prefix enu: <http://www.enu.kz/ontologies/curriculum#>
320    SELECT DISTINCT ?d ?l
321    WHERE {
322         ?d enu:studiedDuring ?s.
323         ?d rdfs:label ?l.
324         FILTER(LANG(?l) = "" || LANGMATCHES(LANG(?l), "en")).
325        ?s rdfs:label '""" + semester.label[0] + """'
326       }
327    """))
328     for c in courses:
329         parent.appendRow(QStandardItem(c[1]))
330     model.appendRow(parent)
331 view.show()
```

FIGURE 4. The program code for visualizing the curriculum.

The curriculum visualization interface is shown in Figure 5. It is implemented using the QTreeView class. When the tree reaches the bottom edge of the window, a scrollbar appears.

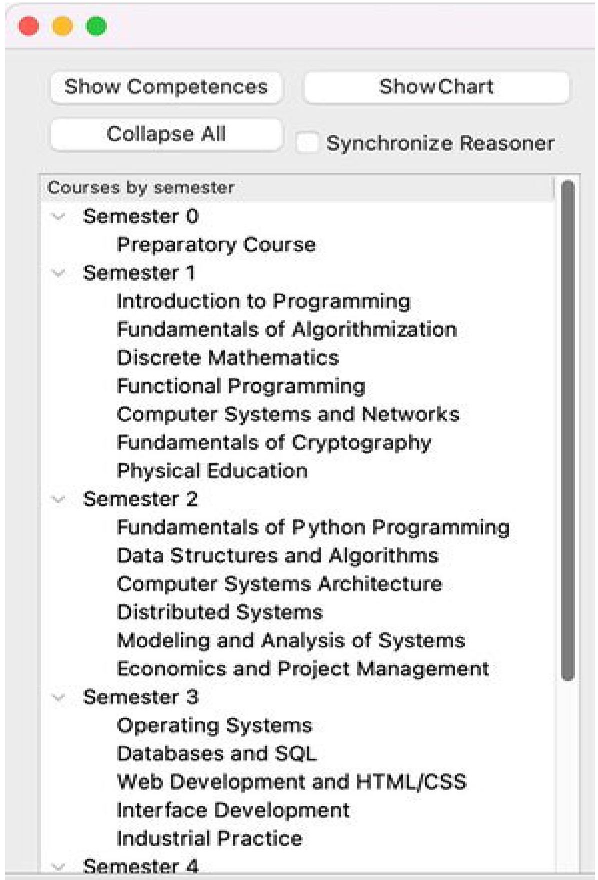

FIGURE 5. The main window of the application.

Upon pressing the "Show Competences" button, a window opens to view the competency tree of the curriculum (Figure 6). Since the number of nesting levels in the competency tree can be arbitrary, a recursive function has been implemented to traverse the tree (Figure 7).

Synchronization of the reasoner is carried out by calling the sync_reasoner function (Figure 8) and is managed using a control element (checkbox control). To disable the reasoner, the ontology is reloaded from the file.

When a user double-clicks on any course in the left window, the program code executes, which extracts from the ontology and displays the following data in the application window (Figure 9), using SPARQL queries:

1) competencies formed by the course;

2) competencies required for studying the course;

3) competencies required for studying the course that the student has not acquired as a result of studying all the courses of the previous semesters (a mismatch between the required competencies and those possessed by the student).

Similarly, the program works when selecting any semester in the left window. In this case, all the competencies formed by the semester's courses are checked for consistency.

To visualize the results of the curriculum consistency analysis, the application generates a diagram (Figure 10). The diagram displays the number of competencies that are formed

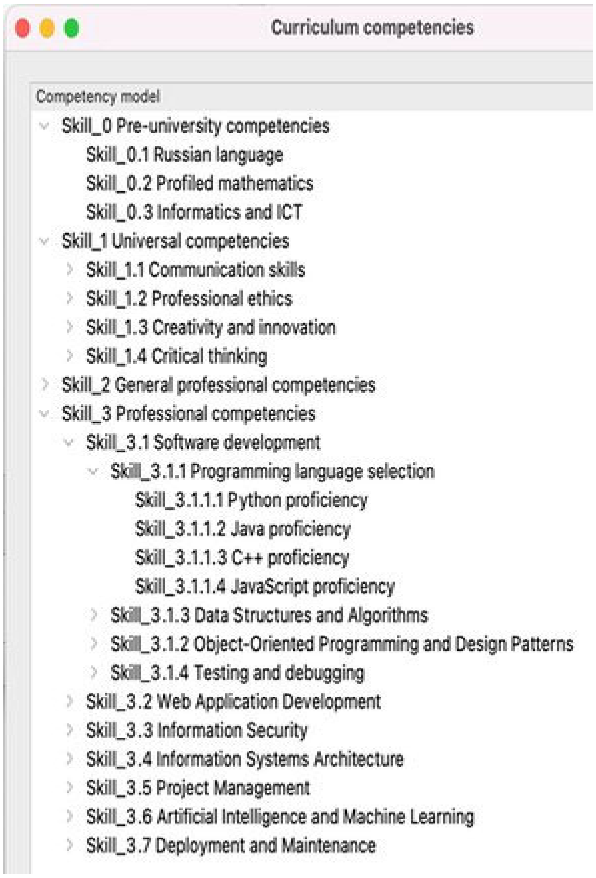

FIGURE 6. Hierarchical model of the curriculum competencies.

