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Supporting the mathematical education of STEM students: development of an adaptive learning course for independent study

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Abstract. The article addresses the issue of the gap between the level of school mathematical training and the requirements of university for students of STEM specialities, especially in the context of current global and local challenges, such as the COVID-19 pandemic and military actions in Ukraine. Based on the analysis of the cognitive, pedagogical and psychological aspects of learning, the main difficulties faced by students are identified, particularly insufficient conceptual understanding of mathematical concepts, lack of basic procedural skills, decreased motivation and psychological discomfort. The authors substantiate the need to create additional resources to support the mathematical education of first-year university students. As one of the possible tools for solving this problem, an adaptive training course in the LMS Moodle is proposed, focused on eliminating knowledge gaps, forming a conceptual understanding of mathematical concepts and developing mathematical thinking. Particular attention is paid to integrating the STACK automated assessment system to develop adaptive tests that allow personalising learning. A description of the course structure, its methodological and technical features, and the challenges associated with implementing this approach are presented. The proposed approach can be used to support first-year students and improve the quality of mathematics education in the context of modern challenges.

1. Introduction

1.1. Problem statement and its topicality substantiation

Mathematics education is a fundamental component of STEM students' training because it forms the ability to think analytically, solve complex problems and master key professional competencies, and mathematical knowledge and skills underpin many disciplines studied at the university level.

However, the transition from school to university education is accompanied by significant difficulties for first-year students. It should be noted that the issue of the gap between school and university mathematics education is not new; it has been documented in numerous studies [1–4]. In particular, studies [2–4] confirm that a significant gap between the level of school mathematics and the university curriculum in mathematics and disciplines that include a mathematical component leads to serious difficulties, especially in the first year. Even 50% of students with high school grades do not succeed in university mathematics. Similar statistics



are provided by Vollstedt et al. [4], who note that in Germany, about half of first-year students in STEM university majors have issues mastering university disciplines that require deep basic mathematical knowledge and skills that were not formed at the school stage.

The global and local crises of recent years have only exacerbated this problem. The COVID-19 pandemic has led to a massive shift to distance learning, which has had a negative impact on the quality of both school and university education due to limited interactivity and insufficient control over the educational process [5–8]. A general decline in students' performance in mathematics has been observed in many countries, as documented by large-scale international studies such as PISA and TIMSS. This trend is also highlighted in a recent report by the Royal Society of New Zealand [9].

In addition to the consequences of COVID-19, Ukraine has an additional burden – the war [10–12]. The destruction of educational infrastructure, mass migration of the population, including schoolchildren, university students, teachers, lecturers, many of whom are still outside Ukraine [13], large-scale missile attacks and destruction of critical infrastructure, and the occupation of territories, the collaboration of some teachers with the occupation authorities, the lack of shelters suitable for full-fledged education, work and study under constant stress and air raids have become unprecedented challenges for the education system and have caused significant educational and training losses.

These losses are particularly pronounced in mathematics education, as mathematics education is most vulnerable for several reasons. **Firstly**, the regularity of learning is disrupted. Long breaks have a detrimental effect on individuals' mathematical skills, as close intra-subject connections characterise mathematics and, therefore, require constant practice. The loss of knowledge and skills in one topic negatively affects the ability to understand and learn other topics. **Secondly**, learning mathematics requires close interaction with a teacher. During wartime, offline learning becomes inaccessible for most students. Asynchronous learning is also limited and ineffective due to technical issues such as power outages, internet connectivity problems, and a lack of access to adequate resources. **Thirdly**, in crisis conditions, when participants in the educational process experience stress, their psycho-emotional state deteriorates, which significantly reduces their ability to focus on learning. Learning mathematics requires high concentration and motivation, so in such circumstances, this subject can be perceived as particularly difficult and its study a lower priority compared to the focus on subjects related to basic life skills and social aspects. **Fourthly**, due to migration, mobilisation and other consequences of Russian military aggression, Ukraine has lost many qualified teachers and lecturers. This creates a shortage of specialists, which directly affects the quality of mathematics teaching.

