On the deployment of an open-source digital learning ecosystem*

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Abstract

The article presents the experience of developing, implementing, and testing a digital learning ecosystem designed to support the learning process in natural and mathematical sciences for students of technical specialties. The potential of using both open-source and commercial software for this purpose is analyzed. The core of the proposed system is the integration of three open-source tools that functionally complement each other: the Atutor LMS for managing educational content, the SageMath computer algebra system, and the GeoGebra interactive visualization environment. The article describes the architecture of the digital ecosystem, its technical implementation features, and the pedagogical scenario of its use in higher education. The ecosystem was piloted within academic courses for students of technical majors under real university conditions. The results of the experimental implementation demonstrate that the proposed digital educational ecosystem contributes to the development of mathematical literacy, algorithmic thinking, and practical skills in working with modern software tools. The study also outlines perspectives for further improvement of the system, particularly in the direction of learning data analytics, mobile access optimization, and the expansion of LMS functionality, including integration with other learning management systems. The proposed model is universal and can be adapted for use in teaching other disciplines that require computational support and visualization of educational content.

Keywords

digital ecosystem, SageMath, Atutor, GeoGebra, higher mathematics, engineering education

1. Introduction

Modern higher education operates under conditions of rapid digitalization. This shift is no longer a matter of trend but has become a tool for survival and, in many cases, the only viable path for development. In the context of the COVID-19 pandemic and the resulting lockdowns, as well as the full-scale invasion of Ukraine by the Russian Federation, hybrid and distance learning have evolved from being convenient alternatives to traditional face-to-face education into, at times, the only possible modes of instruction. Digital platforms such as Zoom, Google Workspace, and others have become integral components of everyday educational life in Ukraine. Strategic documents issued by the Ministry of Education and Science explicitly emphasize the necessity of digital transformation in education (e.g., the Strategy for the Digital Transformation of Education and Science in Ukraine 2022–2026). This transformation requires educational institutions not only to adopt electronic forms of content delivery but also to develop comprehensive digital learning ecosystems that effectively integrate tools for instruction, visualization, and knowledge assessment.

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Despite the wide range of software tools available on the market, most of them present a number of limitations—namely, commercial distribution models, complex configuration procedures, or a lack of integration flexibility. In this context, particular attention is drawn to the use of open-source software, which offers full controllability, scalability, and adaptability to the specific needs of an educational institution.

The objective of this study is to design, implement, and pilot a digital ecosystem for mathematics education, as well as to evaluate its effectiveness under real-world conditions within the instructional process of a technical university.

2. Review of relevant studies

Today, computer algebra systems (CAS) are no longer merely auxiliary tools in the training of competitive professionals; rather, they are becoming central components of modern instruction, particularly within the framework of STEM education.

Using the bibliometric analysis methodology proposed by I. Mintii and S. Semerikov [1], we conducted a search query in the Scopus database with the expression TITLE-ABS-KEY("digital learning" AND (environment OR ecosystem) AND math*) and selected studies that met the following criteria:

- Publications from the period 2010–2025;
- Subject area: Social Sciences, Computer Science, Engineering, or Mathematics;
- Document type: Social Sciences, Computer Science, Engineering, or Mathematics.

As a result, 143 records were retrieved and subsequently visualized using VOSviewer. The map presented in Figure 1 is constructed based on the principle of keyword co-occurrence within the metadata of scientific publications. VOSviewer identifies how frequently different keywords appear together within the same publications. When two or more keywords co-occur above a certain threshold, VOSviewer establishes a link between them and visually represents this connection as a network map. Keywords that frequently co-occur are grouped into clusters, indicating shared scientific interests and revealing latent thematic relationships within the literature.

