THE PRINCIPLES OF DESIGNING AN EXPERT SYSTEM IN TEACHING MATHEMATICS

A. Nurgaliev, L. Salekhova, R. Zaripova

Kazan Federal University (RUSSIAN FEDERATION)

Abstract

This paper introduces a research study of the development and application of the Expert System (ES) in the educational area in Russia. The use of ES in education can simplify the process of teaching subjects. The proper use of the system can significantly reduce the workload of a teacher and leave more time for self-development and improving professional mathematical competence. The ES is built on the Concept-Effect Relationship (CER) model, which represents prerequisite relationships among concepts in a course, in our case, mathematics. The enhanced CER model introduced in this work provides optimal application in real life practice by introducing a general methodology for building dependency tables between topics in a course without linking to a specific subject. The effectiveness of this model heavily depends on the concept relationship knowledge provided by the domain experts (e.g. experienced subject-teachers). The authors of the 8th grade Algebra course books, approved by the Ministry of Education of Russia as the recommended books, represent the domain experts. The ES generates individual exercises for each student based on his/her academic performance which are collected from the didactic materials for the 8th grade students of Algebra course and integrated into the system. The system is developed by using the Java programming language, with the rule-based Java Expert System Shell as the expert system core, which is used to perform expert analysis and provide recommendations to teachers. The pilot implementation of the system is held in one of the multilingual high schools of Kazan (Russia). The preliminary results of the system's usage demonstrate its effectiveness in terms of optimization of teachers' time management without loss of students' academic literacy.

Keywords: Expert systems, teaching, mathematics, education, multilingualism, information systems in education.

1 INTRODUCTION

In present economic and socio-cultural situation it is becoming increasingly important to use perspective individual learning strategies to ensure the educational needs of each student. To provide this individual learning guidance we have developed an Expert System (ES) for teaching Mathematics based on multilingualism (Russian-Tatar-English) for the eighth grade pupils. The proper use of the system can significantly reduce the workload of a teacher and leave more time for self-development and improving professional mathematical competence. Original contribution of our study is researching and development of general didactic concepts of defining relationships between levels of correctness of pupils' answers and level understanding of a subject. Accordingly, every teacher would be able to receive an expert assistance regardless of his location or time.

The project is represented as an application, capable of decreasing the teachers' workload and increasing the effectiveness of a teacher's efforts. The model of analyzing pupils' academic performance is used as a basis for building an individual educational guideline. Per request of a user (teacher) the system detects the root cause of the academic deterioration and provides the most optimal academic load for each individual student as well as for the whole group of students. This helps achieving flexibility during developing and realization of the study course.

Due to the fact that some of the responsibilities of the teacher are taken by the ES, the teacher's workload decreases, at the same time increasing the quality of education.

The structure of the paper is as follows: Section 1 presents an overview of the ES, Section 2 presents the principles of developing a CER model for the ES, Section 3 demonstrates the features of the developed ES with the screenshots, and Section 4 shows the results of the system application in the multilingual high schools of Kazan (Russia).

2   THE EXISTING TECHNOLOGIES AND PRINCIPLES

Nowadays several researches suggests various approaches for developing self-learning systems based on the personal characteristics of the students [1]. Moreover, they have proposed models and mechanisms for diagnosing student learning problems as well as the construction of individual academic curriculum [2, 3].

It has been proved that the Concept-Effect Relationship (CER) model is an effective way of improving the learning performance of students. The CER model represents the prerequisite relationships among concepts in a course. The CER model demonstrates a systematic procedure of recognition the students learning problems with respect to each concept taken into account. It has been successfully used to identify the learning problems of students and to give individual recommendations to them for science and mathematics courses [4].

Hwang et al. [3 proposed his own CER model to demonstrate the prerequisite relationships among concepts that need to be explored in a predetermined order. This model became the basis for the further development of the methods for testing, diagnostic mechanisms and systems for improving the learning performance students. In addition, various applications have revealed the big effectiveness of the CER model.