As a result, we have a very disappointing situation, particularly regarding the level of mathematical knowledge of school graduates. Almost 40% of Ukrainian school leavers who took the National Multisubject Test in 2024 have low levels of mathematics knowledge, nearly 47% have an average level of proficiency, and only about 13% have above-average and high levels of proficiency [14]. That is, the knowledge of most school leavers is superficial and formal, with no conceptual understanding of mathematical concepts, facts, or methods, and many have not developed mathematical thinking or understand the nature of mathematics. Due to gaps in school education, almost 87% of graduates have insufficient knowledge to study STEM-related fields in higher education successfully. This requires the creation of additional support resources to help bridge the gap between the level of school mathematics training of applicants to STEM specialities and the university requirements for their mathematical training.

1.2. Analysis of the latest research and publications

A number of studies have been analysed, and three key aspects of the gap between school and university mathematics education can be identified.

Cognitive. Students are accustomed to procedural problem-solving, which prevailed at school, face difficulties mastering abstract mathematical concepts, conceptual understanding and formal thinking [15, 16]. For example, the concept of a limit, taught intuitively at school, acquires a strict formal interpretation at university, making it difficult to understand and recognise (students often see nothing in common between the school and university interpretations of this concept) [17]. Research also shows that students do not always recognise the same mathematical concepts in different disciplines because they are interpreted from various perspectives [4].

Pedagogical. Differences in teaching approaches at school and university also significantly impact students' adaptation. The school focuses on explaining the material and solving typical problems, while the university programme emphasises independent work, theoretical study of the material, and formal proofs. This transition causes stress and disorientation for students, as they are unprepared for high academic independence [4, 18].

Clark and Lovric [19] emphasise that university mathematics is dominated by a deductive approach and is based on rigorous proofs, which are often absent from school teaching. In addition, unlike school textbooks, university textbooks do not provide adequate didactic support for learning proofs. Formal mathematical language and the use of symbols complicate the adaptation process, increasing the so-called 'shock of the new' among students.

Psychological. Students often experience decreased self-confidence, especially if they have difficulty understanding new material at the beginning of their studies. This can lead to anxiety, loss of motivation, or even dropping out [20]. For example, Greek students reported feeling afraid to ask questions of their teachers because they were scared of looking incompetent [15]. Psychological difficulties are exacerbated by the reduced personal attention students receive from teachers compared to school. Changing environments, new social contexts, and high expectations of teachers create additional pressure [21].

Various researchers have explored different strategies to address educational gaps, demonstrating varying degrees of effectiveness:

- courses focused on abstract thinking, formal logic, and mathematical proofs have shown promise [22, 23];
- delivering lectures at a slower pace and incorporating analogies, visualisations, and metaphors has significantly increased student motivation [24];
- adapting content to meet students' needs by considering their thought processes and prior experiences – especially by simplifying complex ideas without losing their core essence – has been beneficial [25, 26];
- identifying problem areas through testing and self-study of the material has contributed to improved educational outcomes [27];
- the use of the Inquiry-Based Learning (IBL) strategy, which adopts a research-oriented approach to learning and solving open-ended problems, has helped bridge knowledge gaps and enhance student motivation [28];
- development of metacognitive-oriented educational materials for independent work and its guidance in an electronic learning course [29].

Despite some local successes in addressing the gap between school and university mathematics education, a comprehensive approach is needed to consider cognitive, pedagogical, and psychological factors. We require effective mechanisms to support students early in their university studies in STEM fields. High-quality tools are essential for diagnosing and quickly aligning students' mathematical knowledge and skills with the necessary standards. Therefore, the research aims to develop an adaptive learning course that will bridge the gap between school mathematical training and the requirements of university programs.

2. Methods

We used research methods as follows. Firstly, we analysed and reviewed scientific and didactical literature to i) uncover the phenomenon of educational losses and the understanding of the gap between the level of mathematical training in schools and the requirements of universities for students in STEM fields; ii) design an adaptive learning course for independent study. Secondly, we employed empirical methods. In December 2024, we surveyed lecturers of Borys Grinchenko Kyiv Metropolitan University about the issues with the school's mathematical training of first-year students. The survey included 17 participants who teach mathematical or professionally oriented disciplines, focusing on fields that require a significant mathematical component in mathematical, technical or economic specialities. The survey was conducted anonymously, and all participants gave consent. Empirical data were used solely for both quantitative and qualitative analysis.

3. Results

3.1. Results of the survey

A survey conducted among mathematics lecturers revealed that, the overwhelming majority of respondents (12 people or 70.6%) indicated that they experienced challenges in teaching related to insufficient prior mathematical training of students, 8 people, or 47.1%, indicated that these issues were significant and greatly complicated teaching; no lecturer reported that there were no issues.