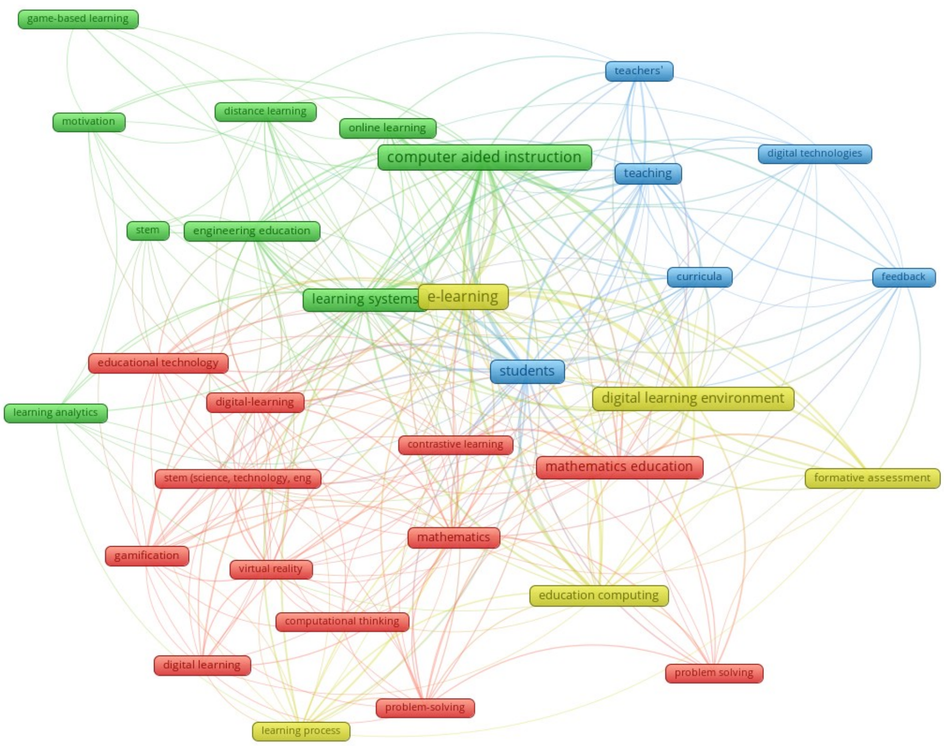

Figure 1: Map of relationships between keywords in VosViewer.

Analyzing Figure 1, several thematic directions (clusters) of research can be identified in the field of applying digital learning ecosystems in mathematics education:

1. The Yellow Cluster pertains to the use of e-learning technologies in education in general. The keywords within this cluster emphasize digital learning ecosystems and student interaction with such environments. Digital technologies serve as a communicative foundation for formative assessment, providing feedback and personalized learning support in adaptive systems [2]. These platforms promote self-regulated learning and are correlated with improved academic performance in mathematics [3].
2. The Green Cluster includes research linked by keywords such as distance and online learning, as well as specific directions such as engineering education and STEM [4]. The studies in this cluster focus on the implementation of educational innovations such as flipped classrooms, blended learning models, and personalized learning experiences [5].
3. The Red Cluster encompasses studies on digital tools—particularly virtual reality, cloud labs and educational games—as components of digital learning environments [6], [7]. This cluster also includes research that explores how digital innovations contribute to the development of mathematical and computational thinking, as well as problem-solving skills [8].
4. The Blue Cluster is focused on the design of digital learning environments. The research here addresses teacher adaptation to digital settings [9] and the transformation of educational programs [10]. In this context, teachers are increasingly viewed as designers of digital resources, developing pedagogical methodologies that integrate digital technologies [11].

Further analysis of the resulting dataframe metadata was performed using package bibliometrix from the language R. It allows you to import metadata through the web interface. So, the influence of the analyzed articles was considered there. It turned out that among the top 10 most cited articles in Scopus is the largest number of studies (2), the subject of which is STEM education [12], [13]. This indicates the relevance and demand for the development of appropriate models. Within the framework of the dataframe selected in the request to Scopus, the most cited are studies concerning the design of a model of interaction in a digital learning environment during mathematical activity [14] and the analysis of student interaction under the conditions of formative assessment in mathematics in a digital learning environment [15].

Time analysis of the use of keywords shows that the basic term "digital educational environment" remains relevant (Figure 2). Although it is not the most used, it takes 4th place after such terms as "educational computing," "teaching."

Another method used in our bibliometric analysis was the construction of thematic maps. These maps serve to represent the conceptual structure of a research field by identifying and visually displaying the principal research themes that dominate the scholarly discourse. Similar to the VOSviewer software, thematic maps utilize clustering techniques. By considering keywords as nodes of a graph and co-occurrences as edges, the bibliometrix package employs network clustering algorithms for metadata analysis (the Walktrap algorithm in our case). Its primary metrics include Callon Centrality, which measures the extent to which a theme (a cluster of keywords) is connected to other themes, and Callon Density, which quantitatively evaluates the strength of relationships among the keywords within a given cluster.

The thematic map constructed for our dataset is presented in Figure 3.