For example, Jong et al. [4] created a learning behavior diagnosis system which was applied in teaching Computer Science at the university and was shown positive experimental results for both learning status and learning achievement. In the meantime, Tseng et al. [5] applied the CER model to provide individual learning guidance in the Physics course of a high school. Hwang, et al. [3] declared the effectiveness of the CER model in improving the students learning achievements in a Mathematics course of an elementary school.

In the presented CER model, the diagnosis of student learning problems mainly depends on the prerequisite relationships between the concepts to be learned. Consider two concepts to be learned, say C_i and C_j. If C_i is a prerequisite to efficiently performing the more complex and higher level concept C_j, then a concept-effect relationship C_i/C_j is said to exist. For example, to learn the concept "addition of decimal fractions," one may first need to learn "comparing decimal fractions", while learning "approximate value of the decimal fractions" may require first learning "addition of decimal fractions" and "subtraction of decimal fractions". For the sake of simplicity let's consider the term "concept" as a topic of a subject. Therefore, if the student does not respond accurately to the majority of questions on the topic «Approximate value of decimal fractions», it is likely that the student studied poorly this topic or previous themes - «Addition of decimal fractions» and «Subtraction of decimal fractions» [6]. Thus, teachers can identify problems of students in studying these topics through monitoring of the concept-effect relations.

In order to provide individual recommendations dependencies between topics should be found. That requires the creation of a table showing their interrelation. The values of relation range from 0 to 1; «1» indicates an absolute dependency, and «0» indicates the lack of any connection between topics. This information is further used in combination with students' marks in order to determine the root cause of academic deterioration.

3   DESIGNING THE MODEL OF THE EXPERT SYSTEM

In practice the problem of determining the dependencies between topics in a course can become laborious [7]. This problem appears because the dependencies between topics are determined by domain experts, but teachers might have different opinions about the relationships between certain topics. As it is very difficult to choose the best experts, using the authors of the course books as the domain experts can simplify the overall process of defining the dependencies between topics.

We have developed a general methodology for defining the dependencies between topics regardless to any specific school subject.

There are essential definitions and initial conditions prior introducing the methodology:

1. Definition: An atomic topic is a topic which doesn't have any prerequisites for its learning. In other words an atomic topic is an initial topic in the logically completed subject matter module.

2. The definition of the concept-effect relationship should be narrowed down in order to avoid developing of an overly complicated table of dependencies with redundant links. A narrow definition of a concept-effect relationship is the following:

If C_i is a prerequisite to efficiently performing the more complex and higher level concept C_j, such that doesn't exist a concept C_k for which C_i also stands as a prerequisite, at the same time C_k is a prerequisite to efficiently performing the concept C_j:

$$C_i \rightarrow C_j \mid \nexists\ C_k: C_i \rightarrow C_k \rightarrow C_j$$

3. The level of dependency between two topics varies from 0 to 1 inclusive. In the case when a complex topic has several prerequisites, we assume that the sum of all dependencies is equal to one. Each topic, no matter how complex it is, is equally important as other prerequisite topics, so if there are N prerequisites for some topic C_j then each degree of dependency is calculated as 1/N, otherwise it contradicts the initial definition of the CER model (Fig. 1).

The step-by-step methodology for developing a dependency table will be described in the following section.