When asked about the percentage of students who successfully master mathematical subjects or subjects with a significant mathematical component, 3 people (17.6%) indicated that this percentage was less than 20 (i.e. not even every fifth), and 9 people (53.0%) believe that this figure is less than 40%. Only one respondent said that most students (more than three-quarters) successfully mastered these disciplines. These results underline the urgent need for additional support for students, in particular, to correct their level of mathematical training.

The survey revealed that a significant majority, specifically 58.8% of respondents, believe that the mathematical training of first-year students from their previous schooling is gradually declining. Additionally, 23.5% of lecturers reported a noticeable deterioration in this level of preparedness over recent years. Furthermore, 70.6% of the educators surveyed indicated that, due to students' insufficient mathematical foundation, they are compelled to lower the pace, complexity, and academic rigour of their teaching or even adjust their requirements. This underscores the seriousness of the issue and indicates the need to improve students' mathematical training at the early stages of their education, in particular by modernising teaching approaches and providing additional learning support.

3.2. Description of the adaptive learning course

We offer an adaptive learning course in the Moodle LMS "Confident Mathematical Start in STEM. Fundamentals of Algebra, Geometry and Mathematical analysis for first-year students". We are actively working on developing this course, which will be an effective tool for eliminating gaps in knowledge and skills and creating a solid foundation for further study. The proposed course is also aimed at developing skills in mathematical proof thinking, forming a conceptual understanding of mathematical concepts, facts, methods and procedures, and gradually adapting students to university education requirements. It should help to improve understanding of complex mathematical concepts, develop procedural proficiency and thus reduce anxiety among students.

An essential condition for effective mathematics teaching is students' active involvement in learning. If students do not actively participate in activities, they will not understand mathematics profoundly, and their learning ability will be significantly limited. Numerous studies [30] confirm that active learning (as opposed to passive learning) positively impacts

educational outcomes. Such strategies contribute to forming a conceptual understanding of mathematical structures, which is the basis for high-quality conceptual and procedural knowledge, the development of creative thinking, research skills, and meta-skills.

The adaptive course is focused on the use of active learning strategies and the development of a student's ability to learn independently. It will be an effective tool to overcome the possible psychological discomfort of first-year students associated with the fear of direct communication with lecturers, especially regarding gaps in their knowledge, as the work with it will be organised in LMS Moodle and will allow students to avoid direct interaction with the lecturer, working independently in a comfortable learning environment. Thanks to the adaptive training tests, students can practice and overcome their difficulties and gaps in mathematical training without fear of judgment or misunderstanding.

The list of content modules (topics) for the course is derived from an analysis of the results of NMT 2023 [31] and 2024 [32], as well as a survey of university lecturers. It also incorporates insights from a study on the expectations of university educators regarding the preliminary mathematical requirements for studying STEM disciplines. This includes a Delphi study conducted with German university lecturers focused on the first semester of mathematics courses in STEM programs [1]. The list features 14 topics from the school mathematics curriculum, including algebra, geometry, and analysis foundation, along with 2 topics designed to enhance general mathematical competencies, namely the fundamentals of mathematical logic and the general theory of equations and inequalities (figure 1).

The peculiarity of the adaptive course will be that it will not require the direct presence of the lecturer and will be worked on by the student independently, remotely, in a convenient mode. The course structure is based on the principles of flexibility and adaptability. The course content modules are relatively independent and self-sufficient and can be used by students either individually or in a particular combination, depending on the need. A student can take 'their' content module in parallel with the study of a particular discipline, filling in the gaps to successfully master that discipline. This will allow for the creation of personalised learning paths to eliminate gaps in understanding and knowledge of mathematical concepts and problem-solving skills.

The content modules have a clear structure that ensures the logic and consistency of the learning material. At the beginning of each module, some keywords help students quickly understand the main idea. This is followed by a brief overview of the content, which introduces students to the general provisions of the topic. Each module clearly outlines the learning outcomes – the knowledge and skills the student must master (figure 2).

Self-diagnostic tests at the beginning of the module and final assessments at the end are provided to determine the initial level of preparation and to assess student progress. The fundamental theoretical information is presented in text format, accompanied mainly by multimedia materials, including videos. Particular attention is paid to analysing common mistakes in understanding and interpreting certain mathematical concepts, facts, and methods. The textual format of the essential theoretical information is organised to compensate for the lecturer's direct, 'live' communication with students. This implements the principle of interactivity and creates conditions for reading the mathematical text in a research manner.

