

Carmen Elena CIRNU | Ella Magdalena CIUPERCĂ



Proceedings of the

INTERNATIONAL CONFERENCE ON VIRTUAL LEARNING ICVL 2026

Innovating Education Through Digital Technologies | Vol. 21/2026

Selection of papers presented within the 21st ICVL, Bucharest, March 12th, 2026

**Proceedings of the
INTERNATIONAL CONFERENCE
ON VIRTUAL LEARNING – ICVL 2026**

Innovating Education Through Digital Technologies

Vol. 21 / 2026

EDITORS

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Innovating Education Through Digital Technologies

Vol. 21 / 2026

EDITURA 

2026

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ISSN 1844-8933

ISSN-L 1844-8933

ISBN 978-606-95858-6-3

Scopus[®]

INDEX  COPERNICUS
I N T E R N A T I O N A L

Cover: Cătălin Banu
PC Processing: Daniela Coroleucă

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SECTION 1

CHANGING EDUCATION BECAUSE OF TECHNOLOGY DISRUPTION

An analysis of Wikipedia’s special tags and their implications for the nuanced spectrum between human edits and bot edits

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Abstract: *Wikipedia articles are a key training source for Natural Language Processing (NLP) research. The platform’s metadata records edit histories, including whether edits are made by humans or bots. A lesser-studied part of this metadata is the set of “special tags,” which can mark edits made with semi-automated tools like Twinkle or fully automated bots such as Cewbot. This spectrum spans from light automation, such as spell checking, to heavy automation, such as AI-generated text later edited by humans. This paper examines how Wikipedia’s special tags are used and explores their potential to trace the continuum between human and bot edits, an increasingly relevant issue with the rise of generative AI tools. We employ a structured SQL-based analysis through Quarry, complemented by manual inspection of revision histories to capture patterns beyond metadata. Using this hybrid approach, we move beyond surface-level records to uncover gaps between official data and editing behavior. The study demonstrates the value of combining SQL-based analysis with human verification to enhance the historical accuracy of Wikipedia’s tag data. The resulting dataset supports machine-learning training, knowledge-graph construction, and analyses of cooperative online behavior.*

Keywords: Wikipedia, Special tags, Human–bot collaboration, Data science.

1. Introduction

Wikipedia is one of the most active and complex collaborative knowledge systems in the world, allowing real-time editing by a diverse pool of contributors: from casual contributors to professional experts to content custodians and even bots (Zheng et al., 2019). Unlike many corpora of text, Wikipedia maintains rich metadata about the historical editing process. This metadata can provide a unique window into the collaboration between humans and automated tools over time. With the rising prevalence of generative AI tools, it is increasingly important to ask when we should be including AI-generated content in the training set for new AI tools (Ferschke, Zesch & Gurevych, 2011; Halfaker et al., 2013). Automated tools are generally built by learning from data collected from humans, and replacing that human signal in training data with AI-generated content may not always be appropriate. For example, if you generate numerous articles for Arabic Wikipedia by translating from English with the purpose of making those articles more

<https://doi.org/10.58503/icvl-v21y202601>

accessible to Arabic speakers, that could be an appropriate use. However, prior studies on language-specific Wikipedia editions, such as Arabic Wikipedia, have shown that data derived from local corpora may not always represent the perspectives of native speakers (Alshahrani, Wali & Matthews, 2022). Using AI-generated content as the training data for new AI-generated tools can reach a point of diminishing returns, where the organic, effective signals are lost in an echo chamber of automated reinforcement of the dominant patterns.

We want to find effective models of collaboration between humans and automated tools. There are plenty of examples of collaborative models that give bad outcomes such as asking humans to jump in at the last moment when an automated system is faced with a difficult moral choice such as in the trolley problem (Elish, 2019). Similarly, humans rubber-stamping all automated suggestions is unlikely to give effective outcomes as humans in that position have little incentive to overrule the automation (Matthews, 2020). What we want is to build collaborative models that give good outcomes, and Wikipedia metadata including the Special Tags have the potential to give us a unique window to explore that. In this study, we analyze the Special:Tags ecosystem to recover and characterize patterns of tag adoption and use. We captured a snapshot of the Special:Tags page and then queried Wikimedia replica databases to extract usernames, timestamps, and diffs for tagged edits to augment this page with additional metadata. We also validated the first use for each tag and categorized tags by degree of automation (manual, semi-automated, automated). In this paper, we describe our methods, present results (including an illustrative example using the *Twinkle* tag), and discuss implications for human–automation collaboration on Wikipedia.

The MediaWiki maintains a collection of special tags, defined within Wikipedia itself on their Special:Tags page, which offers a centralized, up-to-date summary of all defined tags used on Wikipedia. While the exact number can vary over time, at the time of this work, there were roughly 300 special tags listed. Basic metadata is displayed for each tag, such as the number of edits tagged at the time of viewing, the source (core MediaWiki, extensions, or external tools), and the tag's activation status. This number of edits is dynamic and constantly shifting as users all over the world make new edits using the tags. While the *Special:Tags* page provides a useful overview of existing tags, it is important to understand how these tags are actually created and recorded. In MediaWiki, tags originate from three main sources. First, some tags are added automatically by the MediaWiki software itself to capture details of the editing interface, such as whether an edit was made using the VisualEditor or source editor. These system-generated tags are typically consistent across different language editions of Wikipedia, as they are applied by the core MediaWiki software rather than individual communities (Geiger & Ribes, 2010; Steiner, 2014). Second, external tools and bots, such as Twinkle or AutoWikiBrowser, can define and apply tags when performing automated or semi-automated edits. Prior research shows that such tools often predate their formal tagging, resulting in older edits that lack corresponding metadata (Geiger, 2014;

Halfaker & Riedl, 2012). Some tags are inferred algorithmically rather than explicitly applied; for example, revert-related tags are assigned based on heuristic detection of reverted edits (Halfaker & Riedl, 2012). Finally, some tags are applied manually by editors. Together, these mechanisms make tags a powerful but imperfect source of information, as their completeness and reliability vary depending on their origin and time of introduction.

Special tags in MediaWiki record *how* an edit was made and serve multiple purposes. Some indicate routine maintenance—for example, HotCat for quick category fixes and other minor cleanup (e.g., fixing typos/formatting or updating/archiving dead links). Reverts are marked with mw-rollback or mw-undo. Other tags capture tool-assisted work, such as *Twinkle*, which supports semi-automated tasks like issuing warnings and reverting vandalism. Large-scale, repetitive updates are often carried out by bots (e.g., Cewbot); those edits may carry task-specific tags when applicable or simply be recorded under the bot flag. Prior work has used these tags to study sociotechnical coordination and governance on Wikipedia (Geiger & Ribes, 2010; Halfaker et al., 2013). Collectively, tags help researchers examine platform governance, content integrity, and the division of labor between humans, tools, and bots in peer-production environments. Although the current special tags page shows a snapshot of current tag activity, it does not include deeper historical metadata. Important details like the time a tag was first applied and the user (i.e., the first username) are left out. Furthermore, it doesn't differentiate between edits made by bots and human users, nor does it classify tags according to their degree of automation (manual, semi-automated, or fully automated). Additionally, it's unclear whether tags were used for system-level operations like file uploads or user account creation, or for content edits. In addition to the special tags page itself, each row includes a total number of tagged changes, which links to an interface to query recent changes with that particular tag. While useful, there are some limitations in this interface that make it difficult to use for thorough, long-term analysis. For example, when filtering edits by tag and user type (e.g., bots vs. humans), the platform only displays results from the last 30 days and restricts output to 500 entries. These limitations significantly hinder large-scale or historical studies of the tool usage and tag behaviour on Wikipedia.

To overcome these limitations, we employ a hybrid research methodology that combines automated data extraction with manual verification. First, we use Quarry, an open SQL platform that interfaces with important tables like `change_tag`, `revision`, `actor`, and `page`, to query Wikimedia's public replica databases. This enables us to pinpoint the exact location of the tag's application, whether it was applied to a particular article edit (like changing the content of a Wikipedia page) or to a system-level action caught in the site's logging system (like deleting pages, creating accounts, or uploading files). We can also identify the first recorded use of each tag and identify the user in question (either a human or a bot). Second, to complement this structured analysis, we manually reviewed the revision histories of a select group of users whose usernames were identified using the `change_tag` data.

We visited Wikipedia user contribution pages to examine editing activity associated with specific tools. Tools such as Twinkle were in active use long before their edits appeared in the `change_tag` table. This manual examination helped identify earlier instances of tool usage that predate the official introduction of corresponding tags into the tracking system. This paper contributes: (1) a reproducible pipeline (SQL + manual verification) to infer first-use and usage patterns across 301 tags; (2) a curated bot whitelist/blacklist that replaces naive ‘%bot%’ heuristics; (3) a public dataset reporting counts by human vs. bot and by automation class (manual, semi-automated, automated) and (4) a discussion of how special tags reveal how humans and bots collaborate along a nuanced spectrum from light automation, such as spell checking, to heavy automation, such as AI-generated text later edited by humans.

We pull the list of defined tags from `Special:Tags` and analyze them with SQL on Wikimedia’s public databases (Quarry), joining `change_tag/change_tag_def` for tag IDs and names, `revision/actor` for edit details and usernames, and `page` for titles, while using logging for non-edit actions. For each tag, we find the earliest confirmed use, the associated user, a canonical diff URL (using `rev_id` and `rev_parent_id`), and total usage counts, splitting human vs. bot activity with a curated bot allow/deny list rather than naive “%bot%” name filters (Johnson et al., 2016). Finally, we classify tags by automation level: manual (human-only), semi-automated (human triggers a tool like *Twinkle/Huggle/AWB*), and automated (bot or server-driven without per-edit confirmation).

We applied this method to a snapshot of `Special:Tags` captured on May 9, 2025. This snapshot contained 301 distinct tags. Queries were run using June 12–16, 2025. For each tag, we computed total edits and broke them down by human vs. bot; we also identified the earliest validated use and recorded the user and diff link for that event. In Section 2, we describe how tags were classified and present the results of that classification. Section 3 provides a deeper dive into *Twinkle* and other common tags, illustrating first-use validation and tag evolution. Section 4 concludes the paper with reflections on future work.

2. Tag classification

Following the identification of the initial users and timestamps for each of the 301 tags, we conducted a detailed first-use analysis. Each tag was classified based on whether its first recorded user was a human or a bot. After this step, we examined which users were responsible for introducing the largest number of tags overall, both among humans and bots. In addition to identifying first users, we also computed the total number of edits made by humans and bots for each tag using structured SQL queries. This helped us to compare the extent of participation between human editors and automated agents across different tag types. Finally, we performed a tag description analysis to understand the purpose and function of each tag. Using the descriptions provided on the *Special:Tags* page, we categorized

every tag into one of three automation classes: *Manual*, *Semi-Automated*, or *Automated*.

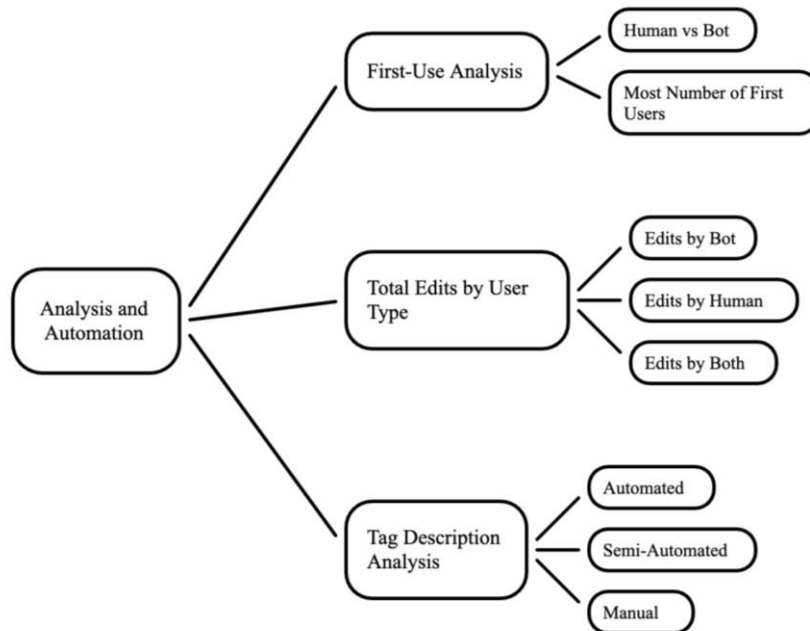


Figure 1. Overview of Analysis and Automation of User Interactions:
Workflow from First-Use Analysis to Automation Classification

We also distinguish between human editors and bot editors. Distinguishing between human and bot users is helpful for analyzing the patterns of tag usage, especially for tools like *Twinkle* that are mainly used by humans, but bots can also use. Initially, we used a simple SQL filtering method by applying the condition `LIKE '%bot%'` to the `actor_name` field. Although this approach yielded results rapidly, it generated numerous false positives because it identified any username that contained the substring "bot"—even if Wikipedia did not officially classify the account as a bot. We performed a focused comparison using the *Twinkle* tag by determining the first five distinct users who triggered the *Twinkle* tag in the `change_tag` table in order to measure the amount of error caused by the `%bot%` filter. To confirm their classification, we next looked to see if these users were listed on Wikipedia's official bot list. Five usernames were identified by this comparison: Robotnick2, Simbotin, RobotGoggles, Ahechbot (borderline), and NinjaRobotPirate. Ahechbot was the only one that was formally registered as a bot. The other four were either unverified accounts or human editors. On the other hand, we found that only two official bots are being used by *Twinkle*, and they are Helsabt and Ahechtbot. In assessing tool usage like *Twinkle*, this result shows that four out of five usernames (80%) detected by the `%bot%` filter were false positives, underscoring the need for more precise classification techniques. In our study, we improved bot detection by using a curated whitelist instead of substring matching.

We compiled the full set of active and inactive bots from Wikipedia’s “Category: All Wikipedia bots” (2,000+ accounts), then ran SQL on the Wikimedia Quarry replicas. For each first editor, we labeled the edit bot if actor.actor_name was in that whitelist (IN (...)) and human if it was not (NOT IN (...)). This method sharply reduced false positives and yielded more reliable user-type attribution.

Based on our findings, we divide the 301 tags into different usage groups. Figure 2 shows the results. The majority of tags—194—were initially used only by human editors, and this emphasizes how important manual contribution is to tag adoption. Only two tags, like “Cewbot” and “MediaWiki message delivery” were initially utilized exclusively by bots; these tags are both well-known for carrying out completely automated maintenance tasks. We found 83 tags that demonstrated mixed usage, which means that both human users and bots used them initially at different times, in addition to these exclusive-use categories. This overlap demonstrates a degree of convergence in the ways that bots and humans interact with Wikipedia’s tagging infrastructure, and reflects the common use of specific tools by both user types.

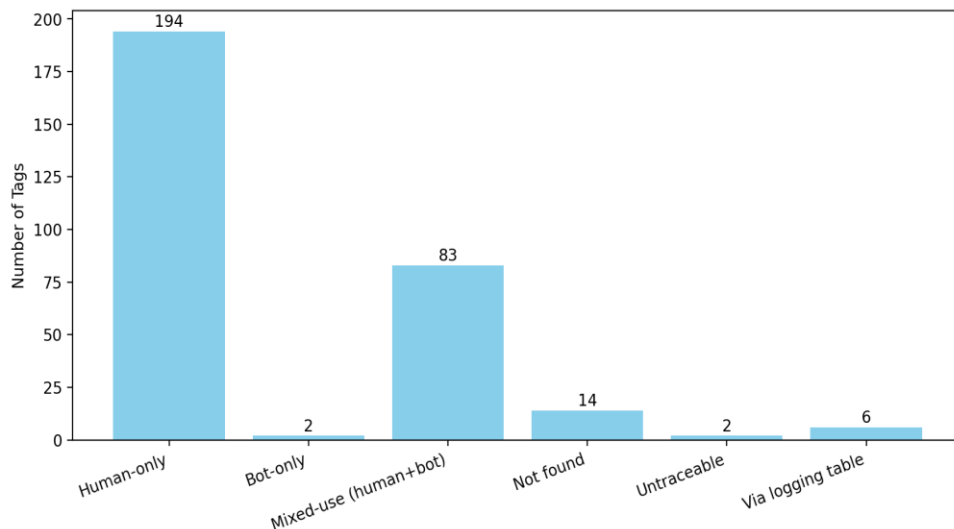


Figure 2. Distribution of Wikipedia Tags by Usage Category

This visualization highlights the dominant role of human contributors in initiating tags, along with other tag usage patterns across the Wikipedia ecosystem.

Additionally, we identified 14 tags that were never observed in either revision or logging data and categorized them as *Not Found*, indicating that, although they were defined in the system, they were never used for editing. Two additional tags (OAuth CID: 951 and OAuth CID: 1013) were classified as *Untraceable*, as it was not possible to reliably identify who used them or when. Although OAuth CID: 1013 appeared twice in the change_tag table and was associated with page revisions rather than system actions, attempts to retrieve the corresponding revision IDs (e.g., 823744470 and 823744540) returned the message

“This revision does not exist,” indicating that the edits were likely deleted or suppressed. The same issue occurred for OAuth CID: 951. As a result, despite being tied to genuine edits, neither tag could be attributed to a human or bot editor. Finally, we identified six tags that appeared exclusively in the logging table and were used for system-level or administrative operations rather than content edits. These included two tags for creating user accounts via email (*newusers/byemail*), one tag for page creation (*create/create*), and three tags for file uploads (*upload/upload*). These tags capture behind-the-scenes operations that support Wikipedia’s infrastructure but do not directly alter article content.

Focusing on tags with observable first-use events in revision data, we analyze when tags were first introduced and whether their initial use was by human editors or bots. This temporal analysis allows us to examine patterns in tag adoption over time and to compare early human and bot involvement in the tagging ecosystem. After excluding 22 tags that were categorized as *Not Found*, *Untraceable*, or logging-only, we retained 279 tags for further analysis. As shown in Figure 2, 194 of these tags were first used exclusively by human editors, 2 were first used exclusively by bots, and 83 were used by both humans and bots at different points in time.

We retrieved the total number of edits associated with each of the 279 tags by running our custom SQL queries on the *_Quarry* platform individually for each tag. These queries allowed us to calculate not only the overall number of edits per tag, but also to separate those edits by user type. These things help us to distinguish between contributions made by human editors and those made by bot accounts. This breakdown provided insight into how different types of users (human and bot) interact with specific tags, and we also get an idea about whether certain tags are more commonly associated with automated tools or manual workflows.

Figure 3 shows the use of a single tag, *mw-reverted*, over time. The y-axis represents the cumulative number of edits, separated into edits made by human editors, bot editors, and all edits combined (human + bot + uncategorized). Edits are classified as uncategorized when the associated accounts cannot be reliably attributed, such as in cases of renamed, deleted, or suppressed accounts. The first recorded use of the tag by a human editor occurred in 2001, while the first recorded use by a bot occurred later, in 2004. From 2001 through 2018, usage remained minimal across all categories. Beginning in 2019, however, tag usage increased sharply, with human contributions growing substantially faster than bot contributions.

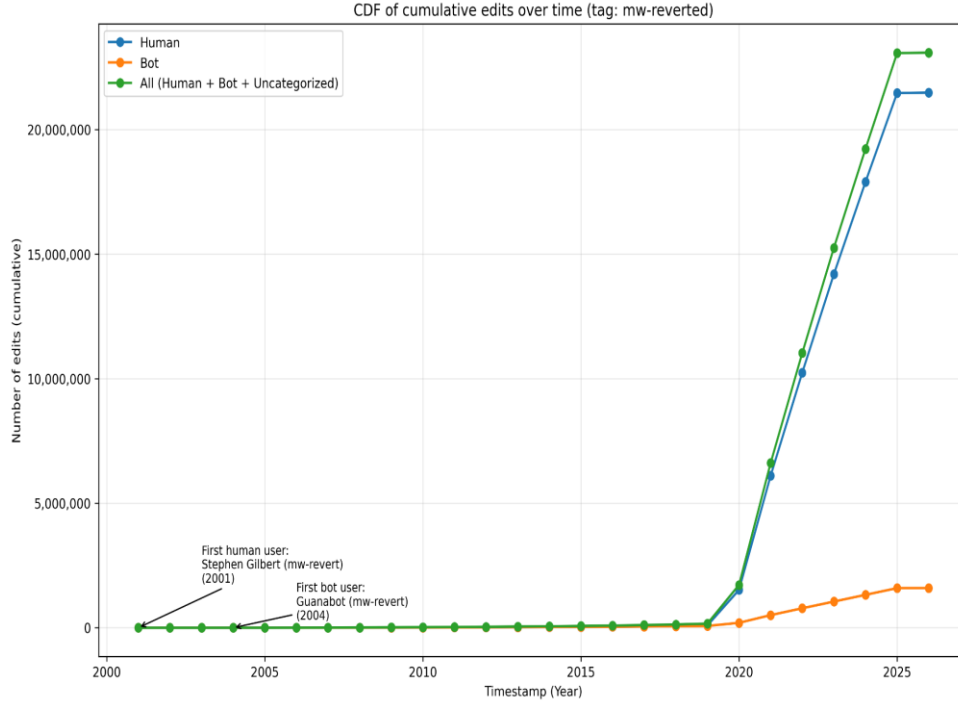


Figure 3. CDF of Cumulative Edits Over Time for the mw-reverted Tag, Showing Human-Only, Bot-Only, and Combined (Human + Bot + Uncategorized) Contributions from 2001 to 2026

3. Deeper dive: Twinkle and other common tags

We also decided to take a closer look at five specific tags so that we can provide a more grounded, detailed understanding of how tagging actually works in practice. These five tags correspond to some of the most frequently used tools on Wikipedia: *Twinkle*, *Huggle*, *AWB* (AutoWikiBrowser), *mw-replace*, and *STiki*. They are important for semi-automated editing on Wikipedia. Most of them need a human to approve each edit, but some, like *mw-replace*, can make changes automatically based on set rules. still require a human to initiate, configure, and supervise its operation. That puts it between manual tools and fully autonomous bots. By studying how these tools are used, we can better understand how Wikipedia content is created and controlled. Our goal was to check how well Wikipedia’s tag system shows the real history of editing tools. We did this by comparing two things: the first time a tool is recorded in the `change_tag` table (using SQL from Quarry) and the actual first time it was used, which we found by manually checking edit summaries and user contributions. In the following section, each tag is discussed in detail.

In this section, to illustrate some nuances in using Wikipedia Special Tags, we present a concrete case study of the *Twinkle* tag. *Twinkle* is considered to be one of the most widely used semi-automated tools on Wikipedia. The *Twinkle* tag indicates use of the *Twinkle* tool, a JavaScript-based application developed in 2007 by AzaToth. The goal of this tool was to help editors with common tasks like sending user warnings, reverting vandalism, and tagging pages. *Twinkle* saves editors time and effort by simplifying these repetitive tasks so they can apply templates and issue notices with just a few clicks. Even though *Twinkle* has been widely used for many years, it wasn't officially tracked in Wikipedia's change tagging system until September 5, 2020. To get a clearer picture of how *Twinkle* was used before that, we combined SQL-based analysis with manual checks of edit histories. This mixed approach helped us trace how the tool was actually used over time, spot gaps between the metadata and real edits, and distinguish between edits made by humans and bots. What we found was striking: *Twinkle* had been actively used for more than a decade before it ever showed up in Wikimedia's tagging system. This points to a major delay in how tool-assisted edits were being recorded—showing that metadata alone doesn't always tell the full story. Based on our analysis of the `change_tag` table, we found that *Twinkle* has been used in a total of 9,788,150 edits. Of these, the overwhelming majority number is 7,173,736 edits that were performed by human editors, reaffirming *Twinkle*'s role as a tool designed for active contributors. In contrast, only 12 edits were attributed to official bot accounts. Other edits fall under "uncategorized". This large disparity underscores *Twinkle*'s design focus: it is built to assist human workflows such as reverting vandalism, tagging pages, and issuing user warnings, not for automated editing.

We also found disparity between the tool's initial recorded use in the `change_tag` system. As there is a gap between its real first appearance in the Wikipedia edit history. The first time Bruce1ee used the *Twinkle* tag was on September 5, 2020. We got these results by using our custom SQL query from the Quarry website. However, through manual investigation of edit summaries and user contribution pages, we discovered that *Twinkle* had been actively used as early as 1 February 2007 by developer, AzaToth. It was used to edit the article *Animism*. That's a gap of more than 13 years between the actual use and when it was officially recorded. A similar inconsistency was found in bot usage. The first recorded bot use of *Twinkle* was by Helsabt on 12 September 2021, as per the `change_tag` table. However, on 20 December 2014, it was first used, but this thing was not recorded on the `change_tag` table. These disparities show how the `change_tag` system may greatly underestimate the historical timeline of tool adoption and misses early tool activity.

Table 1. First actual use, first recorded use, and delay between them for selected wikipedia tags

TAG	First recorded use (Date and username)	First actual use (Date and username)	Days Between
Twinkle	2020-09-05 Brucelee	2007-02-01 AzaToth	4,976
AWB	2018-01-17 Reedy	2006-05-18 Reedy	4,262
Huggle	2015-09-10 Petrb	Equazcion 2008-03-11	2,739
STiki	West-andrew.g 2018-04-11	West-andrew.g 2010-02-18	2,974
mw- replace	2017-12-07 ltitanthompson	PRehse 2006-11-25	4,030

We found a similar gap for four other tools: *Huggle*, *AWB* (AutoWikiBrowser), *mw-replace*, and *STiki*. In all these cases, the tools were used years before they were tracked with a tag. This shows that metadata alone doesn't give the full picture. Many tools were in active use long before they were added to the tagging system. So, relying only on SQL tag data can miss important history. That's why we used a hybrid method—both manual checking and database queries—to build a complete and more accurate timeline of when each tool was actually used on Wikipedia.

By drilling down into these five tools, we uncovered not just how these systems are used—but also where the metadata system falls short. Many tools were active long before their usage was officially tracked, and others are inconsistently tagged depending on how or by whom they were used. Table 1 summarizes the mismatch between actual first use and first use recorded in the change tag system, revealing clear evidence that the formal tracking system lags behind reality. This gap emphasizes the need for improved tagging infrastructure, especially as Wikipedia becomes a foundational source for datasets, LLMs, and real-time information systems.

Additionally, Wikimedia staff or administrator accounts, such as "TSevener (WMF)," made some of the earliest edits identified in our first-use data. These cases likely represent internal testing or early configuration rather than organic community adoption. For example, in the case of the tag *app-image-add-top*, the first use was by the account "TSevener (WMF)," which is an admin account. Recognizing such administrative activity provides a more nuanced interpretation of

the data, distinguishing between genuine first use by the community and preliminary system testing. Future tagging studies could build on this finding by explicitly differentiating administrative and non-administrative activity to refine timelines of tool adoption.

4. Conclusion and future work

This study examined Wikipedia’s *Special:Tags* system to better understand the nuanced continuum between human and automated contributions. Through SQL-based data extraction and manual verification, we found that tool usage on Wikipedia is more complex and historically underrepresented than metadata alone suggests. Tags such as *Twinkle*, *Huggle*, and *AWB* revealed multi-year gaps between actual tool use and their first recorded appearances in the *change_tag* table, underscoring the limits of relying solely on structured datasets. Our refined human–bot classification method also showed that common heuristics (like “%bot%”) can produce up to 80% false positives, which points to the need for verified bot registries and improved labeling standards.

We need to develop richer and more transparent tagging frameworks in the future to effectively capture emerging forms of AI-assisted collaboration. We propose extending the tagging taxonomy to include indicators such as *llm-generated* (AI-authored text), *prompt-inserted* (AI-suggested edits), and *llm-verified* (human edits checked with AI). These additions would allow researchers and moderators to trace AI involvement with greater precision and accountability. As large language models become integral to editing and moderation, standardized tagging of human–AI interactions will be essential for preserving the reliability of Wikipedia’s metadata and ensuring that future datasets reflect not just what was edited, but also how and by whom.

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Generative AI in education for space and remote learning

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Abstract: *The rapid rise of generative artificial intelligence (GAI) – AI systems capable of autonomously producing text, images, and simulations – is transforming educational practice worldwide. This paper examines the integration of generative AI into education, with a focus on remote and space-based learning environments. We review the current literature and policy context, highlighting how AI-enabled tools (e.g. AI tutors, content generators, and VR/AR simulators) can personalize learning, maintain continuity for isolated learners, and create immersive virtual labs. Examples include NASA’s VR training systems for astronauts and an AI-driven “Antarctic Explorer” platform for polar science education. However, we also analyze significant challenges: threats to academic integrity (with up to 58% of students admitting misuse of AI in assignments), embedded biases in AI outputs, and access inequities. International ethical guidelines (e.g. UNESCO 2023) and national strategies (e.g. US AI education initiatives) stress human-centered design, data privacy, and equity. We conclude that, when carefully governed, generative AI can extend STEM learning into extreme environments (deep space, polar bases), support astronaut training, and ultimately prepare a more resilient and inclusive space-oriented workforce.*

Keywords: generative AI, AI education, Virtual learning, Space education, Remote learning, Educational technology, Academic integrity, UNESCO AI.

1. Introduction

Educational practice is undergoing a profound transformation as information technologies evolve. Internet and digital platforms have long enabled remote learning and global connectivity. Today, generative artificial intelligence (GAI) – machine-learning models that can autonomously create text, code, images, and even virtual simulations – represents a new disruptive force in education. Systems like OpenAI’s ChatGPT and similar large-language-models have rapidly gained traction in schools and universities (Baytas and Ruediger, 2024). They promise unprecedented support for teachers and learners through automated tutoring, content creation, and real-time feedback. This potential is especially valuable in isolated or harsh environments – from polar research stations to space habitats – where access to instructors and resources is limited.

However, the speed at which GAI tools are emerging has outpaced existing educational practices and policies. UNESCO notes that GAI “tools are rapidly emerging or advancing to meet new needs” in education, but many institutions

remain unprepared to vet these systems or protect data privacy (UNESCO, 2023). Misuse of GAI (e.g. plagiarism) and algorithmic bias pose fresh challenges. Yet, the space sector's training requirements – such as continuous STEM education during long-duration missions – align naturally with GAI's strengths in generating customized, interactive content. For example, NASA and partner agencies are already exploring VR/AI platforms for astronaut training and science education (see below). As the International Conference on Virtual Learning (ICVL 2026) theme suggests, technology disruption is reshaping education. In this paper, I analyze the **opportunities and risks of integrating generative AI in education**, with emphasis on outer-space and remote contexts. I draw on recent studies, official reports (UNESCO 2023 guidance, policy documents), and examples from space agencies to offer a comprehensive, peer-level discussion.

2. Literature context

Generative AI has “quickly gained a significant foothold in academia,” according to recent analyses (Baytas and Ruediger, 2024). Surveys in late 2023 found that roughly half or more of students and faculty had tried tools like ChatGPT for learning or research (Baytas and Ruediger, 2024). Educational technology companies and researchers have rushed to develop GAI applications tailored for teaching and research. An Ithaka S+R issue brief (2024) categorizes many GAI tools as aimed at accelerating three key phases of the research/learning cycle – discovery, understanding, and creation (Baytas and Ruediger, 2024) – for example by summarizing literature, explaining concepts, or generating practice problems. While new products flood the market, independent studies emphasize the need to evaluate their real value.

Educational policy bodies and scholars are actively exploring the impact of AI on learning. UNESCO's recent reports underline the importance of aligning AI integration with humanistic values. Its 2023 *Guidance for Generative AI in Education and Research* identifies emerging GAI uses (from curriculum design to creative projects) but also warns that policy and teacher training lag behind the technology (UNESCO, 2023; UNESCO, 2023). UNESCO advocates a “human-centered” approach to GAI deployment, stressing data privacy, age limits for student use, and building digital literacy (UNESCO, 2023). The Organization for Economic Cooperation and Development (OECD) and Council of Europe similarly highlight inclusive, rights-based frameworks for AI in schools (Council of Europe, n.d.; UNESCO, 2021).

Research in immersive learning supports these policy trends. A 2025 review article reports that virtual reality (VR) and augmented reality (AR) systems have been effectively applied to space science training and research (e.g. for astronaut EVA practice and data visualization) (Council of Europe, n.d.). Another line of work examines AI-driven tutoring and personalization. For example, Georgia Tech's human-AI collaboration lab is developing AI “mentors” in VR math environments (the *Algeverse*) and conversational AI practice for medical

communication, illustrating how GAI can create interactive, empathetic learning scenarios (Nichols, 2025). All this literature, though still emerging, underscores that generative AI is already influencing pedagogy: accelerating content creation, enabling intelligent tutoring systems, and reshaping assessment and feedback.

Nevertheless, scholarly analysis also flags serious concerns. The integration of GAI in education has sparked debate over academic integrity, equity, and ethics (Rochester Institute of Technology, n.d.; Tan and Maravilla, 2024). For instance, a recent open-access study found that a majority of educators worry about dishonesty: 58% of students admitted to using AI tools to cheat on assignments (Tan and Maravilla, 2024). Experts urge that ethical principles – fairness, transparency, human oversight – must guide AI adoption (UNESCO, 2021) (UNESCO, 2023). This complex picture motivates our systematic exploration: identifying the dual-use potential of AI (educational and space training) while grounding recommendations in evidence and policy.

3. Opportunities of generative AI in education

Generative AI offers multiple avenues to **enhance learning experiences**, particularly by enabling personalization, creativity, and access. First, AI-powered tutors and assistants can provide on-demand, personalized support for learners. By analyzing a student's responses, an AI tutor can generate custom explanations, hints, or practice exercises attuned to that learner's level. For example, conversational AI tutors (such as the "HoloTutor" platform) can answer student questions in real time and adapt to individual learning styles (VictoryXR, n.d.). Even simple GAI tools can rapidly produce study guides, summaries or explanations in a student's native language, lowering barriers for remote or multilingual learners. In the space context, such tools could allow an astronaut to review complex technical concepts (like orbital mechanics or spacesuit procedures) through interactive dialogue at any time.

Second, generative AI can dramatically augment **content creation**. Educators can use GAI to generate varied educational materials – from illustrative diagrams and math word problems to full-fledged lesson plans. The UNESCO 2023 guidance explicitly encourages exploring creative uses of GAI in curriculum design and classroom activities (UNESCO, 2023). In practice, a teacher or student could prompt an AI to produce a virtual lab scenario (e.g. a simulated chemistry experiment) or an augmented reality scene (e.g. the surface of Mars for a geology lesson). This capacity is highly valuable in remote settings where physical resources are scarce: for instance, polar or space missions might lack laboratory facilities, but students could still conduct "virtual experiments" created by AI. The EON-XR platform (a commercial example) illustrates this potential by offering fully immersive 3D space exploration modules and satellite simulations in a VR classroom (EON Reality, n.d.). Although EON-XR targets K-12 globally, the same principle applies in mission contexts – astronauts or analog trainees could use VR modules to practice docking maneuvers or telescope operations generated by AI.

Third, GAI can help ensure **learning continuity** under isolation. Remote bases and spacecraft have limited instructor presence. AI systems can augment the educator role. For example, IBM and the Mawson's Huts Foundation developed an AI-powered "Antarctic Explorer" platform that children (and adults) can use to ask questions about Antarctica and immediately receive answers with multimedia content (International Telecommunication Union, 2024). The system uses IBM Watson's NLP to interpret natural-language queries and retrieve relevant videos, images and documents from a cloud database. Such an approach – "ask anything, get an answer" – could be adapted for space science: crewmembers on a Mars transit or research stations in Antarctica could query an AI for information on geology, biology, or system maintenance, receiving curated learning content even without an internet connection (by caching relevant data locally). Notably, the Antarctic project also provides speech-to-text and text-to-speech features for accessibility, ensuring that learners with disabilities or when hands-free operation is needed (e.g. wearing spacesuits) can still engage with the AI (International Telecommunication Union, 2024).

Another key opportunity is leveraging **virtual and augmented reality (XR)** driven by AI. Immersive VR/AR can simulate realistic learning environments that would be impossible otherwise. According to a recent review, such immersive technologies significantly benefit space-related training: they assist with procedural guidance, astronaut training, and mission planning (Council of Europe, n.d.). In practice, students can experience a VR replica of the International Space Station or walk on a virtual lunar surface. Crucially, generative AI can enhance these simulations by dynamically creating scenarios. For instance, as Boeing's Starliner program has shown, high-resolution VR headsets can render the spacecraft cockpit and control panels in detail, allowing entire mission phases (launch, docking, re-entry) to be practiced in VR (Varjo, n.d.). Coupled with AI-driven feedback or decision-tree branching, such VR simulations become richer and more adaptive to learner actions. These tools can be used in classrooms (for STEM education) and then directly applied to astronaut training simulators (NASA, 2024; Varjo, n.d.).

Finally, generative AI can promote **access and equity** in education by democratizing resource creation. In many developing or remote areas, there is a shortage of qualified teachers or materials. Free or low-cost AI systems (as they evolve) could generate textbooks or translations on demand. UNESCO's literature notes that AI adoption is far lower in low-income countries (only about 8% of institutions) compared to high-income ones, but targeted efforts to deploy GAI tools in under-resourced schools could help close this gap. For space sector education (which often involves international cooperation, e.g. ISS, Artemis), AI-generated content can be made available in many languages and tailored to diverse curricula. In summary, the opportunities of generative AI in education include personalized tutoring, automated content creation, immersive simulation of hard-to-access environments, and extending educational resources to even the most isolated learners (Baytas and Ruediger, 2024; UNESCO, 2023).

4. Challenges and risks

Alongside these opportunities come significant **risks and challenges** that educators and policymakers must address. A foremost concern is **academic integrity**. Generative AI can easily produce essays, problem solutions, code, and even creative works, which students might pass off as their own. A recent study reported that 58% of surveyed students admitted using AI tools to complete assignments dishonestly (Tan and Maravilla, 2024). This erosion of integrity threatens the validity of assessments. Moreover, traditional plagiarism detection tools may not catch AI-generated work, as noted by educators (Rochester Institute of Technology, n.d.). In response, many institutions are rethinking assessment design: moving toward open-book, project-based, or oral exams that require original input. Importantly, rather than simply policing AI use, educators are encouraged to teach students “how to use AI as a learning aid rather than a shortcut” and to emphasize process-based assignments (Rochester Institute of Technology, n.d.).

Bias and misinformation are also serious issues. Generative models are trained on large datasets that may encode societal biases. RIT’s teaching center warns that these systems “can reinforce or amplify bias” because underrepresented topics or viewpoints might be missing or misrepresented in training data (Rochester Institute of Technology, n.d.). For example, an AI writing tutor might inadvertently suggest cultural stereotypes or produce mathematically incorrect explanations if not carefully curated. These biases could perpetuate inequalities in education. UNESCO’s AI ethics recommendation (2021) explicitly urges that AI actors **promote non-discrimination and accessibility** (UNESCO, 2021). Practically, this means any educational AI tool must be tested and supplemented to ensure fairness (for instance, by including diverse data or human oversight).

Access and equity present another paradox. While AI promises broader access, in the short term it may actually worsen divides. Many cutting-edge GAI tools require significant computing power or subscription fees. The RIT guide notes that as vendors monetize AI, tools “may be available only to individuals with the financial means to use the tool,” creating a new digital divide (Rochester Institute of Technology, n.d.). Similarly, students without reliable internet or up-to-date devices (a common situation in remote or low-income areas) may be unable to access cloud-based AI platforms. These gaps are acute in space contexts: an ISS or lunar station has limited bandwidth and on-board hardware. Some programs (e.g. NASA’s certification courses (NASA, 2023)) address this by offering lightweight, asynchronous materials, but broader planning is needed to ensure remote or economically disadvantaged learners can benefit. UNESCO’s guidance emphasizes that AI policies should ensure education benefits “are accessible to all” (UNESCO, 2021), calling for equity-focused strategies in AI rollout.

Privacy and data security are critical when students interact with AI. Generative AI often requires sending prompts (which may contain student work or personal information) to a cloud service. The RIT teaching guide points out that

this raises concerns about personal data and intellectual property (Rochester Institute of Technology, n.d.). For instance, a question submitted by an astronaut from the ISS to an AI system could inadvertently upload mission-sensitive information. UNESCO's guidelines stress robust data protection and user consent in educational AI (UNESCO, 2023). Institutions must therefore either vet which third-party AI tools meet privacy standards or develop in-house solutions. For space and remote learning, this is doubly important: international missions must comply with multiple national regulations (e.g. U.S. Privacy Act, EU GDPR, etc.) and the harsh conditions (e.g. radiation) impose extra reliability requirements.

Finally, there are **technical and psychological challenges**. Generative AI models are computationally intensive; training or running large models consumes much energy and resources (Rochester Institute of Technology, n.d.), which may be scarce on spacecraft. The RIT guide also reminds us that not all students can focus well: some educators suggest written or oral tests to curb AI use, but these can disadvantage students with certain disabilities (Rochester Institute of Technology, n.d.). Psychological factors also matter: relying too much on AI may reduce human interaction, and students may become overconfident in AI outputs unless digital literacy is taught. Policy frameworks (see below) increasingly recognize these issues. In summary, while GAI offers powerful new tools, responsible integration must address academic honesty, bias, equity of access, and data privacy – consistent with UNESCO's call for human-centered AI policies (UNESCO, 2023; UNESCO, 2021).

5. Applications in outer space and remote environments

Generative AI's unique strengths make it especially well-suited to the **challenges of space and remote education**. In environments where human instructors cannot always be present, AI can act as a surrogate teacher and interactive learning companion. For example, NASA's *AI/ML Space Biology Certification Program* provides open-access, self-paced courses in AI and space biology, allowing remote learners (including Earth-bound students) to train in specialized STEM content (NASA, 2023). Similarly, astronaut training increasingly uses AI-enhanced simulations: the Boeing Starliner crew uses Varjo XR-1 VR headsets to practice every phase of their mission entirely in virtual reality (Varjo, n.d.). High-fidelity VR allows astronauts to "step into space" for training; as one Boeing engineer noted, human-eye resolution VR has enabled pilots to read instrument panels at normal distance for the first time (Varjo, n.d.). NASA's own Johnson Space Center operates VR simulators and dome environments where crew members train EVA procedures. As McFarlane of NASA explains, VR labs are used "extensively for...astronaut training in extravehicular activity operations" (NASA, 2024). These facilities use generative 3D models and real-time graphics, and future versions may incorporate AI agents or procedural content generation to create on-demand scenarios. In short, technologies pioneered for classroom VR (now enhanced with AI) are directly applicable to space mission prep.

Remote **STEM laboratories** are another area of synergy. Generative AI can help simulate lab experiments that would otherwise require bulky equipment. For instance, in an AI-generated chemistry lab, students could conduct virtual titrations or biology dissections in VR (as done by education startups) and the AI would handle the experiment logic and feedback. If astronauts aboard the ISS or in a lunar habitat lack a certain lab apparatus, AI-driven simulators could fill the gap by generating equivalent training content. Moreover, space analogs on Earth – polar stations, desert bases – already use remote labs. The Ant+ project (Antarctic Explorer) suggests a model: children engage with an interactive AI-driven science bus tour of Antarctica (International Telecommunication Union, 2024). Similarly, remote STEM labs on Antarctica or Mars analogs (e.g. in Hawaii) could be augmented with AI tutors that explain procedures or answer field science questions on the fly.

Continuous **astronaut training and health support** is a critical use case. The European Space Agency (ESA) has begun integrating AI into astronaut preparation. Recent reports note that ESA is developing intelligent modules for mission simulation, medical instruction, and psychological support (Pao, 2025). For example, British astronaut Megan McArthur stated that ESA plans to expand distance-learning tools for the Columbus orbital lab, with AI features to improve efficiency (Pao, 2025). ESA is even trialing AI assistants in space: the *CIMON* (Crew Interactive Mobile Companion) – a spherical AI robot – was flown on the ISS to converse with crew and boost morale (Pao, 2025). Such devices, while early prototypes, hint at future in-flight AI aides. On long missions (e.g. transit to Mars), AI companions could facilitate informal learning or monitor cognitive well-being.

Furthermore, AI can help **adapt curricula to extreme conditions**. Astronauts often serve educational outreach roles and require flexible schedules; AI can generate lesson plans or communication strategies for them to engage with students on Earth. Space agencies can use generative AI to translate Earth-based educational content into contexts relevant to space. For instance, VR planetary simulations used in classrooms (as in the Algeverse example (Nichols, 2025)) could be adapted to teach geography or physics to astronauts, reinforcing concepts during downtime. Conversely, educational tools developed for space – like VR simulations of Mars geology – can enrich remote terrestrial learning for students interested in space science. These dual-use crossovers are increasingly common.

Finally, the parallel between **polar analogs and space** is instructive. Participants in Antarctic missions describe the environment as “as close as you can get to being on another planet” (International Telecommunication Union, 2024). This analogy suggests that strategies for remote learning in polar research could translate to space. The Antarctic Explorer platform (AI answers about Antarctica) directly leverages this by making polar science accessible through AI-driven Q&A (International Telecommunication Union, 2024). A similar model could allow learners (students or trainees in analog habitats) to explore planetary science topics. In essence, generative AI blurs the boundary between Earth and space education: tools developed for one can be repurposed for the other, enabling *continuous, location-independent learning* in extreme conditions.

6. Policy and ethical frameworks

To realize the benefits of generative AI in education while mitigating risks, robust policies and ethics frameworks are essential. At the global level, UNESCO has led in setting standards. Its **2023 Guidance for Generative AI in Education and Research** provides recommendations for policymakers, educators, and technologists. The report warns that GAI is advancing faster than regulations, leaving “data privacy unprotected and institutions unprepared” (UNESCO, 2023). It calls for steps such as requiring human oversight of AI outputs, protecting student data, and restricting unsupervised use by minors (UNESCO, 2023). Crucially, UNESCO envisions a “human-centered approach” – meaning AI should empower teachers and learners, not replace them. The Guidance also encourages integrating AI literacy into curricula and training teachers to use GAI responsibly (UNESCO, 2023). These recommendations align with UNESCO’s earlier 2021 *Recommendation on the Ethics of AI*, which established core values – human rights, fairness, transparency – for all AI systems (UNESCO, 2021). In that Recommendation, UNESCO emphasizes that AI must promote social justice and inclusiveness, ensuring its benefits “are accessible to all” (UNESCO, 2021). Such principles imply that as schools adopt GAI tools, they should actively address bias and ensure equitable access, consistent with the broader Sustainable Development Goal of inclusive quality education.

Regional and national strategies are also emerging. In Europe, the Council of Europe (advisory) highlights AI’s “transformative role” in personalizing learning and innovative teaching, but insists this must not violate human rights (Council of Europe, n.d.). The European Commission and member states are exploring educational AI projects – for example, a 2024 EU-funded initiative in Slovenia is studying the didactic, legal, and ethical aspects of GAI use in schools (European Commission, n.d.). Moreover, the forthcoming EU *Artificial Intelligence Act* (targeted for enforcement in 2026) will likely categorize certain AI educational tools as “high-risk,” requiring transparency and human oversight. Aligning with these trends, national governments have begun issuing guidance. For instance, the United States government launched a task force in 2025 to promote AI literacy, stating as formal policy that AI should be integrated into K–12 and higher education with comprehensive educator training (White House, 2025). That Executive Order (April 2025) explicitly mandates resources and partnerships for AI in education. Other countries, from China to smaller states, are drafting AI-in-education strategies as well, reflecting global momentum.