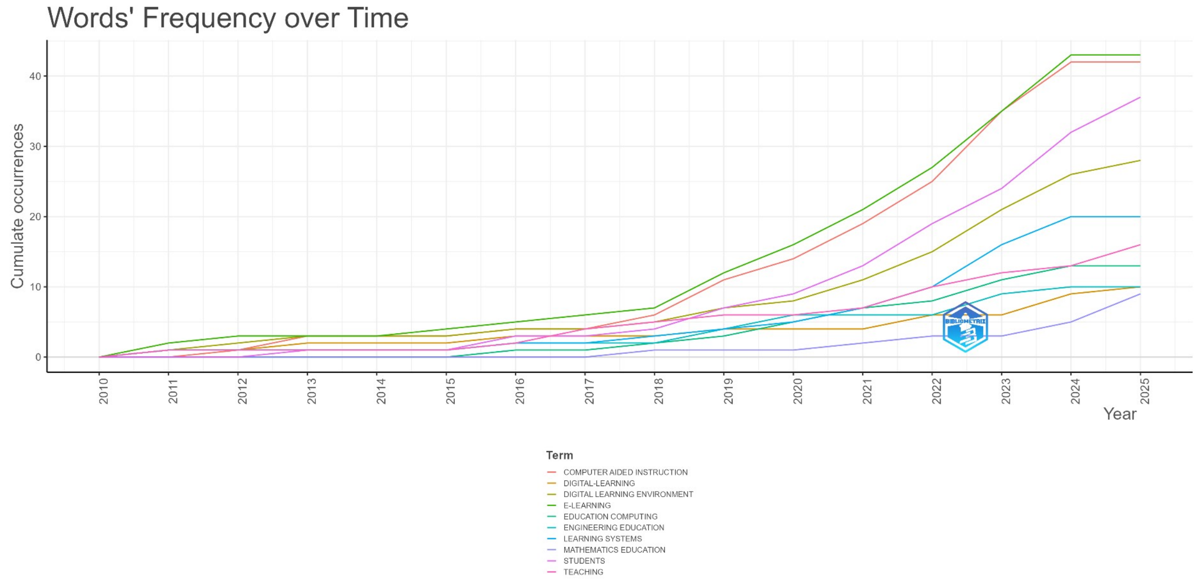

Figure 2: Time analysis of the keywords using.

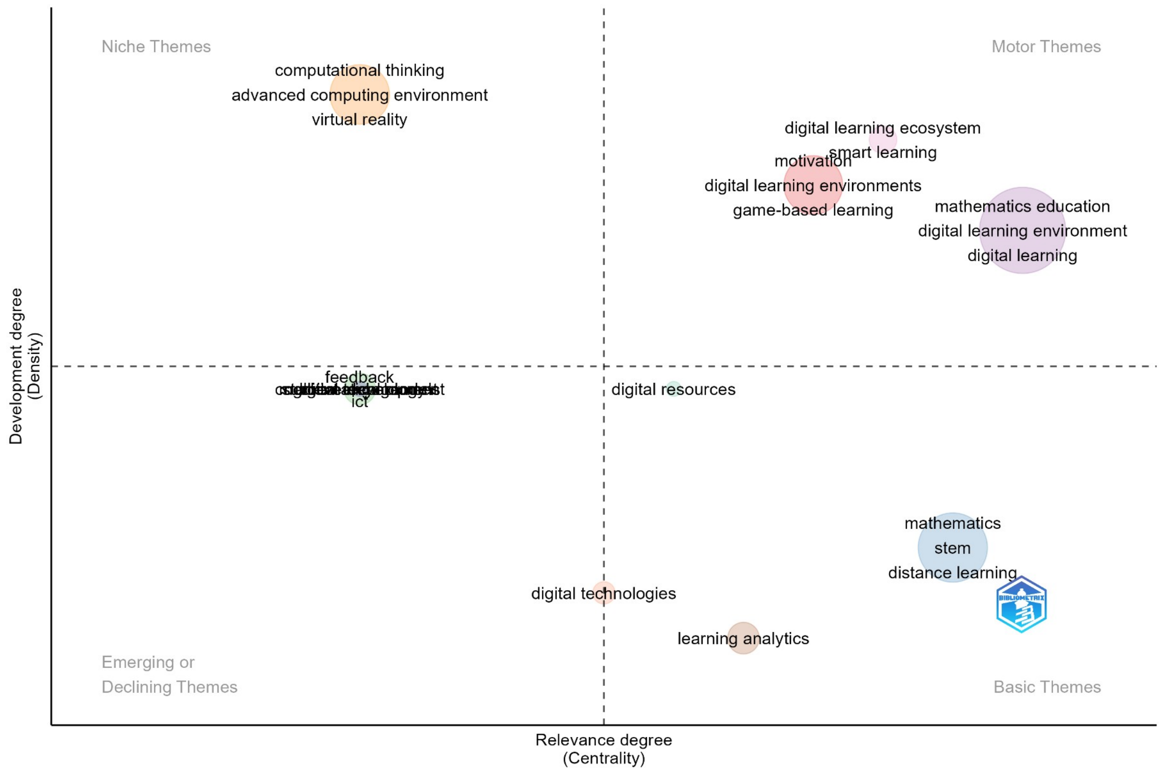

Figure 3: Thematic map for the selected dataset.