For this purpose:

- the theoretical material is divided into short content-completed blocks, and after each of them, questions (or tasks) are offered to test the understanding of the theory;
- the material is presented predominantly dialogically, imitating the student's reasoning (with questions, doubts, objections, searching for and formulating a hypothesis, etc.). Presentation language is not clerical and bookish but 'live', personified, and close to direct communication;

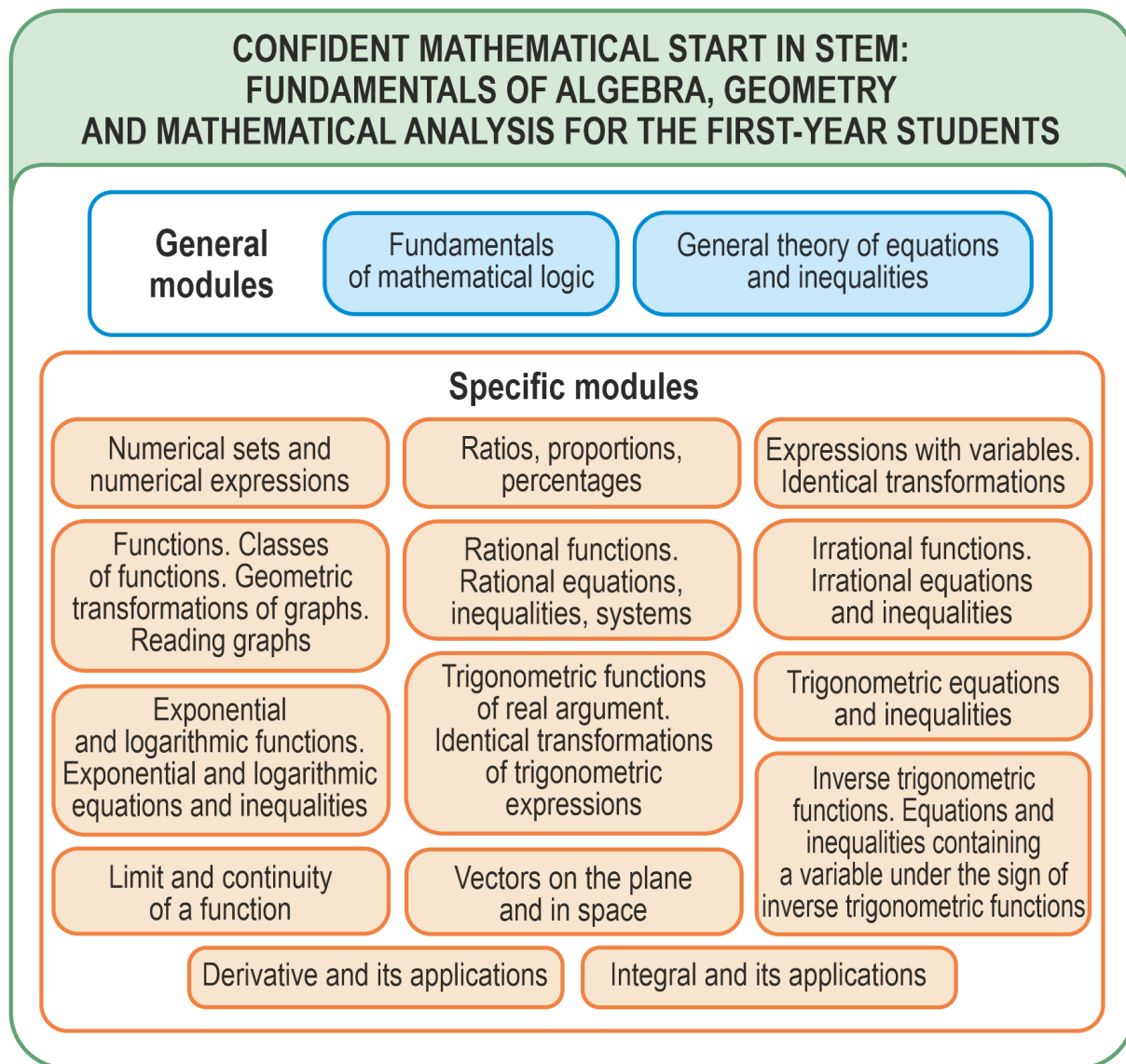


Figure 1. The list of content modules.