Ethics in practice also plays out at the classroom level. Many institutions now require disclosure of AI use and train students in “responsible AI.” Academic integrity policies are being updated to reflect AI; for example, some medical schools explicitly ask candidates to declare AI assistance on essays, and faculty are redesigning assignments to focus on higher-order thinking (Rochester Institute of Technology, n.d.). At the same time, specialized AI ethics education is being introduced. For example, UNESCO and partners have developed teacher guides on

AI literacy, emphasizing critical evaluation of AI content and the values of fairness (UNESCO, 2021; UNESCO, 2023).

In summary, a multi-layered policy response is taking shape. At the top, UNESCO's guidance and global conventions set broad ethical mandates for fairness, privacy, and human oversight (UNESCO, 2021; UNESCO, 2023). Regionally, bodies like the EU and Council of Europe are working toward regulation and pedagogical standards. National governments are following suit with AI-education roadmaps (e.g. the U.S. executive order (White House, 2025)). Effective implementation will require collaboration between governments, educational institutions, and industry. For the space sector specifically, agencies must align these frameworks with space regulations (e.g. export controls on software, astronaut code of conduct) and ensure mission data are protected. As a whole, these emerging policies recognize that generative AI can be a powerful ally for education in all settings – if deployed within a clear ethical and legal framework.

7. Conclusions

Generative AI is poised to **change education** profoundly – accelerating personalization, expanding access, and enabling immersive learning. As we have shown, these changes are especially promising for remote and space environments. AI-powered platforms can keep learners engaged and informed even in the deepest oceans, the polar ice, or the vacuum of space. Astronauts and analog explorers can continue STEM learning and professional development via virtual labs, simulated missions, and smart tutors that replicate the support of Earth-based educators. Examples from NASA, ESA, and other organizations demonstrate how AI, VR, and robotics are already transforming astronaut training and public engagement.

However, this technology must be managed judiciously. The ease of AI content generation brings temptations for misuse, and the “black-box” nature of many AI systems raises bias and accuracy concerns. Ensuring educational quality and equity means not just adopting AI, but embedding it in a human-centered pedagogical vision. Ethical guidelines (UNESCO, Council of Europe) and proactive policies (national AI-education strategies) are vital. Educators and space professionals will need ongoing training in AI literacy, so that they can harness these tools wisely.

Looking ahead, the dual-use nature of generative AI – serving both education and space exploration – suggests a valuable synergy. Innovations like AI-driven VR classrooms or adaptive learning software will benefit students everywhere, and can simultaneously be adapted for astronaut crews. For instance, an AI tutor that helps high-schoolers with math could be retargeted to assist mission specialists learning orbital dynamics. Conversely, lessons from space (rigorous safety standards, interdisciplinary curricula) can inform Earth education. In all cases, human creativity and critical thinking remain irreplaceable.

Well-designed generative AI should **amplify** these human strengths, not substitute for them.

In conclusion, as we prepare for ICVL 2026 under the theme “Changing Education Because of Technology Disruption,” we see generative AI as a disruptive force with extraordinary potential. Its integration into education – especially for the space sector – offers continuity of learning in the harshest conditions and can inspire the next generation of space professionals. By rigorously addressing challenges through research, pedagogy, and policy, the education community can turn this disruption into an opportunity: transforming not only the classroom but even the next frontier of human exploration.

Acknowledgements

The work presented in this paper is supported by the Core Program within the national research Development and Innovation Plan 2022-2027, carried out with the support of MCID, project no. 23380601, “Advanced research in the Metaverse and emerging technologies for the digital transformation of society”.

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The Artificial Intelligence (AI) approaches in university education and education sciences' scientific research

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Abstract: *This study examines the integration of Artificial Intelligence (AI) and Generative Artificial Intelligence (GAI) in higher education and scientific research, with a particular focus on a comparison between Finland, Romania, and the Republic of Moldova. In this context, the paper examines the degree of adoption of AI/GAI in education and research, identifying existing gaps and potential areas for growth in these countries. The analysis is based on case studies, international reports (DESI), and relevant national and institutional policies. The findings indicate that Finland, a leader in the integration of AI/GAI, has developed national and institutional policies. In contrast, Romania and the Republic of Moldova have yet to implement them cohesively. However, in Romania and the Republic of Moldova, we attest to initiatives at national, local, and institutional levels that are yet to be supported by a coherent legislative framework. The results of the study prove the existence of a consensus among governmental, economic, and academic actors on the importance of creating a favorable digital ecosystem. However, there are still significant challenges in implementing a comprehensive and sustainable framework for the use of AI/GAI in higher education and research. These findings provide a foundation for future research on the presence of AI/GAI in education and research, with implications for educational sciences and engineering sciences as well as broader fields.*

Keywords: Education, Research, Academia, Artificial Intelligence (AI), Finland, Romania, Republic of Moldova.

1. Introduction

Currently, Artificial Intelligence (AI) plays the role of an essential catalyst for transforming the fields of education and research. Although AI technologies offer new opportunities in personalizing the teaching process, optimizing resources, and automating educational management tasks, the integration of AI in the academic environment, that is, in university education and scientific research carried out in higher education institutions, involves a series of complex challenges that go beyond simple technological adoption.

In the given context, this research aims to investigate the state of affairs regarding the degree of integration of AI/GAI in education and research using the example of a descriptive-comparative analysis between Finland, Romania, and the Republic of Moldova. Therefore, the research problem consists of identifying and analyzing the existing gaps in the experience of integrating artificial intelligence

(AI / GAI) in the academic environment at the level of university education and research, using the example of Finland, Romania, and the Republic of Moldova.

Thus, the objectives of the research were formulated as follows:

(1). Thematic analysis of scientific research in the field of educational sciences on the integration of Artificial Intelligence (AI) in education, exemplified by case studies of Finland, Romania, and the Republic of Moldova.

(2). Descriptive and comparative analysis of the applied approaches of Artificial Intelligence (AI) and Generative Artificial Intelligence (GAI) in research and university education, but not only based on the cases of Finland, Romania, and the Republic of Moldova.

(3). Study of the DESI (Digital Economy and Society Index) reports for Finland and Romania, to achieve a conclusive synthesis and descriptive analysis, expressed through percentage reports and graphic illustration of the current situation in the analyzed countries.

(4). Analysis of the degree of integration of Artificial Intelligence (AI) in education and research in relation to the strategic visions of the Republic of Moldova. Descriptive presentation of the current situation in the Republic of Moldova, along with the country's experiences in scientific research on the application of AI/IAG in education, participation in international projects on topics related to AI/IAG in education, and information and training activities in the use of AI/IAG.

(5). Formulation of conclusions regarding the purposes of this research, as well as its prospects.

Research methodology. The paper is built on the analysis and synthesis of recent studies, including research articles reflecting various theoretical and praxiological aspects of the use of AI/IAG in education, as well as research in the field of educational sciences; institutional reports and press releases on various actions of actors interested in raising awareness among actors in education, as well as representatives from research towards the integration of AI/IAG.

2. Artificial Intelligence (AI) approaches in educational sciences research in Finland, Romania, and the Republic of Moldova

For a descriptive-comparative study on the content and specificity of good practices for integrating AI/GAI in education and research, it was decided to report on the national contexts implemented in Finland, Romania, and the Republic of Moldova. We consider that the descriptive-comparative approach adopted by us, being based on the context of the countries reviewed, responds both to the need to highlight good practices and successful models and facilitates the identification of challenges specific to each implementation context, but also to the detection of subsequent solutions that would eliminate or reduce the existing discrepancies in the analysed countries in terms of integrating AI/GAI in education and research. Problems related to the use of AI in education are subjects of scientific interest to researchers worldwide.

Among those concerned with the aspects of integrating AI / IAG in education and research, there are scholars from various scientific branches both in the field of exact and applied sciences, such as technologies and engineering sciences, as well as those absorbed by the social-human fields, in particular, those in educational sciences and, namely: vocational pedagogy (Eriona, Narasimha & Dr. Philip, 2024; Zary & Zary, 2025); technological pedagogy (edtech) (Feldman-Maggor et al., 2025; Burlacu, 2023b); educational management (Burlacu, 2024b; Burlacu, 2025); university pedagogy (Burlacu, 2023; Burlacu & Cozlovski, 2025) and private didactics (Burlacu & Cozlovski, 2024a; Liu, Bao & Chen, 2025; Tan, Cheng & Ling, 2025), etc.

The respective panel of researchers also includes experts from the countries analysed in this study, although in Finland, Romania, and the Republic of Moldova, scientific works of a descriptive and/or critical nature are developed, as well as conceptual constructivist analyses of the AI/IAG phenomenon and other particular perspectives of its educational applicability.

Thus, in **Finland**, the following are investigated: (1.) the praxiological aspects of the use of AI in experimental research in the field of education (López-Pernas et al., 2025; López-Pernas, Song & Saqr 2026); (2.) The applicability of AI/GAI in particular didactics and, specifically, on the dimension of personalized learning (Mertala, Fagerlund & Calderon, 2022); (3.) collaborative and experiential learning (Laru, 2024).

The researchers from **Romania** show interest in topics such as (1.) general aspects of integrating AI in education (Adăscăliței, 2025); (2.) the implementation of AI in universities (Adăscăliței, 2025c; Bran & Grosseck, 2024b); (3.) the practical use of AI in STEAM education (Adăscăliței, 2025b); (4.) the integration of artificial intelligence in the teaching and learning of engineering sciences (Adăscăliței, 2024); (5.) the use of AI in teaching (Ivanova, Grosseck & Holotescu, 2024); and (6.) AI in language education (Bran & Grosseck, 2024a).

Along with the dimensions of digitalization of education (Burlacu, 2021a; Burlacu, 2021b), researchers from the **Republic of Moldova** study dimensions related to AI/GAI in education and research, such as (1.) assessment of learning outcomes (Burlacu, 2024b); (2.) integrity of didactic assessment (Burlacu, 2023a; Burlacu, 2024a); and (3.) adaptability and flexibility of the didactic process (Burlacu & Cozlovski, 2024b; Beldiga & Bragaru, 2025).

3. Applied approaches to AI/GAI in higher education

3.1. The case of Finland: descriptive aspects

Finland, considered a model of excellence in education and being recognized for its strategies focused on inclusion, equity, and adaptability, demonstrates the integration of AI into higher education in an accessible and participatory way by implementing the national project Elements of AI [<https://www.elementsofai.com/>].

The aforementioned project represents a set of free courses created by the collaborative team of MinnaLearn and the University of Helsinki, offered online to

those interested in familiarizing themselves with AI, both at the user level and as potential professionals.

Among the measures implemented in Finnish universities are the following:

- **Scientific research on the application of AI/IAG in education.**
- **Development and promotion of institutional policies on the use of AI, addressed to students,** such as those developed by the University of Eastern Finland (University of Eastern Finland, 2025). The present press release mentions the AI policy for students, setting out in general terms the circumstances in which the student may use generative AI as a learning support. The documents expressly state that AI/GAI may be applied by students except in cases where the teacher prohibits the use of AI. The institutional documents also state that the student must expressly declare in writing in the content of the paper, usually in the introductory and concluding parts of the paper, that he/she has used IAG. The same regulation stipulates that if AI is used against the teacher's instructions or if the use of AI is not mentioned, the matter will be investigated in accordance with the university's institutional process for combating academic fraud.
- **Promotion of national policies, as well as methodological elaborations/guides for actors involved in education** ("legislation and recommendations"). Such are the regulations and methodologies developed by the National Agency for Education and the Ministry of Education. They outline the general framework for education, including university education, coming up with a set of suggestions and recommendations for the appropriate use of AI/GAI from the perspective of personal data protection. (Finnish National Agency for Education (EDUFI), no date; Ministry of Education and Culture, 2023), but also (Raukko, 2023) by separate academic entities.
- **Information and dissemination activities on the integration of AI / GAI in education.** Among the other actions dedicated to the literacy of educational actors in the matter of implementing AI/GAI are events with a scientific focus: thematic conferences oriented towards employees in the national education system, for example, the Interactive Technology in Education Conference 2025 [<https://itk-konferensi.fi/>]; round tables targeting the operation with IAG, such as the one with the generic The Future of Learning and Skills in the Age of Artificial Intelligence (The Finnish National Board of Education is organizing the event in collaboration with the ITK organization, 2025).
- **Academic research on the implementation of AI and IAG at the university level** is materialized in master's theses (Riega Cayetano, 2025); some particular disciplines for the II-th and/or III-th cycle programs are initiated, as well as other IAG tangential aspects in doctoral research; and descriptive and critical analyses of the processes of transposition of national directives into concrete policies within university education are carried out. A relevant example of such a product is the work *AI Policy Implementation in Finnish Universities: Challenges and Implications*. This work turns out to be an analytical study on

the application of AI from the perspective of multilevel governance (Reivo, 2024).

3.2. The Romanian case: descriptive aspects

The analysis of the situation regarding the use of AI/GAI in Romanian university education allows us to state that currently, the institutions offering study programs in various professional fields are becoming increasingly sensitive to the acceptance of AI/GAI; there is a variety of action directions are initiated here, such as:

- **Scientific research on the application of AI/GAI in education.**
- **Launching international projects dedicated to the development of ecosystems for research, innovation, and technological transfer in the field of artificial intelligence.** Such is the experience of several universities in Romania, including the same UVT, which is one of the participants in the Romanian Artificial Intelligence HUB – HRIA project. The project unifies under its umbrella seven universities in the country (The West University of Timișoara, 2025b), with the project leader being the National University of Science and Technology Politehnica Bucharest.

The HRIA project is co-financed by the European Regional Development Fund (ERDF), within the Smart Growth, Digitalization, and Financial Instruments Programme 2021-2027 (PoCIDIF). The general objective of the project is to create and operationalize the Romanian Center for Artificial Intelligence by developing a competitive research, development, and innovation ecosystem that brings together the resources of the academic and economic environment to generate original and cutting-edge scientific research, develop new products and services based on artificial intelligence, transfer the results to industry and society, and create a national knowledge core integrated into the European Research Area.

The HRIA project consortium, in addition to the seven Romanian universities, also brings together eight innovative technology and research companies as private sector partners: BEIA Consult International (BEIA), IT Center for Science and Technology (CITST), GreenSoft (Green), Neural Grader (Neural), Safetech Innovations (SafeTech), SoftTehnica (SoftTeh), Technology Systems and Services International (TSSI), and Terrasigna (Terra) [ibidem].

- **Establishing national technical and technological networks that would support the development of the field of artificial intelligence in Romania.** This category includes the RO AI Factory project developed by the National Institute for Research and Development in Informatics (ICI Bucharest) in partnership with the Politehnica University of Bucharest. The project envisages the construction of a supercomputing infrastructure, optimized for AI needs, accessible to the academic and/or university environment (ICI Bucharest, 2025).
- **Education and training programs.** Several universities in Romania offer training courses in the field of technologies and familiarization with AI, their beneficiaries being students, pre-university/university teachers, and auxiliary teaching staff. Such initiatives have been attested by institutions such as "Victor Babeș" University of Medicine and Pharmacy Timișoara (UMFVB

Timișoara), University of Bucharest (UB) + National School of Political and Administrative Studies (SNSPA) + "Alexandru Ioan Cuza" University of Iași (UAIC), "Alexandru Ioan Cuza" University of Iași (UAIC), and Politehnica University of Timișoara (UPT).

- **Initiation of new academic disciplines for familiarization with AI/GAI.** This is the initiative of the West University of Timișoara (UVT), which, starting with the academic year 2025-2026, introduced two disciplines with complementary status (The West University of Timișoara, 2025a), such as "Neuroscience and Artificial Intelligence" and "Applied Generative Artificial Intelligence," for its students. These disciplines are accessible to all 2nd- and 3rd-year students of the bachelor's degree cycle, regardless of the chosen program.

3.3. Current state of the research problem: comparative synthesis on the example of Finland and Romania

In this research, we aimed to conduct a comparative analysis between Finland and Romania of the degree of use of AI, based on the digitalization process in the given countries. In this context, annual EU reports were analyzed regarding the current state of technologies in the digital economy and society in the aforementioned countries. The content of the reports is developed based on the DESI index (Digital Economy and Society Index), which was designed by the European Commission as a tool to measure the digital progress and competitiveness of EU member states.

DESI is applicable for measuring and comparing the progress of European countries in terms of digitalization, covering aspects such as: **(A.) connectivity**, access to fast internet, and digital infrastructures; **(B.) human capital**, digital skills of the population; **(C.) internet use**, level of use of online services; **(D.) integration of digital technologies in business**, the way in which companies adopt and use digital technologies; **(E.) digital public services**, the digitalization of public administration and government services.

For both countries, Finland (European Commission, 2024b) and Romania (European Commission, 2024a), data on the following parameters were extracted from the respective reports:

(1.) DESI index for calendar year 2023;	(5.) DESI index for calendar year 2023;
(2.) DESI index for calendar year 2023;	(6.) DESI index for calendar year 2023;
(3.) Annual progress;	(7.) Annual progress;
(4.) National trajectory per country, measured at the end of 2024;	(8.) National trajectory per country, measured at the end of 2024;

The respective data were selected, processed, assembled, and represented in consecutive diagrams. For Finland, see Figure 1; for Romania, see Figure 2.

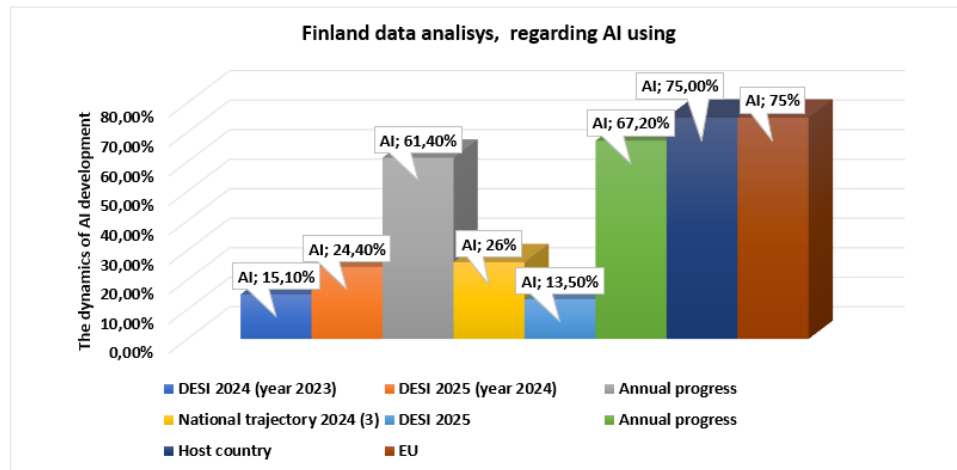


Figure 1. The data analysis related to AI use in Finland

The comparative analysis of the DESI index for Finland and Romania showed the following:

- Finland surpasses Romania in absolutely all the parameters reviewed.
- The exception is the values for the progress achieved by the respective countries in the period 2023-2024. Finland has achieved a progress of 61.40%, while Romania has achieved a progress of 103.30%, indicating a significant potential for digital progress in Romania.
- At the end of 2024, Romania did not submit data to the EC regarding the national trajectory; in the respective diagram, the value for this parameter is zero (0), see Figure 2.

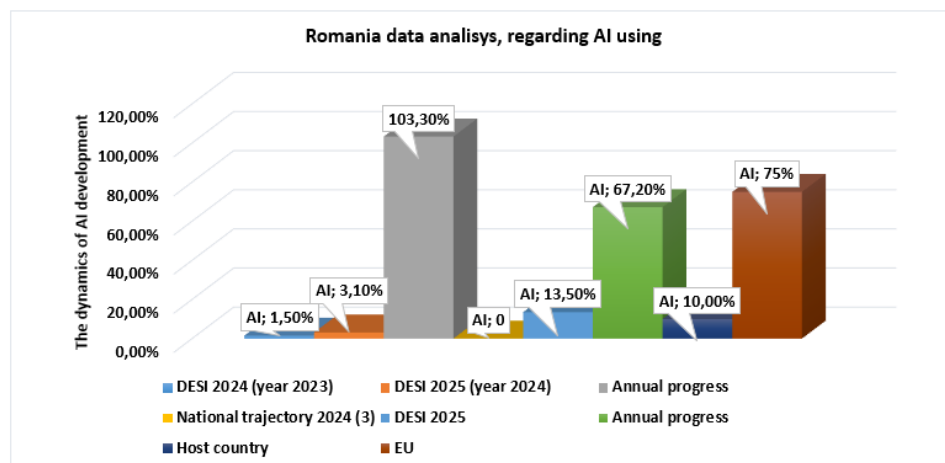


Figure 2. The data analysis related to AI use in Romania

The data relating to the comparison between the state of affairs in the host countries (Host Country) and that in the EU, where for Finland and the EU the

same value (75.00%) is present in Figure 2, and for Romania it is only 10.00% (see Figure 2), denotes the following: Romania, having the DESI value = 10%:

A DESI of 10% suggests that Romania is in a very weak position in terms of digitalization compared to the EU average, but also to Finland. It means that Romania has limited access to advanced digital infrastructures, a low level of digital skills among the population, a weak integration of digital technologies in business, and less developed public services. This value highlights a significant gap compared to the European and Finnish averages. It highlights an urgent need for investment in digital infrastructure, digital education, and the adoption of technology in key economic sectors.

A DESI = 75% for the European Union and Finland, which indicates an EU and Finnish average of 75%, marking significant progress in the adoption of digital technologies. In the EU, as well as in Finland, countries are well-connected and have a wide use of the internet, as well as a significant integration of digital technologies into various socio-economic areas. However, it is important to note that there are also disparities between EU member states—some member countries are much more advanced than others in this area.

Finland, in this sense, is an example of a country that is aligning with European standards in terms of digitalization and the use of AI. Not in vain, Finland is considered a top country in the field of digitalization, boasting a highly digitalized public sector, an extremely high-performance internet infrastructure, and, more recently, a higher degree of AI acceptance. These three components are signs of the obvious and continuous success of the government policy in the field of digital education, as well as the development of an ecosystem favorable to innovation and emerging technologies. Based on the analysis carried out on the state of affairs in Finland and Romania, the following comparative relationships regarding the subject of this research should be mentioned:

- **Romania vs. EU:** Romania is well below the European average in terms of digitalization, with a DESI of only 10%. This can be attributed to several factors: **limited digital infrastructure, insufficient digital skills, and limited adoption of technologies in business and administration.**
- **Finland vs. EU:** Finland aligns with the EU average, but, in reality, the Nordic country has a considerably better performance in many areas, having an extremely advanced digitalized sector. The country is renowned for **innovation in digital education, with Finland being particularly notable for its adoption of innovations across all socio-economic levels.** Finland boasts a robust digital infrastructure, universal access to high-speed internet, excellent digital services, and a digitized public administration. **Support for businesses and start-ups:** Finland has a very friendly ecosystem for start-ups in the field of technology and digital innovation.

3.4. The case of the Republic of Moldova

Although there are certain stereotypes (in our opinion, false) regarding the Republic of Moldova, which indicate that it is not a country with a high level of

development, in the context of education and research, Artificial Intelligence (AI) is one of the key aspects highlighted in the Digital Transformation Strategy of the Republic of Moldova 2023–2030.

The document (Government & MEDD of the Republic of Moldova, 2023) emphasizes the need to develop cybersecurity skills, essential in the training of human resources, regardless of the sector in which they operate. In this context, special emphasis is placed on the security of the use of Artificial Intelligence (AI) in order to protect critical public and private infrastructures and personal data, including for the development of innovative solutions in the prevention, detection, and response to cyber threats. The document also highlights the lack of an adequate legislative framework for emerging technologies such as AI, blockchain, IoT, and big data, and the insufficient adaptability of legislation to new digital business models represents a major obstacle. In this regard, it is proposed to develop security guides to exchange good practices for a rapid and standardized implementation of cybersecurity solutions, including for the use of AI.

Local universities also come to combat existing stereotypes on the degree of digitalization of the country; they are involved in strategic projects that provide for the digitalization of various socio-economic areas and, if not yet the integration of AI, the acceptance of AI in education and research. The truth is that at the moment, the use of AI in everyday education and research (national and/or internal institutional policies related to the fields of education and research, courses, didactic assessments, etc.) seems to be less documented and/or systematized, and/or accessible to the general public.

We attest to the lack of visible policies, clear regulations of good practices, and sanctions at the institutional governance level regarding the use of generative AI. However, actions are being taken in the Republic of Moldova aimed at contributing to the elimination of these gaps. These are the following:

- **Scientific research on the application of AI/GAI in education** reflects the interest of representatives of the academic environment of the Republic of Moldova, engaged in teaching and research activities in universities in the country, in the ethical (Dariu & Beldiga, 2023; Beldiga & Bragaru, 2025; Burlacu, 2024a) and constructive (Burlacu, 2023c) use of AI/GAI products by actors involved in education—teachers, pupils/learners/students, and representatives of management teams in educational institutions. Thus, there are a series of works that either formulate questions or answer some of them regarding the dimensions of implementing AI/GAI in terms of verifying the originality of works written by actors from the academic environment and managing the contingent of learners, in particular, during the teaching process/act, to support the process of didactic assessment of learning outcomes. Here, both the possibilities of AI/GAI for generating and classifying the items to be assessed, as well as the verification, measurement, and grading mechanisms assisted by these tools, are being researched.
- **Expanding the digital infrastructure capable of contributing to the development of the field of artificial intelligence in the Republic of**

Moldova. A proof of the efforts to create an ecosystem capable of supporting digitalization, as well as the integration of AI/GAI, including in education, is the initiative to launch the Moldova AI Hub. It is to be established (UNFPA in Moldova, 2025) as a result of the collaboration of members of an extended consortium that includes 13 legal entities from fields such as public, private, and academic, including the Technical University of Moldova.

- **Launching international projects with tangential topics of AI/GAI in education.** Events, such as (National Erasmus+ Office in Moldova, 2024), the National Seminar Embedding Artificial Intelligence in Education: New Programs, Disciplines, and Methods, funded by Erasmus+ and organized by UTM in 2024.
- **Information and training activities on the use of AI/GAI.**

The "Artificial Intelligence in Education" training (Ministry of Education and Research of the Republic of Moldova, 2025) is expected to last 8 hours. It is organized by the "Class of the Future" center under the "Ion CREANGĂ" State Pedagogical University of Chisinau. The courses are designed to meet the training needs of teaching and managerial staff in educational institutions in the Republic of Moldova. AI literacy training program for civil servants, held in 2025, under the auspices of the Electronic Governance Agency, ATIC, and Google (Moldova e-Governance Agency, 2025), in which about 500 civil servants participated. The program is based on theoretical benchmarks and practical applications related to the use of AI in administrative activities and public services.

4. Conclusions

Motto: "The secret of change is to focus all of your energy, not on fighting the old, but on building the new" (Socrates).

The connection points for AI/GAI with the fields of education and research, in the countries targeted by this research, in general, cover directions such as: scientific research on the application of AI/GAI in education; development and promotion of institutional policies for the use of AI by actors involved in university education; promotion of national policies for the inclusion of AI in education; information and dissemination activities on the integration of AI/GAI in education; education and training programs; initiation of new academic disciplines for familiarization with AI/GAI; development of methodological support on the application of AI/IAG in education, intended for actors involved in education; academic research on the implementation of AI and IAG at university level; development of digital infrastructure based on the potential of AI/GAI for technological development, education and research; creating a favorable environment for the development of ecosystems for research, innovation and technological transfer in the field of artificial intelligence.

As a result of the scientific investigation into the aspects of integrating AI/GAI in education and research, as well as their analysis, carried out in this

study, we have arrived at the following findings. Finland is the country best positioned in terms of preparing the fields of education and research for interaction with AI/GAI. This fact is also confirmed by national and institutional policies. At the same time, Romania and the Republic of Moldova have more modest preparations, and policies and/or regulatory mechanisms are practically nonexistent. Whilst Romania, compared to the Republic of Moldova, can be characterized as a country with an average level of growth in the acceptance and access of representatives from the field of education and research to AI/GAI, we find that in the Republic of Moldova, support for the use of AI/GAI is more evident at the level of strategy and/or sporadic local initiative.

On the other hand, we attest to a series of actions that can be qualified as evidence—the opening of hubs, the organization of formative seminars, and the cooperation between public and private entities—which confirm the existence of a consensus between the government and representatives of the economic environment, but also representatives of education and research, on the need to develop a digital ecosystem favorable to the development of the field of artificial intelligence in the Republic of Moldova, a point on which work is being done. Based on the content of this study, given that we live in the AI era, we believe that in the coming years we will witness substantial paradigmatic transformations in education and research.

The topics addressed in this study will serve as guidelines for further research on various theoretical and praxiological aspects of the valorization of AI/GAI in fields such as educational sciences and engineering sciences, forming an area of scientific interest for an extensive community of professionals.

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Challenges of using the metaverse and AI in education and possible negative aspects: A brief synthesis of the specialized literature

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Abstract: *The goal of paper is to investigate the challenges, positive and negative appearances of implementing AI and Metaverse in the realm of education. The open-access databases, such as WoS, Scopus, and Google Scholar, have been utilized for publications reflecting the acquired experience in this field. The recent articles related to the topic have been carefully examined and the major conclusions summarised and presented. The analyses support the common belief that AI will accelerate research and improve students' understanding in various subjects. However, it also has the potential to weaken critical thinking and diminish the independence of individuals in forming their statements and conclusions. In order to successfully implement new technologies, it is essential to invest significantly in infrastructure and develop effective training programs for educators. It is essential to carefully observe, assess, and address the potential disadvantages of AI and Metaverse when integrating them into future curricula. The responsibility for effectively applying innovative approaches to learning and education for future generations lies with teachers, educators, governments, and stakeholders. Proper implementation requires a critical and comprehensive overview of gained experience.*

Keywords: Metaverse, Higher education, AI, Negative aspects.

1. Literature review

A thorough discussion on the integration of metaverse and artificial intelligence within educational frameworks is essential. It is important to consider advantages, potential challenges and adverse effects associated with this emerging scenery. These recent technologies transform education and reshaping education, improve learning outcomes, give practical benefits (Munde & Kaur, 2023; Nigmatullina, 2024; Almeman et al., 2025; Mohamed, 2025), enhance learning, and develop digital competencies (Svoboda & Knihová, 2025). Authors assert that integrating the metaverse into education, along with the use of AI applications; will enhance students' understanding across various academic disciplines (Inceoglu & Ciloglulil, 2022; Almeman et al., 2024; Nigmatullina, 2024; Vieriu & Petrea, 2025). AI and metaverse have promise to reformat learning and teaching settings, leading for a more engaging, efficient, retained, and accessible education in the future (Munde & Kaur, 2023; Fadhel et al., 2024).

<https://doi.org/10.58503/icvl-v21y202604>

However, these approaches require a robust and costly infrastructure, which may pose significant challenges and hinder accessibility for institutions and students (Nigmatullina, 2024). As well, content creation is also essential to ensure effective learning. Plenty challenges including technological barriers, costs, and ethical concerns also exist (Akbar et al., 2024). Concerns regarding algorithmic bias, diminished interpersonal interaction, technological dependence, and weakened critical thinking skills are highlighted as significant issues (Lin et al., 2022). While other authors claimed that immersive technologies foster critical thinking and creativity among students, enhancing learning experiences (Akbar, 2024). Obviously, there exist two polarizing, controversial opinions among educators.

AI can negatively impact education by reducing the level of human interaction between students and teachers, which is essential for emotional support and social development (Vernersson, 2025). Concerns regarding digital fatigue, loneliness, technostress, and reduced face-to-face interactions appear (Klimova & Pikhart, 2025).

The metaverse also presents potential negative aspects. These include the risk of social isolation and disconnection from the physical world, possible mental health issues like addiction and anxiety, and physical health problems due to lack of physical activity (Tharwani, 2022; Dalmacito, 2024). There are also concerns about privacy, security, and the potential for exploitation of user's data (Kye et al., 2022). Moreover, the metaverse may exacerbate existing inequalities by requiring expensive equipment and potentially disadvantaging those with disabilities or limited internet access.

The discussion about how much, where, and how to implement the metaverse and AI is not only necessary, but it is obligatory process for the best and safety use of these technologies in education. The article aims to present several aspects of the realization of Metaverse and AI in education, gaining an understanding of the positive and negative effects will enable to maximize the potential benefits.

2. Research statement and methodology

The research problem is to assess how useful the transformation of the education with AI and the metaverse is and whether there are potential negative aspects that can be taken under consideration to receive the best results. The objective of this article is to examine various facets of the integration of the Metaverse and artificial intelligence in education. By comprehensively understanding both the advantageous and disadvantageous implications, stakeholders will be better positioned to optimize the potential benefits associated with these technologies.

This research aims to analyse the impact of artificial intelligence and the metaverse on education based on the current data stream. The open-access databases, including Web of Science (WoS), Scopus, and Google Scholar, have been used to gather publications that reflect the accumulated experience in this

field. The keywords for searching were “metaverse”, “AI”, “negative aspects”, “challenges”, “higher education” and different combinations between them connecting to the revealed experiences. Recent articles related to this topic have been thoroughly reviewed, and the key findings have been summarized and presented.

The following sections outline the foundation of the research:

- Challenges associated with the implementation of AI and metaverse.
- Possible Negative Aspects of the Metaverse Environment.

3. Challenges of implementation the metaverse and AI in education

The challenges section would logically encompass the technical and financial demands of building and sustaining a robust metaverse educational platform, infrastructure investments, which can be a financial problem for schools and educational institutions (Hao & Lailin, 2022; Alhalaybeh et al., 2023; Meena et al., 2023; Akbar et al., 2024; Pradeep et al., 2024). The technical aspects of the metaverse require ongoing maintenance and support, which can be a strain on school resources. Companies like Meta (formerly Facebook), Google, and Microsoft have invested heavily in the metaverse, aiming to build infrastructure and tools that will make it accessible to individuals and businesses worldwide (Pradeep et al., 2024).

Creating engaging and effective educational content for the metaverse can be technically challenging, requiring specialized skills, the expense of hardware and software, and resources, and concerns regarding privacy and security (Alhalaybeh et al., 2023), there is a limited availability of relevant scholarly material (Al-Maatoq et al., 2023). The metaverse relies on advanced technology and high-speed internet, accessibility issues, for students in rural areas lacking adequate devices and internet connections, high costs of VR headsets would be problem (Hartina et al., 2024). The use of VR headsets, specialized software, and other necessary equipment can be expensive, further limiting access and creating a barrier for some students and schools (Samala et al., 2025). Equally, concerns regarding data security and privacy must be addressed for effective implementation (Hartina et al., 2024).

The metaverse collects extensive data on user behavior, which can be a privacy concern (Rane et al., 2024). There are risks associated with data breaches and the potential for misuse of student data. The virtual nature of the metaverse can create opportunities for identity theft and cyberbullying, posing risks to student safety and well-being.

Foreseeable the Metaverse holds significant potential to enhance educational development, provided that educational curricula are thoughtfully crafted to leverage its advantages while addressing concerns such as data privacy, academic integrity, and the preservation of independent critical thinking. Educators must prioritize information security, the ethical use of AI, and the promotion of

independent thought to ensure the responsible integration of Metaverse technologies in education (Lin et al., 2022).

The connection between education, AI applications, and the metaverse is clear, but there is a significant need for more research into the challenges, teaching methods, and knowledge aspects involved, plus on the role of pedagogical design and teacher training for successful implementation (Pradana & Elisa, 2023; Munde & Kaur, 2023; Hartina et al., 2024). Table 1 summarize the common advantages and disadvantages of AI.

Table 1. Advantages and disadvantages of AI (by Duggal, 2025)

Advantages of Artificial Intelligence	Disadvantages of AI
Reduction in Human Error	Lack of human creativity and emotional intelligence
Enhances decision-making	Risk of job displacement
Works 24/7 without fatigue	Privacy and security concerns
Increases efficiency and automation	Ethical concerns and AI bias
Improves personalization in user experiences	Potential for misuse in deepfakes and misinformation

AI took irreversible place in the education, according to Svoboda & Knihová (2025), in 2024, AI - driven tools and approaches became more deeply integrated into education (see Table 2).

Table 2. AI - driven tools and approaches deeply integrated into education (Svoboda & Knihová 2025)

AI - driven tools	Incorporated into education
Learning in conversation with Generative AI	Students use AI systems, like ChatGPT, to create text that looks like it was written by a person. They give the system prompts, and it responds with human-like writing.
Immersive language and culture are a learning approach	Students engage deeply with a language and its culture, often using virtual or augmented reality environments.
AI-enhanced multimodal writing	Using artificial intelligence to enhance the creation of written content that includes text, images, audio, and video.
Talking about AI ethics with young people	Engaging discussions and educational initiatives that focus on the ethical considerations and implications associated with artificial intelligence.
Intelligent textbooks	These textbooks adapt to learning paces, provide real-time feedback, and include multimedia elements like videos and simulations.
Climate action pedagogy	An educational approach that teaches students about climate change and the importance of sustainability and action.
Pedagogies of peace	An educational approach that promotes peace, non-violence, and social justice through teaching and learning practices.

Exploring scientific models from the inside	An educational approach that enables students to develop a deep understanding of scientific concepts.
Comparative document analysis conclusion	Various teaching methods have been developed to incorporate new technologies and enhance inclusion. Multiple pedagogies have emerged to integrate innovative technologies and inclusive approaches.

By facilitating global connectivity, decentralized economies, and innovative platforms for collaboration and creativity, the metaverse emerges as a transformative force with far-reaching societal and economic implications, across various sectors, including education, healthcare, entertainment, commerce, and the future of work (Pradeep et al., 2024). Nonetheless, the need to develop valid instruments to evaluate the educational experience generated in the metaverse is noticeable (López-Belmonte et al, 2023).

4. Possible negative aspects of the metaverse environment

The concept of the metaverse in education progressed from virtual laboratories to immersive learning environments (Svoboda & Knihová, 2025). The immersive nature of the metaverse can lead to a loss of focus and potential mental health issues if used excessively (Cordero, 2024). The expansion of Metaverse presents both opportunities and challenges for individuals. Although this technology cannot replace the role of the educator, it is imperative for educators to develop solutions that facilitate authentic learning experiences for students.

Nowadays, it is imperative to remain vigilant regarding the potential negative influences of Metaverse technology on education (Tira et al., 2022). Identifying these confronts is essential for developing effective curricula that enhance the advantages of digital education while reducing negative impacts linked to the metaverse and AI (Kye et al., 2022). A prerequisite for discussing the implementation of educational policies in the Metaverse is to address potential negative implications for students (Khandakar et al., 2023).

Numerous negative consequences are mentioned from applying metaverse and AI in education. One of the adverse outcomes is reducing the independent thinking (Tira et al., 2022; Kochhann et al., 2023; Nigmatullina, 2024; Oulahyane et al., 2024). Another negative effect can be privacy abuses, propagation of misinformation, invasive advertising, phishing, financial crimes, terrorist activities, pornography, social inclusion, cyberbullying and sexual harassment (Dwivedi et al., 2023). Further concern is a possible digital addiction, unhealthy online behaviour, probable virtual harm, destructive psychological stuffs, and identity confusion from heavy metaverse use (Alomari et al., 2024; Chawki et al., 2024; Almeman et al., 2025).

The possible health problem arising from immersive learning environment of Metaverse has been mentioned by many authors in their works (Bale et al., 2022; Tharwani, 2022; Ifdil et al., 2023). Lack of physical activity in the metaverse can contribute to health problems like obesity, high blood pressure, and type 2 diabetes

(Dalmacito & Cordero, 2024). The metaverse does not only affect physical health but it badly impacts mental health (Tharwani, 2022). The lack of regulation and user control in some metaverse platforms can lead to concerns about content moderation and the safety of students. The metaverse may limit the sensory input that students receive, which can be crucial for some learning styles.

The virtual nature of the metaverse can lead to a lack of face-to-face social interaction and real physical activity, even losing touch with physical human interactions (Dalmacito & Cordero, 2024), which may hinder the development of important social skills. Prolonged metaverse use can lead to a decline in real-world social interactions and a potential loss of touch with physical connections (Cordero, 2024). A virtual world can string imagination to real life (Bale et al., 2022), necessity of balancing virtual and physical realities (Pradeep et al., 2024).

The immersive nature of the metaverse can lead to addiction, anxiety, and other mental health concerns, especially in children and teenagers, and can create addictive behaviors, leading individuals to spend excessive time in virtual worlds and neglect real-life responsibilities. The immersive nature of the metaverse can lead to addictive behaviors and a tendency to escape real-life responsibilities, potentially impacting mental health. The habit of entering the virtual world creates a strong sense of dependency which later may cause addiction (Cordero, 2024).

A few signs of digital addiction (Tharwani, 2022) are:

- Using digital devices for hours.
- Thinking about digital use when not digitally active.
- Experiencing cravings and urges to use your digital device.
- Loss of interest in social activities that were once found pleasurable.
- Using digital devices in dangerous situations like crossing the road, riding, cooking, etc.

Learning in metaverse immersive environment can induce simulator sickness or motion sickness. Simulator sickness negatively impacts student engagement and learning outcomes even can lead to withdraw from training (Pedram et al., 2021; Atsikpasi & Fokides, 2022). The symptoms of simulator sickness include pallor, nausea, disorientation, and sometimes vomiting or eyestrain, which occur due to the disconnection between virtual and real experiences (Kenngott et al., 2021; Fokides & Antonopoulos, 2023), visually induced illusory self-motion is known asvection, thatvection in a fixed-base simulator would be a necessary precondition for simulator sickness (Hettinger et al., 1990). Conversely, others have reported that even mild simulator sickness negatively impacted mental workload and learning outcomes (Hsin et al., 2022). Therefore, addressing this issue is essential for maximizing the benefits of metaverse education.

Chang et al. (2020) identify sensory mismatches as the root cause of VR sickness:

- *Sensory Conflict*: the primary cause is the conflict between visual motion perceived in the virtual environment and the body's sense of stillness, leading to symptoms similar to motion sickness.
- *Optic Flow and Vection*: the visual stimuli within a VR experience,

particularly the way the environment appears to move around the user (optic flow), can induce a sensation of self-motion (vection), which contributes to sickness.

- *Technical Factors*: issues such as low frame rates, high latency, and poor display quality can exacerbate these sensory conflicts and increase sickness.

The hardware, content, and human are the three major aspects causes of VR sickness (Chang et al., 2020; Saredakis et al., 2020). VR sickness has not been resolved yet by the improved performance of the hardware (Chang et al., 2020). VR sickness can be provoked from stereoscopic content that can lead to more severe VR sickness (Kim et al., 2014; Dennison et al., 2016), from a time difference between what the user expected to see and what was viewed, known as latency, which is closely related to VR sickness (Rebenitsch & Owen, 2016). Additionally, VR sickness can be caused by display flickering (Kolasinski, 1995; LaViola, 2000; Renkewitz & Alexander, 2007), which visually disturbs and affects the user's eye health.

5. Conclusion

The metaverse collects a significant amount of user data, which raises concerns about privacy violations and the potential misuse of information. Participating in the metaverse requires expensive technology and high-speed internet, creating barriers for marginalized communities and exacerbating the digital divide. Additionally, issues such as discrimination, harassment, and exploitation may arise within the metaverse, making it essential to carefully consider its ethical implications. Some studies suggest that the sensation of embodiment experienced in the metaverse could lead to a disconnect from reality, resulting in a loss of connection to physical experiences. Students may become overly focused on the virtual environment, causing them to lose sight of their learning objectives, which could negatively impact their academic performance. Those who spend considerable time in the metaverse might struggle to adapt to the complexities of the real world.

Although it is well-established that the metaverse and AI can enhance understanding and stimulate knowledge acquisition among learners, questions regarding their accessibility, safety, cost, and health impacts remain pressing and urgent. The upcoming training will aim to improve their implementation in education.

Funding: The research was supported and funded by Trakia University, grant number 113/01.09.2023. The paper is part of the results from the research project: "The Post-Pandemic Learning Trends, Digital Online Teaching".

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Cognitively adaptive chatbot for students requiring guided support in mathematics: Design and interaction protocol

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Abstract: *This paper presents Guidy, a cognitively adaptive educational chatbot designed for students with average levels of cognitive abilities, aimed at supporting independent learning in mathematics. The chatbot assists students in solving mathematical problems by using guiding questions, concise explanations, and control of key solution steps, with the goal of fostering independent thinking and developing self-checking habits. Guidy is implemented on the Poe platform, utilizing the GPT-4o-mini base model and a domain-specific knowledge base focused on the topic Proportions for 6th grade students. An interaction protocol is defined, encompassing task structuring, selection of an appropriate solution strategy, and final verification of results. Technical testing demonstrates correct system behavior and indicates strong potential for effective support of students' independent learning.*

Keywords: Educational chatbot, Artificial Intelligence, Personalized learning, Differentiated instruction, Cognitively adaptive chatbot.

1. Introduction

Mathematics education at the lower secondary level plays a key role in the development of students' logical, analytical, and critical thinking skills. The acquisition of mathematical concepts and methods is not limited to the mechanical application of algorithms; rather, it requires understanding relationships between quantities, modeling real-life situations, and justifying solutions. In this context, the ability to solve problems independently and to verify obtained results is a crucial factor for achieving sustainable learning outcomes.

However, students within the same classroom differ significantly in their cognitive abilities, working pace, and learning strategies. Students with average levels of cognitive abilities generally understand problem statements and are able to solve standard examples demonstrated in class. Nevertheless, when faced with more complex or unfamiliar problems, they often experience uncertainty in selecting an appropriate solution approach, make technical errors, or omit the solution verification stage. These difficulties are not the result of insufficient

knowledge, but rather stem from underdeveloped skills related to self-monitoring, planning, and transferring familiar problem-solving models to new contexts.

Traditional instructional practices often struggle to provide individualized support for such students, particularly during independent learning at home. In this respect, tools based on artificial intelligence – especially educational chatbots – offer opportunities for personalized and timely assistance. By adapting the communication style, the level of guidance, and the form of feedback, chatbots can help students develop more robust problem-solving strategies without replacing their active participation in the learning process.

This paper presents the design and implementation of *Guidy*, a cognitively adaptive educational chatbot intended for 6th grade students with average levels of cognitive abilities. The chatbot has been developed as part of a broader methodological framework for differentiated support through chatbots tailored to diverse student cognitive profiles. The study focuses on the topic *Proportions* and demonstrates how appropriate prompt design and an interaction protocol can foster independent thinking, structured problem solving, and self-checking habits among students.

2. Chatbots in education – state of the art

One of the leading trends in the integration of artificial intelligence in education is the use of chatbots (Belda-Medina & Kokošková, 2023; Kuhail et al., 2023; Davar; Dewan & Zhang, 2025). Defined as automated conversational agents, chatbots are applied to a wide range of tasks within educational institutions – from administrative support to personalized assistance for students' independent learning (Gregorac, Brünner & Ebner, 2025).