The map employs CallonCentrality as the X-axis and CallonDensity as the Y-axis. These axes divide the plane into four quadrants:

- Motor themes (upper right quadrant): Themes located in this quadrant are characterized by both high CallonCentrality and high CallonDensity. This indicates that these themes are not only central to the research field but also well-developed and internally cohesive. Common keywords associated with these themes include mathematics education, digital learning, and digital learning environment. These are considered established research directions.
- Basic themes (lower right quadrant): Themes in this quadrant exhibit high CallonCentrality but low CallonDensity. They represent important topics that are central to the field and closely connected to other themes, yet they remain underdeveloped internally. These

themes often function as foundational or cross-cutting areas. They include topics associated with keywords such as mathematics, STEM, distance learning, learning analytics, and digital technologies. These themes are structurally weak, lacking in robust theoretical frameworks and empirical validation.

- Niche themes (upper left quadrant): Themes in this quadrant display low CallonCentrality but high CallonDensity. In our dataset, these are associated with keywords such as computational thinking, advanced computing environment, and virtual reality. These themes are well-developed and internally coherent but remain specialized and have limited connections with the broader body of research related to the digital learning environment (ecosystem).
- Emerging or declining themes (lower left quadrant): Themes in this quadrant are characterized by both low CallonCentrality and low CallonDensity. In our dataset, these include topics associated with keywords such as feedback, project, diagnosis, students' attitudes, ICT, and digital student project. These themes exhibit minimal relevance and infrequent usage. They may be considered fragmented due to obsolescence or insufficient theoretical grounding.

Within the structure of digital learning environments (ecosystems) for mathematics education, researchers identify CAS as a crucial component [16], [17]. In general, CAS refers to tools that integrate computation, visualization, programming, and modeling. These systems assist instructors in making mathematical concepts more visual and accessible, while enabling students to engage with mathematics at a real-world level. Such systems include both commercial software (e.g., MATLAB, Mathematica, Maple) and open-source alternatives, notably SageMath. It is not surprising that a large number of scientific articles and studies are devoted to the issues of their introduction into higher education.

In particular, as noted by the authors in [18], the integration of MATLAB into the educational process contributes to a more positive student attitude toward mathematics and the use of technology. Students exhibited increased motivation and confidence in their mathematical abilities. The use of MATLAB in courses, especially in online formats, enhances students' comprehension of complex concepts through interactive exercises and simulations. This fosters deeper understanding and the development of practical skills. However, unsupervised use of mathematical software can alter students’ problem-solving approaches by shifting their focus predominantly toward computation, sometimes at the expense of conceptual understanding. This underscores the importance of balanced use of such tools to support analytical thinking. The application of Mathematica and Maple enables students to tackle more complex and realistic problems [19], which were previously inaccessible through traditional instructional methods. This promotes the development of modeling and analytical skills. Their use enhances students’ understanding and application of mathematical concepts in practical contexts, and fosters critical thinking and mathematical communication—particularly when studying topics such as limits and derivatives. As a result, students gain a deeper understanding of the material and achieve higher levels of knowledge retention. Comparative studies indicate that MATLAB, Mathematica, and Maple each offer unique advantages. The selection of a particular software tool depends on the instructional goals, the academic discipline, and the students’ level of preparation. However, a significant barrier to the widespread adoption of these CAS in Ukrainian HEIs is their high cost, which effectively limits their accessibility.

SageMath is an open-source CAS that integrates numerous mathematical libraries based on Python. In [20], the use of SageMath in physics education is examined: students were able to model real-world problems, solve complex equations, and generate graphs—all within the interactive Jupyter environment. Study [21] analyzes methodological aspects of using SageMath Cloud in the teaching of algebra and calculus. The author emphasizes the advantages of cloud-based access to resources, which enables flexible learning and supports the creation of individualized learning trajectories for students. In [22], a methodology for supporting student collaboration using SageMathCloud is presented. The experimental group that worked within the cloud environment demonstrated improved understanding of the material and increased interest in studying mathematical subjects. Similar findings are reported in [23], which focuses on the development of students' digital competence through the use of open platforms in the educational process. The authors discuss both the benefits and challenges of integrating the system into the learning environment and offer recommendations for its effective implementation. Study [24] describes the integration of SageMath with the Canvas LMS platform to create an asynchronous and interactive learning environment. This approach enables students to explore mathematical concepts at their own pace with immediate feedback.

Another powerful tool for visualizing instructional content is the free mathematical environment GeoGebra. A substantial body of scholarly literature has been devoted to examining the effectiveness of its use in mathematics education. Based on the results of twelve related studies, the authors of [25] found that GeoGebra facilitates students' comprehension of geometric concepts by enabling the rapid visualization of abstract geometric objects, enhances student motivation, and contributes to more effective teaching. Article [26] analyzes the potential of GeoGebra to improve the quality of professional training for future teachers. The authors emphasize the importance of integrating modern information and communication technologies into the educational process, particularly through the use of tools that provide visual clarity and dynamic presentation of learning content.