- the proposed test questions (tasks) are primarily open-ended, with programmed errors and adequate corrective comments on incorrect answers. The effectiveness of this approach has been confirmed [33].

The practical part of the content module includes solved examples of key tasks, emphasising typical (or possible) mistakes and training exercises. Training exercises are test tasks that are automatically verified in STACK (figure 3).

Using the STACK system for computer-based testing of test tasks allows, in particular:

- randomly generate many tasks of the same type and automatically check them, which saves the educator a lot of routine technical work;
- develop adaptive step-by-step tests when tasks (or questions) are not fixed linearly. The task of the next stage is automatically generated depending on the student's answer at the current stage;

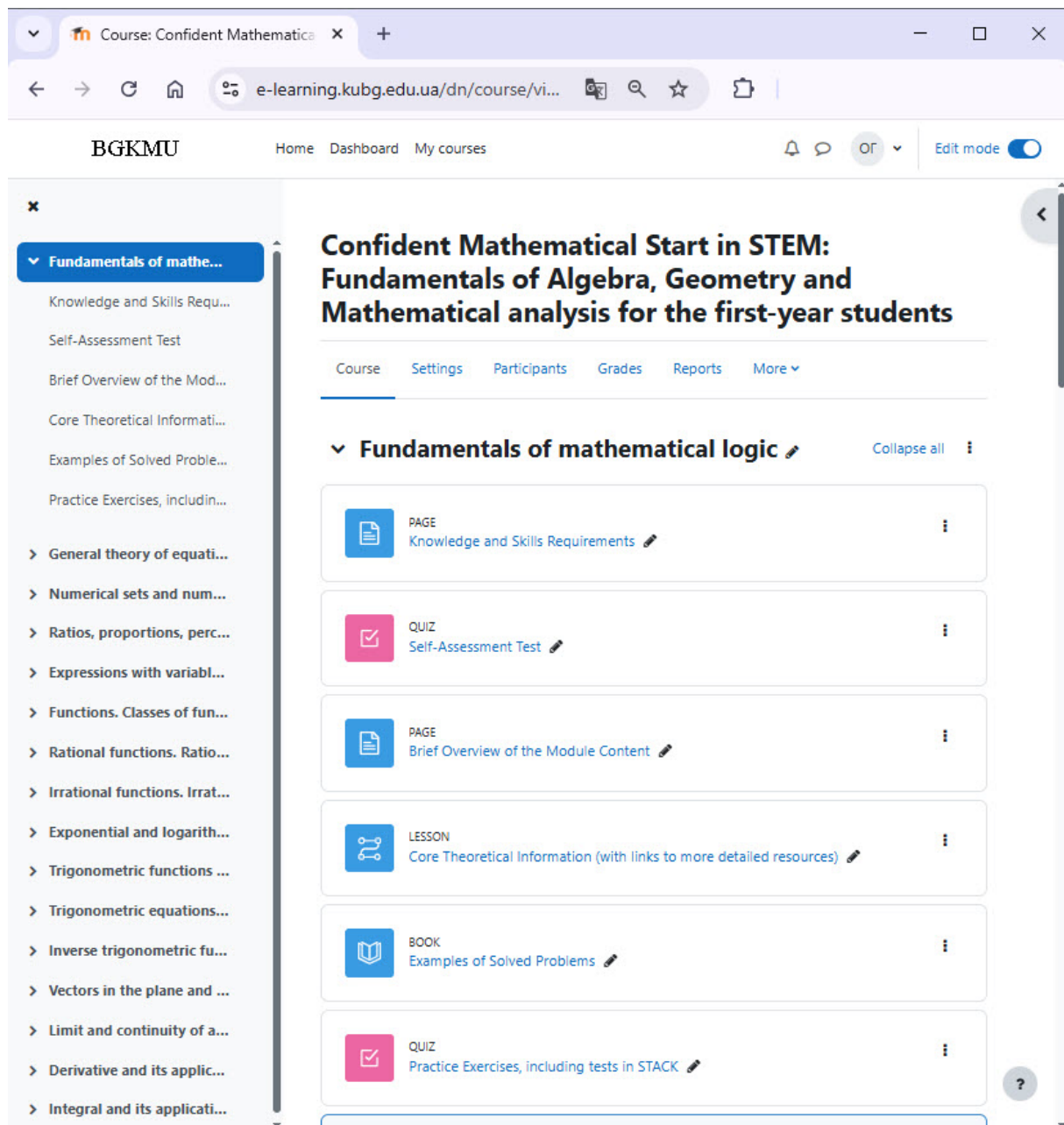


Figure 2. The module structure.