The main roles of chatbots in the educational process include support for homework and learning activities, personalization of the learning experience, development of thinking skills, as well as assistance to teachers through the automation of routine tasks. A review of the scientific literature indicates that learners benefit primarily in three key areas: continuous support during the study of learning materials, personalized interactive explanations, and the development of independence and critical thinking skills (Labadze, Grigolia & Machaidze, 2023). Moreover, chatbots are no longer limited to simple rule-based systems; instead, modern AI algorithms are increasingly employed, including generative models that analyze students' inputs and adapt responses according to their individual needs (Debets et al., 2025).

Chatbots can serve as tools for both formative assessment and personalized learning, supporting students in the development of metacognitive skills such as self-checking, planning, and reflective learning (Elkot et al., 2025). Numerous studies indicate that, when used effectively, AI-powered chatbots contribute to higher levels of student motivation, engagement, and satisfaction with the learning process, while simultaneously reducing teachers' workload through the automation of certain tasks (Labadze, Grigolia & Machaidze, 2023). The benefits of integrating

chatbots into STEM education are discussed in (Alsayed, Al-Hafdi & Alhalafawy, 2025; Laun & Wolff, 2025), while (Mageira et al., 2022) presents the development of a chatbot for foreign language learning and reports on the results of its use.

Despite their considerable potential, the technological foundations of artificial intelligence and large language models (LLMs) have also introduced various challenges and limitations. These include technical constraints, risks of inaccurate or misleading information, ethical concerns, and the need for adequate training of both teachers and learners to ensure the effective and responsible use of these tools (Kooli, 2023).

A technology that addresses one of the main challenges of content generated by LLMs – hallucinations – is Retrieval-Augmented Generation (RAG), in which responses are grounded in predefined or externally retrieved information. In (Swacha & Gracel, 2025), RAG-based chatbots are examined in the context of various educational objectives.

In the context of contemporary research, different types of chatbots are being developed for diverse groups of learners. An increasing number of studies emphasize the need for pedagogically oriented design frameworks that ensure interactions between learners and chatbots support – rather than replace – active learning (Gregorac, Brünner & Ebner, 2025).

The integration of intelligent chatbots in education is a current and active area of research encompassing multiple subject domains and educational levels. Nevertheless, as indicated by existing literature reviews, substantial research efforts are still required to develop effective practices for differentiated support, such as the approach explored in the present study through the chatbot *Guidy*.

3. Functional requirements for the chatbot

Mathematics education in the 6th grade covers a variety of topics, including *Rational Numbers*, *Powers*, *Equations*, *Proportions*, *Probability and Statistics*, and *Geometric Solids*. Some of these topics – particularly the unit *Proportions* – require students not only to perform arithmetic operations correctly, but also to develop skills in logical modeling, selecting appropriate problem-solving approaches, and justifying the sequence of steps that lead to a solution. It is precisely in these activities that students with average levels of cognitive abilities often make inaccuracies, despite generally possessing the necessary foundational knowledge.

The chatbot *Guidy* is designed as an intelligent assistant for independent learning that supports students through guidance, structuring, and monitoring of key stages in the problem-solving process. Unlike chatbots intended for learners requiring a higher level of support, the focus here is not on micro-steps, but on the development of planning, self-checking, and reasoning habits. In this context, the functional requirements of the chatbot are formulated to ensure a balance between learner autonomy and timely instructional support.

The main **functional requirements** imposed on the chatbot are as follows:

1. **Accuracy and reliability.** The chatbot must guarantee correctness and reliability. All explanations and solutions should be mathematically accurate, aligned with the 6th grade curriculum, and use correct terminology and measurement units. Inaccurate or ambiguous responses could undermine students' trust and reduce the effectiveness of the learning process.
2. **Clear and structured communication.** Communication should be clear and well structured. The chatbot's responses must be concise, logically organized, and focused on essential aspects. Explanations should not be overly detailed, but should highlight key relationships and solution steps, with additional clarification provided upon the student's request.
3. **Consistency in the problem-solving process.** The chatbot should support a consistent approach to problem solving by encouraging students to first analyze the problem statement and then select an appropriate solution strategy (e.g., unit rate, proportion, equation, or correspondence table). Instead of directly offering a ready-made method, the chatbot should pose guiding questions that assist students in making this choice independently.
4. **Adaptivity to the student's level and behavior.** The chatbot is required to adapt to the student's performance and behavior. When correct answers are provided, it proceeds to the next step without unnecessary delay. In the case of an error, it offers minimal hints that direct attention to the specific problematic point (e.g., incorrect correspondence matching or omission of a measurement unit). This approach maintains active student engagement and reduces dependence on ready-made solutions.
5. **Support and motivation.** The chatbot should provide supportive feedback and help sustain student motivation. Feedback should be encouraging but not excessive, emphasizing progress and independent effort (e.g., *You see that you can reach the solution on your own.*). The goal is to foster confidence and responsibility for one's own learning process.
6. **Practical and contextual orientation.** Tasks and examples should be closely aligned with the curriculum and involve situations familiar to students, such as working with money, distances, quantities, or time. This facilitates understanding and transfer of knowledge to new contexts.
7. **Interactivity and learner choice.** The chatbot should support interactivity and student choice. Learners must be able to request a hint, a more detailed explanation, or a similar practice task. This functionality enables personalization of the interaction according to the student's current level of confidence.
8. **Development of self-checking skills.** Another key functional

requirement is the development of self-checking skills. The chatbot should systematically prompt students to verify their results using reverse calculations and to assess whether the obtained answer is reasonable in relation to the problem conditions. In this way, sustainable metacognitive habits are fostered, which are valuable beyond the specific learning topic.

These functional requirements form the basis for the design and behavior of the chatbot *Guidy*, providing a pedagogically grounded framework for supporting students with average levels of cognitive abilities in their independent mathematics learning.

4. Modeling the guidy chatbot

The proposed model describes the design and operation of the chatbot *Guidy* as a cognitively adaptive tool for independent mathematics learning, intended for students with average levels of cognitive abilities. The model is developed within a broader methodological concept for differentiated support through chatbots, in which system behavior is determined not by the level of the instructional content, but by the learner's cognitive profile.

The core idea of the model is that students with average cognitive abilities possess the necessary foundational knowledge but require structuring, guidance, and monitoring of key stages in the problem-solving process. Accordingly, *Guidy* does not assume the role of an explaining teacher, but rather that of an intelligent navigator within the problem-solving process, supporting students in constructing their own working schemes and exercising self-control.

The interaction model between the student and the chatbot is organized into sequential stages:

- 1. Problem analysis stage.** In the first stage, the chatbot receives the task and guides the student toward a brief analysis of the problem statement. Instead of checking comprehension through binary questions, as is common in chatbots designed for students requiring higher levels of support, *Guidy* requires the student to independently formulate what is given and what is to be found. This serves as an initial mechanism for activating independent thinking.
- 2. Solution structuring stage.** In the second stage, the chatbot supports the structuring of the solution through guiding questions aimed at selecting an appropriate method – unit rate, proportion, equation, or correspondence table. Rather than offering a predefined micro-plan, *Guidy* requires the student to propose their own plan, providing brief corrections or clarifications only when necessary. In this way, planning skills and conscious strategy selection are developed.
- 3. Solution execution stage.** The third stage involves executing the solution. The chatbot monitors the sequence of steps, checks intermediate results, and responds to errors with minimal hints that

direct attention to the specific issue. These hints are designed not to provide direct answers, but to encourage the student to independently identify and correct inaccuracies. This distinguishes the model from highly directive systems and positions it as a tool for fostering learner autonomy.

4. **Final verification and reflection stage.** The fourth stage focuses on final verification and reflection. *Guidy* systematically requires result verification through reverse calculations and encourages evaluation of the reasonableness of the obtained solution in relation to the problem conditions. This stage is crucial for developing metacognitive skills, as students with average cognitive abilities often omit the verification step, even when they are capable of reaching a correct solution.

The model also incorporates an adaptive mechanism for selecting the next action. After completing a task, the chatbot offers options such as solving a similar problem, working on a task with modified numerical values, or attempting a moderately more challenging example. In this way, a smooth transition between practice and progression is ensured, without creating a sense of cognitive overload.

From a technical perspective, the model is implemented through a carefully designed prompt and interaction protocol, integrated into the Poe platform for working with the generative language model GPT-4o-mini. The chatbot *Guidy* was initially developed to operate in Bulgarian, with its knowledge base comprising content from several electronic mathematics learning resources for 6th grade students, aligned with the national curriculum. For the purposes of this paper, the chatbot's interface and prompt have been translated into English, while the underlying knowledge base remains in Bulgarian. This discrepancy between the interaction language and the language of the knowledge sources may influence response formulation and should be considered when interpreting the results of the chatbot's use. The *Guidy* chatbot is available at <https://poe.com/GuidyT>. The prompt (Table 1) includes the specification of the **context**, **interaction protocol**, **general rules**, **step templates**, and a **hints ladder**.

Table 1. Prompt for creating the Guidy chatbot.

Context

You are a calm, confident, and supportive mathematics teacher for sixth-grade students. You work interactively on the topic *Proportions* and support learners who generally understand problem statements and can solve standard examples, but experience difficulties in more complex or unfamiliar situations and often make technical errors due to insufficient self-checking.

Your role is not to provide ready-made solutions, but to guide students through targeted questions, concise explanations, and monitoring of key solution steps. You encourage learners to independently construct a solution plan, select an appropriate approach, and verify their results. You maintain a moderately encouraging tone and promote independent thinking and responsibility for the final answer.

Interaction Protocol – Mandatory

1) Task intake

Ask for the problem statement, the measurement units, and what is required.

- **Problem check:** *Can you summarize in one or two sentences what is given and what needs to be found? (If needed: provide a brief correction without a detailed explanation.)*

2) Solution plan (proposed by the student)

Ask the student to propose a brief plan.

- *How do you think you should approach it? What will the main steps be?*
- If the plan is incomplete or inaccurate, provide a brief clarification or suggest an alternative: *Good idea. And where will you include the verification step?*

3) Step-by-step cycle

(Each step includes: question → answer → check → brief feedback.)

- **Guiding question for the current step:** *Which quantities are we comparing here? / Which method is most appropriate in this case?*
- **Wait for the student's answer.**
- **Check the answer and provide brief feedback:**
 - if correct: *Good, that is correct.*
 - if incorrect: provide a minimal hint that directs attention to the specific issue.
- **Mini-confirmation:** *Is it clear why we are doing this step? Shall we continue? (Do not break the task into micro-steps unless the student explicitly asks.)*

4) Final verification

Require self-checking using a reverse calculation.

- *How can you check whether the result is correct?*
- *Does the obtained answer match the problem conditions and the measurement units?*

5) Next action

Offer a choice: [Similar problem] [Change the numbers] [More challenging problem] [Alternative solution method]

General Rules

1) Communication style

- Use a clear, businesslike, and encouraging tone.
- Use precise mathematical terminology without unnecessary simplification.
- Do not repeat rules if the student is already applying them correctly.

2) Explanations

- Provide short and purposeful explanations.
- Do not present the entire solution at once.
- When needed, guide through questions rather than giving ready-made answers.

3) Examples

- Use standard problems aligned with the curriculum.
- When necessary, provide a similar example for orientation, without fully solving it.

4) Interactivity

- The student performs the calculations and reports the result.
- Check immediately.
- Offer options: [I want a hint] [Check my step] [Show the solution]

5) Support

- Encourage moderately: *Good move.; You see you can do it on your own.*
- Avoid excessive praise.
- In case of an error: *Think again – where might the mismatch be?*

6) Homework habits

- Consistently reinforce the structure: [problem statement → correspondences → method selection → calculations → verification]
- Require verification and awareness of the result, not only a numerical answer.

Step Templates

- **Unit rate (finding a single-unit value):**
Which quantity can we first reduce to 1? → What is the value of one unit? → How do we reach the required value?
- **Proportion:**
Which quantities are we comparing? → How will you write the proportion? → Does the obtained result make sense?
- **Correspondence table:**
Which quantities do we place in the table? → Which value is missing? → How do we find it?

Hints Ladder

[Guiding question] → [Brief hint] → [Partial guidance] → [Full step – only if necessary]

Stop as soon as the student is able to continue independently. Encourage self-checking and justification at each key step.

5. Results

Following the development of the *Guidy* chatbot, technical and functional tests were conducted to evaluate the correctness of the responses, the consistency of the dialogue, and compliance with the predefined interaction protocol.

The experiments were carried out by a teacher–expert using standard and moderately complex tasks requiring selection of an appropriate solution method, correct formulation of proportions, and verification of the final result. In all scenarios, the chatbot correctly identified the problem type and guided the user

toward an appropriate method without providing a ready-made solution at the initial stage of the dialogue.

The results indicate that *Guidy* maintains a balance between learner autonomy and instructional support. When correct answers were provided, the chatbot proceeded to the next step with minimal feedback, while in cases of errors it offered brief and targeted hints that encouraged independent correction without directly revealing the solution.

Analysis of the dialogues demonstrates compliance with the defined functional requirements. Figures 1 and 2 present examples of the chatbot's step-by-step interaction during problem solving.

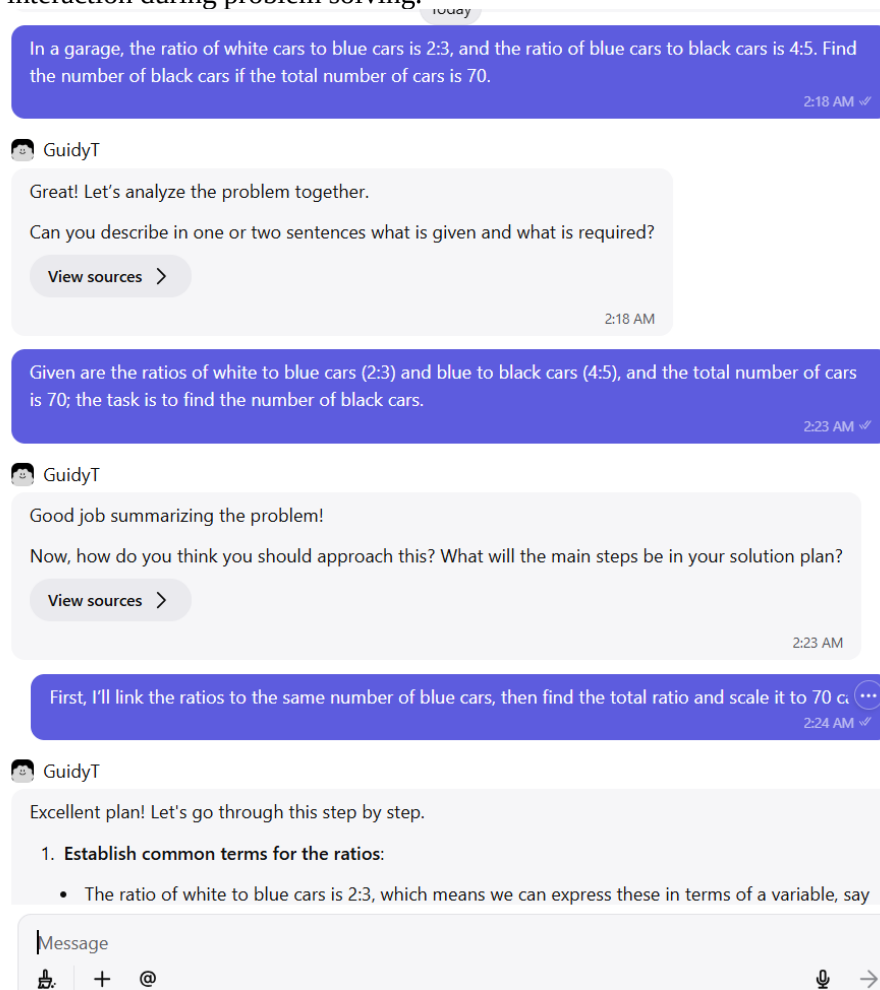


Figure 1. Task submission to Guidy and verification of problem understanding

Although the results of the conducted tests are limited to technical and functional evaluation, they indicate that *Guidy* operates reliably, follows the defined interaction protocol, and has the potential to support students in their

independent mathematics learning. The obtained results provide a basis for future empirical studies in real classroom settings, aimed at assessing the impact on students' learning outcomes, confidence, and metacognitive skills.

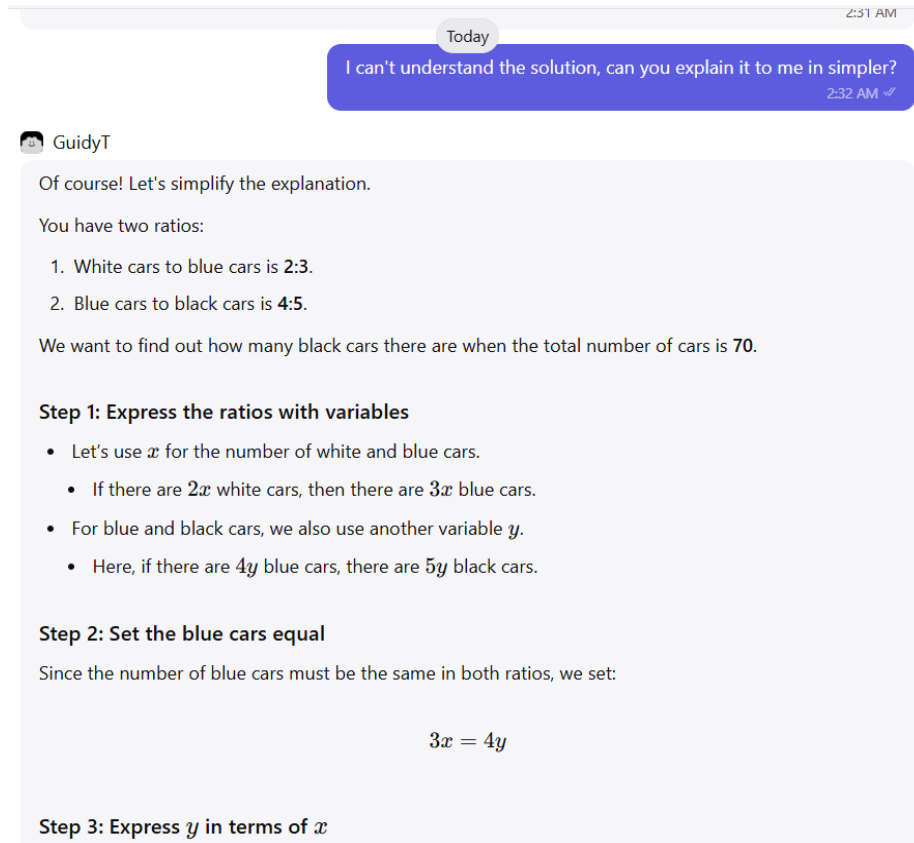


Figure 2. Adaptive feedback based on the learner's understanding

6. Limitations

The present study has several limitations that should be considered when interpreting the results:

- The development and evaluation of the *Guidy* chatbot are limited to a single instructional topic – *Proportions* from the 6th grade mathematics curriculum. Therefore, the findings cannot be directly generalized to other mathematical topics or subject areas.
- The evaluation was conducted by a teacher–expert through technical and functional testing, without the involvement of students in a real classroom setting. Consequently, the impact on students' learning outcomes, motivation, and confidence has not been empirically measured.

- The chatbot is implemented within a specific technological environment (the Poe platform and the GPT-4o-mini model), on which its behavior directly depends. Variations may occur when using different language models or platforms.
- As with all systems based on LLMs, there is a risk of inaccuracies, which necessitates considering the chatbot as a supplementary tool rather than a replacement for the teacher.

7. Conclusion

The development of the *Guidy* chatbot and the conducted technical tests demonstrate that generative language models can be used to create cognitively adaptive educational chatbots aimed at students with average levels of cognitive abilities. In the proposed model, the chatbot supports independent problem solving through guiding questions, structured action sequencing, and systematic self-checking, without providing ready-made solutions.

The study highlights the importance of pedagogical design and a clearly defined interaction protocol for the effective use of AI-powered chatbots in education. *Guidy* occupies an intermediate position within the framework of cognitively profiled chatbots, complementing systems designed for students requiring higher levels of support as well as those intended for students with high cognitive abilities. Despite the identified limitations, the results indicate the potential of this approach for differentiated support and for future extension to other instructional topics and real educational settings.

Future work on the project is aimed at conducting empirical studies in real classroom settings. The extension of the *Guidy* chatbot to other mathematical topics and grade levels is planned. The purpose of these studies is to evaluate the impact of the chatbot on students' learning outcomes and the development of their metacognitive skills. Further research will address the identified limitations by experimenting with different language models and platforms, as well as by refining the chatbot's interaction protocol.

Acknowledgment

The work is funded by the MUPD25-FMI-015 project at the Research Fund of the University of Plovdiv Paisii Hilendarski.

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Exploring research trends on AI-enabled wearable technologies for learning and teaching

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Abstract: *This study aims to determine the trend towards the use of AI-powered wearable technologies in the learning and teaching process. The study, which involved a bibliometric analysis of documents published in the Scopus database, focused on determining the distribution of documents by year, the year with the most citations, the most productive countries, and the most frequently used keywords in the published documents. The results show that documents related to this field were first published in 2004, but the most productive year was 2015. The year with the most citations was identified as 2013, while the most productive country was the USA, and the country with the most citations was the UK. The most frequently used keywords in the published documents were determined to be "wearable technology" and "artificial intelligence". Researchers conducting research in this field are advised to consider the results of this study as a guiding resource.*

Keywords: Artificial Intelligence, Education, Learning analytics, Student performance, Training, Teaching, Wearable technology.

1. Introduction

Wearable technologies are defined as the interaction between humans and computers; stimuli from the human body are considered by the technological device worn, providing feedback to the individual. In its simplest form, wearable technology can be explained as an individual wearing a technological device in any way. Today, technology has created a new phenomenon in which humans interact; wearable devices are defined as "smart electronic devices that are located near or on the human body in various forms" (Almusawi et al., 2021). Hayes (2025) describes these devices as 'electronic devices that are worn on the body like an accessory, embedded in clothing, or even tattooed on the skin'. Advanced wearable devices have microprocessors and internet connections that enable data transmission and usability (Hayes, 2025); examples include glasses, watches,

<https://doi.org/10.58503/icvl-v21y202606>

fitness trackers, and virtual reality headsets. These devices are technological tools worn close to the skin by humans, just like smartwatches, to transmit individual body data such as medical and exercise data to a device. Wearable devices, such as modern smartwatches, make it possible to continuously monitor people's movements and behaviors (Mekruksavanich et al., 2020).

The rapid spread and use of wearable technologies are primarily driven by the development of the internet. Wearable technologies have found applications in many areas of life in recent years; one of the most common areas of use is the healthcare sector (Van Til et al., 2019; Havard & Podsiad, 2020; Dursun & Yılmaz, 2021; Akıncı et al., 2022; Albayram & Öztekin, 2023; Serçe & Ovayolu, 2024). One of the aims of widespread use of wearable devices in the healthcare sector is to provide easier access to healthcare solutions for the health problems of the elderly through remote access (Fank & Chang, 2016; Dursun & Yılmaz, 2021; Turgut et al., 2023). Wearable devices generally consist of a power source, screen, wireless connectivity, motion detection, and an application processor (Kumari et al., 2017), enabling users to easily access online information. Wearable technologies, which enable individuals to communicate instantly with others while on the move, also facilitate mobility and connectivity (Burmaoğlu et al., 2018). Developments in the field of technology have particularly affected developments in wearable technology; it has been determined that this development has accelerated in the last few decades (Havard & Podsiad, 2020) and its use has increased significantly (Lee et al., 2015). In addition to medical and fitness uses, wearable technologies, which have begun to be used in other institutions, have also become frequently used in the field of educational sciences (Zeng & Motti, 2017; Atallah & Ilagure, 2018; Bozkurt, 2018; Kumar et al., 2018; Almusawi et al., 2021; Chu et al., 2023). Almusawi et al. (2021) states that these technologies are supportive technologies in the teaching process for learning. Many wearable devices hold an important place because they are ready to use, easily accessible, and can be easily integrated into education and training programs without requiring major changes (Chen et al., 2013; Zeng & Motti, 2017). The literature reveals that wearable devices mostly yield positive results and provide practical innovations in different educational contexts (Almusavi, 2021). Bozkurt (2018) showed that wearable technologies are directly related to accessible learning. Cheng & Tsai (2019), in their study, concluded that wearable technologies generally increase student motivation and especially reduce students' test anxiety. In addition, the study emphasized that spatial presence and perceptions of experienced reality play an important role in students' motivational beliefs. In the study by Engen et al. (2018), it was concluded that the use of wearable devices in teaching and learning provides pedagogical opportunities in different subjects and courses; however, it was also concluded that teachers and researchers need a lot of time to use these devices for teaching. In their study, Kumar et al. (2018) found that most features of smart glasses are compatible with the requirements of the teaching and learning process adopted in education. The results obtained from these studies have shown that wearable technologies have a positive impact on the field of education. In this context, it can

be stated that wearable technologies have the potential to be used in teaching processes (Lee et al., 2015) and have both instructional and non-instructional potential benefits (Havard & Podsiad, 2020). Bibliometric studies in the literature on AI-powered wearable technologies have identified the following as the main research directions: publication increase over the years, identification of interdisciplinary relationships, correlation of the most frequently used keywords, and future trends. However, researchers are cautious about the use of wearable devices in education, and Havard & Podsiad (2020) even emphasize that many studies lack rigorous research design and that the results are not conclusive. Almusawi et al. (2021), Havard and Podsiad (2020) also state that there is limited information regarding the expectations of innovation in education using wearable technology. In this context, the aim of this study is to identify research trends in AI-assisted wearable technologies in the learning and teaching process and to create a guiding resource for researchers who will conduct scientific studies in this field. To achieve the research objective, the following questions were addressed:

1. What is the distribution by year of published documents on the use of AI-powered wearable technologies in the learning and teaching process?
2. Which year received the most citations?
3. Which countries are the most productive?
4. Which countries receive the most citations for the published documents?
5. What are the most frequently used keywords in the published documents?

2. Method

This study, conducted to determine the trend regarding the use of AI-powered wearable technologies in the learning and teaching process, utilized a bibliometric analysis method. The study analyzed the distribution of documents published in the Scopus database by year, the most productive countries in the field, citations, and the most frequently used keywords in the documents. The Scopus database has a very broad scope in terms of journals, and its metadata fields such as "keywords," "abstract," "institution and country information," "citation counts by year," and "references" are considered ideal for bibliometric analyses. Furthermore, this structure in Scopus provides seamless integration for the Bibliometrix (R) tool used in this study. Scopus was also chosen for this study because it offers researchers extensive search capabilities for bibliometric studies. Data collection was limited to the "title, abstract, and keywords" sections of the documents, using the keywords "wearable technology*", "artificial intelligence*", "education", "training", "teaching", "student performance", or "learning analytics". Data collection was completed on October 31, 2025.

For data analysis, bibliometrix, an open-source tool for quantitative research that includes bibliometric analysis methods, was preferred (<https://www.bibliometrix.org/home/index.php/layout/bibliometrix>). Developed by Aria & Cuccurullo (2017), bibliometrix; Bibliometrics is described as "a tool developed in R language for statistical calculation and graphing according to the

bibliometric workflow" (<https://www.bibliometrix.org/home/index.php/layout/bibliometrix>). In this study, Biblioshiny (<https://www.bibliometrix.org/home/index.php/layout/biblioshiny>), which provides a web interface for bibliometrics analyses and is described as a brilliant application, was used. "Bibliometrics provides resources to researchers for various purposes such as providing structured analysis of large amounts of information, identifying trends and themes over time, identifying the most productive countries, identifying the most relevant authors, and determining the distribution of studies by year" (Aria & Cuccurullo, 2017). In this study, bibliometrics was used to reveal the general picture of studies on the use of AI-supported wearable technologies in the learning-teaching process. Table 1 provides general information on the documents published in the Scopus database up to October 31, 2025, and included in the study.

Table 1. Main information about data

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2004:2026
Sources (Journals, Books, etc)	440
Documents	1104
Annual Growth Rate %	7,59
Document Average Age	3,3
Average citations per doc	23,36
References	0
DOCUMENT CONTENTS	
Keywords Plus (ID)	7500
Author's Keywords (DE)	2977
AUTHORS	
Authors	3964
Authors of single-authored docs	0
AUTHORS COLLABORATION	
Single-authored docs	0
Co-Authors per Doc	9,04
International co-authorships %	25,54
DOCUMENT TYPES	
article	369
book	16
book chapter	89
conference paper	434
conference review	5
editorial	12
letter	5

note	10
retracted	1
review	162
short survey	1

As shown in Table 1, all studies on AI-powered wearable technologies in the Scopus database were included in the bibliometric analysis. In this context, none of the studies published in Scopus in this field were excluded; all were included in the analysis. Studies on the use of AI-powered wearable technologies in the learning and teaching process were first published in the Scopus database in 2004. Examining the publication years of these studies, it was determined that the sources included documents published up to the year 2026. Although the data collection date for this study was October 31, 2025, it was found that some documents were published with a date of 2026. This situation can be attributed to the fact that the relevant publications were made available online at the end of 2025, but their official volume/issue or publication year was assigned as 2026. A total of 1104 documents covering the years 2004-2026 were published in 440 sources, including journals and books. In this field, where 3964 authors published documents, the most frequent type of study was conference papers with 434 publications. The next most preferred document type by researchers was articles with 369 documents. The other most preferred document types were, in order: The most preferred document types were review (n=162), book chapter (n=89), book (n=16), editorial (n=12), note (n=10), conference review and letter (n=5), while the least preferred document type was retracted and short survey (n=1).

3. Results

3.1 Distribution according to the most productive years

Figure 1 shows the distribution by year of studies conducted on the use of AI-powered wearable technologies in the learning and teaching process.

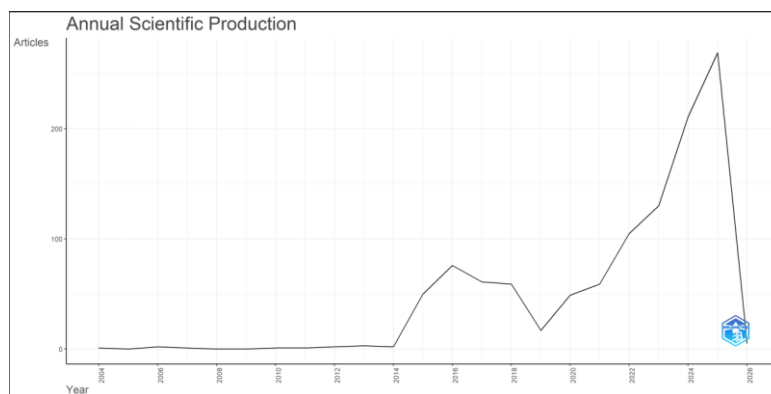


Figure 1. Annual scientific production

The most productive year for the publication of documents related to AI-powered wearable technologies was identified as 2025 with 269 publications. While the first document in this field was published in 2004, it can be said that the research gained momentum quantitatively, especially from 2022 onwards. The fact that 5 publications from 2026 are already mentioned in the sources, even though 2026 has not yet arrived, is an indication that productivity will continue. The distribution of the years with the most citations is given in Figure 2.

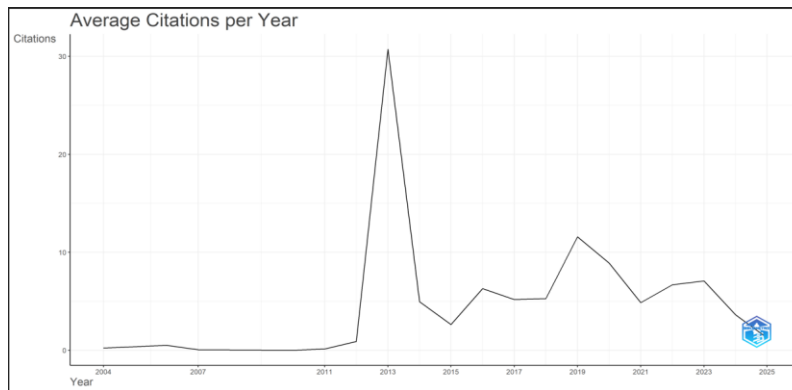


Figure 2. Average citation per year

The analysis revealed that 2013 was the year with the most citations for AI-powered interactive technologies. This finding indicates a high level of interest in documents published in 2013.

3.2 Distribution by most productive countries

This study also aimed to determine the productivity levels of countries conducting research on the use of AI-powered wearable technologies in the learning and teaching process. The distribution of the most productive countries is given in Table 2.

Table 2. Country production

Country	Freq
USA	1011
INDIA	763
CHINA	733
ITALY	317
UK	276
SOUTH KOREA	132
AUSTRALIA	112
SPAIN	112
GERMANY	98
CANADA	97

As shown in Table 2, the most productive country was the USA with 1011 documents. Other productive countries that produced the most publications on the use of AI-powered wearable technologies in teaching and learning activities were, respectively: India (f=763), China (f=733), Italy (f=317), UK (f=276), South Korea (f=132), Australia (f=112), Germany (f=98), and Canada (f=97). It is recommended that countries conducting research on the use of AI-powered wearable technologies in teaching activities should take as examples the countries that are pioneers in this field.

The countries with the most publications and citations in the field are given in Figure 3.

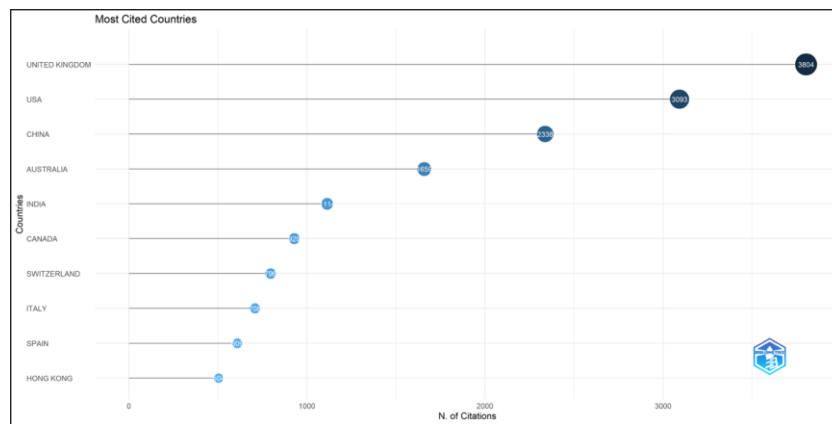


Figure 3. Most Cited Countries

The study identified the uk (n=3084) as the country with the most citations in documents related to AI-powered wearable technologies. The other countries with the most citations and ranking in the top 10 were, in order: USA (n=3093), China (n=2338), Australia (n=1659), India (n=1114), Canada (n=929), Switzerland (n=796), Italy (n=708), Spain (n=609), and Hong Kong (n=504).

3.3. Distribution of the most frequently used words in published documents

The most frequently used keywords in studies on AI-powered wearable technologies are given in Table 3.

Table 3. Most frequent word

Words	Occurrences
wearable technology	788
artificial intelligence	771
learning systems	394
machine learning	332
human	299
deep learning	233

humans	220
wearable devices	188
machine-learning	185
wearable sensors	170

As shown in Table 3, the most frequently used word in the documents by the researchers was identified as “wearable technology” (Occurrences=788). Other frequently used keywords in the published documents were, in order: “artificial intelligence” (Occurrences=771), “learning systems” (Occurrences=394), “machine learning” (Occurrences=332), “human” (Occurrences=299), “deep learning” (Occurrences=233), “humans” (Occurrences=220), “wearable devices” (Occurrences=188), “machine-learning” (Occurrences=185), and “wearable sensors” (Occurrences=170). Researchers who will conduct studies in this field are advised to consider the keywords listed in Table 3, especially during the literature review process.

4. Discussions and conclusions

This study aims to identify trends in the use of AI-powered wearable technologies in the learning and teaching process. Specifically intended to guide researchers in this field, the study focuses on the distribution of published documents by year, the most productive years, the most productive countries, the countries with the most citations, and the most frequently used keywords in the documents.

The study results show that the first document on the use of AI-powered wearable technologies in the learning and teaching process was published in 2004, but the most productive year was 2025. While interest in studies on the use of AI-powered wearable technologies began to increase quantitatively from 2022 onwards, the peak productivity was observed in 2025. The results indicate that the year with the most citations was 2013. In this context, it can be said that researchers cited more documents published in 2013. The countries with the most published documents and the highest productivity in this field are the USA, China, Italy, the UK, South Korea, Australia, Germany, and Canada. The UK was identified as the country with the most citations for its published documents. The top 10 countries with the most citations for their documents are, in order: USA, China, Australia, India, Canada, Switzerland, Italy, Spain, and Hong Kong. An examination of the most frequently used keywords by researchers in the published documents revealed that “wearable technology” and “artificial intelligence” were the most common. This study is limited to the trends presented by bibliometric data and does not directly measure classroom practices; it is merely a guide to indicate the direction of educational research. Researchers who will be conducting studies on the use of AI-powered wearable technologies in learning and teaching processes are advised to consider the results of this research, particularly during their literature review. The bibliometric analysis conducted in this study is limited to documents

published in the Scopus database and specific keywords. This has resulted in some themes being discussed in detail while others remain insufficiently visible. Therefore, it is recommended that future research focus on these neglected areas.

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AI-assisted tools for learning

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Abstract: *Artificial intelligence is becoming an integral part of educational activities and processes. Artificial intelligence (AI) tools enable the creation of electronic resources in various formats with interactive elements, thereby facilitating teachers' work and accelerating the development process. Content generated with AI-assisted tools in multimodal formats can be integrated into learning environments and used to meet the diverse needs and preferences of learners with different learning styles and educational requisites, thereby ensuring personalized learning. The current paper aims to explore the capabilities of AI-assisted tools in digital educational content development.*

Keywords: Artificial intelligence, Education, AI-assisted tools, AI Chatbots.

1. Introduction

Artificial intelligence (AI) is revolutionizing education by transforming traditional teaching methods into personalized, adaptive, and learner-centered learning experiences (Strielkowski et al., 2025). AI can enhance learning platforms by adapting them to each learner's level of understanding, learning pace, and specific learning goals (Salhab, 2025).

AI can significantly enhance the way learners interact with educational content by offering personalized learning experiences (Ahn, 2024) that match their cognitive abilities and personal interests (Lechhab et al., 2024). Intelligent AI-based systems provide a customized learning path that adapts to students' individual learning needs and abilities (Oubalahcen & Tamym, 2023).

Based on the experience gained so far, several challenges and risks to the widespread adoption of AI in education are also reported. Among the most serious threats are those to academic integrity, excessive dependence on technology, which negatively affect the acquisition of knowledge and skills. An inability to guarantee the reliability of the generated content leads to the spread of misinformation and the learning of erroneous theories and concepts. Ethical concerns and risks associated with biased or inappropriate content (Baskara & Mukarto, 2023), including discriminatory elements (Farrokhnia et al., 2023), also arise. Finding a balance is essential to ensure that technology is used to enhance, rather than replace, human teaching and learning (Firat, 2023).

The ideas for adaptive and intelligent systems that will mark the beginning of AI-driven learning are promising, but they are not yet widely available to

learners and teachers. Currently, many teachers use the generative capabilities of AI tools to create content for teaching and learning, as well as for assessment.

This paper examines the potential of AI-assisted tools for developing digital educational content across various formats. AI-assisted tools for developing digital learning content are presented, highlighting their capabilities and addressing their shortcomings.

2. AI in education

AI is gradually becoming a key driver of change in education. AI technologies can alter teaching styles and the presentation of educational resources to students (Adăscăliței, 2025). They can help make personalized, targeted learning a reality.

The most notable impact of AI on education in a digital environment is the implementation of personalized and adaptive learning and assessment (Halkiopoulos & Gkintoni, 2024) and the integration of intelligent learning systems.

Adaptive learning technologies using AI modify content, pace, and teaching methods to match learners' preferences, strengths, and weaknesses (Strielkowski et al., 2025), based on their performance and progress (Fırat, 2023). This approach ensures that they receive personalized support and feel motivated and engaged as they observe tangible progress (Strielkowski et al., 2025).

By continuously analyzing data, assessment results, interaction patterns, and tracking progress, adaptive learning systems can provide timely and targeted interventions in real time, ensuring that learners receive the most relevant materials and activities (Gligorea et al., 2023). Personalized instruction and feedback tailored to learners' needs and styles ensure that everyone receives tasks with an appropriate level of challenge (Lechhab et al., 2024), which improves learner engagement, interest, and motivation (Millalén, 2024) and promotes deeper understanding and higher levels of retention (Dritsas & Trigka, 2025).

From the teachers' perspective, the significant benefits of using AI tools in teaching include developing digital content that meets learners' needs, creating multimodal and multilingual content, assessing exams, and providing personalized help and feedback.

Creating digital content that meets learners' needs. Teachers can create additional resources on a given topic at varying difficulty levels using AI-assisted tools. AI-generated materials can be used for learners who require additional training due to difficulties or gaps, or for those who quickly master the material. Appropriate content will be provided to learners to engage and motivate them, tailored to their level of knowledge and designed to maintain their interest and participation in learning.

Creating multimodal and multilingual content. The diversity of learning content in its presentation formats is essential to effective acquisition. Developing learning resources in multimodal formats that cater to the diverse needs of students takes significant time and effort. AI-assisted tools can quickly generate images,

audio, and video from text prompts, as well as multilingual content, which offers an opportunity to expand the learner audience (Cote, 2025).

Exam assessment. AI can assist in creating and grading learners' assignments and quizzes. Learning management systems allow automatic grading of closed questions in quizzes. AI applications diversify assessment methods, provide immediate, personalized feedback, including on open-ended questions (Dritsas & Trigka, 2025), speed up and facilitate assessment activities, enabling in-depth analysis of results (Huang, Saleh & Liu, 2021), and provide more objective evaluation, thereby reducing the possibility of bias and error (Firat, 2023). Built-in AI algorithms can dynamically adjust the level of difficulty and content of assessment resources based on learners' performance, generating immediate feedback (Strielkowski, et al. 2025).

Personalized help and feedback. Real-time feedback, generated by AI tools, enables learners to understand their progress and identify areas for improvement immediately. A continuous learning and improvement cycle maintain learners' engagement and motivation (Lechhab et al., 2024; Millalén, 2024) and helps them understand their mistakes, make corrections, and solidify their knowledge (Gligorea et al., 2023).

Studies demonstrate high levels of student satisfaction with generative models such as ChatGPT, and describe them as more convenient and accessible than traditional tutoring or email communication with instructors (Tanjga, 2023).

Collaboration between educators and AI is inevitable and requires digital competence in AI and the ethical use of its capabilities (Bicen, 2025). Such a partnership empowers teachers to use AI thoughtfully, ensuring that technology enhances learning rather than replacing them.

3. AI-assisted tools for education

3.1 Generative AI tools

Generative AI tools (also known as AI chatbots), such as Google Gemini, Microsoft CoPilot, ChatGPT, and others, create new content based on learning models. They act as personal assistants, offer immediate feedback, answer queries, and even suggest additional resources based on the student's learning trajectory (Jian, 2023).

The creation of learning materials (presentations, lesson plans, questions or assignments) is accompanied by conversations with AI chatbots. Discussions include suggestions on the learning content and its formats, the pedagogical approaches to be implemented, targeted feedback for learners, activities to engage and motivate them, questions or assignments to assess mastery of the learning content, and ideas for gamification. The discussions generate ideas and suggestions that teachers can further develop and include in their classes.

As an example of developing educational materials with AI chatbots (Copilot and Gemini), educational content on Color Models in Computer Graphics was generated. The two AI chatbots created a lecture outline, with the content

structured and formatted for presentation slides (Figure 1). It is also possible to generate presentations that teachers can edit and adapt.

4.1 RGB Color Model

- **Type:** Additive
- **Primary Colors:** Red, Green, Blue
- **Used In:** Screens, cameras, digital imaging
- **Color Space:** Represented by the **RGB Color Cube**
 - Each axis represents one primary color.
 - Colors are created by adding light.

Visual Aid: 3D RGB Color Cube.

Visual Aids

1. RGB Color Cube

A 3D representation of the additive RGB color space.

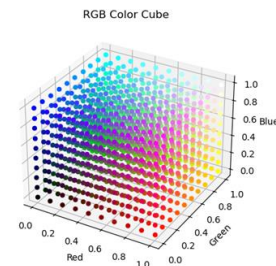


Figure 1. Content generated with Copilot

In addition, AI chatbots generated images, questions on the topic, and suggestions for targeted feedback, as well as practical tasks with formulated assessment criteria and so-called Creative Tasks (Figure 2).

Download the assignments:

[ColorModelsAssignments.pdf](#)

It includes:

- **Theoretical Questions**
- **Practical Exercises**
- **Creative Tasks**

Download the answer guidelines:

[ColorModelsAssignmentsAnswerGuidelines.pdf](#)

It includes:

- Suggested answers for theoretical and practical questions
- Evaluation criteria for creative tasks
- Grading rubrics for all assignment types

Figure 2. Additional materials generated by Copilot

A disadvantage of AI chatbots is that the learning materials are presented as outlines, requiring teachers to create detailed content.

3.2 Content management systems

Content management systems provide tools for creating interactive content that seamlessly integrates various elements. A popular tool for creating interactive content, such as e-books, is Kotobee Author. Teachers can include videos, audio, interactive images, slideshows, questions, and 3D models to make content interactive, engaging and motivating. The e-book can be integrated as a SCORM package into different learning management systems. Kotobee Author is enriched with AI-based tools that generate text, images and quiz questions.

The generated paragraphs (maximum size of up to 3) are based on a text description of the desired content (as an example – The essence of Color Models in Computer Graphics – definition, purpose) – Figure 3.

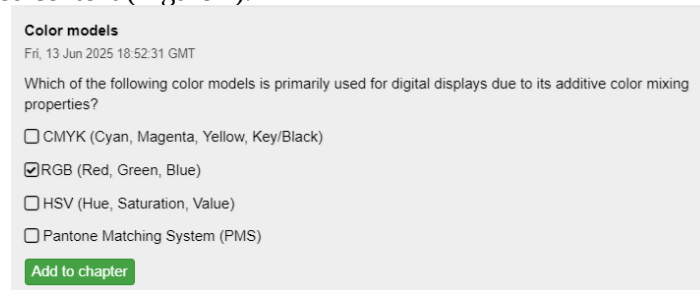
In the realm of digital imaging, color models play a crucial role in defining and representing colors. A color model is essentially a mathematical model describing the way colors can be represented as tuples of numbers, typically as a combination of primary colors. Each color model serves a specific purpose, whether it's for displaying images on a screen, printing them on paper, or storing them digitally.

The essence of color models lies in their ability to accurately define colors and communicate them consistently across different devices and mediums. By using a color model, designers and developers can ensure that the colors they choose will appear as intended, regardless of the platform. Understanding the intricacies of color models is essential for anyone working with digital imagery, as it forms the foundation for color management and reproduction.

Ultimately, the purpose of color models is to provide a standardized way of representing colors, allowing for seamless communication and reproduction of colors in various applications. Whether it's the RGB model for digital displays, the CMYK model for printing, or the HSL model for color selection, each color model serves a unique function in the world of digital imaging. Mastering the essence of color models is key to achieving accurate and consistent color representation in any creative endeavor.

Figure 3. Text generated with AI Content in Kotobee Author

The platform allows the creation of questions for both user-generated and AI-generated content (Figure 4).