3. Digital Ecosystem architecture

The e-learning server at Ternopil Ivan Puluj National Technical University is based on the Atutor Learning Management System, which integrates the BigBlueButton audio and video conferencing system. This software is distributed under the GNU General Public License (GPL), which allows free use and modification. Since 2009, this flexibility has enabled significant improvements, the addition of custom modules, and adaptation to the specific educational needs of TNTU. The platform supports the development of electronic learning courses (ELC), which include lecture materials, tests, assignments, and other instructional resources. Each user is provided with a personal account that grants access to the relevant courses and materials. Every ELC includes access to a videoconferencing environment, essential for attending online classes, consultations, and the defense of academic assignments. This environment offers the following capabilities:

- communication, discussion through audio and video broadcasting and text chat;
- demonstrate presentation materials using a pointer cursor and drawing tools on a virtual board;
- demonstration of the screen (application window or browser) of the speaker (lecturer) as well as live broadcast of video materials (from Youtube, Vimeo, Instruction Media, Twitch, Dailymotion and from cloud drives OneDrive, Google Drive, Dropbox, etc.);
- maintaining a video recording of an online lecture and integrating the recorded video into the course material.

That is why Atutor LMS was chosen as the central node of the digital learning ecosystem. It is ideally suited for the role of a navigation portal , which allows you to supplement the static educational material with various interactive components: dynamic scripts, computer algebra systems (CAS), etc.

One of the most powerful and widely used CAS is MATLAB. However, it is commercial software, and its licensing costs are relatively high, even when accounting for discounts available to educational institutions, instructors, and students.

MathWorks offers several types of academic licenses:

- Individual License – intended for faculty, researchers, and staff at academic institutions. This license is tied to a specific user and allows installation on two devices (e.g., a desktop computer and a laptop), but it may only be used on one device at a time. As of early 2025, the cost of this license is $940 USD per year.

- Designated Computer License – designed for installation on a single computer that can be used by multiple users (e.g., in a computer lab). The annual cost of this license is $1,265 USD.
- Campus-Wide License (CWL) – a university-wide license that allows all students and faculty members to install MATLAB on their personal devices at no additional cost. The price of the CWL depends on the institution's size, number of users, and the range of selected products. Therefore, MathWorks does not publish the cost on its official website and recommends contacting sales representatives for a custom quote. However, according to publicly available sources, in 2024 the Kharkiv National Automobile and Highway University planned to purchase 20 MATLAB user licenses for 1,105,745 UAH. This indicates that the cost of a CWL for a large university can be significantly higher, depending on the scope of the license and included toolboxes.

SageMath can partially replace MATLAB. Table 1 shows a comparison of their main characteristics.

Table 1
Main characteristics of MSS

Feature	SageMath	MATLAB
Cost	Free, open-source	Paid, licensed
Programing language	Python	own language MATLAB
Graphics	2D/3D graphics, interactivity via Jupyter	Advanced graphics, animation
Symbolic calculation	SymPy, Maxima	Symbolic Math Toolbox
Scientific Computation	Provided by connecting SciPy, R, Octave libraries	Specialized toolboxes
Engineering problems, modeling	restricted	Supported very well
Integration with other languages	Python, R, Julia, LaTeX	C/C++, Java, Python (via API)

Table 2
Examples of solving typical problems

SageMath	MATLAB
Solving a equation	
x = var('x') *solve(x^2 + 3*x + 2 == 0, x)*	*syms x* *solve(x^2 + 3*x + 2 == 0, x)*
Graphing a function	
*plot(sin(x) + cos(x), (x, -2*pi, 2*pi))*	*fplot(@(x) sin(x) + cos(x), [-2*pi, 2*pi])*
Finding the derivative of a function	
*f = sin(x) * exp(x)* *diff(f, x)*	*syms x* *f = sin(x) * exp(x);* *diff(f, x)*
Numerical integration	
numerical_integral(sin(x^2), 0, 1)	*integral(@(x) sin(x.^2), 0, 1)*

In our view, SageMath is a more appropriate choice for addressing educational tasks, particularly in the context of teaching mathematics or physics at the school or university level. In addition to being free of charge, its key advantage lies in the use of the widely adopted Python programming language, as opposed to MATLAB's proprietary language. However, for solving professional engineering or complex scientific problems, such as those requiring Simulink, image and signal processing, or real-time system modeling, MATLAB remains indispensable. Table 2 presents examples of solving several basic problems using both SageMath and MATLAB.