For the purpose of simplicity and clarity of presentation of the dependencies between topics, we will use a graph representation. The root (top) of a graph represent the atomic topic(s) and leafs (bottom) represent the most complex topics is a course, they should be learned after learning all other prerequisites.
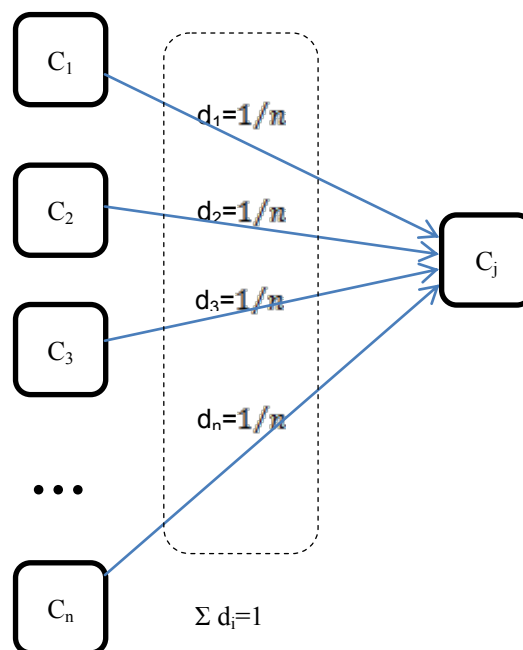

Fig. 1. The levels of dependencies between topics.

3.1 An algorithm for developing a dependency table

Step 1. Define the linear sequence of topics (concepts) $[C_1, C_2, C_3, \ldots C_n]$. Preliminary identification of the sequence of topics in the course can simplify the process of determining the dependency of themes, since more advanced topics are always taught after their prerequisites.

A well-outlined flow of studied topics allows scholar to easily learn a subject without jumping from one chapter to another and then back again.

Three course books, which were approved by Russian Ministry of Education, should be selected in order to accomplish this step. The fact that the book was held a serious review and recommended by the Ministry of Education of Russia for use in schools ensures that it has a clear and the verified logic in the topics sequence that allows students to learn easily and efficiently.

Therefore a general overview of topics' dependencies obtained from defining the linear dependency of topics in their sequence, serves as a basis for further development of the dependency table.

This approach allows us optimizing the process of developing the dependency table:

a. Topics, located to the right of the reviewed concept cannot have regressive dependencies, what means that, a complex topic cannot be a prerequisite for a simpler topic located to the left of it in

the list. So the search for dependencies is limited by remaining concepts to the right from the examined topic.

b. Since there is a high probability that the prerequisite topics are located in a limited locations away in the list $[C_1, C_2, C_3, \ldots C_n]$ the step 3 which requires defining only the adjacent depending topics is simplified. The time required to fill the entire dependency table significantly reduces as there is no need to traverse the full list.

Step 2. On that step the atomic topics are determined according to the following algorithm:

For any C_i, where i=1,2,3,…, n compare C_i and C_j, where j=1,2,3,…,n-1 and j<i.

If for any j ∄ Cj →Ci, then put C_i as one of the origins of the graph and eliminate it from the list $[C_1, C_2, C_3, \ldots, C_n]$.

The atomic topic is determined at this phase if there is no prerequisite topic to the left of the considered one. According to the settings described at the first stage, the first topic in the list $[C_1, C_2, C_3, \ldots, C_n]$ will all the time be an atomic topic.

Step 3. Determine the nearest depending topics for the considered topic. It is accomplished according to the given algorithm:

Determine the list of remaining topics: for any C'_i where i=1,2,….,k and k<n: $[C'_1, C'_2, \ldots, C'_k]$;

Determine the list of topics from the lowest level of the dependency graph at the moment: for any C_j, where j=1,2,…m and k+m ≤ n: $[C_1, C_2, \ldots, C_m]$.

Determine the CER according to the narrow definition.

Place C_i under the dependency of C_j and eliminate it from the list of remaining topics. There may be several prerequisites for C_i, in such case the degree of dependency (which varies from 0 to 1), is calculated according to the initial condition 3.