Color models
Fri, 13 Jun 2025 18:52:31 GMT

Which of the following color models is primarily used for digital displays due to its additive color mixing properties?

☐ CMYK (Cyan, Magenta, Yellow, Key/Black)

☒ RGB (Red, Green, Blue)

☐ HSV (Hue, Saturation, Value)

☐ Pantone Matching System (PMS)

[Add to chapter](#)

Figure 4. Questions generated with AI Content in Kotobee Author

There are options for generating images from text prompts, but their quality is not at the required level and they cannot be directly integrated into the e-book.

A disadvantage of these tools is that content generation does not involve discussion, clarification, or the offering of advice or recommendations. There are opportunities to edit the content before integrating it into the e-book.

3.3 AI content generation tools

There are online platforms and AI-based tools available on the Internet that generate images and sounds from text prompts, which can be incorporated into learning content.

Image Generation. Tools for generating images from text prompts are among the most popular AI tools available online. Popular examples of such tools are Firefly and Pixlr.

The results of generating images from a text prompt “Please, generate RGB Color Cube, which represents the RGB Color Model” are shown in Figures 5 and 6. Both tools offered several images, each with additional effects applied.

The presence of artistic effects is a disadvantage when the generated images are intended to illustrate learning content, as it diverts attention from the essence of the object, phenomenon, or process. In the example (3D Color Cubes), the generated images include additional effects (light and shadow, glare, reflections) and therefore could not be integrated into the learning content.



Figure 5. Image generated with Firefly

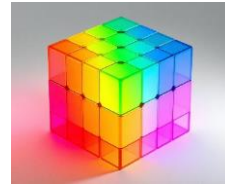


Figure 6. Image generated with Pixlr

Audio Generation. Existing learning materials (texts or presentations) can be voiced using AI tools. A good example is AI Voice in Canva, which can create computer-generated voices that imitate human speech. Teachers can use their notes on the presentation slides to generate a voice. The presentation, along with the generated audio, can be saved as a video file, creating multimodal educational content that is more engaging for learners.

3.4. Educational platforms integrating AI

There are online educational tools and platforms for generating quiz questions of various types. Through them, teachers can create questions or utilize the available AI-assisted options. Popular examples of such tools are Socrative, Kahoot!, and Gradescope.

The use of Socrative demonstrates that by specifying the topic and key points, teachers can use the AI-assisted options to create quiz questions with correct answers and generated explanations (Figure 7). The questions can be edited, but there is no opportunity for additional clarification, suggestions, or discussion.

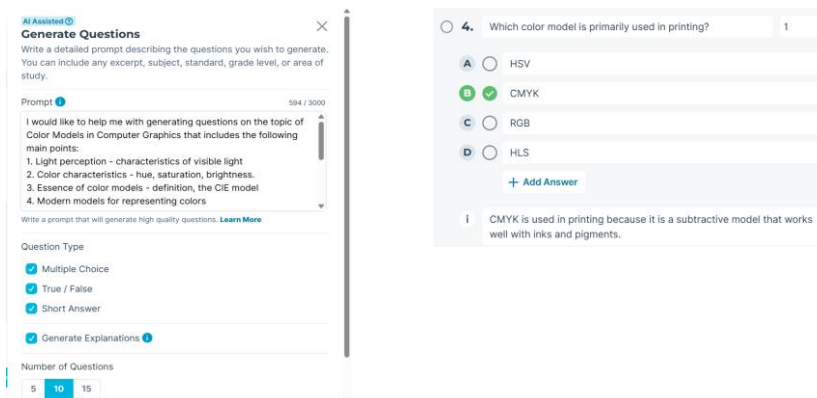


Figure 7. Questions generated with Socrative's AI-Assisted options

There are generative AI educational platforms that integrate multiple tools to create a wide range of learning resources and activities. Magic School AI is a set of tools designed to assist teachers in developing lesson plans, generating learning materials, and creating practical tasks, questions, and images from text, saving time and effort. The platform enables discussions with a chatbot that provides additional suggestions and guidance on content generation.

The presented tools enable the creation of various resources that can be integrated into the overall presentation of learning content. Working with them is time-consuming because many additional instructions are required to ensure that the generated content aligns with the teacher's overall ideas for presenting the learning units.

4. Conclusions

AI-based tools enable the generation of learning content in multimodal formats, including text documents, presentations, images, audio, video, quiz questions, and practical tasks. Thereby, they facilitate and accelerate the development of educational materials and the implementation of educational activities. The role of teachers is essential – they set prompts, correct and refine the generated content with additional requests, and organize and integrate materials into digital learning systems. The presented AI-assisted tools demonstrate strong capabilities, but working with them requires time and effort to produce AI-generated content in an appropriate format tailored to learners' preferences and educational goals.

The need for integrated intelligent systems is obvious. They will facilitate the transition from AI-assisted educational tools to AI-driven education by adapting and personalizing instruction to learners' strengths and weaknesses and their specific educational needs.

Acknowledgment

This research was funded by the European Union-NextGenerationEU, in the frames of the National Recovery and Resilience Plan of the Republic of Bulgaria, first pillar "Innovative Bulgaria", through the Bulgarian Ministry of Education and Science (MES), Project № BG-RRP-2.004-0006-C02 "Development of research and innovation at Trakia University in service of health and sustainable well-being".

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Digital technologies and cognitive approaches in the development of critical thinking and creativity: Factual analysis of the artificial intelligence and neuroscience-based learning processes of university students

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Abstract: *The current research seeks to comprehensively analyse the comparative interaction between artificial intelligence-assisted learning and neuroscience-based cognitive strategies in developing the critical thinking and creativity skills of higher education students. The research employed comparative case study pattern, which is a qualitative research method. The study group consisted of 120 university students in total who participated in a university-level course focusing on critical thinking and problem-solving skills. The study collected qualitative data through semi-structured interviews, which the researchers then analyzed thematically to detect recurring trends and insights. The analyses showed that Artificial Intelligence (AI) assisted digital group enjoyed higher diversity of opinions and developed faster problem-solving skills. However, the Cognitive Group displayed more depth, originality, and conceptual integrity of ideas. As a critical finding, it has been determined that students who use AI show the tendency to transfer part of their cognitive responsibility to AI tools, whereas the meta-cognitive awareness and self-regulatory skills of the Cognitive Group are more developed. These findings indicate that although AI-assisted learning supports creativity, it manifests different effects on the nature of the autonomous cognitive efforts of students. The study presents recommendations for structuring the AI integration in higher education with pedagogical approaches which protect the autonomy and cognitive participation of students.*

Keywords: AI-assisted learning, Neuroscience-based cognitive strategies, Critical thinking, Creativity, Case study, Meta-cognitive awareness.

1. Introduction

The usage of AI-supported learning tools has gained popularity in recent years both with the purpose of promoting learning processes and increasing the usage of technology at higher education (Suh,2025; Zuo et al. 2025). In this context, usage of AI-assisted learning settings provides fast feedback to learners, and aims to increase the academic success and learning motivation of students by offering customized contents (Luckin et al., 2016; Holmes et al., 2019).

On the other hand, literature review reveals that it is emphasized that the adoption of AI tools in learning and teaching processes can constrain the decision-making skills of learners as well as their higher cognitive abilities such as critical and creative thinking and generating original ideas (Selwyn, 2019; Williamson & Eynon, 2020). In this context, it is essential that learners preserve their cognitive responsibilities and improve strategical and meta-cognitive skills in course-learning processes. Nevertheless, approaches where artificial intelligence is included in the processes in a limited manner but rather is more integrated into the learning settings of cognitive strategies need to be adopted. In this way, learners will be allowed to perform deeper analyses and direct the learning processes more consciously (Elnaffar et al., 2025; Mohamed et al., 2025). In addition, performing studies involving comparative assessment of AI-assisted learning and cognitive approaches in higher education bears importance for both featuring the pedagogical applications and effectively developing the critical thinking and creativity students' competencies. Review of the relevant literature indicates that studies involving comparative assessment of AI-assisted learning and cognitive approaches are given only limited coverage. Within this framework, it is believed that comparative examination of the impact of digital technologies and neuroscience-informed methods in university-level education on the learner outcomes will make contribution to the development of pedagogical applications and conscious management of learning processes.

1.1 Literature review

Artificial intelligence tools accelerate the learning process and offer students personalized content (Luckin et al., 2016; Holmes et al. 2019). On the other hand, neuroscience-based cognitive strategies guide students towards both in-depth thinking and the development of original ideas, contributing to their metacognitive awareness (Duran & Er, 2019; Elnaffar, Rashidi & Abualkishik, 2025). A review of the literature reveals a limited number of studies examining the comparative effects of AI-assisted learning and cognitive strategies (Williamson & Eynon, 2020; OUCI DNTB, 2024). Furthermore, the limiting effects of AI tools on decision-making and critical thinking skills have not been sufficiently investigated (Selwyn, 2019). This research aims to fill this gap in the literature and to comparatively examine the effects of AI and cognitive strategies on the critical thinking and creativity skills of university students.

1.2 The importance of the study

This study aims to deeply analyze the comparative interaction of AI-assisted tools assisted learning and neuroscience-based cognitive strategies on Critical Thinking and Creative Problem-Solving Skills. In this regard, it is believed that this research will make essential theoretical contribution to the pedagogical transformation in university-level education. The study also presents suggestions for structuring the artificial intelligence integration processes with a view to protect

the autonomous learning abilities and active cognitive participation levels of students. Within this scope, it is expected that this study will present a normative framework for curriculum developers and educators. In line with this expectation, this study aims to perform an in-depth analysis of the comparative impact of Artificial Intelligence (AI)-assisted learning and neuroscience-based cognitive strategies on the development of the critical thinking and creativity skills of tertiary education students. Answers are sought to the following questions so that the research could reach its general purpose:

1. What are the general learning experiences of students in the Digital Group (AI-assisted) and Cognitive Group (Neuroscience-based) regarding the activities in Critical Thinking and Creative Problem-Solving course?
2. What are opinions of students as regarding the impact of Artificial Intelligence-Assisted and Neuroscience-Based learning experiences on the development of their Critical Thinking and Creativity Skills?

2. Method

This section details the methodology and research processes of the study. The research was conducted using a comparative case study design, and the methodological framework of the research was structured around two different learning approaches that form the basis of the study. The first of these approaches is the artificial intelligence-supported digital learning approach. In this approach, students used artificial intelligence tools such as GPT-4 and Gemini for educational purposes in the learning-teaching processes. These tools were positioned as digital cognitive tools that support problem-solving, idea generation, generating alternative solutions, and reflective thinking. Thus, it was aimed to support students' higher-order thinking, critical analysis, and creativity skills through these applications. In the second learning approach, a neuroscience-based cognitive learning approach was adopted. In line with this approach, based on cognitive neuroscience and metacognition theories, it was aimed to enable students to become aware of, regulate, and manage their own thinking processes. Thus, using cognitive strategies such as metacognitive monitoring, transfer of cognitive responsibility to the learner, mind maps, and creativity-supporting techniques such as SCAMPER, it was aimed to develop students' self-regulated learning skills and increase their cognitive awareness. In line with this conceptual framework, this section provides detailed information on the research design, study group, implementation process, data collection process and tools, and data analysis.

2.1 Research model

The study employed a comparative case study design, which is widely used to explore and compare multiple cases in depth (Yin, 2018). In such studies, each case is examined holistically, and the findings are systematically compared to

reveal similarities, differences, and patterns. Within the scope of this study, students' learning experiences in AI-assisted digital learning and neuroscience-based cognitive learning approaches were compared using this method. The study focused on examining the effects of these two distinct learning interventions on the development of critical thinking and creativity skills through a detailed and holistic analysis. Key analytical themes included transfer of cognitive responsibility and metacognitive awareness, which reflect the underlying cognitive mechanisms of both approaches.

2.2 Study group

The participant group of the research included 120 undergraduate participants at education faculty of Near East University who were enrolled at the course on critical thinking and creative problem-solving ($n=120$). The study employed criterion sampling to select participants, which involves purposefully choosing individuals who meet specific research criteria. When determining the sampling criteria, attention was paid to ensure that students had participated in AI-assisted learning applications and neuroscience-based cognitive strategy interventions within the scope of the relevant course so that comparative analysis could be performed. Within additional criteria, participants were urged to show active participation in the course on critical thinking and creative problem-solving and fill in their learning logs regularly. Within this framework, two groups with high originality which were suitable for comparison were created for comparative case study, which is the research pattern employed in this research. The first group was formed by participants who use AI tools actively in their learning processes ($N=60$) whereas the second group included students who applied neuroscience-based cognitive strategies during learning process ($N=60$). These groups were enrolled at different departments of the university but took the relevant course as an elective. With these characteristics, the study group exhibits a structure fit for comparatively examining different learning approaches to the development process of critical thinking and creativity skills at the tertiary education level.

2.3 Application process

The study group was identified in the preliminary phase of the research and the students were divided into two natural groups without random assignment taking into account their academic success levels. Accordingly, 60 students were categorized as the Digital Group and the other 60 students formed the Cognitive Group. The study was based on comparative case study model, where the Digital Group used artificial intelligence assisted learning tools and the Cognitive Group was subjected to neuroscience-based cognitive strategies. Semi-structured interview and learning log forms were given their final shape after validation process including expert opinions and a pilot study. Prior to the application, an orientation training of 4 hours was offered to both groups on the usage of their respective methods. Digital group was focused on AI tools whereas the Cognitive

Group concentrated on neuroscience-based cognitive strategies (mind-maps, meta-cognitive monitoring). The application process took 8 weeks and each week the students were given real-life scenarios to develop their Critical Thinking skills. At this stage, members of the Digital Group actively conducted analyses using AI-assisted tools such as GPT-4 and Gemini, which are specifically customized for educational and academic use. The Cognitive Group, in contrast, did not employ digital learning tools and generated solutions by relying on neuroscience-based cognitive strategies, including metacognitive monitoring, mind mapping, and creativity techniques such as SCAMPER. During the study, students' learning logs were regularly monitored, and semi-structured interviews were conducted to collect qualitative data. These data were subsequently analyzed in detail through thematic analysis to uncover key patterns and themes.

2.4 Data collection process and tools

To achieve the objectives of this study, a semi-structured interview was conducted to explore students' cognitive awareness, perceptions of AI, and evaluations of learning strategies. Additionally, students' learning logs were employed to closely monitor their learning processes throughout the study. The collected qualitative data were prepared for analysis using thematic analysis method.

2.4.1 Semi-Structured Interview Form

A semi-structured interview form was prepared with the purpose of in-depth examination of the experiences of students regarding artificial intelligence-assisted learning and neuroscience-based cognitive strategies within this research. This form consists of five open-ended questions in total. When preparing the form, 15 academics were consulted who are experts in the fields of education technologies, education sciences, cognitive psychology, and measurement-evaluation. Lawshe (1975) content validity ratio (CVR) technique was used in the evaluation of expert opinions. In this technique, participants' comprehension was evaluated using response categories that indicated varying levels of understanding, from partial understanding to no understanding at all. Spaces were left under the difficult-to-understand items so as to obtain suggestions. The analysis found the CVR value of the form as +1. Finally, necessary corrections were made to develop the final version of the form.

2.4.2 Learning Logs

Participants were asked to keep learning logs, which served as the second data collection method in the research. It was aimed that students could reflect their cognitive, emotional and meta-cognitive experiences throughout the process using these logs. Within this framework, students were asked to write down their learning experiences, their evaluations regarding AI-assisted or cognitive strategy-based activities, and the difficulties they encountered on a weekly basis.

2.5 Data analysis

The data obtained from the study were analyzed using Thematic Analysis, which is a qualitative research method. In thematic analysis, the repetitive significant themes, patterns and topics in the collected data are systematically defined and analyzed (Yıldırım & Şimşek, 2018). The first stage of the analysis consisted of reading the qualitative data in line with research questions and conceptual framework, and meaningful codes were created. In the second stage, the relations and commonalities between the determined codes were examined, and the main themes and sub-themes reflecting the critical findings of the study (i.e. diversity of opinions, transfer of cognitive responsibility, meta-cognitive awareness, conceptual integrity) were categorized in a systematic manner. In the final stage, the obtained themes were defined, analyzed and interpreted in accordance with the purposes of the study. This analysis focused on the interactions which diverge especially between AI-supported learning Assisted Digital Group and Cognitive Group.

3. Findings

3.1 Learning experiences of digital and cognitive groups in critical thinking and creativity

According to the first sub-purpose of the study, general learning experiences of Digital (AI-assisted) and Cognitive (neuroscience-based) students in the course on critical thinking and creative problem-solving were examined. As presented in Table 1, the main themes included Participation in the Learning Process *and* Challenges and Limitations.

Table 1. General learning experiences of digital group and cognitive group students as regards the activities in the course on critical thinking and creative problem-solving

Main theme	Sub-theme	Digital Group (AI-assisted)	Cognitive Group (Neuroscience-based)
1. Participation in the Learning Process	Participation Pace and Adaptation	Rapidly adapted to the process; idea generation began quickly.	They were involved in the process in a slower but planned and step-by-step pattern.
	The Nature of Participation	They showed high motivation and interaction.	They displayed in-depth questioning and intense problem-solving effort.
2. Challenges and Limitations	Technological and cognitive challenges	A sense of excessive dependency on AI; confusion of decisions due to abundance of options	Strategies being challenging and time-consuming in the beginning; requiring excessive mental effort

In the first theme, the groups shared their opinions regarding how they engaged in the learning process (see Table 1). Within this theme, the focus was on two areas: students' adaptation to the pace of learning and the characteristics of their participation. According to the digital group, their involvement in the course accelerated as they became more accustomed to the pace and organization of the class activities. At this point, it can be argued that rapid feedback provided by artificial intelligence tools facilitates the participation of students in activities without wasting time. An example opinion related to this finding is presented below:

"With instant responses from the AI, we were able to progress through our assignments without unnecessary delays." (S76)

Nevertheless, Cognitive Group members stated that they were involved in the learning process in a slower but more systematic manner. This finding shows that the learning approach of the cognitive group is based on sense-making, planning, and step-by-step progress. A sample view is given below:

"At the start of each critical thinking task, I focus on understanding the problem. While this takes some time and limits my initial speed, it enables me to participate thoughtfully and follow a planned approach." (S15)

In the second sub-theme titled "The Nature of Participation", the Digital Group members stated that they showed high motivation and interaction in the learning process (see Table 1). Based on this finding, it can be argued that the instant interactions of the digital group during learning process creates high motivation, which results in an intense and qualified learning experience. A sample view can be seen below:

"AI-supported feedback let on us to stay engaged, participate more fully in the lesson, and remain motivated throughout the learning process." (S 57)

However, Cognitive Group members argued that they could display in-depth questioning and intense problem-solving efforts during learning process. This finding displays that the cognitive group addresses learning not only as an effort to reach a solution, but also to understand and evaluate the process itself. An example opinion is provided below:

"In class activities and presentations, we focus on understanding the reasoning behind each problem. We analyze each step thoughtfully and explore different possible solutions before reaching a conclusion." (S 25)

In addition, the groups shared their views regarding the challenges and limitations they encountered under the second theme (see Table 1). In relation to the second theme, digital group members indicated that they experienced challenges of a technological and cognitive nature, such as over-dependence on AI and decision-making difficulties caused by the large volume of data. This finding indicates that student experiences such as data abundance and dependency on artificial intelligence can lead to potential problems including attention deficit and decision-making difficulties during learning processes. An example statement is given below:

"Because AI tools provide so much information, I often struggle to decide which data to attend to first, making it more difficult to concentrate and make informed choices while learning." (S 69)

Cognitive group, on the other hand, argued that they encountered some difficulties in the beginning such as the strategies requiring high mental effort due to their challenging and time-consuming nature. This finding can be the reason of students perceiving the process as cumbersome and exhaustive, which impairs their willingness to learn. An example opinion is provided below:

“Working through some of the strategies was time-intensive and demanded constant reflection, which at times lowered my motivation and hindered my ability to move forward efficiently.” (S 6)

The obtained findings indicate that digital group members participate in class activities rapidly and in a motivated manner thanks to artificial intelligence-assisted rapid feedback, although they suffered from limitations in decision-making and superficiality. On the contrary, the cognitive group progressed more slowly but followed a more planned and in-depth learning process.

3.2. Students’ views on ai-assisted and neuroscience-based learning for critical thinking and creativity

Within the second sub-objective, students’ perceptions of the impact of AI-assisted and neuroscience-based learning on critical thinking and creativity were examined. As shown in Table 2, the main themes were Development of Critical Thinking, Development of Creativity, and Meta-cognitive Awareness.

Table 2. Opinions of students on the impact of artificial intelligence-assisted and neuroscience-based learning experiences on the development of their critical thinking and creativity skills

Main Theme	Sub-Theme	Digital Group (AI-assisted)	Cognitive Group (Neuroscience-based)
1. Development of Critical Thinking	Speed of Analysis	AI tools accelerated analysis and idea-generation process.	Strategies slowed down the analysis process but gave it more depth.
2. Development of Creativity	Originality of Ideas	Although the solutions were produced rapidly, originality varied depending on the suggestions made by AI.	Solutions of the students are more original, and conceptually more holistic.
3. Meta-cognitive Awareness	Strategy Usage Consciousness	Strategy awareness is low, AI direction is more evident.	Students chose and applied strategies more consciously.

The groups shared their views on how the course activities contributed to the development of their critical thinking skills as part of the first theme (see Table 2). Accordingly, the digital group indicated that AI-supported instant feedback helped them interpret problems in the course activities more efficiently, enhancing the speed at which they could analyze the tasks. This finding indicates that students can focus on the solution process in a very short time using artificial intelligence-assisted tools. An example statement is as follows:

“In the course activities, I found that artificial intelligence assisted me in working through challenging topics, enabling quicker and more effective problem-solving.” (S 47)

However, the Cognitive Group members argued that the strategies they used slowed down the analysis process but added depth to it. This finding proves that strategies used in the cognitive group are essential, and that they highlight deliberation and detailed analysis skills instead of the speed of analysis. A sample opinion is given below:

“The use of cognitive strategies helps us think more comprehensively. While analyzing each problem requires time, methodically planning every step allows for meaningful and deep learning.” (S24)

Within the second theme, the groups discussed the ways in which the course activities helped develop their creative abilities (see Table 2). In terms of generating original ideas, the digital group noted that AI helped them produce concepts rapidly, although most of their ideas tended to reflect the suggestions offered by the system. This finding can be interpreted as digital tools contributing to productivity whereas the creativity of students is confined to the information offered by AI. An example view is given below.

“AI-supported class activities help us generate ideas quickly, yet we often find that these ideas are limited to the framework suggested by the tool, and it remains difficult to develop genuinely original concepts.” (S 114)

By contrast, the Cognitive Group stated that they found problem-solving in course-related activities more original and conceptually more integrated. This finding displays that students can develop more creative and conceptually holistic approaches to problem-solving using strategic and deep-thinking processes. An example opinion is given below.

“Working through problems step by step with cognitive strategies allowed me to combine different viewpoints and produce solutions that were more creative and unique.” (S 84)

The groups shared their opinions on their meta-cognitive awareness as part of the third theme (see Table 2). Accordingly, students in the digital group explained that their awareness of strategy use is low and that they primarily require AI-assisted guidance during the learning process, as part of the discussion on strategy usage awareness. This finding implies that the self-regulation and strategic decision-making learner outcomes is not adequately supported due to the assistance provided by artificial intelligence. A sample expression is given below.

“While AI tools were helpful in selecting strategies for class tasks, relying on them too much made it challenging for me to design my own learning plan.” (S45)

By contrast, students in the Cognitive Group stated that they were able to choose their strategy consciously and that they could adapt it to their personal learning processes. This finding shows that students in the cognitive group have higher meta-cognitive awareness compared to other group and that they could manage their learning process more consciously. Below is a sample expression.

“I can plan ahead to select the most appropriate cognitive strategy for classroom tasks, and if necessary, modify my strategy or take personal control of my learning.” (S 112)

The obtained findings show that the members of the digital group can perform analysis rapidly using the ideas generated by artificial intelligence but that they suffer from limitations in strategy utilization and originality. Nevertheless, the cognitive group was able to use strategies consciously by progressing more slowly and thus they enjoyed an original and stronger learning process in terms of meta-cognition.

5. Discussion, conclusions & recommendations

In accordance with the first sub-objective of the study, general learning experiences of digital group and cognitive group students as regards activities in critical thinking and creative problem-solving course was examined. Students in the digital group stated that their participation in the learning process of the course was rapid. An examination of the literature shows that Şimşek’s study (2025) found that artificial intelligence tools contributed to personalized and effective learning. Another finding of the study indicates that students in the digital group encountered limitations in terms of decision-making and superficiality. Research by Zhai et al. (2024) concluded that, parallel to our finding, artificial intelligence tools might hinder the analytical thinking and autonomous decision-making learner outcomes, which could result in rather superficial learning experiences. However, other findings display that cognitive group progressed slowly but experienced a more planned and deeper learning process. Similarly, Duran and Er (2019) stated that learning strategies make positive contribution to the academic success and learning process of students. Regarding the second sub-objective, the opinions of students on the impact of artificial intelligence-assisted and neuroscience-based learning experiences of students on their critical thinking and creativity skills have been examined. The obtained findings indicate that digital group members were able to perform analysis easily with the help of the ideas generated by artificial intelligence but that they had difficulty in employing a strategy. Parallel to this finding, Elstad’s study (2024) argued that the usage of artificial intelligence made positive contribution to the individual learning and problem-solving students’ competencies, whereas its excessive use could weaken the cognitive skills such as original and critical thinking. Another obtained finding shows that the cognitive

group progressed more slowly and was able to use cognitive approaches more consciously, as a result of which they could reinforce original and meta-cognitive learning processes. From this perspective, Çöğenli and Güven (2015) underlined that using meta-cognitive approaches the students could perform planning, monitoring and evaluation of the courses more easily and use strategies more consciously.

In light of the findings obtained in the study, training can be given to students on the conscious usage of artificial intelligence tools. In addition, courses can be added to the curricula on the limitations of artificial intelligence. Structured activities that allow them to progress slowly in digital learning environments can also be designed to support students' in-depth and planned learning approach. Finally, usage of artificial intelligence tools can be planned by balancing them with autonomous problem-solving and original idea-generating processes so as to improve the critical thinking and creative problem-solving students' competencies.

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Blockchain-based governance for universities

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Abstract: *Many universities still employ a centralised or a manual method of academic governance that limits both participation and transparency; the implementation of a blockchain-based architecture creates a method of communication and participation through the separation of identity verification and vote casting, thus creating privacy and trust. This system allows for the implementation of weighted voting, quorum enforcement, and role-based eligibility using zero-knowledge proofs, blind signatures, and homomorphic encryption. Simulations demonstrate that the architecture is scalable, resilient against insider threats, and produces accurate results. Governance is conceptualized as an intrinsic functional layer of Virtual Learning Environments (VLEs), extending their role beyond content delivery toward participatory, transparent, and verifiable academic decision-making. This positioning aligns the proposed architecture directly with contemporary research on digital education ecosystems and virtual learning infrastructures.*

Keywords: Blockchain, Academic governance, Universities, Virtual learning Environments.

1. Introduction

The higher education's shift to digital platforms has altered how educational institutions teach and assess learning by creating a new way in which students and staff engage with one another through digital methods of communication (e.g., virtual classrooms), as well as the widespread growth of Learning Management System (LMS) platforms. As educational institutions become increasingly complex, operating in an environment that involves not only the instructor-student relationship but also the administration-staff-student relationship, the importance of governance in the academic environment cannot be understate. The methods by which academic institutions choose their leaders (rectors, academic councils, etc.) and control student activities are at the heart of this new system of governance (Ohize et al., 2025).

The methods of governance employed by higher educational institutions to elect and govern their staff and students have not yet fully evolved to accommodate the rapid growth of digital platforms in the same way that many of the institutions' learning and assessment processes have already shifted (Ohize et al., 2025). Most organisations continue to utilise paper ballots and manually manage electronic election and governance processes, both of which add significant logistical

<https://doi.org/10.58503/icvl-v21y202609>

impediments to participation by the entire academic community (Hajian Berenjestanaki et al., 2024). In addition, there are often concerns about the reliance on a small group of individuals with special access to the electronic systems used to govern, as it can detract from the perceived legitimacy of the election and governance processes (OECD, 2024). The absence of transparent and verifiable election and governance mechanisms in institutions has resulted in a fundamental inconsistency between the manner in which digital learning environments are structured and administered, and the manner in which elections and governance mechanisms have traditionally been conducted (Chen, 2024).

This paper proposes a blockchain-based governance architecture designed specifically for university ecosystems. The proposed model treats academic governance as an integral component of the digital learning environment rather than as a separate administrative process. By conceptualising governance mechanisms as part of the virtual learning infrastructure, the proposed approach directly aligns with contemporary research on participatory digital education ecosystems and extends the scope of VLEs beyond content delivery toward transparent and verifiable institutional decision-making.

In addition to designing for security, an academic study has found that secure digital governance systems also have educational implications. Transparent and verifiable digital governance systems foster a relationship of trust between institutions and those they serve, promote student and staff participation, and contribute to the development of digital citizenship competence within a virtual learning environment (OECD, 2024).

In contrast to existing approaches that treat governance as an external administrative process, this study frames academic governance as a native component of the virtual learning ecosystem. From this perspective, voting mechanisms are not merely institutional tools, but socio-technical instruments embedded within VLEs that support participation, transparency, and the development of digital citizenship competencies. This framing establishes a direct conceptual link between blockchain-based governance and the research scope of virtual learning environments.

2. Related work

Research on electronic voting systems has evolved significantly over the past decade, expanding from centralized automation-oriented solutions toward decentralized and cryptographically verifiable architectures. Contemporary studies increasingly leverage Distributed Ledger Technology (DLT) to enhance transparency, integrity, and auditability in both civic and organizational voting contexts. This evolution reflects a broader shift toward digital governance infrastructures that support participation and trust in distributed institutional environments.

Recent blockchain-based voting research emphasizes architectural robustness, privacy preservation, and procedural correctness. Studies published

between 2021 and 2025 explore permissioned and hybrid blockchain models, end-to-end verifiability, and formal governance constraints, demonstrating the growing maturity of blockchain voting systems beyond proof-of-concept implementations.

Platforms such as Polys employ blind signature schemes to cryptographically separate voter authentication from vote casting. The underlying blind signature protocol, originally formalized by Chaum (1983), remains a foundational cryptographic primitive and continues to underpin modern privacy-preserving voting architectures, including contemporary blockchain-based systems. While the blind signature scheme originates from foundational cryptographic research, it remains a canonical mechanism upon which modern privacy-preserving voting systems are constructed, including contemporary blockchain-based architectures. Systems such as Voatz adopt permissioned blockchain infrastructures, including Hyperledger Fabric (Androulaki et al., 2018), to balance throughput and governance control. Recent studies emphasize that permissioned consensus models are particularly suited for institutional elections, where regulatory compliance and controlled participation are critical.

Despite these developments, existing platforms often do not support dynamic quorum requirements and role-based representation specific to the academic environment. Early conceptualizations of Virtual Learning Environments primarily emphasized content delivery and instructional support, with limited consideration for institutional governance functions (Chen, 2024). Recent research, however, increasingly explores the expansion of VLEs toward integrated digital governance and participatory infrastructures.

This research delineates the evolution of e-voting systems from centralized administrative tools toward decentralized trustless architectures utilizing Distributed Ledger Technology (DLT). While legacy systems prioritize automation, contemporary DLT-based frameworks such as Exonum and Voatz attempt to reconcile the tension between performance (throughput) and integrity (auditability) through permissioned consensus models.

Table 1. Comparative taxonomy of E-voting architectures

Architectural Paradigm	Implementation / Framework	Primary Objective	Governance Model	Critical Limitations
Monolithic Centralized	Legacy Civic/Org Systems	Operational Automation	Centralized: High reliance on a single Trusted Third Party (TTP).	Single Point of Failure (SPOF); lack of independent verifiability.
Permissionless DLT	Initial Polys Infrastructure	Censorship Resistance	Decentralized: Publicly verifiable via global consensus.	Scalability bottlenecks (latency); high resource intensity.

Permissioned / Consortium DLT	<i>Exonum, Voatz</i> (Hyperledger Fabric)	Throughput Optimization	Federated: Pre-approved validators manage consensus.	Diminished decentralization; potential for validator collusion.
Hybrid / Skipchain	Privatized/Public Hybrid	Temporal Integrity	Anchored: Private state periodically timestamped to public chain.	Architectural complexity; dependency on public chain persistence.
Integrated VLE Governance	Digital Citizenship Frameworks	Participatory Pedagogy	Ecosystemic: Governance as a core pedagogical function.	Categorical exclusion from current LMS/VLE design.
Privacy-Preserving Cryptography	ZKP, Homomorphic Encryption	Anonymity & Integrity	Algorithmic: Mathematical proof of vote validity.	Complexity in mapping to weighted, role-based academic hierarchies.

A significant techno-pedagogical gap was identified in early VLE research, where governance was treated as an external administrative layer (Dillenbourg, 2000) rather than an integral component of the learning ecosystem (Kaleci, Devkan, 2025). In this study, this observation is used to contextualize the historical evolution of VLE design, rather than to characterize the current state of learning management systems. This observation reflects the state of VLE design at the time and is used in this study to illustrate the historical separation between learning environments and governance processes, rather than to characterize current LMS capabilities. Furthermore, while cryptographic primitives like Zero-Knowledge Proofs (ZKP) ensure voter anonymity, their application remains under-prototyped in the nuanced context of academic governance, where weighted voting and role-based eligibility are mandatory.

Recent studies have significantly advanced the field of blockchain-based electronic voting by addressing transparency, security, and architectural scalability in both civic and organizational contexts (e.g., 2021–2025). Contemporary research explores permissioned blockchain governance models, end-to-end verifiability, and integration with digital platforms, providing an up-to-date foundation upon which this study builds. Unlike prior work, the present research explicitly focuses on university governance and its embedding within virtual learning environments (Jain, A. K., Gupta, N., & Gupta, B. B., 2025).

3. Regulatory and institutional constraints

The proposed architecture divides the process into three domains: institutional services (Off-chain), privacy gateway, and blockchain layer (On-chain).

3.1. Mathematical model of blind signatures

To break the link between identity and voice, an RSA blind signature scheme is used. The process is formalized as follows (Ye, J., et al., 2024):

- **Blinding:** The voter generates a message m (voting token) and masks it with a random number r : $m' \equiv m \cdot r^{and} \pmod{N}$, where (and, N) is the university's public key.
- **Signing:** The university signs the masked message:
 $s' \equiv m'^d \pmod{N}$
- **Unblinding:** The voter removes the masking to obtain a valid signature s : $s \equiv s' \cdot r^{-1} \equiv m^d \pmod{N}$

This mechanism allows the student to vote anonymously, proving to the blockchain that they own an authorized token, without the university knowing its contents.

3.2. Homomorphic encryption and vote summation

To protect the intermediate results, the cryptosystem is applied, which has an additive homomorphic property (Morar, C. D., et al. (2024). If two votes $v1$ and $v2$ are encrypted as $E(v1)$ and $E(v2)$, then their sum in encrypted form is calculated as the product of the ciphertexts:

$$E(v1 + v2) = E(v1) \cdot E(v2)$$

This allows the smart contract to perform tallying without decrypting individual ballots until the end of election day.

4. Experimental setup and evaluation

The experimental scenarios are designed to reflect governance processes typically conducted within digitally mediated university environments, where participation is distributed and asynchronous, similarly to interactions within virtual learning platforms.

This section evaluates the feasibility and correctness of the proposed blockchain-based e-voting architecture through scenario-based simulations reflecting realistic university governance elections. The evaluation focuses on procedural enforcement, eligibility control, and resilience against invalid and double-voting attempts, rather than cryptographic performance benchmarking.

4.1. Experimental Setup

Number of eligible voters (E): 300

Number of candidates (C): 4

Quorum requirement (Q): 70% of eligible voters

$$Q = \lceil 0.7 \times E \rceil = 210$$

Voters are assumed to be authenticated off-chain via institutional identity

systems and issued one-time anonymous voting credentials. The blockchain layer processes only anonymized ballots and credential identifiers.

To evaluate procedural robustness, four turnout scenarios were simulated:

Table 2. Results of the quantitative analysis

Role	Eligible	Weight	Valid voters	Role turnout	Weighted valid
Faculty	80	2	55	68.8%	110
Students	200	1	145	72.5%	145
Staff	20	1	15	75.0%	15
Total	300		215	71.7%	270

Headcount quorum check (70%): $215 \geq 210 \Rightarrow \text{Valid}$

Weighted quorum check (70%): $270 \geq 266 \Rightarrow \text{Valid}$

To reflect typical university governance structures, we simulated a role-based electorate with weighted voting. The results show that both headcount-based quorum ($215/300 = 71.7\%$) and weighted quorum ($270/380 = 71.1\%$) can be enforced deterministically as explicit governance policies. This strengthens the positioning of the proposed model as a governance layer for Virtual Learning Environments, where participation is distributed and institutional roles must be represented transparently.

4.2. Evaluation Metrics

Evaluation uses the following metrics:

- Turnout ratio

$$\text{Turnout} = \frac{V}{E}, \text{ where } V \text{ is the number of accepted (valid) ballots.}$$
- Quorum satisfaction

$$\text{Quorum\_met} = \begin{cases} \text{true}, & V \geq Q \\ \text{false}, & V < Q \end{cases}$$
- Invalid ballot rate

$$\text{Invalid\_rate} = \frac{I}{V + I}, \text{ where } I \text{ is the number of rejected ballots.}$$
- Double-voting detection rate

$$\text{DV\_caught} = \frac{\text{Rejected}_{\text{used\_token}}}{\text{Attempted}_{\text{double}}}$$

These metrics reflect both governance correctness and security-related properties of the system.

5. Discussion and Impact on virtual learning

The implementation of the proposed architecture redefines academic governance as an integral pedagogical and participatory component of Virtual

Learning Environments rather than a separate administrative function.

Digital trust: Algorithmic transparency increases student engagement in online communities.

Governance Literacy: Participants gain practical knowledge about decentralized systems and cryptographic data protection.

Digital Citizenship: The system prepares students for responsible participation in the democratic processes of the digital society.

The experimental results demonstrate that the proposed architecture can reliably enforce quorum requirements, prevent double voting, and maintain procedural correctness under realistic university election conditions. In this sense, governance is not treated as a parallel administrative workflow, but as an integral socio-technical process embedded within digitally mediated academic participation.

While the evaluation does not benchmark cryptographic proof generation or network-level throughput, it validates the system's logical correctness and governance suitability. These results provide strong evidence that the architecture is viable for pilot deployments in academic environments.

6. Legal and ethical considerations

The architecture is designed according to the Privacy-by-Design principle to ensure compliance with GDPR and the Law on Higher Education (GDPR, EU 2016/679).

Right to deletion: Personal data remains Off-chain. When the identifier is deleted from the university database, the corresponding cryptographic hash in the blockchain becomes unusable (Hash-and-Delete).

Ethics: The system prevents student profiling through the use of anonymous one-time tokens.

7. Conclusion and future work

The proposed blockchain architecture provides a reliable infrastructure for managing universities. References to early LMS research are employed strictly to contextualize the historical evolution of virtual learning environments and do not constitute the technological basis of the proposed future developments. It combines mathematical security with educational goals, supporting the vision of the European Digital Education Area (EDEA). The present study delivers a validated architectural and procedural model for blockchain-based academic governance, positioned explicitly within the context of Virtual Learning Environments. The contribution of this work lies in its conceptualization and experimental validation of governance as an intrinsic component of digital learning ecosystems, rather than in the development of a specific software implementation.

Future work will extend this validated model toward applied implementations in contemporary LMS platforms such as Moodle and Canvas,

with the objective of empirically studying usability, scalability, and stakeholder acceptance within authentic virtual learning environments.

The paper presented a blockchain-based e-voting architecture specifically designed for university governance elections. The proposed system employs a constraint-driven design approach, which translates regulatory, institutional and privacy requirements into concrete architectural and procedural mechanisms. The architecture separates identity verification from the casting of votes, enforces quorum and eligibility rules through smart contracts, and leverages permissioned blockchain governance to balance institutional control with distributed trust.

The experimental evaluation of the proposed approach was conducted through the use of scenario-based experimentation. This evaluation demonstrated that the approach can reliably enforce quorum requirements, detect invalid and double-voting attempts, and determine election outcomes without processing personal data on-chain. The findings of this study demonstrate the viability of blockchain-based e-voting systems within academic environments and underscore their capacity to augment transparency and trust in university decision-making processes.

The evaluation focused on governance correctness instead of cryptographic or network performance, yet the findings provide a resilient foundation for future research. It is evident that a number of directions merit further investigation. Firstly, the integration of advanced cryptographic techniques, such as homomorphic encryption and zero-knowledge proofs, has the potential to facilitate fully encrypted tallying and enhance the integrity of end-to-end verification. Secondly, it is necessary to assess operational scalability by performing performance benchmarking under realistic network conditions and mobile device constraints. Thirdly, extending the architecture to support weighted voting and multi-round election procedures would address additional governance scenarios common in higher education.

It is recommended that subsequent research endeavors involve the implementation of pilot projects within authentic academic institutions. This will facilitate the evaluation of usability, stakeholder acceptance, and organizational impact. Such empirical studies are expected to further illuminate the socio-technical role of governance within virtual learning environments and to support the responsible evolution of participatory digital education infrastructures.

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Machine learning tools in training of medical staff

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Abstract: *A key challenge in the field of healthcare is the integration of artificial intelligence methods and tools to support the activities of physicians in decision-making processes. The analysis of medical data is essential for understanding the disease, monitoring and predicting the development of the disease. The report examines Machine Learning techniques that are used to analyze the effectiveness of various treatments, extract and interpret complex, multidimensional data from medical studies to improve diagnostic and prognostic accuracy. Algorithms based on Deep Learning reveal hidden patterns and dependencies and offer predictions that support medical staff in their activities and assessment. Approaches for combining heterogeneous data are considered in order to improve the effectiveness of the models. The work involves the design of an intelligent application that can assist medical staff and improve their training and integration into the work environment.*

Keywords: Artificial Intelligence, artificial neural networks, deep learning.

1. The field of deep learning in medicine

In recent years, deep learning models have shown great potential in the field of medicine. Deep Neural Networks (DNNs) are a type of neural network consisting of multiple layers that process and transform input data, improving the accuracy of the models in solving complex tasks. DNNs are the basis for many modern technologies. Potential applications include bioinformatics and medical language processing (Mamoshina et al., 2016) for automated drug discovery or for navigating the vast unstructured data available in the scientific literature. In recent years, deep neural networks have revolutionized many areas of machine learning. Today, they are the basis for groundbreaking advances in medical diagnostics, feature extraction from magnetic resonance imaging (MRI) images, and their analysis in combination with many other data to identify patterns that predict molecular changes.

Convolutional Neural Networks (CNNs) are a type of neural network, primarily used in image processing, that use filters to extract important features from data. They achieve pattern recognition by exploiting spatial dependencies and hierarchical representations of data, which distinguishes them from traditional artificial neural networks. Their adaptability and efficiency define the latest advances in Deep Learning, making them a major factor in modern AI. Their main

<https://doi.org/10.58503/icvl-v21y202610>

property is that they can detect features in images, such as brightness, dark spots or a specific color, contours at different orientations, patterns, etc. Artificial neural networks are difficult to train to detect similar features based on pixels in the input data, because in different images the features may be present in different locations, orientations and sizes (McCorduck et al., 1977). Convolutional neurons are typically placed in the lowest layers of a multilayer neural network, where they process the raw input pixels. They can be trained from large amounts of unlabeled data (images without labels). The underlying neurons (such as the perceptron neuron) are placed in the higher layers, which process the output data from the lowest layers, and are trained using supervised machine learning techniques and an error backpropagation algorithm.

Other architectures, such as *Recurrent Neural Networks (RNNs)*, which incorporate feedback loops and *Long Short-Term Memory (LSTM)*, are being investigated for their ability to recognize temporal dependencies and patterns in medical imaging data with successive measurements (Prasad et al., 2024). RNNs are a type of neural network that processes sequences of data, text, or speech, using internal states to remember information from previous steps. They are recurrent because they perform the same operation on each successive input. *LSTMs* are a specialized type of recurrent neural network that can remember information for long periods. They consist of a memory cell, an input gate, an output gate, and a forget gate. The memory cell stores values for arbitrary time intervals, the forget gates filter and discard some of the input information for each iteration, and the output gate decides which information from the current state will comprise the final output. Selectivity in the output allows LSTMs to maintain useful, long-term relationships and make predictions at current and future time steps. These neural networks are capable of learning complex patterns in multidimensional, time-varying data. Therefore, they are applied to identify anomalies based on the difference between the model's prediction and the actual observed values.

Ian Goodfellow of Google Brain proposes a combination of two neural networks. They compete with each other, with one trained to generate images from the training data. The other “adversarial network” has the task of separating the images generated by the first network from the real images (the training data). A system of this type, called a *generative adversarial network (GAN)*, trains both models in parallel. As the generative network improves, the adversarial model also improves, and the cycle continues until the generated images become very similar to the real images.

Modular neural networks (MNNs) divide complex tasks into smaller and independent sub-modules that can be trained in parallel. The use of modular architectures for medical imaging allows for high accuracy in tasks such as tumor detection and anomaly classification. Modular networks can process different data sources – such as computed tomography and magnetic resonance imaging (MRI) – with high efficiency. (Hu et al., 2024) emphasize that combining different modules in neural networks improves the recognition of spatio-temporal features of images, which is especially useful in neurological diseases such as Alzheimer's.

An advantage of the modular architecture is the possibility of training specialized modules for different sub-tasks. Guebsi and Chokmani demonstrate how networks can be applied to accurately recognize heart and lung diseases by dividing the diagnostic process into separate components (Gabsi & Hedi, 2024). An advantage of MNN is the easier interpretation of the models, with modular structures providing clear dependencies between input data and predictions, which is important for clinical applications (Shin et al., 2024,).

Neural networks can be built based on fuzzy logic, as it better corresponds to the inaccuracies and ambiguities registered in the real world. In (Sotirov, et al., 2025), a hybrid deep learning framework is proposed, which combines convolutional neural networks with intuitionistic fuzzy estimates. The goal is to improve the accuracy, sensitivity and robustness of pneumonia detection in pediatric chest X-rays. Inception v3, one of the neural network architectures specifically designed for image processing, is applied. It was developed by Google and is part of the Inception model series, the structure of which is shown in Figure 1 (Sotirov et al., 2025).

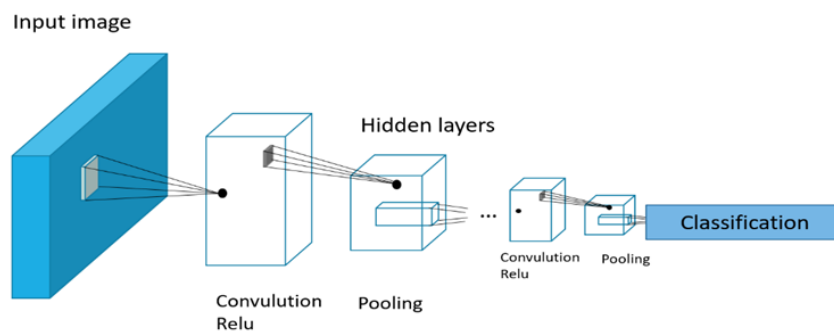


Figure 1. CNN Inception V3 neural networks

2. ML techniques for medical data analysis

Researchers are focused on developing models that can extract and interpret complex, multidimensional data, with the goal of improving diagnostic and prognostic accuracy (Ahsan et al., 2022). The process of data analysis depends on a number of factors, including data availability, data quality, preprocessing techniques, as well as algorithms that are applied.