CoCalc is an open online platform that enables users to work with SageMath, Jupyter, and LaTeX directly in a web browser. It is highly convenient for educational purposes; however, the free version comes with certain limitations. Specifically, it offers low computational priority, projects may enter a "sleep" state or operate more slowly under high server load. Calculations may automatically pause after a few minutes of inactivity. The resources available in the free version are also limited (up to 2 GB of RAM, basic CPU performance, and a few gigabytes of cloud storage). Moreover, projects in the free version are not entirely private, meaning CoCalc administrators may have access to their content. Therefore, deploying an own SageMath server represents a sound strategic decision for Ukrainian HEIs.

Accordingly, we propose the following layered architecture of the digital educational ecosystem:

1. Infrastructure Layer
   - A physical or virtual server environment based on Linux (Ubuntu Server);
   - Docker Engine installed to support containerized application deployment;
   - Containers:
     - *SageMath* – computation server accessed via Jupyter;
     - *Atutor* – Learning Management System with an integrated database (MySQL/PostgreSQL).
2. User Access Layer
   - Students and instructors access Atutor via a web browser;
   - SageMath is accessed through the JupyterLab interface;
   - GeoGebra is embedded directly into the instructional content pages.
3. Security and Authentication Layer
   - VPN or internal network with IP filtering;
   - User authentication (students/instructors) through Atutor login credentials.
4. Integration Layer
   - The LMS integrates: links to Jupyter notebooks; embedded GeoGebra content via iframes;
   - Atutor serves as the central navigation portal.

4. Implementation in the educational process

The development of the digital ecosystem was carried out within the educational process for first-year students of the Faculty of Engineering of Machines, Structures, and Technologies at Ternopil Ivan Puluj National Technical University (specialties 131 Applied Mechanics, 133 Industrial Machinery Engineering, and 192 Civil Engineering), as part of the “Higher Mathematics” course covering the topics: Linear Algebra, Vector Algebra, Analytic Geometry, Mathematical Analysis, and Differential Equations. The primary objective was to create a fully functional interactive environment accessible both on campus and remotely, without requiring the installation of additional software on students’ personal devices.

The ELC "Higher Mathematics" (ID 2270) for students of the aforementioned specialties was developed in 2014 within the Atutor Learning Management System at Ternopil Ivan Puluj National Technical University. The course includes lecture and practical class notes aligned with the official curricula, a glossary, a complete set of individual assignments for practical exercises, and test tasks for students knowledge assessment. Over the years of its use in the educational process, the static illustrations accompanying lecture and practical notes have been gradually enriched with dynamic GeoGebra scripts, which have significantly enhanced students' comprehension of the relevant theoretical material. Figure 4 presents a fragment of a lecture on the topic "Equations of a Straight Line in the Plane," featuring an embedded GeoGebra applet that enables students to independently select points through which the line passes and instantly observe how changes in position affect its equation.

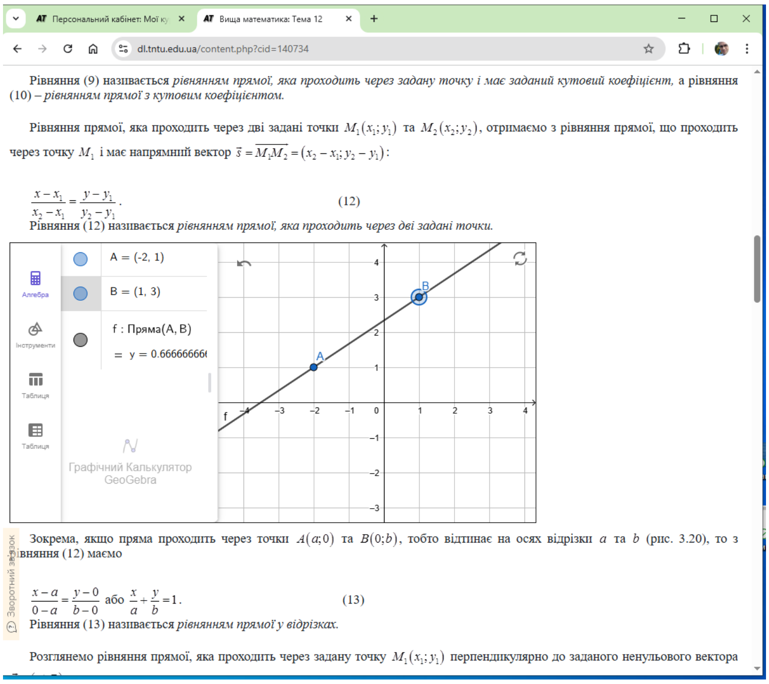

Figure 4: Screenshot of a browser window with a fragment of educational material containing a straight line dynamic GeoGebra model.