It is essential to define the topics that directly influence on the effective learning of the considered topic. Therefore every concept from the remaining list of topics is verified for reliance among all topics currently located on the leafs of the dependency graph (Fig. 2). Repeat step 3 until the list of the left behind topics gets empty.
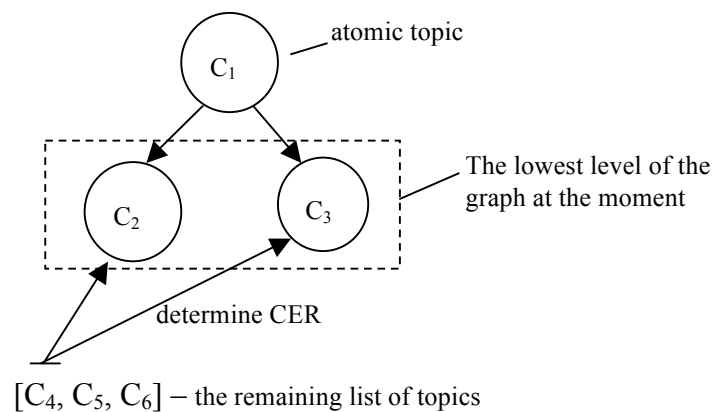

Fig. 2. Developing a dependency graph.

The suggested algorithm has been used in order to develop the dependencies between topics for the 8th grades Algebra course.

The program logic holds expert analysis and evaluation of all incoming data in accordance with the specified conditions and assumptions that have been programmed into the system in accordance with the methods of teaching the subject, in this case, mathematics.

On the basis of conclusions obtained from calculation findings, the system should identify possible gaps in the knowledge of the individual student and generate tasks for independent work on poorly assimilated topic. Additional modules can be plugged into an expert system to adapt it for specific requirements of individual teachers (for example, a module for automatic synchronization with the database marks or random exercise generator module).

4 DEMONSTRATION

The architecture of the system is described in Fig. 3. A teacher interacts with a graphical interface which includes such information as academic performance of a student as well as the identification of possible gaps in the knowledge of an individual student in order to improve his/her academic performance.
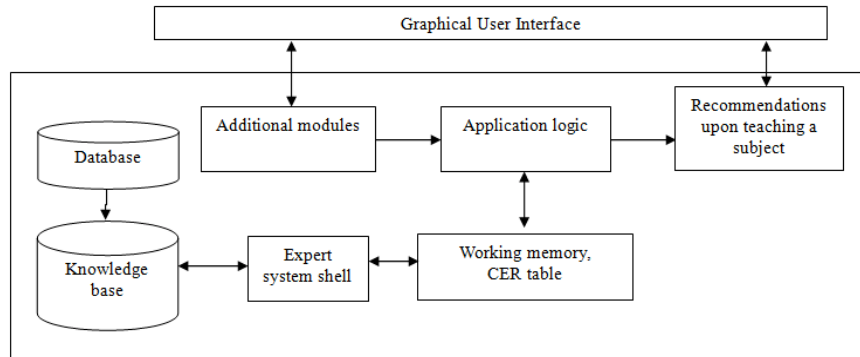

Fig. 3. The architecture of the ES for teaching Mathematics.

The program logic carries out expert analysis and comparison of all the incoming data with the relevant conditions and the assumptions that were programmed into the system according to the methodologies of teaching a subject, particularly, mathematics.

Additional module plugged into the system uses the analysis information in order to generate individual tasks with the emphasis on the poorly learned topics.