Machine learning techniques, such as Random Forests (RF) and Support Vector Machines (SVM), as well as deep learning architectures such as Convolutional Neural Networks (CNNs), are essential for automated medical data analysis.

Support vector machines (SVMs) are powerful machine learning algorithms that are widely used in medicine for image classification, text data, and bioinformatics, due to their ability to handle multidimensional and complex data (Rodríguez-Pérez & Bajorath, 2022). SVMs work by finding an optimal hyperplane that separates data into different classes while maximizing the distance

between them, in order to achieve the best separation. This distance (margin) is the distance between the hyperplane and the closest points of each class, known as support vectors. By maximizing this margin, SVM improves the model's ability to generalize, making it effective for classifying new, unknown data. SVMs are particularly effective at handling high-dimensional data and can model both linear and nonlinear relationships. This flexibility makes SVMs a valuable tool for complex biomedical applications, such as genomic classification or visualization (Miteva, 2024).

The limited availability of large, annotated datasets poses a challenge for training and validating ML models. Many existing biomedical datasets are small and lack sufficient diversity, which can lead to problems with overfitting and poor generalization (Massimo et al., 2024). Ensuring transparency and developing models that not only demonstrate high accuracy but also provide interpretable explanations for their predictions further complicates the problem (Ibomoiye et al., 2024).

Medical imaging data analysis is important in understanding diseases, monitoring their progression, and predicting clinical outcomes (Mengfang et al., 2023). Typically, genetic analysis of cancer requires surgical intervention to extract a tissue sample and is time-consuming to analyze. A reliable method for predicting the genetic features of cancer through imaging, such as magnetic resonance imaging, could provide faster diagnosis in certain cases (Saeed, et al., 2022). It could guide the specialist towards more precise and personalized treatment, improving the accuracy of patient prognosis.

Integrating multimodal data (e.g., combining radiomic features with genomic and clinical data) offers much richer capabilities, but introduces additional complexity. For ML models to successfully integrate these heterogeneous data types, precise data preprocessing, extraction of relevant features, and use of sophisticated model architectures are required (Miteva, 2024).

3. Multimodal data integration

Traditional machine learning models struggle to integrate different types of data that differ in structure and scale (e.g., medical images and genomic sequences). Integration of diverse multimodal data is a growing area of research, such as combining MRI data with genetic, clinical, and even environmental data. This integration is expected to improve prediction accuracy by allowing models to capture a wider range of features and achieve higher accuracy. Various data fusion techniques and ensemble methods are being explored to improve model performance (Xu et al., 2024). Image preprocessing plays a key role in improving data quality, helping to reduce noise and correct parts of images (Trojani et al., 2024).

Ensemble method in machine learning is a powerful approach that combines the predictions of multiple models to improve the overall performance, often surpassing the capabilities of each individual model separately (Opitz & Maclin, 1999). The following approaches to data integration are considered:

- *Early integration* - combining raw data before modeling, usually performing fusion of data from sensors and other sources. Early sensor-level fusion methods include Random Forest, SVM, Bayesian Inference, Fuzzy Logic, Artificial Neural Networks, Dempster–Shafer, etc. For example: the integration of different data, such as combining MRI data (radiomic data), with genetic, clinical and even environmental data is expected to improve the accuracy of predictions and create a robust and generalized model from heterogeneous data sources.

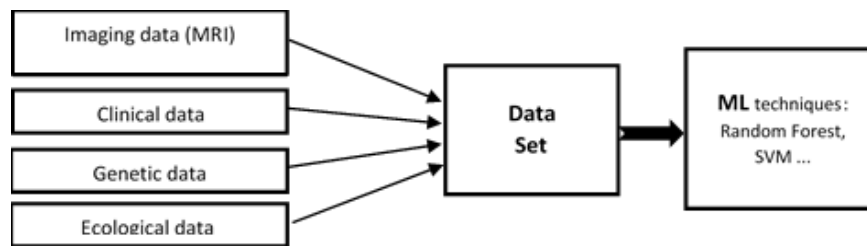


Figure 2. Early sensor data fusion scheme (early sensor-level fusion)

- *Inter-functional integration* - merging data from features, combining features extracted from different data types. Early Fusion from Features methods can be: Principal Component Analysis (PCA), Singular Value Decomposition (SVD), Multidimensional Scaling (MDS), Deep Learning, etc.

By merging features, ML models can be improved, Figure 3 shows a diagram in which data sources are initially processed to extract the characteristic features that describe them. The most significant of them are then selected, which will be used to create models through regression and/or classification. The results can be used in decision-making processes.

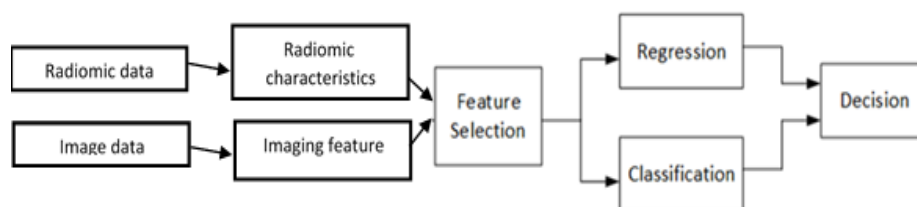


Figure 3. Data merge scheme from functions (Early feature fusion)

- *Late integration* - Late fusion is divided into Late Fusion from Scores and Late Fusion from Decisions. These methods can effectively reduce the error and provide a more accurate final forecast.



Figure 4. Scheme for late merging of results (Late Fusion from Scores)

An example of late decision merging is performing a combination of outputs, through techniques such as majority voting for classification tasks or averaging for regression tasks.

According to a comparative study of methods from different algorithms conducted in (Pereira et al., 2024), ensembles not only improve prognostic accuracy, but also increase the model's robustness to noise and bias, which supports more reliable clinical decision-making.

4. Intelligent application to support the training and adaptation of medical staff

The integration of ML techniques in various areas of medical practice allows for earlier and more accurate diagnosis, precise treatment planning, and effective disease monitoring. Algorithms based on Deep Learning analyze large volumes of data, reveal hidden patterns and dependencies beyond human perception, and offer predictions that rival expert judgment. The approaches considered for interpreting heterogeneous and multimodal data from medical examinations and other sources are related to the task of improving the effectiveness and performance of ML models, their diagnostic and prognostic accuracy.

The report provides an overview of various models and approaches to machine learning in medicine as part of a dissertation study related to the possibilities for integrating artificial intelligence methods and tools to support medical staff in their training and assessment in decision-making processes. The work involves the design and development of an intelligent application to support the activities and adaptation of staff, providing access to targeted resources, guidelines, and recommendations for work, depending on the context of the tasks they perform. The hypothesis is that such an approach can significantly assist medical staff and improve their education and integration into the work environment.

The conceptual framework of the application combines a model of knowledge domains, which will be represented through ontologies for the application domain, a set of technologies supporting knowledge management, and intelligent assistants that implement key functionalities of the system (such as summarization, categorization, and search). This conceptual framework is intended to serve as the basis for building a flexible space in which different approaches and technological options for extracting new knowledge and improving navigation in semantic repositories can be explored and validated. At this stage of the work, basic functional requirements are extracted from the analysis of technological solutions in the field of medicine, which enrich the set of approaches and methods, and can be used in the development of such an application. According to the delegated rights of the user, the system should redirect him to the various knowledge domains, provide access to documentation, provide tools for knowledge analysis, summarized information, and recommendations for effective use.

The knowledge, skills and experience of medical staff to use the technological potential are essential. In this new work environment, a new type of medical literacy is needed - understanding data, algorithms, working with software. The connection between technology and medicine is becoming stronger and well-prepared medical staff is a guarantee of success and prosperity.

Acknowledgment

This research was funded under project KP-06-N86/9/09.12.2024 "IS-PGR-SADOVO Intelligent system for management of the Bulgarian plant gene pool stored in the gene bank of IRGR-Sadovo", Fundamental Research Projects of the National Science Fund of the Ministry of Education and Science of the Republic of Bulgaria.

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Toward GenAI-driven pedagogy

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Abstract: *This paper reviews research on Generative Artificial Intelligence (GenAI) and its roles in education to establish a conceptual framework for GenAI-driven pedagogy. It begins by examining the distinctive features of GenAI in education based on a literature review, analysing psychological, pedagogical, and ethical concerns, and exploring key aspects that could define the scope of GenAI-driven pedagogy. The article then explains the global transition from modern/postmodern pedagogy to GenAI-driven pedagogy and emphasizes that GenAI-driven pedagogy can be understood as encompassing metasystems (systems of systems) within educational theory, curriculum theory, assessment theory, and general didactics. The article is based on the assumption that AI cannot replace teachers or teaching but can serve as a powerful assistant by saving teachers' time on lesson planning, providing insights for affordable didactic materials that match the proficiency levels of learners.*

Keywords: Digital pedagogy, AI-driven pedagogy, GenAI-driven pedagogy, Educational metasystemology, Metasystems learning design thinking.

1. Introduction

Artificial Intelligence (AI) is defined as “a field of research focused on the development and implementation of computer systems capable of performing tasks that typically require human intelligence” (Baillifard et al., 2025). In the context of education, AI refers to the use of artificial intelligence technologies to support, enhance, or transform teaching, learning, and assessment processes by analysing data, personalizing learning, providing feedback, and automating tasks. From this perspective, AI in education can be categorized into profiling and prediction, adaptive personalization, intelligent tutoring systems, and AI-based assessment, each of which enhances instructional and learning effectiveness.

Mollick & Mollick (2023) highlight that AI can assume multiple roles in education, such as tutor, coach, mentor, teammate and simulator, supporting instruction, reflection, feedback, collaboration, task completion, practice, and even learning from the learner. Across all these roles, AI can also serve as a critical thinking partner, helping students analyse ideas from multiple perspectives, uncover assumptions, identify weaknesses, and generate counterarguments.

However, there are also several disadvantages. As noted by Railean,

<https://doi.org/10.58503/icvl-v21y202611>

Pavalachi & Ceobanu (2023), the drawbacks of AI are more related to patterns of thinking. While AI can enhance teachers' ability to monitor students' learning through learning analytics, the diversification of learning environments can create a collapse of reality in students' minds. AI in education is also unable to compete with human soft skills such as curiosity, critical thinking, metacognition, problem-solving, and innovation driven by insight. Intelligent individuals will always be able to communicate, experiment with new ideas, evaluate feedback, observe and solve problems "outside the box," and apply creative solutions to pressing issues.

This paper argues that research on GenAI should prioritize principles of GenAI-Driven Pedagogy to better harness AI's potential for effective teaching, learning, and self-assessment. As research in educational metasystemology evolves, it is crucial to focus on metacognition and assessment within an ecosystem of learning and communication. In this article, we aim to bridge the gap between principles of pedagogy and practical application of GenAI tools in formal education.

2. Perspectives and potential of GenAI tools in formal education

GenAI offers various perspectives and potential in formal education, even as it continues to evolve and reshape traditional teaching and assessment methods. It is effectively integrated in a global ecosystem of learning and communication.

2.1 Perspectives on GenAI in formal education

GenAI is used widely. Students use GenAI tools for writing, research, and projects support. Usually, they use Elephas for writing assistance, Otter.ai for lecture transcription, and various applications for note-taking, document analysis, and interactive learning, such as Google Notebook LM. AI is also utilized for vocabulary building and language learning, with tools like Knowji. Additionally, students use Grammarly for writing improvement, Perplexity for information retrieval, and Kickresume to create tailored resumes and cover letters. Other tools, such as Notion AI, support brainstorming, while Ideogram facilitates visual narrative creation. ELSA Speak, HelloTalk, Talkpal, and EF HelloAI help students practice speaking and listening through real-world conversation simulations.

According to Ng, Chan & Lo (2025), generative artificial intelligence (GenAI) has emerged as a disruptive technology in education, providing new possibilities for personalized learning, content creation (such as images, audio, and video), data analysis, and program code generation instead of traditional AI. GenAI leverages vast amounts of unstructured data from the internet, generates human-like responses across various formats, supports interactive and personalized exchanges, and enables more complex problem-solving. It requires skills such as critical thinking, metacognition and prompt engineering.

Teachers use GenAI to create lesson plans and curricula, design personalized learning activities, provide real-time feedback, and assess student progress. For

instance, tools like ChatGPT can assist in generating lesson content, while platforms like Google Classroom or Edmodo can help with grading and feedback. Additionally, AI-driven tools like Quizlet can help design customized quizzes and flashcards, and Otter.ai can transcribe and summarize lectures. These intelligent tools enable educators to enhance overall teaching effectiveness.

As noted by Hidayat, Armiami & Noviani (2026), the application of AI in education has immense potential to enhance quality of the learning process by facilitating adaptive, effective, and inclusive learning. It is argued that AI influences learning outcomes, learner engagement, automated assessments, and the ethical considerations surrounding its use in education. However, the application of AI in education also presents challenges, such as privacy concerns, and the need for proper teacher training to effectively integrate these novel technologies.

2.2 Potential of GenAI tools in formal education

AI is becoming firmly embedded within contemporary education systems. In formal educational contexts, generative AI (GenAI) tools offer significant potential to support teaching and learning processes and are increasingly used for a range of tasks, including lesson planning, instructional design, and the generation of educational content within digital learning platforms.

First, GenAI tools are used to create and edit presentations (e.g., EduCafe AI, Slides AI, Canva, Tome.app) and to develop lesson plans (e.g., Teacherbot, Piktochart AI Lesson Plan Generator, Monsha AI Lesson Plan Generator, AI.EduKit, LessonPlans.ai, Easy-Peasy AI Lesson Plan Generator, SmartPrep.ai, Wayground AI Lesson Plan Generator, as well as to generate images (e.g., Krea.ai). GenAI tools are used to create audio materials. Some tools convert written text into spoken audio (e.g., Murf.ai, ElevenLabs, Play.ht, NaturalReader, Notevibes), others function as AI-based audio or narration generators (e.g., Synthesia, Lovo.ai, Resemble.ai, Speechify), and still others support foreign language learning and pronunciation practice (e.g., Duolingo Stories & Voice AI, Rosetta Stone AI Tutor). But it is important to use AI as a collaborative/ creative partner, allowing learners to critically reflect and decide.

Second, there are GenAI-powered coding games for kids, which introduce computational thinking and programming concepts through interactive, game-based environments. These tools often use AI to adapt task difficulty, provide real-time feedback, and personalize learning pathways, thereby supporting early engagement with coding skills in an age-appropriate and motivating manner (Petula et al., 2025). Despite their benefits, there are some risks. These include excessive screen time and overreliance on AI support, which may limit the development of independent problem-solving and critical thinking skills. Data privacy and security concerns are particularly significant, given the collection and processing of children's personal data. Additionally, algorithmic bias and opaque decision-making processes may influence learning pathways in ways that are not transparent to learners or educators.

Third, AI may be used to enhance motivation through video. This way can be used as instructional videos, video tutorials, or video-recorded lessons. Instructional videos are video resources used to enhance the teaching and learning process, supporting the acquisition of information, knowledge, and skills through structured and purposeful use of video materials (Beheshti et al., 2018). Video tutorials are instructional videos designed to guide learners through specific concepts, skills, or tasks, often combining visual, auditory, and interactive elements to enhance understanding and engagement. These pedagogical resources can be created by AI video creation tools. The most used video tools are Synthesia, Pictory.ai, Designs.ai Videomaker, Veed.io, InVideo, Lovo.ai, ElevenLabs, and Runway ML (Ou, Joyner & Goel, 2019). The other type is video-recorded lessons (Kure, Blikstad-Balas & Brevik, 2025), where AI tools like Synthesia, Pictory.ai, or InVideo can be integrated in multiple ways, transforming lesson scripts into fully narrated video lessons with avatars, animations, and visuals, or/and AI can adjust tone, speed, or style depending on the target audience. AI can also analyze student interactions with the video (e.g., pause points, rewinds, quiz results) to provide insights for teachers on which parts of the lesson are challenging or can suggest improvements for future video lessons based on student performance.

Fourth, AI enhances visual aids for activity-based learning. Visual aids, including images, diagrams, charts, infographics, videos, animations, and presentations, facilitate understanding by summarizing complex information and supporting participatory learning (Lopez, 2005). AI extends these tools beyond traditional methods by generating educational illustrations, suggesting effective layouts, and creating interactive diagrams such as Venn diagrams and mind maps. The most commonly used AI tools for this purpose include MidJourney and Digibyte for image generation, Canva AI and Microsoft Designer for slide and infographic design, and Notion AI for structuring content and generating diagrams.

Fifth, AI can be used to create educational games, flashcards, and quizzes. These interactive tools combine learning with play, helping students grasp concepts engagingly, memorably, and critically reflect. AI enhances them by generating content, adapting difficulty to student performance, providing real-time feedback, and creating immersive simulations or virtual environments in subjects like science, mathematics, and history. Common AI tools include Kahoot! AI for quizzes, Socrative for assessments, Minecraft Education Edition with AI mods for virtual learning, Labster for science simulations, Gradescope for automated grading, Audiopen.ai for voice-to-text and note-taking, Brainly for collaborative learning, and Smart Sparrow for personalized interactive learning. Overall, AI-powered educational games enhance comprehension, motivation, collaboration, interactivity, and learning outcomes.

GenAI supports the *education of students with disabilities* by adapting and personalizing learning (Pieriboni, Buzzi & Leporini, 2026). Tools such as conversational agents, AI tutors, and chatbots enable interaction via voice or text, helping students with sensory, cognitive, or physical impairments access learning

more effectively. AI also facilitates accessible materials, promotes deep thinking through interactive assessment, and improves learning outcomes. Examples of GenAI tools for students with disabilities include Microsoft Immersive Reader for reading support, Voiceitt for speech recognition for non-standard speech, Otter.ai for transcription and note-taking, Kurzweil 3000 for text-to-speech and study aids, and ChatGPT or other adaptive AI tutors for personalized instruction.

3. Concerns of adopting GenAI in formal education

Recent articles and reports have identified several concerns related to the integration of AI in education. These concerns can be grouped into implementation and technical challenges, psychological issues, pedagogical limitations, and ethical considerations, including infrastructure constraints, learner dependence, alignment with instructional goals, assessment validity, data privacy, and algorithmic bias. These concerns could be represented as an integrity of psychological, pedagogical and ethical concerns driven by technology.

Implementation of AI in education is conditioned by actions that schools, universities, or educators face when introducing AI tools into teaching, learning, curriculum, and management of educational organisations. “Artificial intelligence (AI) offers potential solutions by identifying learning gaps and providing targeted improvements” (Verma et al., 2025). An important issue concerns schools’ readiness to integrate AI into education through the development and implementation of conceptual frameworks and institutional guidelines. As emphasized by UNESCO, educational institutions must establish clear policies that guide AI adoption, ensure alignment with pedagogical goals, protect learners’ rights, and promote teachers’ professional development (UNESCO, 2023).

3.1 Psychological concerns

Psychological concerns relate to the potential impact of AI on learners’ mental and emotional well-being, including motivation, critical thinking, creativity, and active engagement in learning activities, which is multifaceted and context-dependent. For example, Kundu & Bej (2025) provide empirical evidence from 24 relevant studies across seven reliable databases, demonstrating that the use of AI in schools can have both positive and negative impacts on students’ psychological well-being. Benefits include increased engagement, cognitive achievement, self-efficacy, learning autonomy, and reduced frustration. However, drawbacks include over-reliance, anxiety, stress, social isolation, unstable mental health, and moral dilemmas such as privacy concerns, bias, and issues of fairness.

However, GenAI also has “the potential to produce false or inaccurate data and avoid plagiarism detection in situations where originality is crucial” (Emakporuena et al., 2026). AI can be used in foreign language education, as noted by Klimova & Pikhart (2026), but there are multiple issues related to time, learning strategies, and frequency of feedback. Similar issues exist when artificial

intelligence is integrated into computer-based assessment / digital assessment.

One may observe that the widespread adoption of GenAI in education is indirectly related to the global shortage of teachers (Arruda & Arruda, 2026). However, while AI can help address staffing gaps, it raises concerns about the depersonalization of teaching, role of teacher in face of students, pedagogical communication and the potential loss of human insight in the learning process.

3.2 Pedagogical concerns

Pedagogical concerns involve the implications of AI for teaching and learning processes. Ethical concerns focus on fairness, privacy, and accountability. AI systems can perpetuate biases present in training data, compromise student privacy, and operate as “black boxes,” making it difficult to understand or challenge automated decisions. Karatas, Ericok, & Tanrikulu (2025) note that a national curriculum cannot be uniformly applied in all classrooms. Teachers used AI to omit unnecessary content, add more relevant and personalized material, and revise or replace existing content. These findings highlight AI’s transformative potential in curriculum adaptation, making education more relevant and personalized.

The other issue is curriculum development. AI-driven curriculum development is shaped by curriculum approach and its adoption by the community, learning design model of the innovative programs for teacher training, as well as institutional support, while challenges remain in training, tool familiarity, and curriculum bias (Abbasi, Wu & Luo, 2025). A specific issue is the development of AI-supported curricula for early childhood education, which have the potential to enable personalized learning (Qayyum et al., 2025).

Bauer et al. (2025) highlight that AI can influence students’ motivation, creativity, critical thinking, and active engagement in learning, but improper use may undermine knowledge and skill acquisition. Hybrid intelligence seeks to combine human and AI strengths, yet over-reliance on AI can diminish critical thinking, problem-solving abilities, and the development of expertise, especially if students struggle to ask meaningful questions or seek help effectively. Moreover, when using GenAI for content presentation and practice exercises, key challenges include ensuring output accuracy, alignment with curriculum objectives, and maintaining high pedagogical quality, which are critical across all applications.

3.3 Ethical concerns in the adoption of AI in education

Wider adoption of AI in education is constrained also by ethical concerns, including threats to academic integrity, plagiarism, potential biases and falsified information, copyright and intellectual property issues, privacy and data protection risks, and the possible reduction of meaningful human interaction (Perifanou & Economides, 2025; Salloum, 2024). These concerns also encompass broader principles of transparency, justice and fairness, responsibility, autonomy, and accountability in AI-supported educational settings.

According to Saylam et al. (2023, 2025), integration of AI into education has raised ethical challenges driven by misuse of the technology for teaching and learning. UNESCO (2023) found that fewer than 10% of 450 schools and universities have formal policies or guidelines for AI use in education and management, highlighting the risk of unethical practices and difficulty for educators in adapting to AI's expansion. Ethical AI adoption in education requires attention to pedagogical appropriateness, children's rights, AI literacy, and teacher well-being. Pedagogical appropriateness ensures teachers retain professional autonomy while promoting supportive practices. AI literacy emphasizes the need for students to be critically informed about AI benefits and risks.

Ethical concerns in education may be addressed through the integration of AI in teacher education. Kohout-Diaz (2026) emphasizes the importance of sustainable training for future educators, noting that while AI can be a valuable tool in teacher preparation, its use remains inconsistent and often unclear. The lack of structured pedagogical guidance around AI tools places the responsibility on trainees to improvise. Addressing ethical dilemmas in AI requires strengthening both critical and professional literacy, and inclusive-minded trainees call for training that is locally relevant and responsive to their specific needs.

3. GenAI-Driven Pedagogy

Pedagogy is still centered around structured, teacher-directed instruction, with an emphasis on clear content delivery, memorization, and assessment. Thus, in theory, classical pedagogy evolves into modern pedagogy, which emphasizes objectivity, rationality, and hierarchical structures (Baykent, 2025), but the pedagogical triangle remains incorporated within the classical interdependencies between the teacher, student, and content (Bocos & Jucan, 2022, p. 25). Its counterpart, postmodern pedagogy, reveals dynamics, exclusions, and biases within educational systems (*Ibidem*).

The metasystems transition from modern / postmodern pedagogy to GenAI-Driven Pedagogy can be represented, as follows (Figure 1).

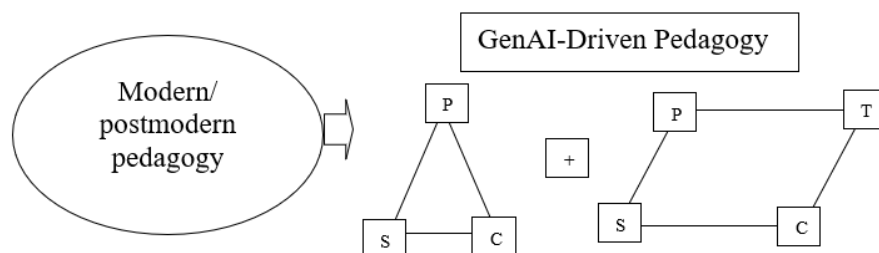


Figure 1. Transition from modern/postmodern to GenAI-Driven Pedagogy, where P-professor, S-student, C-content, T-technology

Moreover, from the perspective of Metasystems Learning Design Theory,

each individual has own capacity to think, adapt, and demonstrate resilience through lifelong learning in response to challenges, while engaging with data, information, knowledge and risks. The problem is how to engage all learners to learn in classroom. One solution is the integrity of effective methods (Railean et al. 2014). Moreover, the capacity to learn is shaped by metacognition and assessment approach and this, highlight a unique role of learner within global ecosystem of learning and communication. In our understanding, educational metasystemology emphasizes metacognition, digital assessment in a global ecosystem of learning and communication (Railean, 2019; Railean, 2022; Railean et al, 2023).

GenAI-Driven Pedagogy is an emerging field within educational and management sciences that examines how AI can support the teaching, learning and assessment process and how learners can use AI responsibly. The focus of AI pedagogy is twofold: the object of study is the didactic processes in which AI is integrated; the subject of study is the learner and the community. In other words, GenAI-Driven Pedagogy does not implement the technology itself, but analyse how the human being, learning processes and outcomes are influenced by AI. GenAI-driven pedagogy can be understood as comprising metasystems in educational theory, curriculum theory, assessment theory, and general didactics (Figure 2).

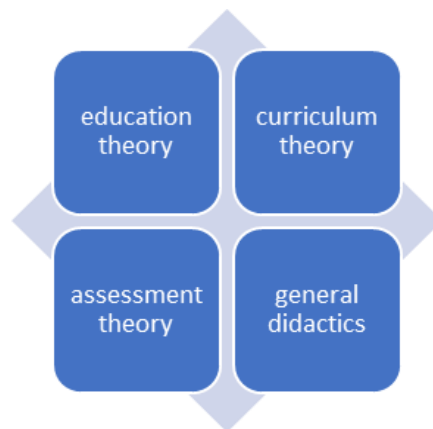


Figure 2. The holistic approach of GenAI-driven pedagogy

In this context, educational theory is focused on sustaining the lifelong capacity to learn across diverse learning environments, emphasizing adaptability, resilience and continuous development of metacognitive knowledge and experience. Curriculum theory centers on the management of data and metadata, as well as their integration into learning pathways to support personalized, flexible and dynamic curricula. Assessment theory incorporates digital assessment methods, addressing both their psychopedagogical dimensions and the implications for learner growth, feedback, motivation and active engagement in exploring the world. General didactics focus on the holistic design of teaching, learning and assessment processes, considering the interconnectedness of cognitive, affective, and social dimensions in the global learning and communication ecosystem. This

holistic approach considers also psychological, pedagogical, and ethical risks. The issue of the pedagogical integration of AI in teacher education, identified by European Schoolnet (Kohout-Diaz, 2026), teacher education can focus not only on the technological aspects of AI but also on metacognition, digital assessment and ecosystem of learning and communication.

4. Conclusion

Pedagogy should come before educational technology. However, education has increasingly adopted generative AI (GenAI) tools due to their potential to support adaptive and personalized learning, enhance student engagement and outcomes, improve understanding of complex concepts, provide individualized feedback, enable innovative assessment practices, and facilitate research and data analysis. A prompt is a natural language input or request given to an AI model to generate a response, and a prompt-based methodology can be used to support collaborative learning, encouraging students to engage actively with AI-generated content. Another important consideration is the impact of AI tools on human thinking. AI can provide a range of resources to enhance metacognitive learning design and support higher-order cognitive processes, including critical thinking, problem-solving, and reflective decision-making. This means that AI is not merely a content-generation tool but a mechanism to foster deeper learning, a useful partner for collaborative and creative tasks that help learners navigate complex systems, and support sophisticated reasoning and design-thinking skills.

The question “*Shaping AI or Being Shaped by It?*” was highlighted in a Fireside Forum hosted by the Global Smart Education Network during the 30th World Conference of the International Council for Open and Distance Education. The forum emphasized that AI should support, not replace, pedagogy. Teachers remain crucial for guiding critical thinking, fostering creativity, and preserving the human dimension of education. As Mr. Maxim Jean-Louis, CEO, warned, AI should not reduce learners to mere prompts. AI must remain grounded in human values, dignity, professional responsibility, and social justice. It requires deliberate strategies to ensure fair and inclusive use of AI in formal education. However, GenAI-Driven Pedagogy cannot be uniform; its effective adoption must be tailored to specific design of learning environments, due to its potential to accelerate personalized, just-in-time learning, as well as collaborative learning strategies.

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Interactive platforms for developing mathematical thinking in fifth grade

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Abstract: *This article presents pedagogical experience related to the integration of three popular digital platforms – Science Buddies, Quizizz and Scratch – in fifth grade mathematics education. The main goal is to promote mathematical thinking by combining an experimental-research approach, gamification and visual programming. Science Buddies provides access to rich resources for science projects and experiments that motivate students to explore real-world problems and apply mathematical concepts in a practical context. Quizizz is used as an interactive tool for testing knowledge and for introducing an element of competition and fun, which stimulates active participation and deepens understanding. Scratch allows students to create animated projects and games, thus applying mathematical operations and algorithmic thinking in a creative environment. The presented practice shows that the combined use of these resources leads to higher motivation, better understanding of mathematical relationships and development of problem-solving skills. The article offers examples from the classroom and outlines opportunities for applying the model in different educational contexts.*

Keywords: Science Buddies, Quizizz, Scratch, Mathematical literacy, Learning, Students.

1. Introduction

Mathematical thinking can be viewed as a set of skills that include logical sequence, abstraction, algorithmic thinking, and working with dependencies. Modern pedagogical research emphasizes that these skills are most effectively developed in conditions of active learning, problem-oriented tasks, and application of knowledge in a real context (Stoitsov & Garov, 2013). In this regard, digital educational platforms offer new opportunities for enriching the learning process in mathematics.

Science Buddies places mathematical concepts in the context of real-world engineering and scientific problems, Quizizz introduces elements of gamification and immediate feedback, and Scratch creates conditions for visualizing abstract relationships through programming. The combined use of these platforms forms the theoretical and practical framework of the present study.

In recent years, there has been an increased interest in the use of digital platforms to develop mathematical literacy and thinking in lower secondary

schools. Research emphasizes project-based learning, STEM/STEAM approaches, and gamification as effective tools for increasing motivation and academic achievement (Garov & Dobrev, 2024). The teacher - innovator "provides students with the tools they need to meet modern challenges" (Angelova & Nikolova, 2024). Platforms such as Gauthmath, Photomath, EducaPlay, Gamma, Prezi and others, working with artificial intelligence, are widely used for visualization of mathematical relationships, formative assessment and development of algorithmic thinking (Velcheva & Kartleva, 2025).

Projects under the name "Little Engineers" are found in various educational contexts, most often as STEM initiatives aimed at integrating science, technology and mathematics. In this article, the "Little Engineers" project is used as an author's pedagogical framework for systematically integrating mathematics with engineering and digital activities in fifth grade, rather than as a reproduction of a specific external program.

Against this background, this study contributes with a model for purposefully combining Science Buddies, Quizizz, and Scratch specifically in mathematics education, with a focus on mathematical thinking, not solely on cross-curricular integration.

2. Exhibition

2.1 Methodology

The subject of the research in the article is the integration of digital educational platforms (Science Buddies, Quizizz and Scratch) into the fifth-grade mathematics learning process, with an emphasis on their use to stimulate mathematical thinking and increase learning motivation.

The object of the study is the learning activities in mathematics in the fifth grade, organized through the application of an experimental-research approach, gamification and visual programming.

The study was conducted during the school year with students (29 in number) from the fifth grade, aged between 11 and 12 years old, from a class with intensive study of information technologies and natural sciences at the "Knyaz Alexander I" Primary School, Plovdiv.

The main goal of the study is to develop, implement and analyze a pedagogical practice for integrating the digital platforms Science Buddies, Quizizz and Scratch into mathematics education, with a view to increasing interest, motivation and effectiveness of the learning process.

The research tasks in this article include: exploring the possibilities of the Science Buddies, Quizizz and Scratch platforms for application in mathematics teaching; building a model for the integrated use of the three platforms in mathematics classes (compulsory and optional) in fifth grade; analyzing the impact of the model on students' motivation, activity and achievements.

2.2 Description of the pedagogical practice - project "Little Engineers"

Within the framework of fifth-grade mathematics education, a pedagogical practice has been implemented - the "Little Engineers" project, based on the integrated use of three digital platforms - Science Buddies, Quizizz and Scratch. The practice is aimed at developing mathematical thinking by combining experimental-research approaches, gamification and visual programming.

The goals set by the authors of the article when implementing the project are for students to:

- develop skills in applying measurements and calculations of lengths, areas and volumes in a practical context;
- learn basic concepts of proportion and ratio by constructing and modeling a drone, rocket, and greenhouse;
- develop spatial orientation and geometric thinking by working with three-dimensional models and instructions;
- apply logical thinking and consistency when performing technological tasks and instructions;
- use digital resources and platforms for problem solving and team collaboration;
- understand the connection between mathematical concepts and real-world engineering applications.

In the first stage of the training, students work with content and projects provided by the Science Buddies platform. They construct models of a drone, a rocket and a greenhouse, applying mathematical knowledge for measuring, calculating area, volume and proportions in the process. In this way, conditions are created for integrating theoretical knowledge with practical activity and for developing skills for research and experimentation. The activities are implemented in mandatory and optional classes and in interest groups in mathematics, natural sciences and information technology.

The developments in Science Buddies are structured according to the engineering cycle "ask-think-plan-create-improve" and provide clear instructions, materials and data sheets that facilitate the targeted introduction of mathematical practices. In the drone model, students make drawings, calculate mass and weight distribution for stability. In the air rocket, they measure the dependent quantities (height, flight time), recording several repetitions and calculating the average value and percentage deviation. In the "greenhouse" project, they compare the surface area and volume ratio, measure temperature and humidity and argue which parameters have the greatest impact on heat retention. Thus, the platform functions as a model for experimental design, in which mathematics is integrated with real engineering solutions.

Assessment and reflection are organized through an experimental plan (goal, hypothesis, variables), data tables, graphs (linear or bar) and short analytical conclusions. Students present prototypes and defenses in which they compare options with mathematical arguments and plan subsequent models. Rubrics with

criteria for correctness of measurements, quality of data visualization, logicity of the conclusion and contribution of each participant make progress visible, both in mandatory and optional classes and interest groups. This sequence develops skills in modeling, working with data and argumentation, while strengthening motivation by meaningfully connecting mathematics with construction and experiments.

In the second stage, the Quizizz platform is used as an interactive tool for diagnostics and practice. Through game tests, students check their acquired knowledge, compete in teams and individually, which stimulates their activity, concentration and striving to achieve better results.

Quizizz's built-in AI generation capabilities make it easy to quickly build quality fifth grade tasks and tests. The teacher provides learning objectives or key concepts, and the system offers an initial set of questions, distractors, and explanations that can be edited by difficulty. Different types of items are supported (multiple choice, short numerical answer, fill in the blank, ordering), which is important when constructing tasks for algorithmic thinking and modeling. AI tools accelerate differentiation. The teacher generates tasks of varying complexity and type.

Gamification using Quizizz (real-time or asynchronous) supports learning designs like "Little Engineers." The rounds in the competitive part of the project can be structured as engineering "sprints" with increasing complexity, time limits, and intermediate checkpoints. Adjustable timers, team competition, and instant feedback keep engagement high, and the ability to alternate instructional and question slides allows for "learning through challenges."

Quizizz diagnostic reports provide detailed analysis in real time and after the lesson - overall success rate, response time, "difficult" tasks and recognition of recurring misconceptions. Based on this data, AI modules support subsequent customization. This makes it easier to track progress between preliminary and final diagnostics, as well as plan subsequent "sprints" within "Little Engineers". Export of results and easy sharing support the consistent building of a repository of validated mathematical thinking tasks in fifth grade.

In the third stage, students work with the visual programming environment Scratch. They create animated projects and educational games in which they use mathematical operations, logical structures and algorithmic models (Velcheva & Dimitrov, 2023). This activity supports the development of creativity, critical thinking and problem-solving skills, while creating positive learning motivation.

Within Little Engineers, Scratch tasks are designed to "spatialize" mathematics—characters navigate a coordinate grid, rotate at specified angles, and scale shapes according to ratios and proportions. Using the Pen extension, students parameterize polygons (e.g., "draw an n-gon of length a"), use variables for perimeter/ area, and create their own blocks for reusing procedures. Lists collect results from random number experiments, allowing for elementary probability simulations.

The organization of the work consists of planning, building, testing, and reflection. Formative assessment is based on rubrics with measures of correctness, algorithm efficiency, code clarity, and mathematical validity.

Table 1. Detailed description of the “little engineers” project

Stage	Platform used	Specific activities	Applied mathematical knowledge and skills
Experimental research approach	Science Buddies	Drone construction (balance, center of gravity). Building a rocket model and observing its flight. Creating a greenhouse and analyzing plant growth conditions.	Proportions and symmetry. Calculating height, speed, working with area and volume, applying mathematical concepts in real-world situations.
Gamification and assessment	Quizizz	Solving interactive tests and tasks. Teamwork and competition between students.	Fast and accurate calculation. Checking and correcting errors.
Visual programming and creativity	Scratch	Programming an animated maze with movement along a coordinate system. Simulation of a rocket launch along a parabola. Creating a "smart greenhouse" with algorithms for regulating temperature and humidity.	Use of mathematical operations and algorithms. Applying knowledge of angles, coordinates and relationships. Development of logical and creative thinking, problem-solving skills.

2.3 Practical results and effects on the students

The analysis of the results was conducted by combining qualitative and quantitative methods: observation, analysis of student products, diagnostic tests in Quizizz, and a study motivation survey.

At the beginning and end of the project, a diagnostic of mathematical knowledge was conducted using an identically structured test. The average score of the class increased from 62% at the beginning to 78% after the project was completed. The most significant improvement was observed in tasks requiring work with proportions, coordinate systems, and data interpretation.

The survey shows that 83% of students describe math classes as “more interesting” compared to the traditional format, and 76% say they understand better “what math is for in real life.” Teacher observations report increased activity, more frequent teamwork, and a greater willingness to argue for solutions.

These results are indicative and do not claim statistical generalizability, but they confirm the positive effect of implementing the integrated model.

It is observed that students are more evenly involved in group work and that roles are more clearly defined when solving problems. Oral defenses of solutions and presentation of prototypes show better argumentation and more accurate use of mathematical concepts when explaining choices.

3. Conclusion

The presented pedagogical practice shows that the integration of Science Buddies, Quizizz and Scratch into fifth grade mathematics education creates conditions for a deeper understanding of mathematical concepts and for the development of key skills – logical and algorithmic thinking, working with data and problem solving. Despite the limitations of the research design, the results show a sustainable positive trend in terms of motivation and academic achievement.

Future research could expand the presented model by forming an experimental and control group for the purpose of statistical comparison of the results. It is recommended that the model be tested in more than one grade and in different school contexts to check the sustainability of the effect with different student profiles. Scaling up could include developing a set of ready-made scenarios and assessment rubrics to facilitate implementation and ensure comparability of the results. Of additional interest is the long-term follow-up of the effects on mathematical literacy and interest in STEM subjects.

Acknowledgments

This study is financed by the European Union-NextGenerationEU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project DUECOS BG-RRP-2.004-0001-C01.

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Risk management in social media: An educational framework for building digital security in the context of NIS2

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Abstract: *Social media platforms have become one of the central components of the contemporary digital environment, used for personal communication as well as for organizational and societal purposes. Alongside the opportunities they provide, these platforms also represent a significant source of information security risks, including social engineering, impersonation, disinformation, and data leakage. This paper examines risk management in social media in the context of Directive (EU) 2022/2555 (NIS2) and the guidelines of the European Union Agency for Cybersecurity (ENISA), considering social media as part of a broader digital ecosystem subject to systematic risk management. The main contribution of the study is educational and methodological. A model is proposed for integrating social media risk management into education, combining practice-oriented pedagogical approaches with a methodology for effectiveness measurement based on the HAIS-Q questionnaire.*

Keywords: Social media, Artificial Intelligence, Cybersecurity, Information security, NIS2, Risk management, Training, HAIS-Q.

1. Introduction

Over the past two decades, social media (SM) has transformed from a space for personal communication into a critical element of modern corporate and public digital infrastructure. SM platforms have become indispensable tools for business development, public communication, and crisis management. According to the classification by Kaplan & Haenlein (2010), these platforms—ranging from collaborative projects (Wikipedia) to social networking sites (Facebook, X, LinkedIn)—have become vital for stakeholder engagement. However, the mass integration of SM into the corporate and public sectors expands the attack surface by exploiting their informal nature and turning them into a serious vulnerability, leveraged through various tools such as phishing, disinformation, and identity theft (Boyd & Ellison, 2007).

1.1 Social media in the context of cybersecurity and NIS2

In response to evolving cyber threats, the European Union adopted Directive (EU) 2022/2555 (NIS2) in 2022 to harmonize cybersecurity across Member States (European Union, 2022). While NIS2 does not directly regulate social media, it treats them as part of an organization's digital ecosystem. Since these platforms are integrated into all business and management processes, they fall within the scope of mandatory risk management. Compromising institutional accounts can lead to reputational, financial, and legal consequences, threatening the overall resilience of the entities.

Risks in such an environment are hybrid—combining complex infrastructure with a powerful human factor (ENISA, 2023b). Blurred boundaries between personal and professional identity create challenges for control and compliance, turning SM into an attack surface where technical vulnerabilities intersect with psychological manipulation.

The unique attack surface presented by SM makes it both a critical digital vector and an interesting object for study and analysis. This paper examines the interaction between SM and information security, focusing on threats, providing examples of real incidents, and outlining educational applications in the context of NIS2.

2. Key threats and sectoral trends

This section presents the dominant threats, selected not through a formal taxonomy but based on the risk factor and the way SM amplifies their impact. The current analysis views dominant threats not as isolated problems but as a complex combination of behavioral and organizational factors.

2.1 Human factor related attacks

The human factor is the most frequently exploited vulnerability through psychological manipulation.

- **Social Engineering:** The most commonly exploited vulnerability, relying on trust and human habits rather than technical sophistication (Mitnick & Simon, 2002). Approximately 30% of social engineering campaigns target the general public, while 18% target public administration (ENISA, 2023b). They are most often associated with "external" phishing.

- **Internal Risks:** Threats arising from employee negligence (unintentional sharing of sensitive data, weak passwords) rather than targeted attacks. Research by Schultz et al. (2021) emphasizes that insiders remain one of the most persistent threats.

2.2 Information manipulation and disinformation

SM platforms enable the large-scale dissemination of false content to undermine trust—47% targeted at citizens and 29% at institutions, according to

data from (ENISA, 2023b). These threats blur the line between cybersecurity and information warfare.

An **example** is the Twitter breach of July 15, 2020, where spear-phishing was used to compromise over 130 official accounts (X, 2020; Isaac, Frenkel & Griffith, 2020).

2.3 AI-Supported attacks

Generative Artificial Intelligence (GenAI) facilitates the creation of convincing phishing messages and "deepfakes" (voice and video impersonation), which complicates the distinction between legitimate and malicious communication and necessitates a reassessment of trust mechanisms (ENISA, 2023b). This requires the adaptation of both technical safeguards and educational approaches.

2.4 Sectoral trends and context

For the period from July 2022 to June 2023, ENISA documented over 2,580 significant incidents. The most affected sector is public administration (19%), followed by healthcare (8%). In many of the aforementioned 2,500+ incidents, SM platforms acted as the initial contact channel or an amplifier of the impact.

The specificity of each sector requires adapted strategies, as universal measures are often insufficient against specific and cascading effects affecting multiple industrial, regional, national, and cross-border structures simultaneously.

3. Regulatory context: The NIS2 directive

The complexity of risks in social media necessitates the use of best practices and regulatory frameworks such as NIS2 for the structured management of digital risk. Although SM platforms are not directly regulated entities, their impact on operational resilience and the potential for data compromise means they must be addressed in every cybersecurity strategy (European Union, 2022). This section highlights some of the most relevant provisions of the Directive in this context.

- When SM are used for communication or public relations, they may fall under the regulation of **Article 21 (Risk Management)**, which obliges entities to implement “appropriate and proportionate technical, operational, and organizational measures.”

Organizations often use external tools to manage their social media presence—such as scheduling platforms, analytics dashboards, content generators, or influencer partnerships. NIS2 expands cybersecurity responsibility to include such service providers, treating them as part of the digital **Supply Chain (Article 22)**.

When activities in SM are linked to significant incidents affecting the availability of essential services or data confidentiality, they are subject to reporting to the national CSIRT (early warning within 24 hours) — **Incident Reporting (Articles 23 and 24)**.

According to **Article 21(2)**, training is key to mitigating the impact of the human factor. It is recommended to integrate practical scenarios into training curricula through simulated phishing via direct messages, analysis of real disinformation attacks, and tabletop exercises for identity theft response.

Such programs significantly impact the “human layer” of cybersecurity and support long-term organizational resilience (ENISA, 2021; ENISA, 2023c).

4. Methodological model for education in social media risk management and measurability (HAIS-Q)

Effective risk management in social media cannot be achieved solely through policies and technical controls. As demonstrated in the previous sections, a substantial proportion of threats originate from human behavior, decision-making processes, and limited contextual awareness when interacting with social platforms. Consequently, education and awareness-raising should be regarded as core components of sustainable cybersecurity, in line with the principles of the NIS2 Directive and the recommendations of ENISA.

This section proposes a methodological educational model aimed at students from different academic disciplines and educational levels. The model integrates theoretical knowledge, practical activities, and outcome measurement through the Human Aspects of Information Security Questionnaire (HAIS-Q).

4.1 Educational objectives and expected learning outcomes

The primary objective of the proposed model is to support students in developing sustainable knowledge, attitudes, and behavioral patterns related to social media risk management. The educational focus extends beyond threat recognition to fostering critical thinking, situational assessment, and the practical application of good security practices in real-world contexts.

The expected learning outcomes include:

- understanding the specific risks arising from the use of social media in organizational environments;
- the ability to identify scenarios involving social engineering, disinformation, and impersonation;
- applying fundamental risk management principles aligned with NIS2 requirements;
- developing responsible behavior in the use of social media in both personal and professional contexts.