- enable dynamic interactions such as object movement in the GeoGebra applet, which offers clear advantages over static images;
- support different answer formats, including text, formula, mathematical expression, graph, etc;
- provide feedback and comments on the answers at each stage and the test results in general immediately, without delay;
- develop multi-level tasks in which students can receive instant feedback and explanations for each stage of the solution. This will help them gradually improve their skills, understand their mistakes, and correct their reasoning;

Question 1
 Not complete
 Marked out of 1.00

1. Differentiate $x^2 + 2 \cdot x - 1$ with respect to x .

2*x

Your last answer was interpreted as follows:
 $2 \cdot x$
 The variables found in your answer were: $[x]$

Incorrect answer.

2. Evaluate your derivative at $x = 3$.

6

Your last answer was interpreted as follows:
 6

Correct answer, well done.

The answer to this part is correct, but you got the first part wrong, try both parts again

Figure 3. The example of a test in STACK.

- use variable task parameters to stimulate and support IBL. This encourages experimentation and adaptive feedback, which can be used to express hypotheses and explore general patterns.

In other words, STACK tests are used not only for assessment but primarily for learning, which increases its efficiency [34, 35].

However, it should be noted that preparing test items that shift the focus of assessment from reproduction, reproduction or use of routine procedures and trivial exercises to assessing conceptual understanding of mathematics, the ability to apply knowledge in a new situation, which is emphasised by researchers [34, 36], is not an easy task. In addition, the integration of STACK into content modules is also associated with specific challenges. Complex and time-consuming tasks include:

- developing well-structured tasks with variable parameters, considering various possible answer formats, such as numeric, symbolic, and graphical options;
- creating adaptive feedback for different common student errors, including automated prompts and comments that assist students in understanding their mistakes, to enhance assessment while teaching;
- STACK programming tasks require a basic understanding of the Maxima syntax, which is used for symbolic calculations within the STACK system.

To gather feedback on using thematic modules in self-study, students can engage in discussions on forums, complete surveys, and leave comments. Given the limited personal interaction between the lecturer and students and among students, it is crucial to provide alternative methods that foster an engaging and supportive learning environment.

Discussion forums play a crucial role in fostering social presence among students, helping them feel more connected to the learning community. Beyond these social benefits, forums also enhance cognitive presence by encouraging active participation in discussions and collaborative problem-solving in mathematics [28, 37, 38]. Consequently, forums are vital components of e-learning courses, as they provide a platform for meaningful interaction between students and teachers [39]. Furthermore, as noted by Durak and Ataizi [40], communication tools such as

forums, emails, and chat modules are essential for facilitating effective learning. This interactive approach not only increases students' knowledge levels but also enhances their communication skills and teamwork abilities.

It's essential to recognise that the course's content and style are crucial for achieving the established goals. The course offers supportive and friendly guidance, acting as an electronic tutor. This approach effectively supports students on their individual educational paths.

4. Conclusions

The gap between school graduates' mathematical knowledge and university program requirements, which manifests itself in cognitive, pedagogical, and psychological aspects, is one of the main obstacles to the successful education of students in STEM specialities. This problem is exacerbated during times of crisis, such as the pandemic and the war in Ukraine, which increase educational and learning losses.

An electronic adaptive training course that considers students' individual needs helps them independently eliminate knowledge gaps, thereby overcoming the cognitive gap and promoting their gradual adaptation to university education requirements. Integrating the STACK system for automated assessment allows for the implementation of adaptive learning trajectories.

The course's distance format, based on flexibility and personalisation, and its interactivity allow students to personalise their learning comfortably. This reduces anxiety and creates a comfortable learning environment, which is critically important for first-year students.

The training course in the Moodle LMS, which integrates adaptive tests based on STACK, provides individualised learning, personalised lecturers, and support for students' independent learning.

In the near future, it is planned to pilot the adaptive course with a broader audience of first-year STEM students, analyse its impact on their academic performance, and evaluate its effectiveness.

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