```
# Recursive function for obtaining child competencies
def get_skills(self, skill, i, parent):
    skills = list(default_world.sparql("""
    prefix enu: <http://www.enu.kz/ontologies/curriculum#>
    SELECT ?s ?l
    WHERE {
        ?s enu:isPartOf ?x.
        ?s rdfs:label ?l.
        FILTER(LANG(?l) = "" || LANGMATCHES(LANG(?l), "en")).
         ?x rdfs:label '""" + skill[0].label[0] + """'
    }
    ORDER BY ?s
""")
    i += 1
    for skill in skills:
        child = QStandardItem(skill[0].name + ' ' + skill[1])
        parent.appendRow(self.get_skills(skill, i, child))
    return parent
```

FIGURE 7. Recursive function for obtaining a list of child competencies.

```
def toggle_reasoner(self):
    if self.toggleReasonerCheckBox.isChecked():
        sync_reasoner(infer_property_values=True)
    else:
        self.loadOntology("ontology.rdf")
```

FIGURE 8. Managing the operation of the reasoner.

by the courses of each semester, the number of competencies obtained by the student during previous semesters, and the number of missing competencies (inconsistencies).

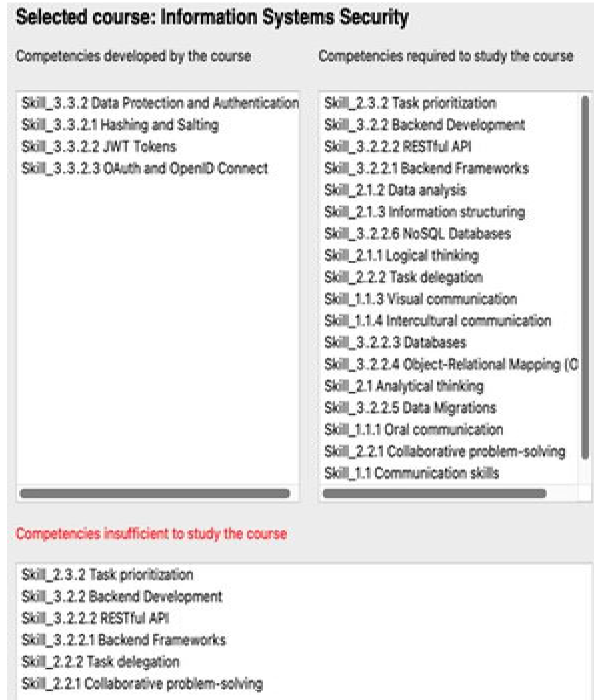

FIGURE 9. Verification of the consistency of the curriculum for a specific course.

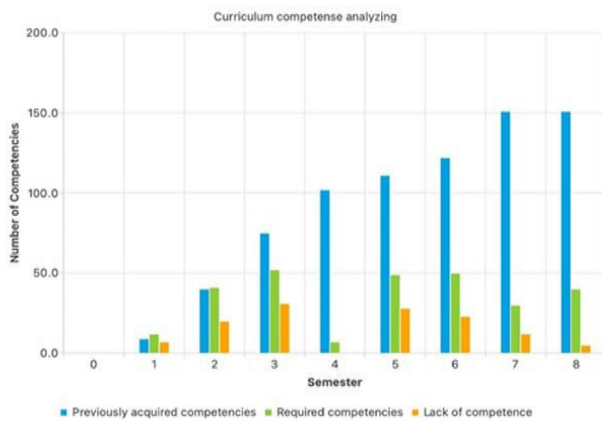

FIGURE 10. Analysis of the consistency of the curriculum.

VI. RESULTS AND DISCUSSION

The main results of the work performed are as follows:

1. An analysis of scientific publications dedicated to the problem of developing software for working with ontological models of competency-oriented curricula has been conducted.

2. A mathematical model has been developed that does not depend on the format of the set of control tasks for tests, colloquiums, written assignments, or exams, but is based exclusively on data about skills and competencies obtained from a standard examples.

3. The ontological model of a competency-oriented curriculum has been developed has been developed using the Owlready2 library for working with the ontological model

of a competency-oriented curriculum, which allows for the extraction of data from the ontology and provides a Graphical User Interface for interaction.

4. A recursive algorithm for traversing and extracting data from the competency tree with an arbitrary number of nesting levels and their visualization has been implemented.

5. An algorithm for checking the inconsistency of an educational program has been implemented using SPARQL queries and Python code. It involves determining the difference between the set of competencies required for studying the courses of the semester and the set of competencies already formed in the student. The results of the analysis are displayed in the form of a diagram.

The conducted research made it possible to answer the research questions posed.

Q1. Is it possible to create applied software that provides tools for working with the ontological model of a competency-oriented curriculum? The answer to this research question is YES, such software has been developed.