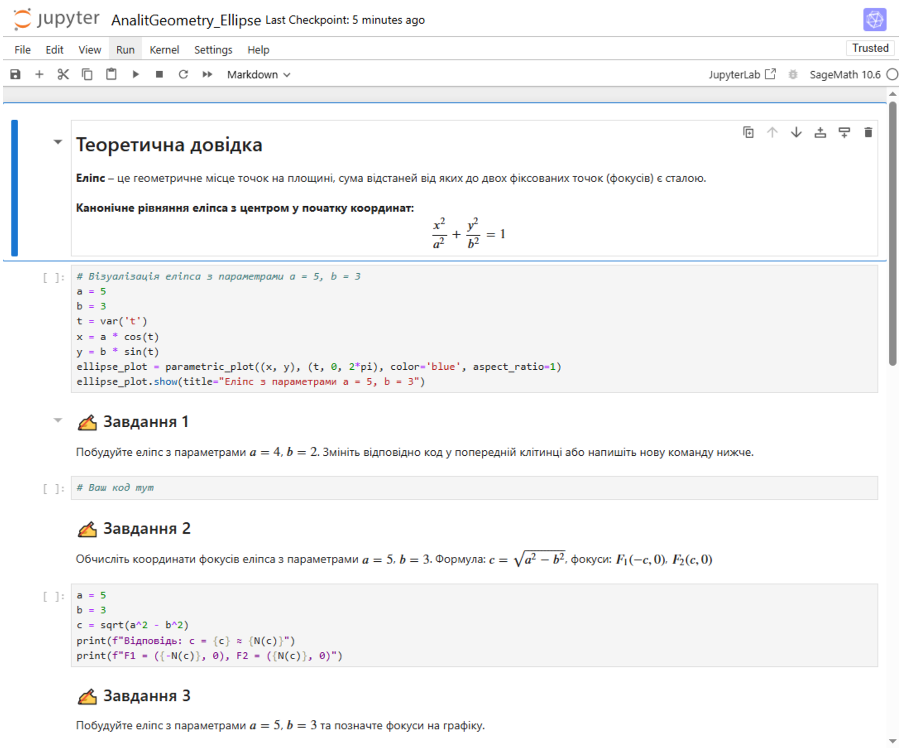

Figure 5: Screenshot of a browser window with a Jupyter notebook. An example of constructing an ellipse in SageMath and calculating its main characteristics.

Subsequently, the instructional content of the ELC was supplemented with interactive assignments in the form of Jupyter notebooks (SageMath). During the completion of these tasks, students perform mathematical computations directly in the browser window, without the need for specialized software, by following provided examples. Figure 5 illustrates a fragment of a Jupyter notebook containing exercises on the topic "Second-Order Curves in the Plane."

The SageMath package simplifies the use of a mathematical apparatus in solving applied problems and performs visual analysis of the results. Consider this on the example of a specific physical problem: «Find the heat released on the load by the resistance of 10 Ohm in 0.08 s, if the current varies uniformly sawtooth-like increasing with a period of 0.02 s. The average value of the current 1A. Draw the graph of the current strength and the heat versus time»

To solve the problem, first write down the mathematical model for the sawtooth current, determine its average value, use the formula for power, and then find the amount of heat released in one period.

Let's describe the functions that implement this mathematical model in SageMath.

- Function of current strength. This is a triangular (sawtooth) function:

$$I(t)=\frac{I_{max}}{T}\cdot t, 0\leq t\leq T.$$

```
# Constructing a sawtooth current as a numerical function
    def i(t):
        t_mod = t - floor(t / T) * T
        if t_mod == 0 and t != 0:
            return 0
        return (I_max / T) * t_mod
```

Given the average value of the electric current over a period, the corresponding maximum value is determined:

$$\langle I\rangle=\frac{1}{T}\int_0^T I(t)\,dt=\frac{I_{max}}{2}, I_{max}=2\cdot\langle I\rangle=2\,A.$$

- Instantaneous power:

$$P(t)=I^2(t)\cdot R$$

```
# Power (numerical function)
    def P(t):
        return i(t)**2 * R
```

- Heat per period:

$$Q=\int_0^T P(t)\,dt$$

```
# Heat
    def Q(t_val):
        return numerical_integral(P, 0, t_val)[0]
```

Next, graphs of the current strength and the amount of heat versus time are plotted and numerical data are outputted:

```
# Current strength graph
    plot_i = list_plot([(t, i(t)) for t in srange(0, t_max, 0.0005)], plotjoined=True, color='blue', legend_label='I(t)', axes_labels=['t, s', 'I, A'])
# Heat graph
    plot_Q = list_plot([(t, Q(t)) for t in srange(0, t_max, 0.001)], plotjoined=True, color='red', legend_label='Q(t)', axes_labels=['t, s', 'Q, J'])
    show(plot_i, figsize=5)
    show(plot_Q, figsize=5)
```

Output the value of heat in time t

print("Q = : {:.2f} J".format(Q(t_max)))

The result of the program is the graphs shown in Figure 6 and the numerical value Q = 1.07 J, which corresponds to real data and makes it possible to visually observe the change in values over time.