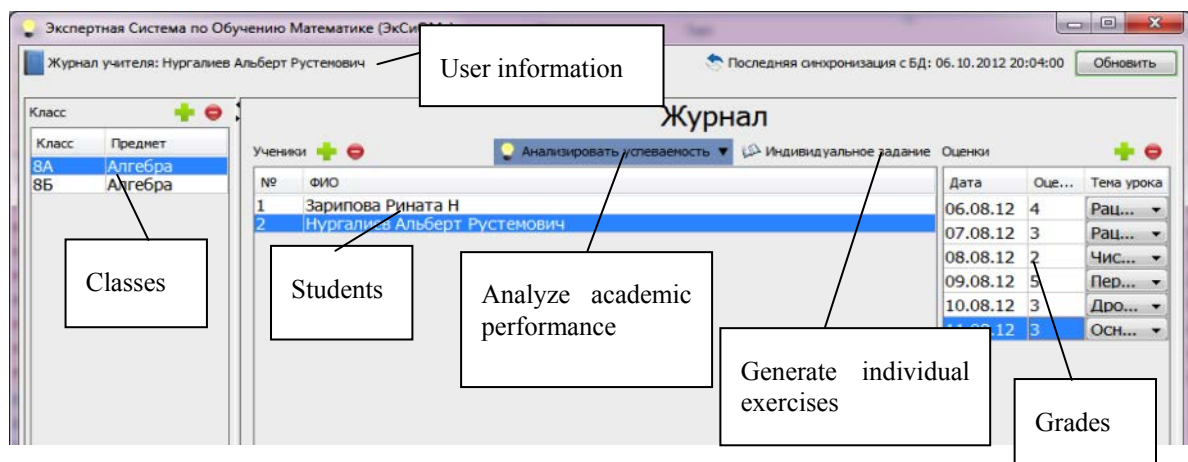The main dialog window of the expert system is presented in the Fig. 4.

Fig. 4. Main window of the ES for teaching Mathematics.

Main window of the system was developed with the aim to resemble the appearance of a traditional class journal. The information about the current user is presented on the top of the window. Left column presents the list of the classes where the current teacher teaches his/her subject. When one of the classes is selected from the list, its corresponding list of students is shown in the middle column. By analogy, when one of the students is selected from this list, his/her corresponding grades are displayed along with such information as the date of the grade and topic for which this grade was given. All the lists can be edited using the corresponding buttons on the toolbar above each column.
Main advantage of our system relies in its ability to analyze the academic performance of each student individually as well as of the entire class. The user interface is designed to be intuitive to use by a person with basic knowledge of computer technologies. The analysis of academic performance is accomplished by pressing a single button on a toolbar located on the middle column above the list of students, while the analyzing mode (for the entire class or individual) is done using drop down menu (Fig. 5).
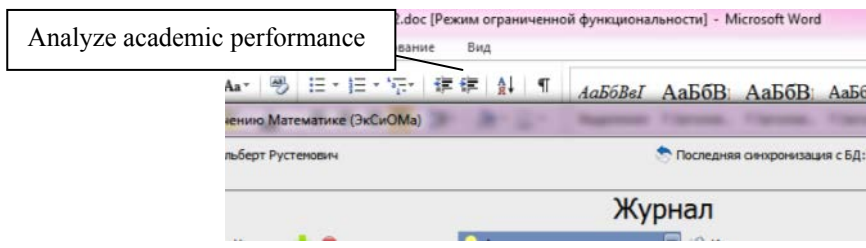
Fig. 5. Analyzing feature of the ES for teaching Mathematics
(two analyzing options: individual and for entire class).

As the result of the analysis for both of these modes would be building of the tree of problematic topics, which represents the weakly learned topics and the order in which they should be learned. For example, if the topic "Fractional expressions" cannot be learned before "Rational expressions", it is not worth trying to eliminate the knowledge gap in a more complex topic "Fractional expressions" when a student has poorly learned a prerequisite topic "Rational expressions". In cases when some problematic topics don't have dependencies between each other, they are displayed as separate roots of a tree (Fig. 6). The list of problematic topics for the entire class is defined by analyzing the academic performance of each student in this class with further statistical analysis to determine the most popular problematic topics. If the problematic topic is met in more than the half of the class, it is considered as the knowledge gap for the entire class and is displayed in the resulting tree.
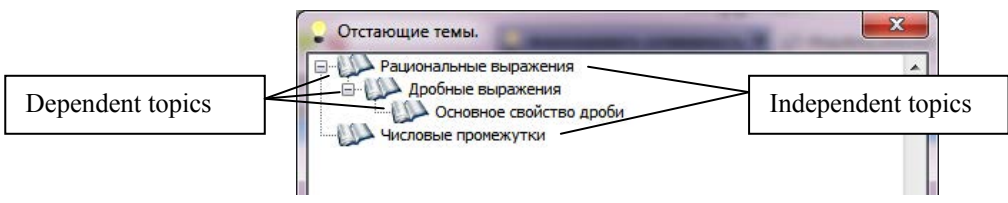

Fig. 6. The tree of problematic topics.