Q2. Is it feasible to dynamically implement logical reasoning procedures for analyzing the consistency of a competency-oriented curriculum? The answer to this research question is YES, the developed application has implemented reasoning procedures that allow for the dynamic display of reasoning results in the user interface.

Q3. Are there effective options for constructing a user interface to display the structure and results of consistency analysis for a competency-oriented curriculum represented in the form of an ontological model? The answer to this research question is YES, the developed application has implemented a user interface that displays the structure of the curriculum with the distribution of courses across semesters, as well as the results of the curriculum's consistency analysis in both text and graphical form.

Q4. How can the software processing of the competency tree of a curriculum be organized, taking into account an unlimited number of hierarchical levels within it? The answer to this research question is that software processing of the competency tree has been implemented in the application as a recursive procedure that returns a list of child nodes. This method of processing makes the program code independent of the number of hierarchy levels in the graph.

VII. CONCLUSION

In this article, the authors describe software developed in the Python programming language for working with the ontological model of a competency-oriented curriculum. The curriculum model used by the authors is distinguished by the fact that competencies are organized into a hierarchical data structure with an arbitrary number of levels of nesting, while the prerequisites for studying a course are defined as dependencies of the competencies formed by this course on the competencies formed by other courses [26].

The developed application performs the following functions:

1) Loading the ontological model from an OWL file.
2) Displaying the structure of the curriculum as an expandable list of semesters and courses.
3) Supplementing the model with axioms obtained as a result of logical inference.
4) Outputting a list of competencies formed by a course.
5) Outputting a list of competencies formed during previous periods of study.
6) Outputting a list of competencies that are prerequisites for studying a course or a set of semester courses.
7) Retrieving and displaying a list of missing competencies for studying a course or a set of semester courses (inconsistencies).

The consistency analysis of the educational program was also implemented using SPARQL queries. With the application, it is possible for any course or semester to obtain a list of missing competencies — competencies that are prerequisites for semester courses but were not formed in the student during previous semesters.

The application can help implement the advantages of the competency approach in education by providing adequate tools for designing and analyzing the educational program. The code of the developed application is available in an open repository. Future directions for the development of the developed software include adding the following functions:

1. Working with competency models of different subject areas.
2. Managing a library of educational programs.
3. Editing the curriculum.
4. Preparing printable forms of documents.

Furthermore, it is advisable to implement the application using a client-server architecture with the possibility of multi-user access.

It is planned in further research to include the assessment of student competencies into the educational program system and automate the processing of control tasks.

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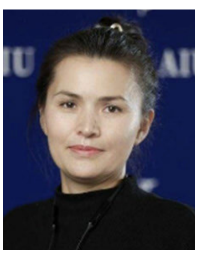

AIZHAN NAZYROVA received the degree from the Doctoral Program in the Educational Programs–D094 Information Technology, L. N. Gumilyov Eurasian National University, Kazakhstan, in 2023. Currently, she is a Senior Lecturer with the Higher School of Information Technology and Engineering, Astana International University, Astana, Kazakhstan. Her research interests include the development and design of information systems, theoretical substantiation of computational algorithm, and artificial intelligence.

MAREK MILOSZ received the Ph.D. (Eng.) degree. He is a University Professor with Lublin University of Technology, Poland. He is also the Head of Department of software engineering and database systems. He was the Deputy Dean for students of computer science with the Faculty of Electrical Engineering and Computer Science, for many years. He is a Lecturer and an Expert in software engineering, database management, business process modeling, management information systems building and developing, IT solutions developing in e-business, and project management. He has supervised approximately 180 M.Sc. thesis, most of them in software engineering field. He is the author or co-author of 44 books and approximately 350 scientific papers in computer science.

ASSEL MUKANOVA received the Ph.D. degree in computer science from L. N. Gumilyov Eurasian National University, Kazakhstan, in 2015. Currently, she is an Associate Professor with the Higher School of Information Technology and Engineering, Astana International University. Her research interests include artificial intelligence, natural language processing, ontology modeling, and intellectual knowledge base.

GULMIRA BEKMANOVA received the B.S. and M.S. degrees in information systems from D. Serikbayev East Kazakhstan Technical University, Oskemen, Kazakhstan, in 2004 and 2006, respectively, and the Ph.D. degree in computer science, computer engineering and control from L. N. Gumilyov Eurasian National University, Kazakhstan, in 2010. She is a Candidate of technical sciences on specialty: 05.13.11-mathematical software for computers, complexes, and computer network. Her research interests include artificial intelligence, natural language processing, ontology modeling, and intellectual knowledge base.

DMITRII KUZIN is an Associate Professor with the Higher School of Information Technology and Engineering, Astana International University. His research interests include ontology modeling, software development, and machine learning.

SHADI ALJAWARNEH is a Full Professor with the Department of Software Engineering. His research is centered in software engineering, web and network security, e-learning, AI, machine learning, and cloud computing. He has presented at and been on the organizing committees for a high number of international conferences and esteemed Journals, he is also a board member of the International Community for ACM, Jordan ACM Chapter, ACS, and IEEE. A number of his papers have been selected as "Best Papers" in conferences and journals.