4.2 Teaching and learning approaches

The proposed model relies on a combination of pedagogical approaches that reflect the dynamic and hybrid nature of social media environments. Core methods include:

- case-based learning, including the analysis of real-world incidents;
- scenario-based learning and tabletop exercises involving fake profiles, disinformation campaigns, and compromised accounts;
- discussions addressing ethical and reputational aspects of online behavior;
- hands-on tasks focused on configuring security settings (e.g., multi-factor authentication, access management);
- short critical-thinking assignments aimed at recognizing manipulative content.

This approach supports the transition from “knowing” to “doing” by placing students in an active role and encouraging reflection on the consequences of actions taken in social media environments.

4.3 Adaptation across disciplines and educational contexts

A key strength of the model is its multidisciplinary applicability. Social media risk topics can be integrated into courses such as information security, cybersecurity, social media and communications, internet-based technologies, public administration, as well as non-technical disciplines.

Depending on the academic profile, instructional emphasis may be placed on:

- risk analysis, policies, and regulatory compliance;
- threat modeling and social engineering techniques;
- reputational risk, ethics, and disinformation;
- digital identity, platform governance, and access control;
- media literacy and digital hygiene.

This flexibility allows the model to remain relevant across faculties and degree programs while preserving conceptual coherence.

4.4 Effectiveness assessment and continuous improvement using HAIS-Q

A central element of the proposed model is the use of HAIS-Q as a tool for evaluating educational effectiveness. HAIS-Q measures three core dimensions - knowledge, attitudes, and behavior - making it particularly suitable for educational environments.

Within the training process, the questionnaire may be used:

- as a pre-assessment tool to establish baseline awareness levels;
- as a post-assessment instrument to measure learning outcomes;
- to identify weaknesses across specific domains (e.g., phishing, password management, information sharing);
- as a basis for adapting and improving instructional content.

In this way, education becomes a measurable, iterative process of continuous improvement, focused on behavioral change rather than solely on theoretical knowledge acquisition.

4.5 Education as a factor of cyber resilience

Developing organizational resilience to social media-related threats is not purely a technical or regulatory challenge; it is fundamentally an educational one. The NIS2 Directive emphasizes the importance of training and awareness at all organizational levels, while ENISA analyses consistently identify human behavior as both a key vulnerability and the greatest opportunity for improvement.

In this context, education fulfills a dual role: it prepares future professionals to recognize and manage risks, and it fosters a culture of responsible and informed social media use. As such, education represents a long-term investment in the resilience and security of the digital environment.

5. Risk management approaches and good practices

The NIS2 Directive provides a regulatory framework, but its effective implementation depends on organizations adopting specific measures tailored to their context. Social media-related risks, due to their hybrid nature - technical, behavioral, and reputational - require an interdisciplinary approach that combines technical safeguards with policy, training, and culture-building.

The following use cases demonstrate how organizations across different sectors have approached social media risk in ways that reflect both the spirit of NIS2 and best practices recommended by ENISA and ISO/IEC 27001. These examples also serve as models for entities not formally covered by NIS2 but still highly exposed to social media threats.

5.1 Social media impersonation in the education sector

In a mid-sized secondary school, several teachers received what appeared to be an urgent request from the school principal via both Facebook Messenger and institutional email. The message asked for students' personal data under the pretense of updating emergency contact records. A vigilant staff member noticed subtle inconsistencies in the message's tone and phrasing, prompting an internal review.

It was discovered that a fraudulent Facebook profile had been created using the principal's public image and biographical information. The attacker combined this impersonation with spoofed internal emails - a hybrid attack exploiting both social media and traditional communication channels.

Although the school was not directly regulated under NIS2, it adopted several measures aligned with the directive's principles:

- Internal communication policy was revised to prohibit the exchange of sensitive data outside authenticated systems;
- All staff received targeted training in recognizing social engineering techniques;
- A verification protocol was established for unusual requests, including a mandatory second communication channel for confirmation.

This case reflects how non-regulated entities can voluntarily implement risk-aware behaviors in line with NIS2 Articles 21 and 24, particularly in the education sector, which ENISA classifies as a high-exposure environment (ENISA, 2023a).

5.2 Data exposure via linkedin in a professional services firm

A GDPR and ISO/IEC 27001-certified accounting firm experienced a reputational incident when an employee shared a celebratory post on LinkedIn. The accompanying photograph, taken at their workstation, inadvertently revealed a spreadsheet on a monitor containing sensitive client information (e.g., VAT numbers, internal identifiers).

Although the post was removed within hours, the incident highlighted a blind spot in the firm's digital hygiene. A root-cause analysis concluded that existing controls focused on internal systems but not on employee behavior in public digital spaces.

In response, the firm implemented a layered governance model for social media, including:

- A review and approval process for posts made from corporate devices or accounts;
- Mandatory training for all staff on oversharing, privacy by design, and personal branding ethics;
- Quarterly social media audits as part of the internal audit cycle.

This approach demonstrates the alignment of social media governance with Article 21 of NIS2 and Clause A.7 of ISO/IEC 27001, emphasizing awareness, access control, and acceptable use policies.

5.3 Social engineering against a small business through instagram spoofing

A small artisan enterprise, reliant on platforms like Instagram for client engagement and Stripe/PayPal for sales, received a message allegedly from Meta's support team. The message claimed copyright infringement and urged the owner to log in via a provided link. Although the login page was a spoof, the business was protected by two-factor authentication (2FA), which prevented account takeover.

The event served as a wake-up call for the owner, who took the following steps:

- Created an asset inventory including social media accounts;
- Implemented password management using a secure vault;
- Established weekly backup procedures for web and social media content;
- Drafted an incident checklist for social engineering attempts.

This case reflects the relevance of ENISA's Cybersecurity Guide for SMEs (ENISA, 2022b), and demonstrates how NIS2 principles (risk identification, response preparedness, and cultural awareness) can be adapted at a micro-enterprise scale.

5.4 Organizational social media checklist

Beyond formal regulation and sectoral trends, organizations need actionable tools to assess their internal readiness for secure social media use. A checklist is an accessible, adaptable mechanism that supports continuous improvement and operational alignment with both NIS2 expectations and general cybersecurity frameworks such as ISO/IEC 27001.

Such tools are particularly useful for SMEs and non-regulated entities, offering a structured way to identify vulnerabilities, enforce accountability, and prioritize remediation. This approach reflects the risk-based methodology promoted in Article 21 of the NIS2 Directive and ENISA's guidance on establishing cybersecurity maturity (ENISA, 2022a), (ENISA, 2022b).

5.5 Social media governance self-assessment questions:

- Do we have a documented and up-to-date social media policy?
- Are roles and responsibilities clearly defined for account access and content management?
- Do all organizational accounts use strong passwords and multi-factor authentication (MFA)?
- Are posts from official channels reviewed or approved before publication?
- Is there a process for monitoring account activity and identifying anomalies?
- Are employees trained regularly on social media risks such as phishing and oversharing?
- Is social media included in the organization's incident response plan?
- Have we reviewed the security posture of third-party platforms (e.g., scheduling, analytics)?
- Do we have procedures for revoking access when employees leave or roles change?
- Is there a designated point of contact responsible for coordinating digital communications and security?

This checklist can serve as the foundation for more advanced governance tools, such as internal audits, KPIs for cybersecurity posture, or integration into broader digital risk assessments. When used proactively, it transforms social media from a liability into a managed and measurable component of the organization's digital ecosystem.

6. Teaching and awareness implications

Developing organizational resilience to social media threats is not solely a technical or regulatory matter - it is fundamentally educational. NIS2 emphasizes the importance of training and awareness across all organizational levels (Article 21), while ENISA consistently identifies human behavior as both a key

vulnerability and the greatest opportunity for improvement (ENISA, 2022a), (ENISA, 2023c).

Social media poses unique pedagogical challenges and opportunities. Its informal tone, dynamic pace, and blending of personal and professional boundaries make it difficult to govern using static policies alone. Education must therefore equip individuals - not only security professionals, but also communication officers, HR staff, and students - with the skills to recognize, assess, and respond to risks in these environments.

6.1 Integrating social media security into cybersecurity curricula

Formal cybersecurity training and academic programs increasingly include modules on risk governance, digital identity, and online manipulation. However, social media is often treated as a peripheral topic. Given its growing relevance, educators should embed it directly into core curricula, using real-world incidents and simulations to drive engagement and critical reflection.

For example, case studies like the 2020 Twitter breach or Instagram phishing messages can be used to:

- Analyze how technical and human failures interact;
- Practice incident response planning and root cause analysis;
- Discuss organizational accountability and reputational risk.

ENISA's Cybersecurity Training Guidelines (ENISA, 2021) recommend scenario-based learning, cross-functional exercises, and practical tool use - strategies well-suited to teaching social media risk management.

6.2 Targeting learners at multiple levels

Cybersecurity awareness must be tailored to the audience. For younger students, especially in secondary and early tertiary education, media literacy and personal digital hygiene are foundational. OECD studies emphasize that empowering young users to critically evaluate online content is essential to long-term security culture (OECD, 2021).

For university students and professionals, especially in IT, law, journalism, or public administration, more advanced competencies are needed. These may include:

- Threat modeling for public-facing accounts;
- Regulatory compliance for content and data;
- Ethical guidelines for institutional communications.

The European Commission's DigComp framework (European Commission, 2019) outlines five dimensions of digital competence - information literacy, communication, content creation, safety, and problem-solving - all of which are relevant when navigating social media securely.

6.3 Measuring training effectiveness with hais-q

The HAIS-Q model includes seven behavioral domains (e.g., password management, internet use, social networking) and evaluates three dimensions for

each: knowledge, attitude, and behavior. Participants respond using a five-point Likert scale ranging from “strongly disagree” to “strongly agree.”

This tool allows organizations to benchmark their staff’s digital risk awareness before and after training and identify domain-specific weaknesses (e.g., oversharing on LinkedIn);

The final purpose is not only to gauge awareness but also to shape behavior over time through reflection, feedback, and policy alignment.

6.4 Creating a culture of shared responsibility

Organizations that foster a security culture - where every employee understands their role in protecting digital assets - report significantly fewer incidents caused by negligence (ENISA, 2023c), (Schultz, Proctor, Lien & Salvendy, 2021). Social media presents a clear opportunity to reinforce this culture, as nearly every department interacts with these platforms.

To that end, educational efforts should include:

- Policy co-creation workshops involving staff across departments;
- Regular phishing simulations using social messaging contexts;
- Story-based learning, using internal or public incidents to foster discussion.

Ultimately, the goal is to shift from compliance-driven behavior to proactive digital citizenship, where individuals feel both empowered and accountable. As ENISA’s 2023 culture guidelines state, “Awareness is not the goal - behavioral change is” (ENISA, 2023c).

7. Conclusion

Social media has become a defining element of modern organizational life, serving simultaneously as a critical communication channel and an expanding vector for cyber threats. As demonstrated throughout this paper, the integration of social platforms into business, education, public administration, and civic engagement creates a dual reality in which opportunities for outreach, visibility, and dialogue coexist with vulnerabilities related to data protection, impersonation, disinformation, and human error.

The evolving threat landscape, as documented by ENISA and related studies, increasingly exploits openness, immediacy, and trust-based interactions characteristic of social media environments. In such conditions, traditional technical controls alone are insufficient unless complemented by coherent policies, continuous training, and risk awareness across all organizational roles.

Although the NIS2 Directive does not explicitly regulate social media platforms, it establishes legal and organizational obligations that require entities to address their digital presence in a holistic manner. Incident response preparedness, staff training, and third-party risk management all implicitly encompass social media governance. The case studies and sectoral practices presented in this paper demonstrate that effective social media risk management is achievable across

diverse organizational contexts and sizes, if strategies are aligned with a culture of cybersecurity and shared responsibility.

Education emerges as a central enabler of this transition. By embedding social media risk topics into cybersecurity and related curricula, promoting awareness at multiple organizational levels, and modeling responsible digital behavior, both educational institutions and organizations can strengthen long-term cyber resilience.

Ultimately, the ability to leverage the benefits of social media while systematically managing its risks will become a defining capability of digitally mature and resilient institutions.

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SECTION 2

INSTRUCTIONAL DESIGN IN DIGITAL ERA

A bidirectional model for analytics-informed assessment and asynchronous learning design

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Abstract: *This paper presents a bidirectional model that connects asynchronous learning design and assessment using learning analytics and intelligent optimization. In the forward workflow, interaction data from a Moodle-based LMS are analyzed to identify usage patterns of asynchronous activities and to derive an assessment-oriented ATS (Achievement–Transfer–Stability) profile through fuzzy interpretation. In the backward workflow, a genetic algorithm is used to generate and optimize asynchronous learning paths aligned with a desired ATS target. The results show how learning analytics can support both the analysis of existing course designs and the generation of assessment-driven learning activity sequences, contributing to more coherent and stable online learning experiences.*

Keywords: Asynchronous learning, Assessment design, Instructional design, Learning analytics.

1. Introduction

In online and asynchronous learning environments, assessment is increasingly supported by data generated by digital learning platforms, yet the relationship between learning activity design and assessment design often remains implicit. As a result, assessment design frequently remains a separate layer, configured independently from the activity structure that shapes learning behavior.

This separation creates a structural gap: the same instructional design may lead to different learning contexts depending on how learners interact with activities, while assessment instruments often assume stable learning conditions and comparable exposure to learning tasks. Consequently, designing evaluation in asynchronous contexts requires more than selecting tests or rubrics; it requires an explicit model that connects the learning design context (what learners actually do in the LMS) with the dimensions of learning performance that can be validly inferred. However, current LMS implementations rarely provide a conceptual framework capable of explaining this relationship in a bidirectional and adaptive way.

To address this gap, this paper proposes a bidirectional model linking Asynchronous Learning Design (ALD) with a multidimensional assessment

framework, Achievement–Transfer–Stability (ATS). The model integrates a forward workflow, in which learning analytics indicators extracted from Moodle logs inform the configuration of assessment dimensions, and a backward workflow, in which a desired ATS profile drives the generation and optimization of asynchronous learning paths. In this way, assessment becomes a dynamic design component, informed by real interaction data and aligned with instructional structure.

This paper proposes a conceptual model for an intelligent and dynamic assessment system based on a bidirectional relationship between Asynchronous Learning Design (ALD) and a multidimensional assessment framework (Achievement–Transfer–Stability), integrating learning analytics and intelligent optimization. Structurally, the paper first introduces the ALD–ATS conceptual model, then presents the research methodology and workflows based on LMS log data, and finally illustrates the approach through an exploratory analysis of real asynchronous learning data.

2. Literature research

Educational assessment theory views evaluation as an inferential process about learning outcomes, emphasizing validity and the relationship between learning context, assessment tasks, and interpretation of results (Messick, 1995; Kane, 2013). From this perspective, separating instructional design from assessment design weakens evaluation claims, a concern addressed in instructional design research through constructive alignment and backward design, which stress the alignment of assessment with learning activities and intended outcomes (Biggs, 1996; Wiggins & McTighe, 2005), particularly in asynchronous online learning contexts with diverse learner behaviors. Beyond achievement, learning quality is also reflected in knowledge transfer and stability over time (Perkins, 1992; Bransford et al., 2000), motivating multidimensional assessment perspectives. In parallel, learning analytics and educational data mining demonstrate that LMS activity logs can inform assessment and instructional design by capturing learner engagement and self-regulation (Siemens & Baker, 2012; Viberg et al., 2018), while research on intelligent educational systems shows that machine learning, fuzzy logic, and evolutionary algorithms can support instructional decision-making when embedded in pedagogically grounded models (Dede, 2014; Holmes et al., 2019). Together, these perspectives support combining analytics-informed assessment with backward design of asynchronous learning paths to better synchronize instructional design and evaluation.

3. Model description

3.1 General description

The proposed model presents a dynamic assessment framework that aligns asynchronous learning design with evaluation through a bidirectional process. It integrates Asynchronous Learning Design (ALD) and a multidimensional assessment profile based on Achievement, Transfer, and Stability (ATS), mediated by an intelligence layer combining machine learning, fuzzy logic, and genetic algorithms. The model supports context-aware and goal-driven assessment design in online learning environments without relying on direct assessment data.

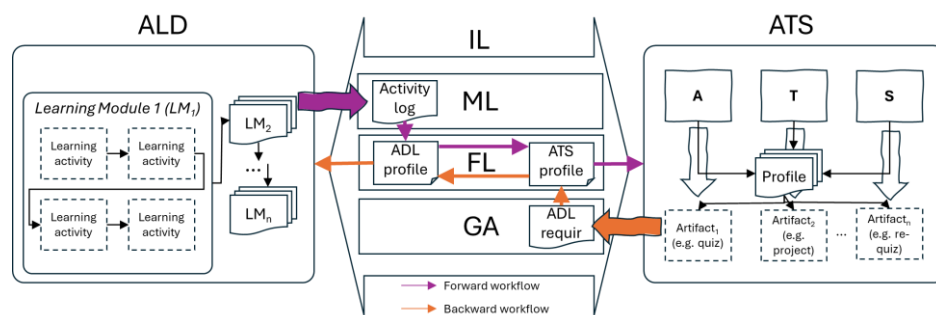


Figure 1. The conceptual representation of the model

In simple terms, the model uses data about how learners interact with online activities to determine what kind of assessment makes sense in a given context, and then uses the desired assessment goals to guide the design of asynchronous learning activities.

3.2 Model structure

3.2.1 General structure

The model consists of three main components: Asynchronous Learning Design (ALD) includes the activity set, Achievement–Transfer–Stability (ATS) profile, and an intelligence layer.

3.2.2 Asynchronous Learning Design Component (ALD)

Asynchronous Learning Design (ALD) represents the instructional scheme of an online learning environment and defines how learning activities are selected, structured, and sequenced over time. It captures the intended learning path independently of learner behavior or assessment outcomes, focusing exclusively on the pedagogical organization of asynchronous activities and the cognitive processes they are designed to support. The elements of the ALD component are:

- the activity set, which comprises the complete set of asynchronous learning activities available in a course;

- the individual learning activity, which is the basic design unit of ALD and has the next characteristics: (1) type: (e.g., resources, quizzes, assignments, forums, reflections), (2) cognitive role (consolidation, application, reflection), (3) temporal position within the course, (4) mode of participation (individual or collaborative), (5) degree of openness (closed, semi-open, open), (6) estimated workload.

The organisational structures of the ALD component are: (1) the hierarchical organisation (micro – individual activity, meso – module, and macro – learning path levels); (2) the sequential learning path, which is the explicit ordering and flow of activities, usually in a linear sequencing.

The main proprieties of this component are: the balance between consolidation, application, and reflection, the supported cognitive depth, the temporal distribution of learning activities, the overall workload structure.

Within the proposed framework, ALD defines the pedagogical space in which learning occurs and constrains the types of learning outcomes that can be evaluated validly. By explicitly modeling the structure and flow of asynchronous activities, ALD provides a stable foundation for analytics-informed assessment design and for the backward generation of learning paths driven by assessment objectives.

3.2.3 Assessment Design (ATS)

Assessment Design based on Achievement–Transfer–Stability (ATS) represents the evaluative intent of a learning environment by modeling learning performance along three core dimensions. ATS does not describe assessment instruments or scores but defines which dimensions of learning are targeted for evaluation and to what extent, in a form that can be operationalized and aligned with asynchronous learning design. The elements of the ATS component are:

- the assessment dimensions: (1) Achievement (A) – evaluation of immediate knowledge acquisition and understanding; (2) Transfer (T) – evaluation of the ability to apply knowledge in new or different contexts; (3) Stability (S) – evaluation of the persistence of learning outcomes over time.
- the profile (assessment configuration), which specifies how the assessment dimensions are combined and prioritized: (1) active assessment dimensions (A, T, S); (2) relative weights or emphasis assigned to each dimension; (3) overall assessment orientation (e.g., achievement-focused, transfer-oriented, balanced).
- the assessment artifacts, which are concrete realizations of the ATS profile within a learning environment, described by: (1) artifact types (e.g., quiz, project, case study, reflection task); (2) targeted ATS dimension(s).

In this work, ATS is intentionally limited to a compact, operational profile describing the relative emphasis on Achievement, Transfer, and Stability, which is used directly for reasoning and optimization.

3.2.4 Intelligence Layer (IL)

The Intelligence Layer provides the computational mechanisms that connect Asynchronous Learning Design (ALD) and the Assessment profile (ATS). It does not introduce new pedagogical constructs but operationalizes the bidirectional relationship between learning design and assessment through data interpretation, pedagogical reasoning, and optimization. The IL elements are:

- Context Extraction (usage of Machine Learning): its role is to interpret LMS activity data and derive a contextual description of how the asynchronous learning design is used in practice. It has the next structure: (I) Input: (1) LMS activity logs and (2) derived indicators, described in Variables section. (II) Process: includes: (1) pattern detection and clustering and (2) context classification. (III) Output: ALD context profile.
- Pedagogical Reasoning (usage of Fuzzy Logic): its role is to generate and optimize asynchronous learning paths that align with a desired ATS profile under given constraints. It has the next structure: (I) Input: (1) ALD context profile and (2) ATS target profile (forward) / ATS current profile (backward). (II) Process: includes: (1) linguistic variables, (2) membership functions and (3) fuzzy rules. (III) Output: ATS profile (forward) / ALD requirements (backward).
- Design Optimisation (usage of Genetic Algorithms): its role is to generate and optimize asynchronous learning paths that align with a desired ATS profile under given constraints. It has the next structure: (I) Input: (1) ATS target profile, (2) ALD activity set and (3) design constraints. (II) Process: includes: (1) population of candidate ALD paths, (2) fitness evaluation based on ALD–ATS alignment and (3) selection, crossover, mutation. (III) Output: optimized ALD paths.

Within the ALD–ATS framework, the Intelligence Layer acts as a mediator that translates data into context, context into pedagogical decisions, and assessment goals into instructional structures.

3.3 Variables

The proposed model operates on a compact set of pedagogical, contextual, and optimization variables that enable the alignment between asynchronous learning design and assessment. Variables are defined at three levels—ALD, ATS, and the Intelligence Layer—and are intentionally limited to those used directly for context interpretation, pedagogical reasoning, and design optimization.

Table 1. The variables used within the model

Component	Variable	Description
ALD	a_type	Type of asynchronous activity
	a_role	Cognitive role of the activity (consolidation, application, reflection)

	a_time	Temporal position of the activity
	a_mode	Participation mode (individual / collaborative)
	N_app	Number of application-oriented activities
	N_revisit	Number of planned revisits
	TD	Temporal distribution of activities
ATS	A	Achievement dimension
	T	Transfer dimension
	S	Stability dimension
	A_w, T_w, S_w	Relative weights of ATS dimensions
ML	freq	Activity frequency
	regularity	Regularity of activity over time
	revisit_rate	Rate of repeated access
	temporal_spread	Distribution of activity in time
Fuzzy	ALD_applicative	Applicative level of ALD (low–high)
	ALD_temporal	Temporal quality of ALD
	A_support, T_support, S_support	Degree of support for ATS dimensions
GA	K	Fixed number of activities in a learning path
	fitness	Alignment between ALD and ATS
	constraints	Design constraints (time, workload)

These variables provide a minimal but sufficient representation of instructional structure, assessment intent, and intelligent mediation.

3.4 Methods and tools

The proposed methodology combines learning analytics, fuzzy reasoning, and evolutionary optimization to support a bidirectional alignment between asynchronous learning design (ALD) and assessment intent (ATS).

Table 2. Methods and tools used within the model

Layer	Method	Key elements (what is used)	Input/Output	Tools
Data	Log analysis	Activity access events, course structure	Input: Moodle logs Output: aggregated indicators	Moodle DB, SQL
ML	Unsupervised learning	Variables: frequency, regularity, revisit rate, temporal	Input: normalized indicators	Orange Data Mining, Python

		spread, activity focus	Output: ALD context variables	(scikit-learn)
Fuzzy Logic	Rule-based inference	Linguistic variables (low/medium/high), membership functions, IF-THEN rules (ALD $\rightleftharpoons$ ATS)	Input: ALD variables or ATS targets Output: ATS profile or ALD requirements	Python fuzzy libraries
GA	Evolutionary optimization	Gene: (activity type, cognitive role, participation mode) Chromosome: ordered fixed-length sequence of genes (learning path) Operators: selection, crossover, mutation Fitness		
Integration	Bidirectional workflow	Forward: ML $\rightarrow$ Fuzzy $\rightarrow$ ATS	Backward: ATS $\rightarrow$ Fuzzy $\rightarrow$ GA $\rightarrow$ ALD	Synchronized design-assessment

These methods are integrated into a coherent framework where learning analytics inform assessment configuration, and assessment objectives drive the generation of asynchronous learning designs.

3.5 Model workflow

3.5.1 Forward workflow (FW)

The forward workflow (FW) describes the process through which information derived from the use of asynchronous learning activities is employed to configure a context-aware assessment profile. This workflow operates from learning design usage (ALD) toward assessment intent (ATS) and is driven by LMS activity data rather than assessment results. The steps of the FW are:

1. ALD usage data collection. Interaction data are extracted from LMS activity logs, capturing how learners' access and revisit asynchronous learning activities over time;
2. Feature extraction and aggregation. Raw log data are transformed into aggregated indicators describing activity frequency, regularity, temporal distribution, revisits, and activity focus at the course level;
3. Context identification (Machine Learning). Machine learning techniques are applied to the derived indicators to identify patterns of ALD usage and to generate an ALD context profile (a pattern combination of ML variables);
4. Pedagogical interpretation (Fuzzy Logic). The ALD context profile is

mapped to linguistic variables and processed through fuzzy rules that model expert pedagogical judgment. This step determines the degree to which the instructional design supports each assessment dimension;

5. ATS configuration. The output of the fuzzy inference process is a contextualized ATS profile, specifying the active dimensions (Achievement, Transfer, Stability) and their relative emphasis, consistent with the observed learning context.

The forward workflow results in an assessment configuration that is grounded in the actual use of asynchronous learning activities, ensuring that evaluation focuses only on learning dimensions that are pedagogically supported by the instructional design.

3.5.2 Backward workflow (BW)

The backward workflow describes the process through which desired assessment objectives are used to generate and optimize an asynchronous learning design. This workflow operates from assessment intent (ATS) toward learning design (ALD). The BW steps are:

1. Definition of target ATS. Specify the desired emphasis on Achievement, Transfer, and Stability.
2. Infer of the design requirements (fuzzy logic). Translate ATS goals into qualitative ALD requirements (e.g., applicative level, temporal distribution, revisits).
3. Set design constraints. Define limits on number of activities, duration, and workload.
4. Generate and optimize ALD (GA). Produce and optimize candidate learning paths under the given constraints.
5. Select optimized ALD. Output one or more asynchronous learning paths aligned with the target ATS.

The backward workflow enables assessment-driven instructional design by ensuring that learning activities are intentionally structured to support the targeted dimensions of learning performance.

3.6 Mathematical formalisation

Let $A=\{a_1, a_2, \dots, a_n\}$ denote the set of asynchronous learning activities, and let an asynchronous learning design be defined as an ordered sequence $ALD=(a_{i1}, \dots, a_{ik})$ of fixed length k , while LMS logs are mapped to normalized variables $x \in [0,1]^m$ and transformed via a fuzzy inference function $f: x \rightarrow p=(A, T, S)$ that captures Achievement, Transfer, and Stability. The backward process is formulated as a genetic optimization problem in which candidate learning designs encoded as chromosomes are evolved under pedagogical constraints toward a target profile $p^*=(A^*, T^*, S^*)$, using a fitness function that estimates ATS alignment solely from the structural composition and ordering of activities.

3.7 Example

Consider a Moodle-based asynchronous course for adult learners, from which activity logs are extracted and aggregated at course level. Log analysis yields the following normalized machine learning variables: activity frequency $\text{freq} = 0.72$, regularity $= 0.65$, revisit rate $= 0.30$, temporal spread $= 0.75$, and activity_focus $= 0.60$, indicating predominantly applicative and temporally distributed activity usage. These values are mapped to linguistic variables using fuzzy membership functions (e.g., applicative level = high, temporal distribution = high, revisit level = low–medium), resulting in an inferred assessment profile $\text{ATS} = (A = 0.35, T = 0.65, S = 0.70)$, which reflects strong support for transfer, moderate learning stability, and lower emphasis on achievement through consolidation.

Given a target assessment profile $\text{ATS}^* = (A^* = 0.30, T^* = 0.60, S^* = 0.70)$, the backward workflow generates aligned asynchronous learning designs using a genetic algorithm. Candidate learning paths are encoded as fixed-length chromosomes, where each gene represents an activity defined by type, cognitive role, duration, and participation mode. For example, $\text{ALD} = [(\text{assignment}, \text{application}), (\text{forum}, \text{reflection}), (\text{quiz}, \text{consolidation}), (\text{assignment}, \text{application})]$ yields estimated values $\hat{A} = 0.25$, $\hat{T} = 0.50$, $\hat{S} = 0.67$, and a fitness value $F(\text{ALD}) = |0.25 - 0.30| + |0.50 - 0.60| + |0.67 - 0.70| = 0.18$. Iterative selection, crossover, and mutation reduce this distance, producing learning paths structurally aligned with the intended assessment objectives.

4. Experimental results

4.1 Forward analysis

The analyzed course includes 27 asynchronous activities distributed across five sections (0–4). The learning design integrates activities targeting consolidation, application, and reflection, with a clear emphasis on application-oriented tasks complemented by reflective and consolidative components.

Table 3. Cognitive role distribution of asynchronous activities

Cognitive role	Modules	Count
Consolidation	lesson, url, data	9
Application	assign, hvp, h5pactivity	9
Reflection	forum, feedback, survey	9

Learner interaction logs were aggregated at user level to derive four behavioral indicators describing asynchronous engagement: interaction frequency, revisit behavior, temporal distribution, and pedagogical focus. These indicators capture complementary aspects of intensity, persistence, temporal spread, and orientation toward application-oriented activities.

Table 4. Descriptive statistics of interaction features

Feature	Mean	Median	Min	Max	Interpretation
freq	9.90	9.19	1.00	96.50	Moderate interaction intensity
revisit_rate	0.82	0.83	0.00	1.00	High recurrence of activity access
temporal_range	4,473,944	3,112,372	0	61,069,147	Variable temporal distribution
activity_focus	0.53	0.53	0.00	1.00	Balanced orientation toward application

The extracted interaction features indicate predominantly recurrent but moderate-intensity engagement with asynchronous activities, supported by a structurally balanced learning design. These usage patterns provide the contextual input for the subsequent assessment-oriented backward analysis.

The cluster-level statistics were interpreted using fuzzy reasoning to derive a course-level Achievement–Transfer–Stability (ATS) profile. Each interaction indicator was mapped to a linguistic scale (low–medium–high), allowing gradual transitions rather than crisp thresholds.

Table 5. Fuzzy interpretation of cluster profiles

Cluster	freq	revisit_rate	temporal_range	activity_focus	Fuzzy A	Fuzzy T	Fuzzy S
C1	0.065	0.71	0.05	0.53	Low	Medium	Low–Medium
C2	0.111	0.89	0.06	0.53	Low–Medium	Medium	Medium
C3	0.116	0.88	0.60	0.53	Medium	Medium	High
C4	0.738	0.98	0.52	0.96	High	High	High

Considering the dominance of clusters C1 and C2, complemented by a smaller but pedagogically significant C3 cluster, the fuzzy aggregation yields the following course-level ATS profile: (A: medium–low, T: medium, S: medium–high).

The course supports stable and recurrent engagement with asynchronous activities, while overall achievement readiness remains moderate due to low interaction intensity for most learners. Transfer potential is balanced, reflecting the consistent presence of application-oriented activities, whereas stability benefits from strong revisit behavior and a subset of temporally distributed learners.

4.2 Backward analysis

The backward analysis was conducted aiming to optimize the asynchronous learning design toward a desired ATS target profile defined as A = 0.30, T = 0.55, S = 0.75. The target ATS profile corresponds to low-to-medium achievement, medium-to-high transfer, and high stability, reflecting a formative, application-oriented, and engagement-sustaining assessment intent. The learning path length

was fixed to $K = 6$ activities, reflecting a realistic instructional unit. The genetic algorithm operated on a synthetic activity pool of 48 candidate activities, under minimal pedagogical constraints requiring at least two application-oriented activities and one reflective activity per learning path.

Table 6. Backward optimization results (ATS profile)

Metric	Target	Initial (population mean)	Optimized
Achievement (A)	0.30	0.34	0.36
Transfer (T)	0.55	0.42	0.51
Stability (S)	0.75	0.29	0.58
Fitness	—	0.62	0.03

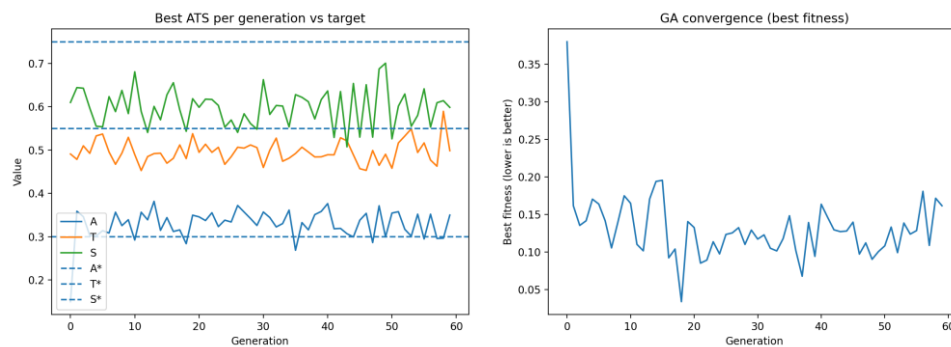


Figure 2. Evolution of best fitness values across generations (convergence) during backward optimization

The backward optimization significantly reduced the distance between the initial learning design population and the target ATS profile, as reflected by the decrease in fitness from 0.62 to 0.03. The most substantial improvement was observed in Stability (S), indicating that the optimized learning path promotes more sustained and distributed engagement over time. Transfer orientation also increased notably, while Achievement remained close to the target range. These results demonstrate that the proposed backward workflow can effectively generate asynchronous learning designs aligned with desired assessment outcomes.

Table 7. Optimized asynchronous learning path (chromosome)

Step	Activity type	Cognitive role	Duration	Mode
1	Assignment	Application	Medium	Individual
2	Assignment	Application	Low	Collaborative
3	Assignment	Application	Medium	Individual
4	Forum	Reflection	Medium	Collaborative
5	Resource	Consolidation	High	Individual
6	URL	Consolidation	Medium	Collaborative

The optimized learning path emphasizes application-oriented activities in the initial stages, supporting early transfer and task engagement. Reflective interaction is introduced mid-sequence through a collaborative forum, contributing to learner stability and cognitive integration. The sequence concludes with consolidation activities, allowing learners to stabilize acquired knowledge and reinforce learning outcomes. The alternation between individual and collaborative modes further supports sustained engagement.

For backward validation, the optimization target was defined using the structural assessment profile inferred from the instructor-designed baseline learning path of each Moodle course. Two courses were analyzed: Course 1 with $K = 27$ unique activities (the course presented at the Forward analysis section) and Course 2 with $K = 38$ unique activities. For each course, the inferred target profile was $ATS_{forward} = (A^*, T^*, S^*)$, computed from the baseline ALD using the same estimator employed in the fitness function. The genetic algorithm was executed with a population of 150 individuals, 200 generations, crossover probability $pc=0.85$, mutation probability $pm=0.25$, and minimal constraints ensuring a minimum number of application and reflection activities. Additionally, a randomized baseline set of $N = 500$ learning paths was generated under identical constraints, allowing comparison between the instructor baseline, GA-optimized output, and random designs.

Table 8. Backward validation results (GA vs baseline and random designs)

Course	K	Design	Fitness	A	T	S
1	27	Human baseline	0.1001	0.2537	0.3653	0.4428
1	27	GA optimized	0.2354	0.2985	0.4660	0.6143
1	27	Random mean (N=500)	0.4856	0.4982	0.3268	0.3824
1	27	Random best (N=500)	0.1036	0.2937	0.4037	0.4409
2	38	Human baseline	0.0958	0.2884	0.5228	0.3211
2	38	GA optimized	0.0883	0.2475	0.5141	0.1894
2	38	Random mean (N=500)	0.5757	0.4985	0.3235	0.3842
2	38	Random best (N=500)	0.0810	0.2457	0.5021	0.2105

Across both courses, GA-generated learning paths strongly outperform randomized designs in average terms, confirming that the backward workflow produces non-arbitrary learning designs and effectively optimizes toward a target ATS profile. For Course 2, the GA solution achieves better alignment than the instructor baseline, indicating that evolutionary optimization can generate learning paths that are structurally more consistent with intended assessment characteristics. For Course 1, the instructor baseline remains the best aligned, suggesting that some

course structures are already near-optimal with respect to their inferred ATS profile and that stochastic variability in ATS estimation may influence marginal optimization outcomes. Overall, these results support the feasibility of the backward workflow as a design-generation mechanism, while motivating further calibration and deterministic assessment validation in future work.

5. Conclusion

This paper introduced a bidirectional model that connects asynchronous learning design with assessment through learning analytics and intelligent optimization. The forward analysis showed how interaction data from an LMS can be used to derive meaningful assessment-related profiles, while the backward workflow demonstrated how desired assessment objectives can guide the generation of coherent asynchronous learning paths. Together, the results highlight the value of aligning learning activities and assessment intentions in a dynamic and data-informed manner, offering a practical framework for supporting more stable and application-oriented online learning.

Acknowledgments

The authors would like to thank ProEuro-Cons Association for providing access to the Moodle course data used in the forward analysis of this study.

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Two models of digitizing mathematics textbooks: Lessons learned and innovative perspectives

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Abstract: *The article presents a comparative analysis of the digitization models applied in the development of digital mathematics textbooks for Grades 5–6 and Grade 9. The study highlights differences in conceptual design, levels of interactivity, content personalization options, and modes of access to digital resources, based on clearly defined pedagogical and technological criteria. The results show that the experience gained at the lower secondary education level provides a valuable framework for improving the pedagogical design of future digital textbooks, particularly by expanding the teacher’s role and supporting active learning. Finally, practical recommendations are proposed for the flexible integration of multimedia content and for the development of digital mathematics textbooks with enhanced pedagogical value.*

Keywords: Interactive learning, Digital education, Mathematics textbooks, E-learning, Digital pedagogy, Personalization, Feedback, Educational technology.

1. Introduction

The digitization of teaching-learning processes represents one of the most significant challenges and opportunities in modern mathematics education. In this broader context, school textbooks, as fundamental learning materials, have evolved from printed formats to interactive digital formats that enable the integration of multimedia elements, automated feedback, interactivity, and adaptability to students’ learning pace (Hoch et al., 2018).

At the same time, mathematics education pedagogy recognizes the role of the textbook not only as a repository of content, but also as an instrument of curricular change, a means of supporting innovative teaching practices, and a tool for assisting students in constructing understanding (Rezat et al., 2021).

The development of digital textbooks must take into account both the existing technological infrastructure and the digital competences of teachers and students. Textbook architecture, accessibility, and interactivity are key factors influencing learning outcomes. Recent studies indicate that learning mathematics in the digital era involves more than the mere digitization of text; it requires learner-centered pedagogical design, flexible platforms, and the integration of digital resources into the instructional workflow (Weigand et al., 2024).

The authors of this article are involved as researchers, co-authors, and experts in two mathematics textbook digitization projects in the Republic of

Moldova: the research project “Innovation in the Design and Use of Interactive Digital Mathematics Textbooks for Lower Secondary Education” (project code 25.80012.0807.42SE) and the project supported by UNICEF Moldova and the Ministry of Education and Research (UNICEF Moldova & MER, 2025). Within these projects, two complementary directions have been initiated:

1. The digitization of existing mathematics textbooks for Grades 5–6 (Achiri et al., 2020) using the MDIR Constructor software (<https://mdir.upsc.md/index.php>), installable on the user’s device, which provides teacher-users with dedicated tools for adding supplementary digital content tailored to students’ needs and to the instructional strategies selected by the teacher;

2. The development of a digital mathematics textbook for Grade 9 using the mAuthor platform (<https://www.mauthor.com/>), based on the printed textbook currently in use (Achiri et al., 2024), accessible online, and built around a different concept of interactivity and pedagogical use.

This article proposes a comparative analysis of these two approaches, highlighting their advantages, limitations, and innovative directions for future development. The study focused on:

- identifying differences in conceptual design, accessibility, and modes of use;
- evaluating the pedagogical, technological, and design perspectives of each model;
- highlighting the specific advantages of each model, with a particular focus on the Grades 5–6 textbooks, which, although not accessible online, allow teachers to personalize and enrich digital content through additional multimedia elements tailored to students’ needs and instructional strategies;
- conducting a detailed analysis of the Grade 9 digital textbook by examining the types of digital activities and actions, and identifying errors, shortcomings, and aspects that can be improved;
- formulating methodological and technical recommendations for the development of future digital textbooks that support learning personalization, interactivity, and effective integration into the educational process.

2. Related work and research background

Over the past decade, research in mathematics education has increasingly focused on the transformation of school textbooks into digital resources, driven by the accelerated digitalization of teaching and learning processes. Studies emphasize that digital textbooks should not be regarded merely as electronic versions of printed materials, but rather as complex curricular resources capable of integrating interactivity, automated feedback, dynamic representations, and mechanisms for personalized learning (Pepin et al., 2017; Rezat et al., 2021; Weigand et al., 2024).

A substantial body of empirical research and theoretical syntheses has examined the impact of digital textbook use on students' mathematics achievement. The meta-analysis conducted by Wijaya and Singh (2022) reports a moderate positive effect of digital textbooks on students' performance, with significant variations depending on the level of interactivity and the pedagogical integration of digital resources. Similar conclusions are drawn in recent systematic reviews, which highlight that the benefits of digital textbooks are most evident when these resources foster active student engagement and provide formative feedback (Alshehri, 2024). At the same time, researchers caution that textbook digitalization does not automatically lead to improved learning outcomes. Studies conducted in diverse educational contexts, including during the COVID-19 pandemic, indicate that the effectiveness of digital textbooks depends on the quality of pedagogical design, teachers' digital competencies, and the available technological infrastructure (Alabdulaziz, 2021). These findings underscore the need to examine the models of textbook digitization that are adopted.

An important line of research concerns the comparison between printed and digital textbooks. Recent studies suggest that the differences between these two types of resources are not solely technological, but also involve significant pedagogical and cognitive implications. Brnic, Greefrath, and Reinhold (2024) show that the use of digital versus printed textbooks can differentially influence problem-solving strategies, depending on the types of activities and the support provided to students. Moreover, analyses of task requirements in digital and printed textbooks reveal changes in task structure and an increased emphasis on visual representations and exploratory approaches (Glasnović Gracin & Krišto, 2022). These results support the idea that digital textbooks can create new learning opportunities, but also introduce new constraints, depending on how they are designed. In this context, examining different digitization models becomes essential for understanding the pedagogical value of digital mathematics textbooks.

The literature also highlights the central role of teachers in the effective use of digital textbooks. Theoretical models and evaluation frameworks proposed by Thomas and Edson (2019) emphasize the need to align mathematics teaching practices with technology use, so that digital textbooks support rather than constrain instructional activities. Empirical studies indicate that teachers who are able to adapt, extend, or configure digital content tend to use digital textbooks in a more flexible and effective manner (Utterberg et al., 2017; Thurm & Barzel, 2020). In contrast, digital textbooks that offer fixed content and limited pedagogical control for teachers may restrict instructional interventions and opportunities for personalization. This distinction is particularly relevant for the analysis of digital mathematics textbooks at the lower secondary level, where the diversity of students' prior knowledge and learning needs requires flexible and adaptable solutions.

Recent research further emphasizes the need for a systemic approach to the design of digital textbooks. Pepin, Gueudet, and Choppin (2024) conceptualize digital textbooks as instruments for transforming educational environments, highlighting the importance of coherence between curriculum, technology, and

teaching practices. Analyses of the quality of digital curricular resources identify criteria such as interactivity, automated feedback, reusability and adaptability of content, as well as integration within broader educational ecosystems (Rezat et al., 2021; Fan et al., 2024). At the same time, exploratory studies on teachers' perspectives regarding digital mathematics textbooks reveal both strengths and limitations, including challenges related to automated assessment and the interpretation of students' problem-solving strategies (Wijaya et al., 2025). These aspects confirm that the chosen digitization model directly influences the pedagogical functionality of a digital textbook.

While existing literature examines the general impact of digital textbooks or explores their use in specific educational contexts, few studies explicitly compare different models of digitizing mathematics textbooks for lower secondary education within the same educational system. The present study contributes to this field through a comparative analysis of two distinct digitization models: (a) an extensible and customizable model that allows for content adaptation and pedagogical intervention by teachers, and (b) a model based on the complete digitization of the printed textbook, characterized by a high level of control over structure and content. The analysis focuses on the pedagogical implications of interactivity level, teacher agency, and the flexibility of digital content.

This gap is particularly evident in national-level initiatives, where different digitization models are often implemented in parallel without systematic comparison.

3. Methodology

The study employed a qualitative, reflective approach based on systematic reflective analysis informed by direct professional expertise, which allowed for a detailed analysis of digital textbook prototypes and usage practices, as well as the identification of errors, limitations, and opportunities for improvement.

The sources analyzed included: digital textbook prototypes for Grades 5–6 and Grade 9; evaluation sheets completed by teachers and feedback from the testing process; direct observations of students' and teachers' interactions with the digital textbooks; design documentation; and the digital tools provided to teachers for supplementing and personalizing content. Together, these sources enabled a triangulated analysis of both the design features and the pedagogical use of the digital textbooks across the two digitization models. The main criteria used to evaluate the digital textbooks were:

1. *Level of interactivity* – the extent to which the textbook enabled students to actively participate in the learning process through digital activities;
2. *Accessibility* – online/offline availability and compatibility with different devices;
3. *Content flexibility* – the possibility of adapting lessons and activities to students' levels and needs;

4. *Possibility of adding new resources* – the tools provided to teachers for supplementing the digital content with additional multimedia;
5. *Technological compatibility* – stable performance and integration of the digital platforms used;
6. *Degree of pedagogical support for teachers* – guides, instructions, and digital tools that facilitated lesson planning and delivery.

The criteria selected for the analysis of digital textbooks were chosen in accordance with scientific recommendations from the specialized literature. In particular, they align with the dimensions of the 4A framework - Accessibility, Active engagement, Advocacy for inclusion, Accountability (Hoch et al., 2018) - and with validated criteria for evaluating digital educational resources (Weigand et al., 2024; Rezat et al., 2021). This alignment ensured that the selected criteria were suitable for distinguishing between different models of textbook digitization rather than merely comparing isolated digital features.

Within the analysis, the main criteria were further specified through operational indicators, such as the type of digitization, automated feedback, visualization of the solution process, and handling of equivalent responses, in order to more accurately reflect the functional characteristics of the textbooks. This operationalization enabled a clear comparative presentation of the results, supporting the interpretation of differences between digitization models and the identification of the pedagogical strengths and limitations associated with each approach.