Based on the analysis of the academic performance of a student, the system is capable of providing individual tasks with the emphasis on the problematic topics. In order to use this feature a user needs to press the button "Individual tasks". The system generates five (by default, but the number can be configured) the most suitable exercises for a student (Fig. 7).
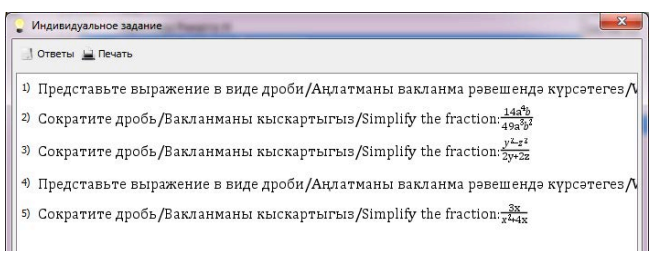

Fig. 7. Individual exercises for a student, based on the academic performance analysis.

The exercises can be printed. Also a teacher can see the answers for the tasks.
This way a teacher will not face the problem of fast analysis of academic performance of his/her students and will effectively differentiate the academic load in the class. This problem is quite relevant these days, taking into account that in average there are 20-25 students per class and a teacher can teach in up to six classes. Therefore the analysis of academic performance of 120 students can become a time consuming routine work, but nevertheless which doesn't require significant efforts from the teacher.

5   EXPERIMENT RESULTS

To evaluate the effectiveness of our novel approach, an experiment in the Mathematics course in one of the multilingual high schools of Kazan (Russia) was conducted from September 2013 to January 2014. Sixty five students from three classes taught by the same teacher participated in the experiment

and were separated into two groups, A (control group) involving 2 classes and B (experimental group) the third class, each containing above 20 students. The students in group B received regular teaching without learning guidance while those in group A received learning suggestions and relevant homework on a regular weekly basis. Also the students were given two tests within the space of one semester (including a pre-test and a post-test). The statistical analysis results are presented in Table 1.

Table 1. Statistical analysis of the experiment

	Sample size	Min.	Max.	Mean	Median	Variance	Mann–Whitney U-test
A (pre-test)	21	3	5	3.5714	4	0.3571	0.8346
B (pre-test)	44	2	5	3.7045	3	0.399	
A (post-test)	21	2	5	2.8571	4	0.6286	2.5811
B (post-test)	44	2	5	3.6591	4	1.3462	

The U-test value = 0.8346 < 1.96, implying that hypothesis H_0 can be accepted; that is, the performance of Groups A and B does not differ significantly in the pre-test. Therefore, we can conclude that in the pre-test, the mean score of Group A equaled that of Group B.

After the experiment the U-test value = 2.5811 > 1.96, implying that hypothesis H_0 should be rejected. Consequently, we can conclude that Group B performed significantly better than Group A because it benefited from the novel approach developed herein.

6   CONCLUSION

The developed ES has been tested for any bugs in the code and the design implementation and after this stage it was actively tested in real life environment. Results of the experiment held during the 2013/2014 academic year demonstrated that the system is capable of accurately analyze the academic performance of students.

According to these results the use of expert systems in education can simplify the process of teaching of subjects, in our case, mathematics. Proper use of the system can significantly reduce the workload of a teacher and leave more time for self-development and improving professional mathematical competence. With the popularization of computer and communication technologies it is very important to create modern system of education in a new information society.

The experimental results show that this approach is able to develop quality CER models, and hence the low-achievement students who received the generated learning suggestions had significantly better learning achievements than those who learned with the traditional approach.

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