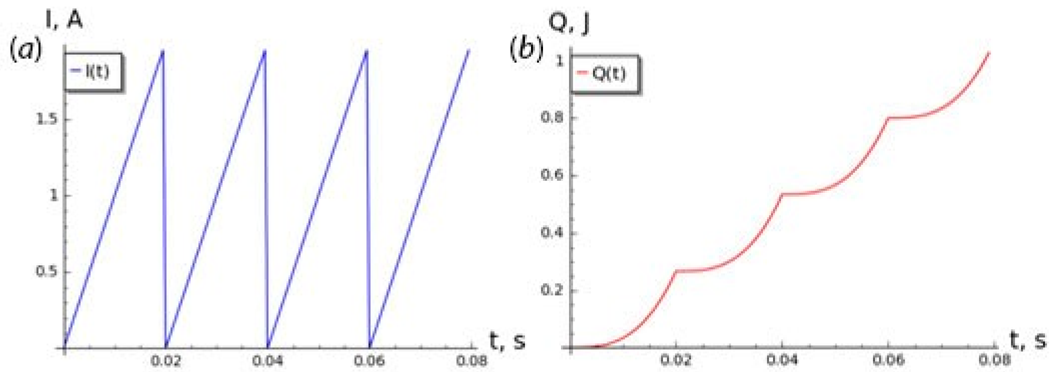

Figure 6: Graphs of the Current strength (*a*) and the Heat (*b*) versus time.

Students' knowledge was tested using the Atutor testing system (automatic assessment) and by checking individual tasks completed by the students (expert assessment).

Conclusions

As part of this study, a model of a digital educational ecosystem for the study of natural and mathematical disciplines was developed. It is based solely on open source software and is focused on the needs of students of technical specialties. The key components of this system are:

- Linux server with Docker Engine installed;
- Docker-container with Atutor, which allowed the structured organization of courses, tasks, knowledge control and feedback;
- Docker container with SageMath, which provided convenient access to a powerful mathematical computing environment;
- GeoGebra-applets, which played the role of a means of visualizing mathematical concepts and contributed to the formation of a deeper understanding of educational topics.

The system underwent pilot testing over the course of one academic semester as part of the "Higher Mathematics" course for first-year full-time students at Ternopil Ivan Puluj National Technical University. In addition to accessing educational materials through the Atutor LMS, students performed practical assignments within the SageMath, employed GeoGebra for model construction and hypothesis verification, and participated in knowledge assessments. The involvement of students in the experimental implementation demonstrated that the proposed system significantly enhanced learning motivation, increased classroom engagement, and fostered greater interest in the practical application of acquired competencies.

The proposed digital ecosystem has demonstrated high efficiency in both technical and didactic aspects. Its modular architecture has created an integrated, scalable and accessible educational environment.

From a technical point of view, the use of containerization provided simple deployment and support of the system, with the ability to flexibly update individual modules without stopping the entire infrastructure. This is especially important in the face of limited IT resources in most Ukrainian HEIs. An additional advantage is independence from commercial software and external cloud services, which guarantees autonomy and control over the safety of training data. On the didactic side, the application of SageMath greatly expands the ability of students to independently explore mathematical models, experiment and test hypotheses, and the visual components of GeoGebra improve the understanding of abstract mathematical concepts. Atutor LMS, in turn, provided content structuring, systematic knowledge control and feedback support.

At the same time, the introduction of such an ecosystem requires increasing the IT competencies of teachers and certain technical training. At the initial stage of the project, there were difficulties in adapting students to work in the SageMath Jupyter environment, but after several classes, the level of confidence increased significantly. In the future, this can contribute to the development of digital and mathematical literacy, which is an important competence of a modern specialist.

In view of the results obtained, we see several directions for the further development of the project:

1. Extension of LMS functionality. It includes the integration of Sage tasks directly into Atutor tests and the creation of adaptive courses that select complexity based on the level of training.
2. Adaptation of interfaces for use on tablets and smartphones.
3. Use of training data analytics: collecting statistics from LMS and Jupyter to assess progress, automated monitoring of activity and level of student engagement.
4. Integration with Moodle or other LMS.
5. Participation in international initiatives: publication of open courses (Open Educational Resources) and exchange of experience with partner institutions on STEM education based on free software.

Thus, the pilot implementation of the developed digital educational ecosystem based on open source software has proven its effectiveness in the context of modernization of higher education. It not only contributes to the formation of professional and digital competencies among students, but also opens up new horizons for pedagogical innovations in the digital era. The results of the study confirm the feasibility of further development of this approach.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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