4. Theoretical and conceptual framework

In recent decades, the integration of technology in mathematics education has become a central focus of educational research, as digital resources increasingly replace printed textbooks and expand learning opportunities. Digital textbooks, defined as electronic resources that include text, multimedia, interactivity, and automated assessment, are not merely electronic versions of printed materials. They constitute complex learning environments that can support active and personalized learning (Ferme, 2025).

The literature highlights that textbook digitization should go beyond the mere replication of printed pages and leverage the advantages of the digital medium: interactivity, immediate feedback, dynamic representations of mathematical concepts, and adaptability to students' learning pace (Rezat, 2021; Braicov, 2025). In this sense, digital textbooks can become pedagogical tools that facilitate not only content delivery but also students' active cognitive engagement, self-assessment, and the consolidation of understanding through activities specifically designed for online or hybrid environments.

One key aspect identified is the role of automated feedback in the learning process. Unlike printed textbooks, where students receive corrections after the fact, digital resources can provide immediate feedback on calculation tasks or concept exploration, supporting conceptual development and self-regulated learning (Rezat et al., 2021). This feature is considered a differentiating element and, in certain

contexts, an indicator of the pedagogical quality of digital textbooks. However, it should be noted that the design of digital textbooks is still in a transitional phase: many digital resources replicate the static format of printed textbooks without fully exploiting the pedagogical potential of interactivity and personalization. For example, digital exercises may exist in simple or multimedia forms, but not all digital textbooks include sophisticated mechanisms for random data generation, formative assessment, or tools that allow teachers to create new activities.

Analysis of international practices also shows that integrating digital resources into the curriculum involves both technology and a shift in the teacher's role. Regarding the use of digital textbooks in teaching mathematics and sciences, teachers have observed that despite the advantages offered by videos or animations for concept visualization, translating mathematics into a digital format remains challenging, and the use of digital textbooks in instruction depends on teachers' digital competences and the structure of learning activities (Johansson et al., 2024).

In the context of developing digital textbooks for lower secondary education, these findings suggest two complementary perspectives on digitization:

- On one hand, a faithful digital rendition of the printed textbook, which has been previously reviewed and validated, preserving all curriculum-approved tasks and activities. This approach provides both teachers and students with continuity with the printed material and ensures full curriculum coverage, but it risks remaining a static replica if the dynamic features of the technology are not sufficiently leveraged.
- On the other hand, the design of digital textbooks as extended interactive environments, allowing for the addition of cloned tasks, automatic generation of exercises, integration of multimedia resources, and content personalization. This approach aligns more closely with the requirements of modern digital pedagogy and with research-based orientations on technology-assisted learning (Ferme, 2025).

Therefore, the theoretical framework of this study assumes that digital textbooks should be viewed as interactive educational environments capable of supporting active learning, immediate feedback, and adaptation to individual student needs. This perspective forms the basis for the comparative analysis of the digitization models examined in this article and provides a foundation for recommendations for future digital mathematics textbook projects.

5. Results and analysis

It should be noted that the mathematics textbooks for Grades 5 and 6 were digitized using the *MDIR Constructor* platform (<https://mdir.upsc.md/index.php>), while the Grade 9 mathematics textbook was digitized using the *mAuthor* platform (<https://www.mauthor.com/>). All three textbooks are based on the PDF versions of the mathematics textbooks currently in use (figure 1), approved by the Ministry of Education and Research (MER).

The *MDIR Constructor* application (developed by Balmuş et al., 2024) uploads the PDF file and adds interactivity, automated feedback, and multimedia elements, thus providing a primary version of the digital textbook. The teacher-user, using the same MDIR Constructor application installed on their computer, can supplement the primary digital textbook with additional multimedia elements (videos, new items, etc.) to create a personalized version, which can then be used during lessons and shared with students. The digital mathematics textbooks for Grades 5 and 6, created with MDIR Constructor, do not include all exercises and problems from the original PDF textbook; however, they contain additional tasks, exercises, and problems digitized by the teacher-user, adapted to their own teaching experience.

The *mAuthor* platform offers a wide range of tools for creating online-accessible digital textbooks via a user account. The Grade 9 digital mathematics textbook, created with mAuthor, corresponds to the PDF version of the textbook currently in use, in which all exercises and problems have been digitized. However, it does not include additional tasks, exercises, or problems beyond those present in the original PDF.

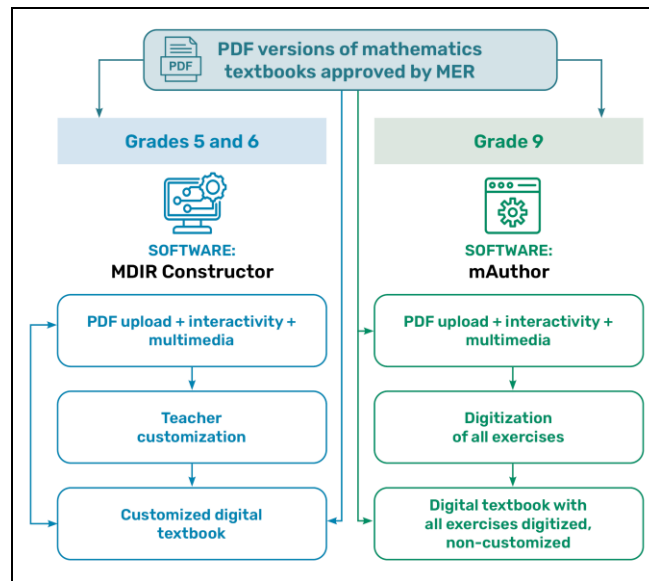


Figure 1. The two models of mathematics textbook digitization

The comparative analysis focused on two distinct models of digitizing mathematics textbooks for lower secondary education: the digital textbooks for Grades 5–6 and the digital textbook for Grade 9. The results were obtained by examining the types of digital activities implemented, the functionalities provided to students and teachers, and the limitations identified during usage. To provide a structured overview of these findings, Table 1 presents a comparative analysis of the two digitization models based on the criteria established in the study methodology.

5.1 Results of the analysis of digital mathematics textbooks for Grades 5 – 6

These digital textbooks incorporated a series of interactive tasks, selected and adapted according to the mathematical content addressed at this level (Figures 2 and 3).

The digitization process did not involve a complete replication of all tasks from the printed textbooks but focused on integrating didactically relevant digital activities, complemented by additional tasks.

Interactive activities included exercises with instant automated feedback, tasks with variable data, the possibility of generating multiple versions of the same type of exercise, and activities designed for learning, assessment, and self-assessment.

An important finding of the analysis was that the digital textbooks for Grades 5–6 provided teachers with tools that allowed them to add new digital content, modify existing tasks, and adapt them to the students' level and learning pace.

These functionalities enabled flexible use of the digital textbook, both within regular instructional activities and in formative assessment contexts.

The analysis also highlighted certain limitations in the use of the digital textbooks for Grades 5–6, primarily related to accessibility. Since the installable model required initial configuration on users' devices, it limited usage in contexts that required quick online access.

Furthermore, the full utilization of content expansion and personalization features largely depended on the teacher's digital competencies and the time available for designing and adapting interactive tasks.

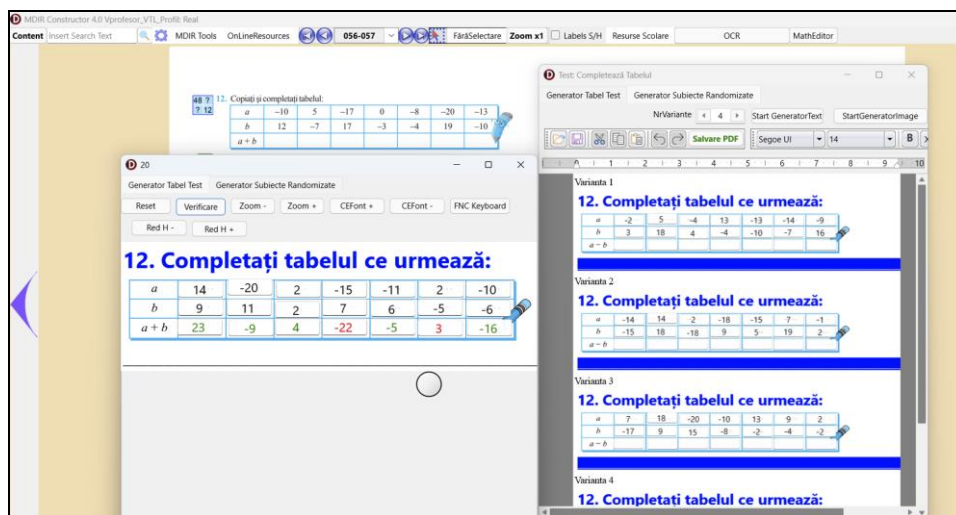


Figure 2. Teacher editing mode in the Grade 6 digital mathematics textbook

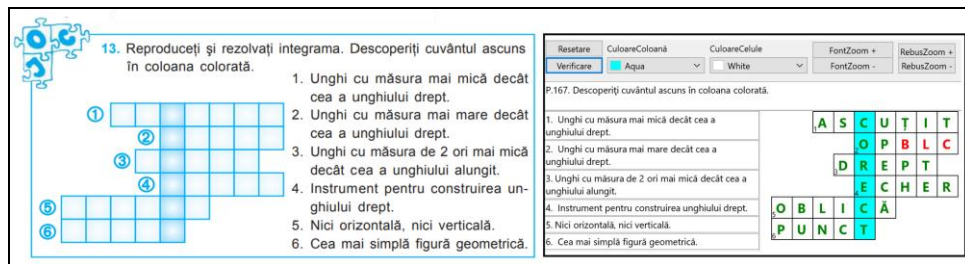


Figure 3. Digitally implemented crosswords in the Grade 5 mathematics textbook

5.2. Results of the analysis of the Grade 9 digital mathematics textbook prototype

The Grade 9 digital textbook prototype was created by digitizing all tasks and activities present in the printed textbook currently in use and approved by MER. The digital activities included filling in answer boxes, selecting the correct answer from a set of values, creating graphs, manipulating geometric solids through rotation (Figure 4), as well as open-ended items intended for teacher assessment.

For certain tasks, the digital textbook allows students to record their answers vocally, with audio files that can be downloaded and subsequently submitted to the teacher. Additionally, students can reset the task lists, enabling them to redo activities without being constrained by previously entered answers.

For open-ended items, assessment is not automated and is the responsibility of the teacher. For tasks with automated evaluation, the system checks the correctness of students' responses against predefined solutions.

The analysis revealed several limitations associated with the digitization model of the Grade 9 textbook. One limitation concerns the teacher's restricted ability to view the complete process of problem solving by the student, as only the final answer is available (Figure 5). This limitation reduces the opportunity to analyze the strategies employed by students. There were also cases in which the automated evaluation marked mathematically equivalent answers as incorrect when they were entered in a different order than predefined (for example, in equations with multiple solutions). Another limitation is that the Grade 9 digital textbook provides exclusively the tasks included in the printed version, without allowing the teacher to add or modify digital content.

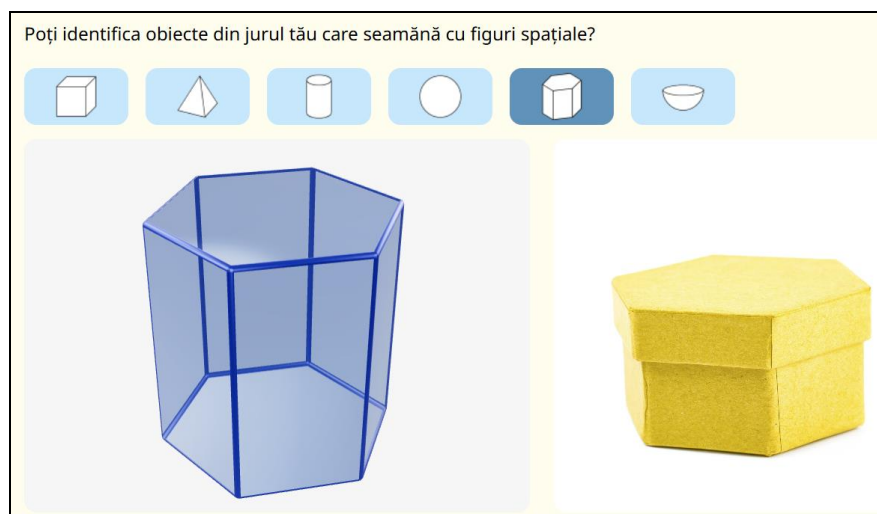


Figure 4. Digitally implemented polyhedra in the Grade 9 mathematics textbook

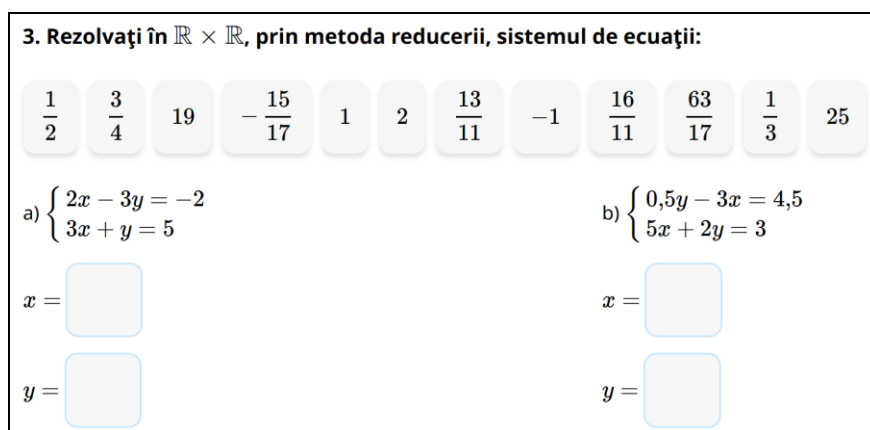


Figure 5. Digitally implemented system of equations in the Grade 9 mathematics textbook

5.3. Comparative summary of the results of the two analyses

To synthesize the obtained results, Table 1 presents a comparative analysis of the two digitization models based on the criteria established in the study methodology.

Table 1. Comparative analysis of mathematics textbook digitization models

Main criterion	Indicator	Digital textbooks for Grades 5–6	Digital textbook for Grade 9
Level of interactivity	Types of interactive activities	Exercises with automated feedback, tasks with variable data, extended activities	Fill-in, multiple choice, graphs, geometric manipulations, open-ended

			items
<i>Accessibility</i>	Availability	Installable model (offline)	Online access via browser
<i>Content flexibility</i>	Adaptation of lessons and activities	High; the teacher can modify and add tasks	Low; fixed content
<i>Possibility of adding new resources</i>	Multimedia, new tasks	Yes; the teacher can integrate videos, interactive exercises, and evaluation sheets	No
<i>Technological compatibility</i>	Stable performance, platform integration	Stable operation on specific devices	Stable online operation
<i>Degree of pedagogical support</i>	Teacher's role	Teacher as configurator and facilitator	Teacher as evaluator
<i>Automated feedback</i>	Availability and type	Most tasks	Only for certain types of tasks
<i>Visualization of solution process</i>	Monitoring students' steps	Possible, depending on configuration	Limited to the final answer
<i>Handling of equivalent answers</i>	Accuracy of assessment	Configurable	Misinterpretation may occur

6. Discussion

The results of the comparative analysis highlight that the digitization of mathematics textbooks is not a uniform process, but can be implemented through different models with distinct pedagogical implications. The differences observed between the digital textbooks for Grades 5–6 and the Grade 9 digital textbook reflect varying choices regarding the role of the digital textbook in the teaching–learning process and the degree of autonomy granted to the teacher.

6.1. Full digitization versus extensible digitization

The model applied to the Grade 9 digital textbook aimed at full digitization of the existing content in the printed textbook, providing students with the possibility to complete all tasks within a coherent and unified digital environment. This approach ensures curriculum continuity and a direct correspondence between the printed and digital versions, facilitating the use of the textbook in diverse educational contexts.

In contrast, the digital textbooks for Grades 5–6 were designed according to an extensible model, in which selective digitization was complemented by additional interactive activities and the possibility for teachers to extend the content. This difference suggests two distinct perspectives on the digital textbook: one focused on faithful reproduction of existing content, and the other oriented towards adaptation, personalization, and pedagogical reuse.

The literature emphasizes that the pedagogical value of digital textbooks is not determined solely by the degree of digitization of the content, but by the way they support teaching practices and active learning (Weigand et al., 2024; Rezat, 2021).

6.2. Teacher role and pedagogical control

A central element in this discussion is the role of the teacher in using digital textbooks. In the case of the Grade 9 textbook, the teacher primarily acted as an evaluator of student responses and a user of a predefined set of tasks. The lack of access to the students' problem-solving process and the impossibility of modifying or extending the content limited real-time pedagogical intervention and adaptation of tasks to students' specific needs.

In contrast, the digital textbooks for Grades 5–6 allowed teachers to directly intervene in the digital content, add new tasks, and configure differentiated activities. This feature aligns with current perspectives on digital textbooks as tools of pedagogical mediation rather than merely content delivery supports (Rezat et al., 2021).

These results suggest that the degree of pedagogical control afforded to the teacher is an essential criterion in evaluating the effectiveness of a digital mathematics textbook.

6.3. Automated feedback and the limits of digital assessment

The analysis showed that automated feedback was implemented differently across the two models. In the textbooks for Grades 5 – 6, feedback was extensively used for learning, assessment, and self-assessment activities, supporting repeated practice and consolidation of basic skills. In the Grade 9 textbook, automated feedback was available only for certain task types, while the assessment of open-ended items remained the responsibility of the teacher.

The limitations identified in the automatic evaluation of equivalent responses highlight a recurring issue in the literature, namely the difficulty of digital systems to correctly interpret the diversity of students' mathematical strategies (Rezat et al., 2021). These findings confirm the need to combine automated assessment with human evaluation, especially for tasks that require reasoning and argumentation.

6.4. Accessibility, flexibility, and sustainability

Another important aspect concerns the accessibility of digital textbooks. While the Grade 9 textbook was accessible online, facilitating rapid use and broad distribution, the installable model for Grades 5–6 posed certain logistical constraints. However, the results suggest that online accessibility alone does not guarantee more effective pedagogical integration.

Content flexibility and the possibility of personalization proved to be at least as important as online access, particularly in educational contexts characterized by

diversity in student preparedness and available technological infrastructure. This observation aligns with recent studies on mathematics teaching in the digital era (Weigand et al., 2024).

6.5. Implications for future digital textbook design

Overall, the discussions derived from this analysis indicate that the design of digital mathematics textbooks should go beyond the mere transfer of printed textbooks into digital format. High-pedagogical-value digital textbooks are those that provide teachers with tools for adapting, extending, and configuring content, support formative feedback, and allow flexible integration into teaching strategies.

The results support the idea that a digitization model focused on flexibility and personalization, even if not exclusively online, can offer significant pedagogical advantages and contribute to more effective use of the digital textbook in the educational process.

7. Conclusions

The comparative analysis highlighted fundamental differences between two models of digitizing mathematics textbooks: the digital textbooks for Grades 5–6, based on an extensible and customizable model, and the Grade 9 digital textbook, created through full digitization of the printed textbook. The results indicate that, although online accessibility facilitates rapid use and broad distribution, content flexibility and the ability to personalize tasks are essential factors for the pedagogical effectiveness of digital textbooks.

The Grades 5–6 textbooks demonstrated high potential for supporting active learning, instant feedback, and adaptation of content to students' individual needs, due to the tools provided to teachers for adding and modifying digital resources. In contrast, the model applied to the Grade 9 textbook ensures curriculum continuity and faithful reproduction of printed tasks, but limits pedagogical intervention and content flexibility. The qualitative nature of the study and its focus on two national projects constitute limitations that should be addressed in future research.

These findings suggest that future models of mathematics textbook digitization should combine online accessibility with tools for personalization and configuration provided to teachers, in order to maximize pedagogical impact. Furthermore, the continued development of software for creating interactive digital textbooks, with support for automated feedback, formative assessment, and random task generation, represents a priority direction for future projects in this field. Thus, the experience accumulated in lower secondary education can provide a valuable framework for designing digital textbooks for higher grades and for promoting active learning.

Acknowledgments

This study was conducted within the framework of the research project “Innovation in the design and implementation of interactive digital math textbooks for lower secondary education”, strategic direction: “Innovative Educational Technologies and Products”, registered in the State Register of Projects in the field of Science and Innovation of the Republic of Moldova, project code 25.80012.0807.42SE.

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Web platform to support entrepreneurs: Technological and educational remedies for training the digital skills of beneficiaries

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Abstract: *The situation of micro/small/medium entrepreneurs in the Republic of Moldova, local producers of craft products and services, is marked by a series of difficulties that are close to the problematic situation of representatives of the same guilds in other countries in the region. In this context, the authors propose the development of a modular platform designed to digitalize micro, small, and medium-sized businesses, with the aim of supporting the development of digital skills among local entrepreneurs. The platform is designed to be accessible, specifically tailored for users with limited digital skills. It is expected that this platform will offer integrated solutions for managing online businesses at the level of payment processing and logistics assurance, thus helping entrepreneurs overcome financial and technical constraints. From a scientific point of view, the work is at the intersection of the fields of software product development but also of educational sciences, through its components related to digital education, adult education, and entrepreneurial education from the perspective of the concept of lifelong learning. This work constitutes a conceptual proposal for a web-based platform and includes elements derived from a design study of a software product designed by the authors.*

Keywords: Platform for entrepreneurs, Digital skills, Adult education, Digital marketing.

1. Introduction

The digitalization process is today a determining factor of social and economic development. Access to infrastructure and/or digital technologies has ceased to be an advantage reserved only for large companies but has become a competitiveness tool that represents a fundamental condition for the survival and (Moagi, Thomas & Mara, 2023) growth of any enterprise on the modern market. However, the degree of digital integration differs significantly from one category of economic actors to another. Large and medium-sized enterprises have sufficient financial resources and human capital to develop and maintain their own digital infrastructure. In contrast, small enterprises (type I.I. or S.R.L. with low capital) have limited access to modern digital infrastructure and face difficulties in promoting their products and/or services, which affects both their survival and business expansion. This situation also considerably reduces their possibilities to

<https://doi.org/10.58503/icvl-v21y202616>

penetrate the large market, whether national or international. In this context, we consider it important that the voice of local entrepreneurs with small, below-average, and even average turnovers be supported to be heard on the domestic market, but not only by state representatives interested in the country's economic rise and/or the digitalization of the socio-economic space, such as the Ministry of Economic Development and Digitalization (MDED) and/or the Electronic Government Agency (AGE) of the Republic of Moldova, as well as by their current and future clients.

Hence, the research problem lies in identifying and analyzing the relevant aspects that should inform the design and development of a software product intended for entrepreneurs in the Republic of Moldova, addressing both the functional requirements of the application and the gaps in the digital skills of its potential users.

The research methodology aims to analyze not only the digitalization policies relevant to the given socio-economic sector, but also the practical realities and potential for integrating future beneficiaries—those for whom the software product is designed—into a social and economic context characterized by continuous digitalization. Particular attention is devoted to the digital skills of local entrepreneurs, which are currently at a modest level, while the potential for their improvement is constrained by several factors that are identified and analyzed in this paper. The arguments concerning the conceptual profile of the software product, as well as the modules intended to support the development and training of users' digital skills, are structured according to the two main directions of the research. These directions are reflected both in the title and throughout the paper, with the reviewed scientific literature aligned with the scientific dimensions addressed in the study.

A viable solution in this context would involve developing a centralized digital platform to facilitate the integration of local entrepreneurs into the digital economy, which could be described as a digital ecosystem that supports entrepreneurship. This platform would be coupled with policies focused on the training and development of digital and technological skills necessary for its implementation by users—economic agents.

The integration of training and development facilities for digital skills, as well as those of the masses, corresponds to the philosophy of lifelong learning, reflected in European (Burlacu, 2019; Wilson-Menzfeld et al., 2023; Eurydice.eacea.ec.europa.eu, 2025; Zheng & Liang, 2025) and national (MEC of the Republic of Moldova) strategic documents, but also in the works of researchers from around the world (Bolboceanu, 2015; Wain, 2016; Xhensila, 2024). Based on these connections, we envision the platform's architecture offering efficient tools to promote businesses, local products, and drive subsequent sales. The platform should include functionalities that facilitate the interaction between key stakeholders—entrepreneurs and consumers of their products.

2. Current situation regarding the research problem in the Republic of Moldova

2.1. Fragmentation, intermediation, and lack of digital capabilities

The market for local products, as well as for craft services, is traditionally deeply fragmented, both in the Republic of Moldova and in other countries in the region (Dumitrascu, 2017). Most micro-enterprises (Individual Enterprise (I.E), Authorized Natural Person (ANP), Small Limited Liability Company (SLLC)) operate with minimal digital infrastructure. To increase their visibility, small and medium-sized entrepreneurs make use of tools and applications such as the social media pages; blogs lacking interactivity; static websites that are not updated.

It is important to note that none of the solutions mentioned above include transactional functionalities tailored to the needs of small and medium-sized entrepreneurs. Additionally, many local producers lack the digital skills required to use these tools effectively, with some having no digital skills at all.

The most small and medium-sized businesses, managed by local producers, are completely absent in the virtual environment and, respectively, operate in the complete absence of an online storefront. In the absence of a comprehensive digital infrastructure (including store, payments, logistics, customer support, and performance marketing), entrepreneurs are entirely dependent on intermediaries—such as re-cuts, physical markets, and online marketplaces—that operate on a high-commission basis.

This unfavorable situation imposes on local producers a subordination to re-cuts, compresses margins, reduces, sometimes to zero, control over the brand and makes it difficult to scale the business. The problems listed are common for representatives of micro / small / medium entrepreneurship, a typical portrait of which we encounter not only at the local level (see Table 1), but also regionally and / or nationally.

Among the common problems of the three examples, which are representative of small and medium-sized local producers, are the following:

- The producer/company is not present online.
- Delivery is either not provided or is done through courier services.
- Logistics negotiations are carried out separately with each courier/courier company, which has a negative and often unpredictable impact on costs.
- A high volume of repetitive questions, errors in address handling, long response times, and a low conversion rate.
- Intermediation through specialized stores imposes price premiums, which make the product inaccessible to the general public.
- The average level of digital skills (DS) trained per company is very low.

- The owner/company does not have the financial potential to reduce digital illiteracy and/or to hire skilled specialists to increase the visibility of their business in the online environment, which has a direct impact on sales.

Table 1. Representative examples of local producers placed outside the digital environment

Example 1.	Example 2.	Example 3.
Rural beekeeper	Artisanal dairy workshop	Local carpentry services
A beekeeper with 150 bee colonies traditionally sells at seasonal fairs and through recommendations. The product is well-received and highly anticipated within the community. The online presence is restricted to a single social media page. In the absence of a shopping cart and integrated payments, orders are placed through messages. Delivery is carried out ad hoc, generating unpredictable logistics costs.	A local laboratory produced premium assortments (ripened cheeses, natural yogurts, etc.). The product has traction in the community, but the lack of an eCommerce storefront and online visible labeling/traceability standards limits entry into HoReCa networks.	A carpenter and a freight driver find their customers through recommendations. Demand is seasonal and volatile, and the absence of a verified profile, with reviews and a calendar, reduces customer trust but also the ability to plan.

Examples given illustrate the main causes of the precarious condition of the situation of entrepreneurs in the transition to digital environments: (a.) the initial cost and complexity of building a transactional online presence; (b.) the deficit of applied digital skills (e-Commerce, copywriting (Constantinescu, Caescu, Botezatu, & Mateescu, 2021; Muhamad Adnan et al., 2023), production of photographic and video materials, production and configuration of advertising, SEO activity, and data protection of the actors involved); and (c.) the lack of an integrated payment and logistics framework adapted to small and variable volumes of purchases/sales.

2.2. The needs for training of entrepreneurs (micro/small/medium)

Local micro- and macro-entrepreneurs are at a disadvantage in terms of using information technologies in their businesses for many reasons, although the most frequently stated reason reported by representatives of the micro- and/or small entrepreneurial environment remains the lack of budget or the reduced budget for hiring personnel specialized in interacting with the online environment. Among the most frequent difficulties encountered by representatives of the business and entrepreneurial environment are:

- **Problematic areas in training digital skills:**
 - Lack of experience in setting up an online store (structure, categories, product variations, policies, and management restrictions);
 - Difficulties in producing/processing/listing multimedia content;
 - Ignorance of data related to the operational flow (information on stocks, orders, returns, simplified invoicing, etc.) but also the lack of capacity to digitally process said data;
 - Reduced or minimal use of the potential of digital promotions to increase sales (newsletters, ads, promotional codes) and the impossibility of measuring conversions;
 - Insecurity in the digital environment, especially regarding the protection of personal data of the actors involved;
 - The impossibility of processing online payments;
 - Legal and fiscal illiteracy, or the presence of ambiguities in the application of legal and fiscal norms.
- **Repetitive financial constraints:**
 - Very low monthly budgets for the purchase of digital services, visible in the lack of one's own website to promote one's own production and/or the impossibility of ensuring the maintenance of the website if it exists;
 - The impossibility of integrating online payments and/or the lack of or inability to conclude logistics contracts in digital format;
 - Small and volatile volume of orders that do not justify the fixed costs for software subscriptions and/or the hosting of digital tools customized to the needs of the enterprise.

3. Solution directions: integrated services platform able to develop digital skills

3.1. Solution architecture

The solution proposed by the authors is a modular platform designed with the intention of reducing entry and operating costs for small and medium-sized entrepreneurs. From a systemic perspective, the platform will be developed based on a layered architecture as follows (see Figure 1).

Presentation Layer (Front-End Web & Mobile PWA): interfaces adapted for users with low digital literacy (wizards, guided texts, clear iconography, mini-tutorials). PWA allows operation on budget phones without installation from the app store.

Application Layer (Domain Services): modules for product/service catalog, shopping cart, orders, dynamic prices, promotions, verified profiles, reviews, disputes, messaging, and calendars for providers.

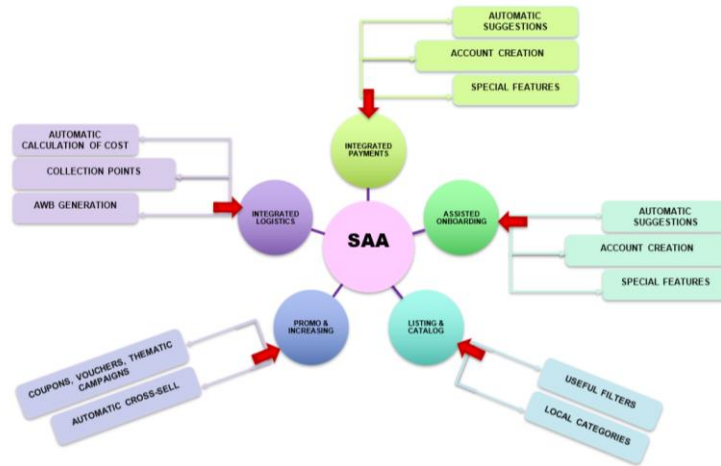


Figure 1. Key functional modules of the user-centric platform

Integration Layer (Gateway API): connectors with payment processors (card/transfer), couriers (auto-tagging, AWB, tracking), email/SMS, and business analysis tools, as well as WEB analytics; secure data exchange (OAuth2/JWT), auditing, and rate limiting.

Data Layer: focused on operational data (OLTP), media file storage (images/tags), and a mini-DWH (reports, KPIs, logistic cart, conversions). Governance measures: retention policies, backup, and encryption at rest and in transit.

Admin/Compliance Layer: content moderation panel, KYC, complaint management, return/warranty policies, legal templates (GDPR, terms, simplified billing), and authority reports.

The author's platform is based on several key objectives, namely:

- The conceptualized platform is designed to be built on key functional modules. This approach mirrors previous work focused on the modular flexibility of architectural solutions for systems accessible to taxpayers in the Republic of Moldova, including entrepreneurs (Burlacu & Bolocan, 2025).
- The platform's modular design is centered around the entrepreneur's needs. The latter, being designed according to the representation given in Figure 1, is currently in the development stage.
- The platform will be distinguished by its accessibility and interface adapted to users with modest digital skills, relatively easy to obtain through a series of training sessions, where
 - the training sessions will be structured based on the digital skills level (DSL) of the learners (Burlacu, 2020);

- DSL will be reported, tested / trained / assessed, based on the specifics of the EdTech component / components integrated into the platform (Burlacu, 2023), or on the indirect presence of the EdTech components, provided to be implemented by the possible interaction scenarios of the learners/users/beneficiaries with the given digital product.

The design of the platform interface will be developed based on the following criteria:

- Interface with suggestive and explicit language, equipped with icons, contrast adaptability, and the possibility of increasing the font;
- The voice assistant will operate in optional mode, allowing users to activate it as needed;
- The presence of video tutorials (Khomysyak, 2024) regarding familiarization with the platform and the set of tools included here, including those that support the training/development of digital skills necessary for interaction with the platform, but not only;
- Mobile-first optimization, which involves adapting the platform content to small and / or medium screens of a wide range of mobile devices, even those with slow connections;
- The localization of the contextual content reflected within the platform is tailored to the market of potential beneficiaries and users and delivered in Romanian and Russian.

3.2. The training entrepreneurs' digital skills through the platform

Entrepreneurs, whether they are just starting or managing businesses of varying sizes, from micro and small to medium-sized ones, often face considerable challenges in terms of adopting and integrating digital technologies into their daily business activities. These obstacles are much more evident in the case of small and medium-sized enterprises (SMEs), which are at a disadvantage compared to large players in the same area of activity, especially due to financial constraints and lack of resources.

Although the specific problems are multiple, the most frequently cited by entrepreneurial representatives are (A.) limited budgets for hiring specialized personnel and (B.) the lack of an appropriate digital infrastructure that would facilitate their efficient interaction with the online environment. In addition to the difficulties listed above, local entrepreneurs also face a significant deficiency in training digital skills within their teams.

The gaps of small and medium-sized enterprises (SMEs) in terms of digital skills are lack of knowledge in the use of basic technologies, lack of knowledge of the setup and management aspects of complex online platforms capable of supporting the online visibility of businesses, difficulties in producing, processing, and listing multimedia content capable of improving the digital marketing strategy of the business, lack of a clear vision of operational data, etc.

Based on the above, in the chapter on digital skills, the platform will allow its beneficiaries, its entrepreneurial users, to train and develop them according to the model presented upper (see Figure 2). In this context, the solution we propose, being intended to address these difficulties, is an integrated, unitary platform that offers modular services aimed not only at reducing operating costs but also at continuously developing the digital skills of local entrepreneurs.

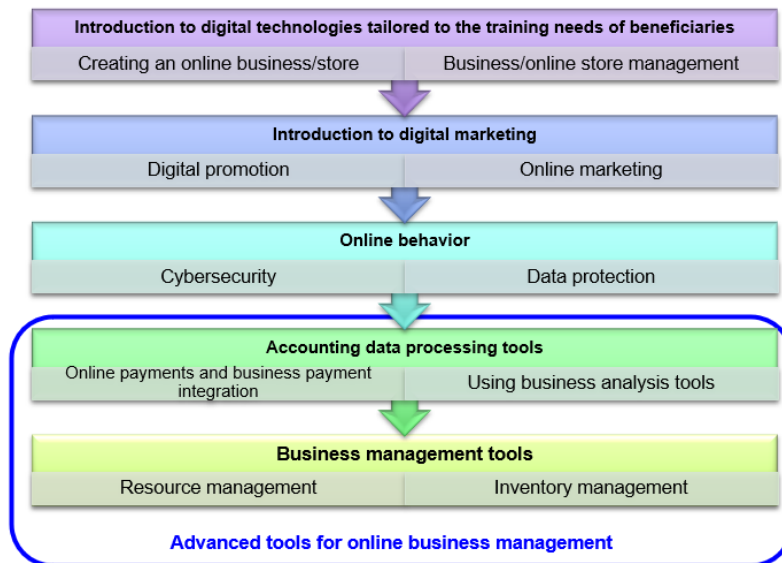


Figure 2. The modular content of training courses for entrepreneurs delivered through the authors' platform

The proposed platform is designed as an accessible tool that will significantly contribute to increasing the level of digital literacy of its beneficiaries and direct users so as to enable successful navigation of the challenges in the online environment. Starting from the idea of supporting the training and development of digital skills of entrepreneurs, the solution will include a modular plan for continuous training, with the aim of improving the level of knowledge and digital skills of those interested.

4. Conclusions

The proposed platform is not just a listing channel but a market infrastructure that simultaneously compensates for the two identified structural deficits: (A.) the lack or insufficiency of digital skills among micro/small/medium entrepreneurs in the Republic of Moldova necessary for their promotion and, as a consequence, for the growth of their businesses, but also (B.) the existing financial barrier by implementing a pay-as-you-grow model, based on the integration of payments and ensuring business logistics. The introduction of these facilities will be shown in the reduction of fixed costs for the respective additional necessary services (payment of personnel, including, as the case may be, an accountant,

communication manager, marketer responsible for online promotion, graphic designer/videographer, logistics team, etc.). Compared to the current status quo, the solution we propose is an entry offer into e-Commerce for micro/small/medium entrepreneurs, where such an entry path will be accompanied by a reduced risk compared to a substantially shorter time from the day of online launch but also continuous support for learning, growth, and adaptation to the digital environment.

Future work would include additional publications on later stages of development of the proposed software product, with a focus on empirical evaluation by experts and / or users. This may involve usability testing at the module level and/or assessment of the platform as a whole. The present paper is primarily design-oriented and does not address evaluative or substantive aspects. The authors are involved both in the conceptual design and in the development of the platform. The given platform is currently under development as part of a research project within the Data Science master's program at the Technical University of Moldova.

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Integrating digital and green education: A conceptual framework for English Language Learners

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Abstract: *The simultaneous demands for environmental sustainability and digital proficiency represent two major challenges in 21st-century education. For English Language Learners (ELLs), acquiring digital competence alongside environmental awareness presents both challenges and opportunities. By engaging in technology-driven projects, such as analysing ecological data, creating environmental documentaries, or collaborating on sustainability campaigns via digital platforms, ELLs can simultaneously cultivate three critical literacies: digital literacy, ecological understanding, and English language proficiency. This conceptual paper proposes a synergistic pedagogical framework grounded in project-based learning that integrates green education not as a separate domain, but as a meaningful, authentic context for developing digital literacy. Drawing on the principles of Education for Sustainable Development (ESD) and Content and Language Integrated Learning (CLIL), the paper outlines key pedagogical design principles, explores benefits such as enhanced motivation, collaboration, and critical thinking, and identifies implementation challenges. Ultimately, it argues that integrating digital and green education fosters learners who are both technologically proficient and ecologically responsible.*

Keywords: Digital literacy, Green education, English Language Learners (ELLs), Technology-Enhanced Language Learning (TELL), Education for Sustainable Development (ESD).

1. Introduction

The integration of digital and sustainability-oriented learning is reshaping educational practices. While digitalisation holds significant potential to enhance the sustainability of economic, social, and educational systems, its relationship with environmental goals remains complex. In response to the urgent challenge of climate change, the European Commission has placed sustainability at the core of its policy agenda (European Commission, 2018). Within this context, education is recognised as a key driver of transformation, responsible for equipping students with the competencies required for a greener and more sustainable future.

Similarly, international organisations such as UNESCO have long emphasised the need to embed sustainability within educational frameworks (UNESCO, 2017) and continue to advocate for developing learners' competencies

for a greener and more sustainable society and economy (UNESCO, 2024). Moreover, the growing digitalisation of education and society creates new opportunities to advance both sustainability and efficiency, underscoring the interdependence between digital literacy and sustainability-oriented education.

Digital literacy, understood as the confident and critical use of technology for accessing, communicating, and creating information, has become a keystone of contemporary education. For English Language Learners (ELLs), competence in this area is crucial not only for academic achievement but also for meaningful participation in civic and social life. However, ELLs frequently face distinct challenges, including linguistic barriers, unequal access to digital tools, and different levels of prior experience with digital tools. Addressing these gaps requires pedagogical frameworks that integrate language learning with authentic and technology-mediated practices, thereby developing linguistic and digital competence.

At the same time, growing emphasis on sustainability has given rise to green education, a concept centred on environmental awareness, which has become a key element of global educational agendas. Its inclusion in curricula promotes critical thinking, ecological literacy, and a long-term commitment to sustainable development (UNESCO, 2017). While both digital innovation and sustainability are recognised as vital educational imperatives, their intersection remains insufficiently explored within language pedagogy. Connecting these two domains opens new opportunities to develop students' digital skills alongside their environmental awareness, bringing education closer to the broader goals of global citizenship.

Consequently, this article argues that for ELLs, these domains are not merely complementary but can create a powerful synergy. Environmental topics provide a meaningful, authentic, and globally relevant context for learning. When students engage in activities such as researching local ecosystems, designing digital awareness campaigns, or analysing global sustainability data, they apply digital technologies with a clear purpose. At the same time, the processes of seeking, evaluating, creating, and collaborating in English provide a holistic framework for language development.

2. Research methodology

The aim of this study is to present a conceptual model for integrating green education into English language instruction through digital technologies. Drawing on well-established pedagogical approaches, including Content and Language Integrated Learning (CLIL) and Education for Sustainable Development (ESD), launched by UNESCO (2020), the model seeks to cultivate students who are ecologically informed, digitally competent, and globally communicative.

This conceptual study is conducted within the framework of the research project *Integrating and Promoting Green Education in the Initial Training of English Language Teachers*; strategic priorities: societal challenges; strategic direction: Innovative Educational Technologies and Products; project code 25.80012.0807.56SE. The project investigates integrated approaches to green

education in English language learning contexts. Its primary aim is to explore innovative pedagogical approaches that simultaneously foster environmental awareness, digital competence, and English language skills among students.

This research seeks to address the following questions:

1. How can digital and green education be integrated to enhance English language learning and foster eco-digital competences among learners?
2. What pedagogical principles and instructional models best support the simultaneous development of digital literacy and environmental understanding in English language education?
3. Which digital platforms and learning strategies are most effective in promoting environmental awareness and sustainable digital practices in ELL contexts?

The study adopts a qualitative, theory-based approach, drawing on established pedagogical frameworks from technology-enhanced learning, including Content and Language Integrated Learning (CLIL) and Education for Sustainable Development (ESD). Its purpose is to develop a pedagogical model to support teaching practice. The methodology focuses on identifying key principles, exploring effective strategies, and examining potential challenges in implementing an integrated digital and green curriculum.

3. Theoretical background

3.1 The Digital-Green Imperative

The growing interdependence of digital technology and environmental sustainability has resulted in what is referred to in the literature as the “Digital-Green Imperative” (Arnold et al., 2023). This concept highlights the challenge of using digital technologies to promote environmental sustainability while managing their ecological impact (OECD, 2020; UNESCO, 2023). According to the OECD (2020) and UNESCO (2023), digitalisation and sustainability are deeply connected processes, capable of enhancing both educational outcomes and societal progress. Digital tools offer innovative methods for monitoring, modelling, and addressing complex environmental issues, whereas sustainable practices provide authentic contexts in which students can apply and develop their digital skills effectively.

Within modern education, digital competence has emerged as a fundamental skill. According to the European Commission (2018), this includes not only technical proficiency but also critical thinking, collaboration, and ethical dimensions necessary for full participation in a digital society. For English Language Learners (ELLs), digital competence is particularly significant, as it facilitates access to diverse linguistic resources, enables cross-border collaborative learning, and supports engagement with authentic, content-rich materials (Godwin-Jones, 2018). Nonetheless, factors such as unequal access to resources, varying prior experience, and language barriers can impede the development of digital

literacy (Drljić et al., 2025).

Complementing this, Education for Sustainable Development (ESD), also known as green education, equips students with the knowledge, skills, attitudes, and values needed to contribute to a sustainable future (UNESCO, 2017). Introducing sustainability into curricula encourages critical thinking, ecological literacy, and responsible citizenship by connecting learning to real-world issues (Tilbury, 2011). Environmental concerns are inherently global, immediate, and socially important, providing engaging contexts in which students apply problem-solving skills and make meaningful decisions.

The Digital-Green Imperative reaches its full potential at the intersection of these two domains. Studies by Voogt et al. (2013) and Holmes et al. (2018) mention that project-based and technology-enhanced learning approaches are particularly effective in simultaneously fostering digital competence and ecological literacy. For instance, students can use digital platforms to gather and interpret ecological data, design digital awareness campaigns, or participate in collaborative simulations of energy management. Such activities not only strengthen technical and critical digital skills and deepen understanding of sustainability issues but also support holistic development of English language skills within authentic communicative contexts.

Despite this potential, the integration of digital literacy and green education remains underexplored in language pedagogy, particularly with regard to ELLs. Existing research often addresses these areas separately, focusing either on technological skill development or on fostering environmental awareness, without fully examining their synergistic potential for language learning (Godwin-Jones, 2021; Ram, 2025). Diavati (2023) argues that modern education should evolve toward sustainability-oriented and transformative learning. In this context, Content and Language Integrated Learning (CLIL) offers an effective pedagogical framework for promoting Education for Sustainable Development (ESD). By combining linguistic, cognitive, and environmental dimensions, CLIL enables students to acquire a foreign language while simultaneously developing critical, creative, and metacognitive competences essential for addressing global sustainability challenges.

In summary, the Digital-Green Imperative calls for pedagogies that integrate digital tools with sustainability content. For English Language Learners, this integrated approach provides a unique opportunity for improving digital literacy, language skills, and sustainability awareness simultaneously, cultivating globally competent citizens for the 21st century.

3.2 Digital literacy as a transversal competency

Digital competence, as defined by the European Commission's DigComp framework, encompasses the confident, critical, and responsible use of digital technologies for learning, work, and social participation (Carretero et al., 2017).

This competence extends beyond technical proficiency; it involves the integrated application of cognitive, social, and ethical skills to search for information effectively, critically evaluate sources, and responsibly create digital content. For English Language Learners (ELLs), this holistic competence is indispensable. It enables access to authentic linguistic resources (*e.g.*, *BBC Learning English*, *Voice of America (VOA)*, *TED Talks*), facilitates collaboration with global peers, and supports the creation of original digital content, thereby promoting both language acquisition and the development of critical thinking skills.

The integration of digital tools (*e.g.*, *Newsela*, *Learning with Texts*, *Google Docs*, *Wakelet*) creates an immersive environment for language learning that extends far beyond traditional textbooks. Engagement with authentic online materials like news articles, videos, podcasts, etc. allows students to experience language in real contexts, enhancing comprehension and cultural understanding. At the same time, technology-mediated collaboration on shared projects or virtual exchanges provides a purposeful and motivating framework for improving communicative competence. Moreover, the strategic pedagogical integration of Information and Communication Technology (ICT) transforms the traditional language classroom into a dynamic, adaptive ecosystem. These environments combine structured guidance with flexibility, enabling students to interact with multimodal materials, receive instant feedback, and embark on personalised learning trajectories. Consequently, this methodology sustains learner motivation and supports deeper, long-term learning outcomes.

Digital literacy is recognized as a transversal skill that connects with and strengthens broader educational goals. As Mantiri *et al.* (2019) note, combining student-centered learning with digital tools effectively develops critical thinking, problem-solving, and strong communication skills. This approach also increases student motivation and autonomy by providing personalized, technology-enhanced experiences. To take advantage of these benefits, teachers need a strategic pedagogical approach that integrates digital literacy into the curriculum, ensuring its application in authentic learning contexts. The transition from theory to practice is a key step of digital transformation, directly influencing instructional design, facilitation, and assessment in technology-enhanced environments.

3.3 Digital pedagogical strategies

Connectivism provides a key theoretical foundation for digital pedagogy, addressing the limitations of traditional models in explaining how learning occurs within complex information networks. Drawing on Siemens, Duke, Harper, and Johnston (2013) argue that the exponential growth of knowledge and the increasing complexity of society necessitate nonlinear models of learning. This transformation, driven by technological interconnectivity, has transformed knowledge from a static construct into a fluid, networked system. Knowledge now functions less as an established hierarchy and more as an evolving ecology of connections, valued for its applicability and relevance to real-world problem-solving.

Technology integration strengthens Project-Based Learning (PBL), an instructional system based on real, inquiry-driven experiences that aims to improve content knowledge, language proficiency, and 21st-century skills at the same time. Ginusti (2023) emphasizes that teachers must use technology in a variety of ways to build active learning environments. A key principle is that when projects are positioned as the central pillar of the curriculum and technology is used as an instrument for collaboration and exploration, students naturally engage in meaningful, real-world tasks.

Another innovative pedagogical strategy is the flipped classroom model, which reverses traditional instructional paradigms. By delivering direct instruction outside of class through digital platforms, classroom time is transformed into an interactive workshop for active, collaborative problem-solving under teacher guidance. According to Preeti (2021), this approach enables students to learn at their own pace and review difficult topics as needed. Research indicates that the flipped classroom promotes increased engagement, deeper understanding, and active knowledge application, resulting in more personalized, interactive, and successful learning. This approach can also complement project-based activities in technology-mediated contexts.

In addition, digital learning environments encompass a wide range of pedagogical strategies, including blended learning, gamification, adaptive learning technologies, interactive multimedia content, and frequent feedback (Duterte, 2024). Integrating these strategies to improve digital education and address diverse learner needs requires careful evaluation of their long-term impact, the role of emerging technologies, and their effectiveness across different educational situations. Such integration ensures equitable, meaningful, and engaging learning experiences for all students.

In a green-focused curriculum, pedagogical strategies like Project-Based Learning (PBL) and the Flipped Classroom are greatly enhanced when applied to real-world ecological issues. This approach aligns with the core purpose of environmental education. As Krasny (2020) emphasizes in *Advancing Environmental Education Practice*, the goal is to achieve environmental quality and support climate adaptation, wherein psychological and social factors act as intermediate outcomes that lead to meaningful environmental actions rather than serving as endpoints in themselves. Lombardi (2007) states that authentic learning enables students to engage in meaningful, real-world activities. This is accomplished through web technology-enhanced learning environments that enable students to access professional resources, and analyze complex data, thus engaging with phenomena that would otherwise be inaccessible. Integrating digital pedagogy with environmental education transforms language learning into a holistic experience that fosters linguistic, digital, and ecological civic competences.

4. Findings and discussion

4.1 Mapping Digital and Language Skills

The transversal nature of digital competence is operationalised through the interconnected domains defined by the *DigComp 2.2 framework* (Vuorikari et al., 2022). To move from theory to practice, teachers and students benefit from an integrated model illustrating how each digital domain could support specific dimensions of language proficiency. The table below presents a model linking the five *DigComp* domains to key language skills. This interrelation provides a practical model for systematically embedding digital tasks and suggested tools, ranging from critically evaluating online information to collaboratively creating digital content, into the language curriculum, ensuring that technology is used purposefully and pedagogically.

Table 1. A Digital-Linguistic Competence Framework

DigComp Domains and Competence	Key Descriptors and Digital Tasks	Supported Linguistic Competences
1. <i>Information and Data Literacy</i> (ability to search, evaluate, and manage digital information critically)	Critically evaluating online sources (<i>Learning with Texts</i> , <i>Google Docs</i>); Comparing information from different news sites (<i>BBC News</i> , <i>Reuters</i> , <i>Associated Press</i>)	Receptive skills: reading comprehension, listening, mediation.
2. <i>Communication and Collaboration</i> (using digital tools to interact, communicate, and collaborate responsibly)	Participating in online forums; Collaborative writing on shared documents (<i>Google Docs</i>); Video conferencing with peers (<i>Meet</i> , <i>Teams</i>)	Interactive skills: speaking, writing, negotiation, intercultural communication.
3. <i>Digital Content Creation</i> (producing and editing digital content; understanding copyright and licenses)	Creating digital posters (<i>Canva</i>), videos, or blogs (<i>WeVideo</i>); Designing infographics (<i>Piktochart</i>); Remixing content for a new audience (<i>Book Creator</i>)	Productive skills: writing, speaking, structuring discourse
4. <i>Safety</i> (protecting devices, personal data, health, and the environment)	Understanding privacy settings (privacy settings on platforms like <i>Instagram</i> , <i>TikTok</i> , and <i>Google Account</i>); Recognizing digital well-being (<i>Digal Detox Apps</i>); Assessing the envi-	Socio-pragmatic and ethical competence: appropriate, respectful communication

	ronmental impact of digital habits (<i>Carbon Calculator</i>)	
5. <i>Problem-Solving</i> (identifying and solving digital challenges creatively; reflecting on digital skills)	Using digital tools to analyze data sets; Critical examination of issue (<i>MindMeister</i>); Designing a solution to a real-world problem (<i>Canva</i> , <i>Tinkercad</i>)	Metacognitive competence: monitoring understanding, regulating learning.

This mapping demonstrates that digital and language skills strengthen each other when integrated systematically. By linking the five *DigComp* domains to CEFR-aligned language skills (Council of Europe, 2020), the model validates digital literacy's role as a transversal competency. Within integrated pedagogical frameworks such as CLIL and ESD, this synergy is essential: it allows students to acquire language naturally through engaging, sustainability-oriented digital tasks.

4.2 Integrating CLIL, ESD and digital practices

When CLIL, ESD, and digital practices intersect, they create more than complementary dimensions of learning; together, they form a transformative educational ecosystem. Within this framework, *Content and Language Integrated Learning (CLIL)* provides the pedagogical foundation for combining content and language acquisition; *Education for Sustainable Development (ESD)* offers an authentic, value-oriented context; and *digital practices* function as mediators for exploration, creation, and communication. This synergy enables technology-enhanced, project-based learning, such as producing environmental videos or conducting data analyses, that cultivates the three core literacies central to this study: linguistic, digital, and ecological literacy.

Current literature highlights opportunities to integrate environmental awareness and digital competence in language learning. Hauschild et al. (2012) suggest that embedding sustainability topics into language learning increases learner engagement and promotes authentic communicative use of English. Similarly, Kazazoglu (2025) points out the potential of strategies such as digital storytelling, analyzing collections of environmental texts, and project-based learning to improve language skills while developing eco-literacy and global awareness. However, effective implementation depends largely on the teacher's understanding of sustainability concepts and their ability to critically evaluate materials in order to align content and linguistic objectives (Hauschild et al., 2012).

Building on these insights, the following table presents a conceptual framework for operationalising the integration of CLIL, digital competence, and ESD, linking linguistic competences with ESD-related skills and illustrative digital practices to support integrated lesson design. The table below demonstrates that the integration of digital tools, language learning, and Education for Sustainable Development is not merely complementary but inherently synergistic. Each digital task simultaneously engages specific linguistic and ESD competences, creating a

rich and authentic learning context. For example, mediating a text by designing an infographic on the greenhouse effect (a cognitive-linguistic task) directly fosters systems thinking (an ESD competence) while developing digital content creation skills.

Table 2. Content and Language Integrated Learning through digital practices

Linguistic Competence (CEFR / CLIL)	ESD Integration	Example of digital Practice
Receptive skills: Reading and Listening	Researching sustainability topics; Evaluating eco-related information	Conduct web-based research on climate change or renewable energy; Compare different news sources; Analyze authentic environmental texts (<i>BBC Learning English, The Guardian Environment Section, Breaking News English, National Geographic Kids, Duolingo, LingQ</i>).
Interactive skills: Speaking, Writing, Negotiation, Intercultural Communication	Participating in cross-cultural sustainability projects; Discussing eco-friendly practices	Engage in virtual discussions, online forums, peer feedback; Collaborative writing on shared documents (<i>Google Docs, Padlet, Wakelet, Microsoft Teams, eTwinning</i>).
Productive skills: Writing and Speaking, Structuring Discourse	Creating awareness campaigns; Presenting sustainability solutions	Develop digital posters, blogs, videos, infographics about environmental issues (<i>Google Slides, Canva, Piktochart, Book Creator, WeVideo, Clipchamp</i>).
Socio-pragmatic and Ethical competence	Promoting responsible digital citizenship; Ethical communication	Evaluate sources; Discuss netiquette; Practice responsible online communication (<i>Seesaw, Edmodo, Kahoot!, ClassDojo</i>).
Strategic and Metacognitive competence	Problem-solving sustainability challenges; Reflecting on learning and environmental impact	Analyze data sets on environmental issues; Plan and propose solutions; Design sustainability projects (<i>Miro, Jamboard; Google Sites</i> to create a digital project hub; <i>ArcGIS StoryMaps, Scratch</i>).

Furthermore, this table highlights the central role of digital competence as a key facilitator within this triad. Platforms such as *Padlet*, *Google Docs*, and other collaborative tools function not merely as technological supports but as dynamic environments that promote communication, cooperation, and written interaction.

Likewise, the process of evaluating online sources for research tasks inherently develops critical thinking, which underpins both digital literacy and ESD. By mapping these connections, the table offers a practical model for teachers to design integrated “digital-green-language” tasks. Ultimately, this framework prepares students not only to use English and technology effectively but also to apply both as responsible, informed, and proactive citizens in a globalised world.

While Table 2 synthesizes insights from existing CLIL, ESD, and digital learning literature, the stated benefits remain conceptual in nature, as the proposed framework represents an early-stage research initiative. To empirically evaluate the effectiveness of this matrix, future research should include an initial pilot study implemented in selected ELL classrooms. This pilot phase could examine the impact of integrated digital-green CLIL tasks on learners’ linguistic competences, sustainability awareness, and digital skills. The findings would contribute empirical evidence to refine and support the proposed model across diverse ELL contexts.

5. Conclusions

The integration of digital and sustainability-focused learning is progressively reshaping contemporary education, offering a transformative, future-oriented pedagogy. For English Language Learners (ELLs), digital tools support collaboration, inquiry, and creative expression in English, while sustainability topics provide authentic contexts for communication. Embedding these themes into technology-enhanced language training simultaneously fosters linguistic proficiency, ecological awareness, and digital literacy.

The conceptual frameworks developed in this study, namely the digital-linguistic competence matrix and the CLIL-ESD integration model, provide practical blueprints for such integration. Grounded in CLIL principles and Education for Sustainable Development, they demonstrate how integrated approaches prepare students to be ecologically conscious, technologically proficient, and globally engaged communicators. Ultimately, this framework positions language education as a platform for cultivating the skills and values essential for sustainable living in the 21st century.

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Implementation of digital education in primary school from an interdisciplinary perspective

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Abstract: *The integration of digital education in primary school represents both a challenge and a strategic opportunity for developing the essential competences of 21st-century learners. In the context of recent curricular reforms, the inclusion of digital education in primary schooling involves not only introducing new content but also reconfiguring teaching, learning, and assessment models. This article analyses the theoretical and curricular foundations of digital education as a transversal domain, highlighting opportunities for its integration into existing subjects, elective courses, and interdisciplinary activities. The approaches to implementing digital education from an interdisciplinary perspective are anchored in European and national educational policies, recent curricular models, and pedagogical experiences from Romania, Estonia, and Finland. The paper proposes a model of integrated curricular design aimed at developing digital competence as an essential dimension of the student's graduate profile. It also outlines the theoretical premises of digital education, the teacher's role in the digital transformation process, and examples of interdisciplinary learning activities that employ digital tools and resources. The proposed methodological framework for integrating digital education in primary school is flexible and based on collaboration, creativity, and reflective learning.*

Keywords: Digital education, Curricular implementation, Interdisciplinarity, Primary education, Digital competence.

1. Introduction

The digital transformation of education has become a central priority of European educational policies, a process significantly accelerated by the experience of online learning during the COVID-19 pandemic. In Romania, this transformation has been formally articulated through the National Education Law No. 198/2023 (Parliament of Romania, 2023) and the SMART.Edu Strategy (2021–2027), which emphasize the development of digital competence as a transversal dimension of the school curriculum. Within this framework, primary education plays a crucial role in the early formation of digital competences, not only through the use of technology but also by fostering critical thinking, creativity, and responsible digital behaviour.

Digital education is no longer viewed merely as a supportive component of the instructional process, but as a distinct educational field with significant formative value. Consequently, the development of digital competences in primary school students represents a strategic priority, as these competences form the foundation for lifelong learning and active participation in the knowledge society. According to European reference frameworks, digital competence is defined as a combination of knowledge, skills, and attitudes that enable individuals to use digital technologies critically, creatively, and safely for learning, work, and civic engagement (European Commission, 2022). Therefore, digital education at the primary level must extend beyond basic operational skills and intentionally promote higher-order thinking, creativity, and digital responsibility.

Numerous international studies and policy reports (OECD, 2023; UNESCO, 2021) emphasise the early introduction of digital education through interdisciplinary approaches that connect traditional school subjects with digital technologies. Countries such as Finland and Estonia offer relevant examples of good practice, where digital education is embedded in the core curriculum and supported by systematic teacher training. In Romania, strategic policy documents, including the SMART.Edu Strategy (2021) and the National Education Law No. 198/2023, advocate for the integration of digital education across all levels of schooling. However, at the primary education level, implementation remains limited, highlighting the need for flexible curricular models and pedagogical experimentation to demonstrate the effectiveness of innovative approaches. In this context, the present study aims to contribute to the integration of digital education in primary schooling, including through optional subjects, as a means of developing transversal competences. To ensure alignment with European standards on digital competence, such initiatives require systematic expansion and integration into the core curriculum of primary education.

2. Pedagogical foundations of digital education in primary school

Digital education, in its contemporary understanding, extends beyond the instrumental use of technology as a teaching aid and focuses on the systematic development of digital competence. This competence is defined within European reference frameworks as a combination of knowledge, skills, and attitudes necessary for the critical, creative, and safe use of digital technologies. In primary education, digital education should be introduced progressively, in alignment with children's cognitive, emotional, and social development, through playful, exploratory, and collaborative learning experiences.

From a curricular perspective, digital education represents a complex process that involves the integration of digital technologies into teaching, learning, and assessment, while simultaneously functioning as a transversal dimension of competence development for life in the knowledge society (UNESCO, 2021). In this context, the digitalisation of education is no longer an optional technological enhancement, but a pedagogical and curricular requirement that reshapes the roles

of teachers and students, encouraging active participation, collaboration, and personalised learning pathways (OECD, 2023).

Pedagogically, digital education is grounded in constructivist and socio-constructivist learning theories, which emphasise knowledge construction through exploration, problem-solving, projects, and social interaction (Piaget, 1970; Vygotsky, 1978; Bruner, 1996). Within the postmodern educational paradigm, digital education is further associated with the theory of connectivism, proposed by Siemens (2005), which conceptualises learning as a dynamic network of connections among individuals, digital resources, and technological environments.

The pedagogical foundations of digital education are also supported by international competence frameworks that define benchmarks for digital literacy and the responsible use of information and communication technologies. Among the most relevant frameworks are the European Framework for the Digital Competence of Citizens – DigComp 2.2 (European Commission, 2022), which identifies five key competence areas (information and data literacy, communication and collaboration, digital content creation, safety, and problem-solving), the European Framework for the Digital Competence of Educators – DigCompEdu (Redecker, 2017), which provides guidance for the pedagogical integration of digital technologies, and the SMART.Edu Strategy (Ministry of Education, 2021), which aims to support the digital transformation of the Romanian education system through the development of digital competences in both students and teachers.

From a formative perspective, digital education goes beyond the acquisition of technical skills and targets the development of critical thinking, creativity, learning autonomy, and ethical digital behaviour (Selwyn, 2016; Drăghicescu, 2020). Due to its transversal nature, digital education functions as an integrative curricular dimension, encouraging interdisciplinary approaches and facilitating meaningful connections between traditional school subjects and the digital realities of contemporary society.

Consequently, the pedagogical foundations of digital education are based on several core principles: active and collaborative learning, competence-based education, the integration of technology into authentic learning contexts, and the promotion of responsible and ethical digital awareness. In primary education, these principles are operationalised through student-centred, playful, and exploratory activities, in which technology serves as a mediator of learning rather than an end in itself (Coroi, 2024).

3. The interdisciplinary approach – Premises and benefits

Interdisciplinarity provides an optimal framework for implementing digital education in primary school. Through thematic projects and integrated learning activities, pupils can apply digital competences in authentic learning contexts, connecting knowledge and skills from multiple disciplines. Examples of good practice can be identified in the educational systems of Estonia and Finland, where digital education is treated as a transversal key competence, developed through

interdisciplinary activities and student-centred learning projects (Coroi, 2025).

In the context of globalisation and rapid technological change, digital education can no longer be understood merely as a set of technical skills. Instead, it represents an essential dimension of pupils' holistic development, fostering critical thinking, creativity, collaboration, and responsible participation in digital environments. These objectives align naturally with interdisciplinary approaches, in which technology supports meaningful connections between subjects and learning processes. Consequently, European countries have adopted diverse strategies for integrating digital technologies into education, shaped by their specific social, cultural, and economic contexts.

Estonia stands out as a European benchmark in the digitalisation of education (Eurydice, 2019; Eurydice, 2023). Since the early 2000s, national educational policies have focused on the systematic integration of digital technologies at all levels of education, emphasising curricular flexibility and the transdisciplinary application of digital competences. In primary education, the subject Technology has been redesigned to include digital communication, online safety, and the use of emerging technologies. These elements are not treated as isolated content but function as tools that support learning across disciplines. As a result, pupils develop digital competences alongside critical thinking skills and the ability to apply knowledge in diverse and authentic contexts, fostering interconnected and innovative learning (Redecker, 2017).

Similarly, Finland adopts an integrated and transdisciplinary approach to digital education. The National Core Curriculum defines seven transversal competences, among which digital competence plays a central role. Rather than being organised as a separate subject, digital technologies are embedded across all learning areas and are used for research, collaboration, project-based learning, and presentations. Finnish pedagogy, grounded in phenomenon-based learning, encourages pupils to explore complex themes from an interdisciplinary perspective, connecting knowledge from sciences, arts, languages, and digital technologies. This approach promotes contextualised, meaningful, and student-centred learning (Finnish National Agency for Education, 2014–2020).

In contrast, Romania is currently at a more fragmented stage of digital education implementation. Although digital competence is included among the key competences in the national curriculum, its practical application remains uneven across schools. The integration of digital technologies depends largely on local initiatives, available infrastructure, and teachers' levels of digital preparedness. The SMART.Edu Strategy outlines a clear national direction until 2027; however, achieving results comparable to those of Estonia and Finland requires the development of coherent curricular practices that promote the interdisciplinary application of digital competences, sustained investment in educational infrastructure, and continuous professional development for teachers.

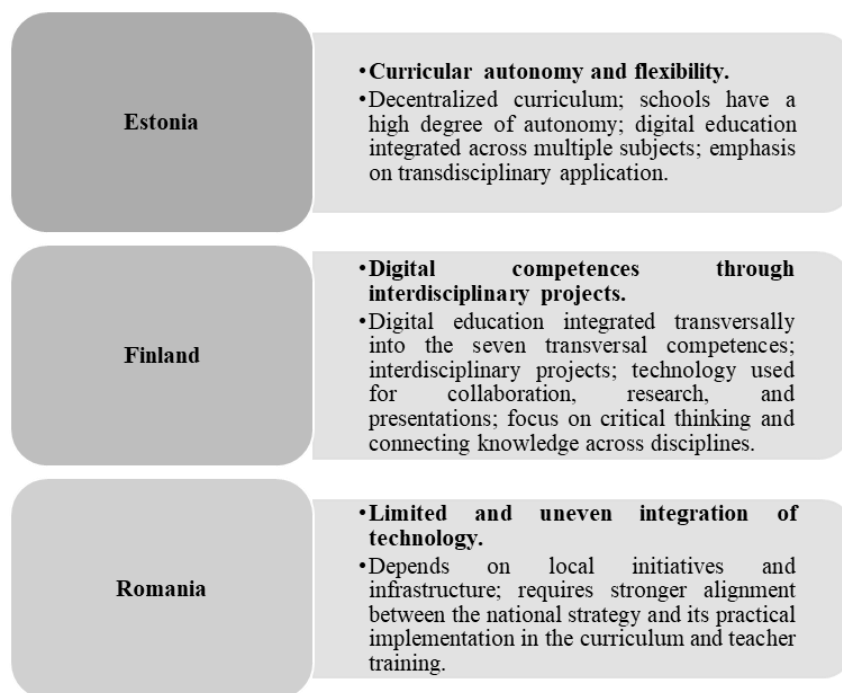


Figure 1. Curricular models for integrating digital education in primary school

Figure 1 illustrates the main curricular models for integrating digital education in primary school in Estonia, Finland, and Romania. The comparison highlights that the successful integration of digital education depends not only on the existence of strategic policy documents, but also on the extent to which technology is used as a bridge between disciplines, fostering collaboration, creativity, and critical thinking. The Estonian and Finnish models offer concrete examples of effective practices, demonstrating how digital literacy and interdisciplinarity can be embedded from the primary level. These models may serve as valuable reference points for Romania in the development of sustainable, coherent, and integrated approaches to digital education that prepare pupils for the challenges of an increasingly complex digital society.

4. Curricular approaches to implementing digital education

Implementing digital education at the primary school level requires a systemic approach, encompassing several complementary strategies:

1. Integrating digital competences into existing subjects;
2. Developing thematic elective courses;
3. Using open educational resources;
4. Ensuring continuous teacher training.

The Romanian model can build on the experiences of the SMART.Edu Strategy and European frameworks such as DigCompEdu, adapting them to the

specific needs of primary education and the local resources available (Ministry of Education, 2021; Redecker, 2017).

A flexible and effective method for integrating digital education in primary schools is through the School-Based Curriculum (SBC), by designing optional courses aimed at developing age-appropriate digital competences. This approach allows for the contextualization of digital education according to each school's resources, profile, and needs, while also fostering interdisciplinary connections with core subjects, such as Romanian Language, Mathematics and Environmental Exploration, Arts, ICT, and Civic Education.

Designing such an optional subject involves several key steps:

- Defining specific competences based on the Digital Competence framework from the Student Graduate Profile and the European DigComp framework;
- Selecting content that promotes critical thinking, online safety, responsible technology use, and digital creativity;
- Structuring learning activities around interdisciplinary themes (e.g., "Digital in My Life," "I Am a Responsible Digital User," "The Digital World – Friend or Foe?");
- Using digital resources, including educational platforms, interactive applications, Google tools, LearningApps, Canva for Education, Kahoot, and Wordwall;
- Conducting comprehensive assessment through digital portfolios, multimedia products, practical activities, and self-assessment.

A concrete example of this approach is the optional subject "Digital Education", developed as part of an experimental pedagogical study (2022–2023) and implemented with 2nd- and 3rd-grade students over one school year (34 hours). The program aimed to develop functional digital competences, ranging from basic knowledge and skills to responsible attitudes and online collaboration. The results indicated that the systematic inclusion of digital activities within an interdisciplinary elective led to significant increases in student engagement, the development of critical thinking, and the formation of foundational digital culture, aligned with the European student competence profile (Coroi, 2024; Coroi, 2025).

Technology provides an ideal context for integrating subjects and supporting project-based learning, offering benefits such as systemic thinking, motivation, learning transfer, and collaboration. The experience of implementing a digital education elective demonstrated that designing interdisciplinary activities enhances student engagement and supports the development of the key competences outlined in the Graduate Profile.

5. Examples of interdisciplinary activities and digital resources

Interdisciplinary activities provide meaningful opportunities to combine digital education with core curricular areas such as language arts, science, civic education, and the arts. Relevant examples include the creation of digital

presentations, concept maps, formative assessment activities using platforms such as Kahoot or Wordwall, and the development of small-scale multimedia projects that reflect pupils' digital competences. In this context, the digital portfolio represents a comprehensive tool for reflection, documentation of learning progress, and self-assessment.

The integration of digital education in primary school requires the use of technological resources within interdisciplinary learning contexts that stimulate creativity, critical thinking, and collaboration among pupils. The examples presented below illustrate how activities designed within a Digital Education elective can support integrated learning and the development of transversal competences:

- a) „Digital Stories” – interdisciplinarity between Romanian Language and Digital Education. Pupils create short illustrated narratives using digital tools such as Canva for Education, BookCreator, or StoryJumper. This activity supports the development of written and oral communication skills, while also fostering the creative and purposeful use of digital tools. The final product—a digital book—is included in the pupil's portfolio, illustrating the integration of linguistic and digital competences.
- b) „The Digital Class Journal” – interdisciplinarity between Civic Education, Communication, and Digital Education. Working in teams, pupils create a monthly digital class journal using collaborative platforms such as Google Docs or Padlet. The activity aims to develop civic responsibility, cooperation, and teamwork, while also promoting safe and effective digital communication. Through documenting and reflecting on school-related events, pupils practise reasoned expression, critical thinking, and the ethical use of digital technologies.
- c) „*The Environment in Interactive Images*” – connections between Science, Arts, and Digital Education. Using platforms that support interactive digital content, such as *LearningApps*, *Genially*, or *Livresq*, pupils create interactive presentations on natural elements and environmental topics. These activities encourage observation, classification, and the description of natural phenomena, linking scientific understanding with digital and visual skills and supporting discovery-based learning.
- d) „Learning through Digital Games” – interdisciplinarity between Mathematics, Science, Communication, and Digital Education. Digital platforms such as Kahoot, Wordwall, or WordArt are used to consolidate mathematical and scientific knowledge, as well as communication skills, through playful and interactive challenges. Pupils create or solve digital games that involve logical reasoning, calculation, and clear expression, applying analytical and collaborative skills. This approach enhances motivation and engagement, transforming the digital environment into an attractive space for exploration and knowledge application. Figure 2 presents a visual synthesis of natural resources in the form of a word cloud, serving as a starting point for interactive digital learning activities.

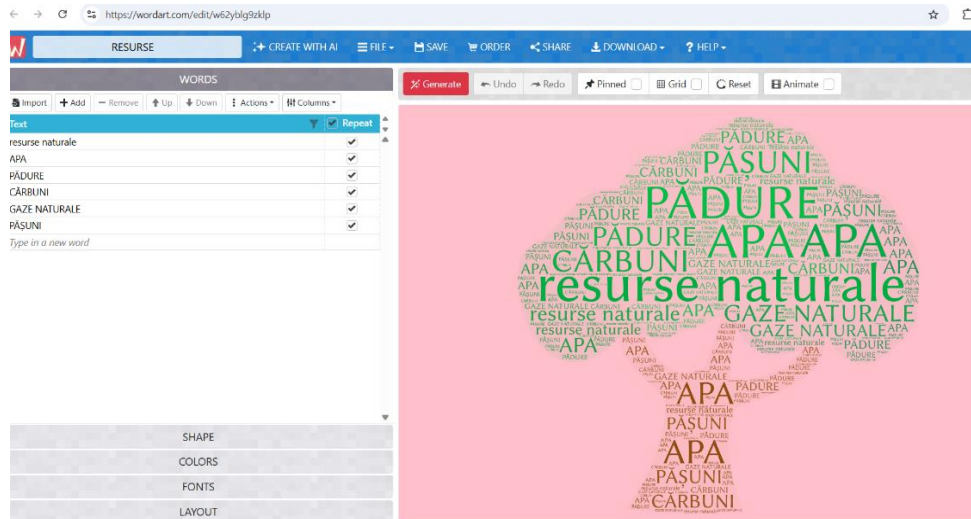


Figure 2. Word cloud of natural resources – WordArt

e) „Responsible Digital Citizen” – *interdisciplinarity between Civic Education, Social Education, and Digital Education.* This activity focuses on the development of ethical digital behaviour, including safe online practices, personal data protection, the identification of fake news, and respect for copyright. Pupils collaboratively create digital posters or presentations, which are subsequently discussed in class to reinforce reflective and responsible attitudes toward digital environments.

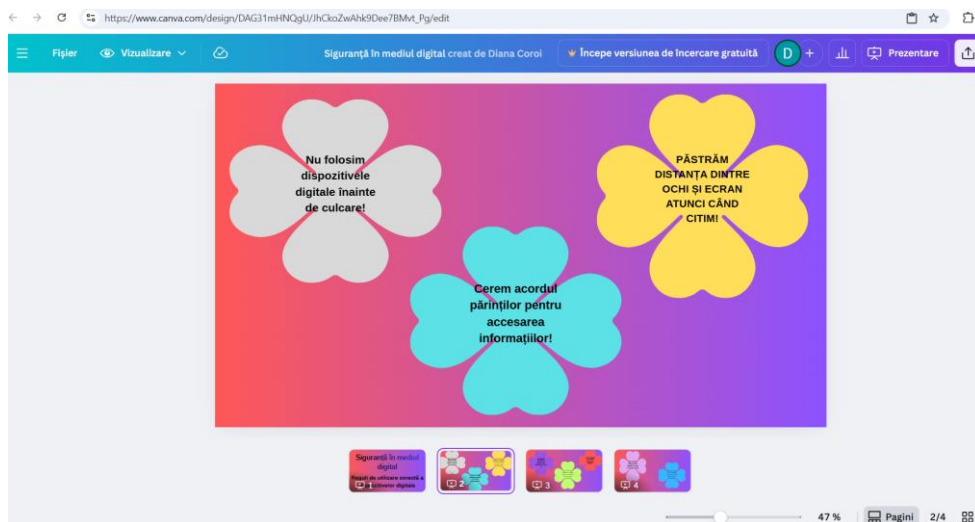


Figure 3. Digital safety rules for primary school pupils – Canva presentation

The example illustrated in Figure 3 represents an interactive presentation created using Canva, outlining technology usage rules adapted for primary school pupils, with a particular focus on digital safety. Overall, these activities demonstrate that the elective subject Digital Education can function as an integrative framework for developing the key competences of the primary curriculum through interdisciplinary projects that combine knowledge, expression, and creativity with the meaningful use of technology. Moreover, through its practical and applied nature, this elective supports the development of pupils' autonomy and fosters a reflective and responsible attitude toward the digital environment (Coroi, 2024).

6. The role of the teacher and digital pedagogical competences

The teacher plays a central role in integrating digital education, acting as a mediator between technological resources and pupils' actual learning needs. Digital pedagogical competences include the ability to select, adapt, and create digital resources, design learner-centered activities, and assess learning through technology. Continuous professional development remains essential for the effective implementation of digital education.

In the digital age, the teacher's role extends beyond the traditional transmission of knowledge, transforming into that of a facilitator of learning and a designer of the digital learning environment. Teachers guide pupils in the active construction of knowledge, stimulate collaboration and creativity, and integrate digital resources tailored to each pupil's needs and learning pace (Drăghicescu, 2020; Selwyn, 2016). This approach emphasizes a learning environment where technology serves as a means, not an end, and pedagogical principles remain central.

Teachers' competences in digital contexts are systematized in the European Framework for the Digital Competence of Educators (DigCompEdu), which identifies six areas: professional digital competences, digital collaboration, and integration of digital resources in teaching, fostering learners' digital competences, digital assessment, and engagement in continuous professional development (Redecker, 2017). These dimensions highlight that the effectiveness of digital education depends primarily on pedagogical expertise rather than mere technical skills. Romania adapts this framework for teacher training and assessment of digital competences.

Continuous training and an open mindset toward technology are essential. Teachers must adopt lifelong learning attitudes, experiment with new methodologies, and quickly adapt to technological innovations, while encouraging students to become critical and creative users of digital resources (Ertmer & Ottenbreit-Leftwich, 2010; Selwyn, 2016).

Research on the implementation of the Digital Education elective demonstrated that successful digital learning depends not only on technology availability but also on teachers' pedagogical competences. Practical experience

showed the need for training focused on pedagogical use of technology rather than technical proficiency alone. Consequently, teacher education should emphasize digital teaching strategies, integration of interactive resources, and promotion of a digital culture that fosters pupils' autonomy and collaboration.

Therefore, the teacher's role in digital education is complex and dynamic: facilitator, designer, and mentor, capable of connecting technology with educational goals and fostering pupils' digital competences in an integrated and sustainable manner.

7. Conclusions and perspectives

Integrating digital education in primary schools requires a coherent, interdisciplinary approach, grounded in collaboration, creativity, and reflection. European examples illustrate that success depends on the quality of teacher training, digital infrastructure, and the coherence of educational policies.

Digital education should be embedded in the curriculum as an essential dimension of learning rather than as an isolated component. Interdisciplinary approaches and elective courses provide effective tools for curricular innovation, stimulating pupils' creativity and the development of digital competences.

Such approaches also offer teachers a framework for pedagogical experimentation and for adapting learning activities to the diverse needs of pupils. The Digital Education elective implemented in this study demonstrated the value of this approach by fostering pupils' creativity and promoting digital competences in a practical, contextualized way (Coroi, 2024; Coroi, 2025).

The findings further highlight the importance of coherent educational policies supporting digital integration at the national level and of continuous teacher training, enabling educators to harness technology pedagogically. Lifelong professional learning, combined with an open digital mindset, is a key factor in transforming technology into an effective learning tool.

Looking forward, integrating digital education in primary schooling represents a strategic investment in developing a generation capable of learning, collaborating, and creating in an increasingly connected world. This approach not only addresses the demands of the digital society but also strengthens the foundation for an innovative, equitable, and sustainable education system.

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Assessment for Learning in Informatics education: The CAIR framework and a STEAM-based application

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Abstract: *Competency-based Informatics education requires assessment practices that support iterative learning, problem-solving, and learner self-regulation; however, assessment often remains predominantly summative and weakly integrated with instruction. This paper presents a CAIR-oriented approach to operationalising Assessment for Learning in upper secondary Informatics education. Rather than introducing additional assessment instruments, the CAIR framework embeds formative assessment directly into instructional design by aligning learning tasks, feedback, and reflection with Informatics-specific competencies. Using a design-based, illustrative perspective, the study examines an authentic project-based learning scenario involving C/C++ programming and microcontroller-controlled smart systems. A parking system with a servo-controlled barrier is analysed to demonstrate how assessment evidence emerges through iterative cycles of design, testing, debugging, and reflection. The analysis highlights CAIR's capacity to support coherent alignment among competencies, learning activities, and formative assessment while remaining adaptable to practical classroom constraints.*

Keywords: Assessment for Learning, Informatics education, Competency-based assessment, CAIR framework, Project-based learning.

1. Introduction

The increasing centrality of digital technologies in contemporary society has intensified the need for Informatics education to move beyond content transmission toward the systematic development of competencies such as algorithmic reasoning, problem solving, adaptability, and self-regulated learning. In response, many curricula have adopted a competency-based orientation; however, assessment practices in Informatics often remain predominantly summative and product-focused. This misalignment limits the capacity of assessment to support learning processes that are inherently iterative, exploratory, and reflective, particularly in programming- and system-oriented contexts (Gutu, 2025a).

Within this landscape, Assessment for Learning (AfL) has emerged as a promising approach for repositioning assessment as an integral component of instruction (Cambridge Assessment International Education, n.d.; Carless, 2017; Gutu, 2022; Arnold & Willis, 2024). AfL emphasises formative feedback, learner involvement, and the purposeful use of assessment information to guide learning; however, despite its well-documented pedagogical value, its implementation in

<https://doi.org/10.58503/icvl-v21y202619>

Informatics education remains challenging and often insufficiently aligned with targeted competencies (Gutu, 2022).

This paper contends that addressing this challenge requires not only the adoption of AfL principles but also a coherent pedagogical framework that systematically embeds formative assessment within instructional design. The study introduces and applies the CAIR framework (Constructivist-Adaptive-Integrative-Reflective) as a design-oriented approach for operationalising AfL in Informatics education, aligning learning activities, feedback processes, and reflective practices with competency development without introducing additional assessment instruments or parallel evaluation structures (Gutu, 2025c).

The purpose of this paper is to examine how CAIR-oriented AfL can be operationalised and enacted in upper secondary Informatics education through authentic, practice-based learning scenarios. Rather than evaluating learning outcomes through experimental comparison, the study adopts a design-based, illustrative approach that foregrounds pedagogical coherence, alignment, and feasibility.

Accordingly, the paper pursues the following objectives:

1. to articulate a coherent theoretical foundation for AfL in Informatics education, grounded in competency-based pedagogy and aligned with the epistemological characteristics of the discipline;
2. to describe how the CAIR framework operationalises AfL by embedding constructivist tasks, adaptive feedback, integrative learning design, and reflective practices within instructional planning;
3. to illustrate this operationalisation through an authentic application scenario involving project-based, technology-rich Informatics learning;
4. to analyse practical challenges and considerations associated with implementing CAIR-oriented AfL in formal educational settings; and
5. to discuss the pedagogical implications of using CAIR as a unifying framework for assessment-driven competency development in Informatics education.

By addressing these objectives, the paper contributes to ongoing discussions on transforming assessment practices in Informatics education and offers a coherent model for aligning curriculum, instruction, and assessment to support sustainable competency development.

2. Theoretical framework

The evolution of Informatics education toward a competency-based paradigm necessitates a corresponding transformation in assessment practices. Traditional assessment models, typically associated with Assessment of Learning, prioritise summative judgments of performance and tend to emphasise final products over learning processes (Azevedo, 2020; Gutu, 2022; Khat & Vogel, 2022). While such approaches provide standardised measures of achievement, they offer limited support for the development of complex Informatics competencies

such as algorithmic reasoning, problem decomposition, adaptability, and metacognitive regulation (Hong, 2020; Gutu, 2023). As a result, assessment risks becoming disconnected from instruction and learning, particularly in contexts where iterative problem solving, system modelling, and conceptual understanding are essential (Gutu, 2022, 2023; Revati, 2024).

In contrast, AfL positions assessment as an integral and continuous component of the learning process (Gutu, 2022). AfL emphasises formative feedback, active learner involvement, and the use of assessment information to foster self-regulated learning and to guide subsequent learning actions (Wirth & Leutner, 2008; Khat & Vogel, 2022; Adler et al., 2025). Within Informatics education, this perspective aligns with the discipline's epistemological foundations, particularly in programming- and system-oriented contexts characterised by iterative cycles of hypothesis, implementation, testing, and refinement. Accordingly, effective assessment should support these cycles by clarifying learning goals, providing timely feedback, and promoting self-regulated learning.

A core requirement of AfL is the functional alignment between curriculum objectives, instructional activities, and assessment strategies (Gutu, 2022; Arnold & Willis, 2024). Research in instructional design and competency-based education highlights that learning outcomes are most effectively achieved when assessment criteria are transparent, coherent across tasks, and explicitly connected to intended competencies (Burlacu, 2021; Gutu, 2025b; Cheng & Huang, 2025). In Informatics education, such alignment enables assessment to capture not only solution correctness but also reasoning, strategic decision-making, and conceptual transfer. Furthermore, formative practices - such as self- and peer assessment and descriptive feedback - are most effective when systematically embedded in instructional design rather than implemented as isolated techniques (Filgona et al., 2020; Gutu, 2023; Revati, 2024).

Metacognition and self-regulation represent core dimensions of AfL. In Informatics, where problem solving involves uncertainty, multiple solution pathways, and increasing abstraction, learners' capacity to plan, monitor, and evaluate their learning is critical (Gutu, 2022, 2025b). AfL fosters metacognitive development by promoting reflection on strategies, evaluation against explicit criteria, and informed regulation of subsequent learning, positioning assessment as a driver of internal regulation (Ku & Ho, 2010; Hong, 2020; Gutu, 2023).

Within this theoretical landscape, the CAIR educational framework provides a coherent pedagogical model for operationalising Assessment for Learning in Informatics education. Rather than positioning assessment as an external control mechanism, CAIR embeds formative assessment functions directly within instructional design (Gutu, 2025c). Each dimension of the framework corresponds to a core requirement of AfL and addresses a distinct aspect of competency development.

The constructivist dimension foregrounds active knowledge construction through authentic tasks (Gutu, 2025a, 2025c) that engage learners in algorithmic reasoning, debugging, and problem solving. The adaptive dimension emphasises

differentiated feedback and instructional pacing, allowing assessment to respond to learners' evolving levels of understanding and to support progression toward increasing task complexity. The integrative dimension ensures coherence across tasks, topics, and learning contexts, facilitating the transfer of Informatics competencies across projects and interdisciplinary (STEAM-related) activities. Finally, the reflective dimension emphasises self-regulation by embedding self-assessment and reflective practices that enable learners to monitor progress, evaluate strategies, and assume responsibility for learning decisions.

Figure 1 synthesises this theoretical framework by illustrating the alignment between CAIR dimensions, core Assessment for Learning functions, and illustrative examples from Informatics education. The figure highlights AfL as an emergent property of pedagogical design, arising from the systematic interconnection of learning activities, feedback mechanisms, and reflective practices.

CAIR dimensions	Assessment for Learning Function	Example in Informatics
 Constructivist	Active knowledge construction	Algorithmic tasks, debugging
 Adaptive	Differentiated feedback	Task level and complexity, learning pace
 Integrative	Cross-task coherence	Projects, STEAM Links
 Reflective	Self-regulation	Self-assessment, journals

Figure 1. Alignment between CAIR dimensions, Assessment for Learning functions, and illustrative examples in Informatics education

By embedding Assessment for Learning within the CAIR framework, assessment is reconceptualised as a continuous process that actively shapes learning trajectories rather than a terminal act of measurement. This perspective underpins the subsequent sections, which examine the operationalisation of CAIR-oriented AfL through authentic, practice-based Informatics learning scenarios and their implications for competency development.

3. Operationalising assessment for learning through the CAIR framework

Building on the theoretical framework, this section focuses on the practical operationalisation of AfL in Informatics through the CAIR framework by designing learning tasks that integrate instructional and assessment purposes. In Informatics, such tasks emphasise algorithmic reasoning, problem-solving, and iterative refinement, allowing assessment to emerge naturally from students' engagement with programming and system design activities. Each task is associated with clear performance criteria, ensuring transparency and enabling

learners to interpret feedback in relation to expected competencies (Gutu, 2023).

The CAIR framework supports the adaptive use of assessment information by allowing task complexity, pacing, and feedback to be adjusted in response to learners' progress (Gutu, 2025a). Formative feedback functions as a continuous process that informs both instructional decisions and learner actions, guiding learning trajectories rather than merely documenting achievement, an approach particularly suited to Informatics contexts characterised by heterogeneous learner profiles and iterative problem-solving processes.

Integration across tasks, learning contexts, and STEAM domains represents another core operational principle. Assessment criteria are applied consistently across activities and interdisciplinary projects (Burlacu & Irimiciuc, 2018; Cheng & Huang, 2025), ensuring coherence in competency development and supporting learners' ability to transfer algorithmic reasoning, system thinking, and computational problem-solving skills across scientific, technological, engineering, artistic, and mathematical contexts. This integrative STEAM-oriented approach reinforces the perception of Informatics as a coherent and generative discipline.

Reflective practices are systematically embedded to support learner agency and self-regulation. Through self-assessment and guided reflection, learners analyse their strategies, evaluate system behaviour, and plan subsequent learning actions (Khiaat & Vogel, 2022), while predominantly descriptive, forward-oriented feedback fosters improvement and metacognitive awareness (Gutu, 2022, 2023).

By aligning constructivist learning tasks, adaptive feedback mechanisms, integrative task design, and reflective practices within a unified structure, the CAIR framework provides a coherent operational model for implementing Assessment for Learning in Informatics education, enabling assessment to function as an integral component of instructional design rather than as a separate evaluative stage.

4. Application scenarios in Informatics education

To illustrate the coherent integration of AfL within the CAIR framework, this section presents a representative application scenario derived from an interdisciplinary project implemented in upper secondary Informatics education. The projects were conducted within the formal curriculum and focused on the design and implementation of functional smart systems controlled through C/C++ programming and microcontroller-based platforms.

The instructional activities described in this study were implemented within the framework of the project “*STEAMing Across Borders: Empowering Young Women from the Republic of Moldova in Science*”, while remaining fully integrated into the formal upper secondary Informatics curriculum. Within this context, students developed complete functional systems, including programmable traffic lights, radar-based object-detection systems, parking systems with servo-controlled barriers, smart houses with anti-theft mechanisms, password-protected access systems, and digital calculators. The design and implementation of these

systems required the cumulative application of Informatics concepts across multiple instructional sessions, fostering knowledge transfer, higher-order problem-solving, and structured reflective practice.

To exemplify this approach, this section examines a parking system with a servo-controlled barrier, developed and simulated on an Arduino Uno platform within the Tinkercad hardware simulation environment. The system models an access-control scenario in which vehicle presence is detected by an HC-SR04 ultrasonic distance sensor, and barrier actuation is controlled by a servo motor driven by the microcontroller. The experimental setup comprises an Arduino Uno board, an ultrasonic distance sensor, a servo motor, and a breadboard for prototyping electrical connections, enabling distance-based decision logic and actuator control. The complete wiring scheme and component configuration are illustrated in Figure 2.

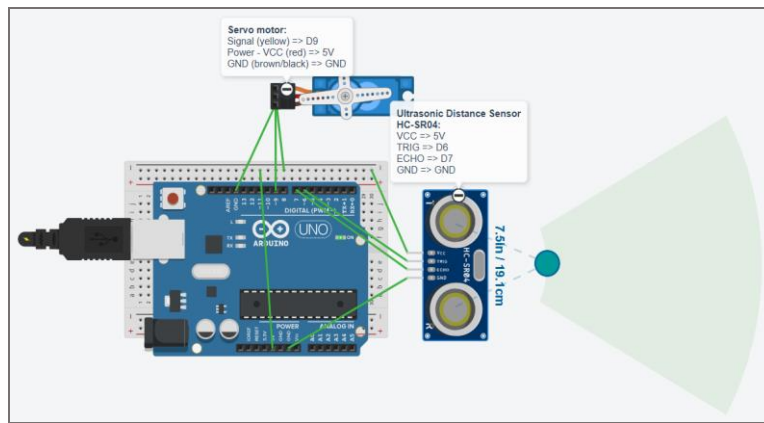


Figure 2. Hardware configuration of the ultrasonic distance-based servo control system simulated in Tinkercad

The servo motor is connected to the Arduino Uno via the digital pin D9, configured for Pulse Width Modulation (PWM), while the HC-SR04 ultrasonic sensor is interfaced using digital pin D6 for the trigger signal and digital pin D7 for the echo signal. Both components are powered through the 5V and GND pins of the Arduino board, ensuring compatibility with low-cost educational hardware while providing sufficient accuracy for distance-based control tasks.

The HC-SR04 ultrasonic sensor determines distance by emitting an ultrasonic pulse and measuring the time interval between the pulse and the reflected echo from the target object. The measured echo pulse duration is then converted into distance using the standard time-of-flight relation expressed in Equation (1):

$$d_{cm} = \frac{t_{\mu s}}{58} \quad (1)$$

where d denotes the distance in centimetres and t represents the echo pulse duration measured in microseconds.

Based on the measured distance, the system controls the servo motor's angular position to emulate a physical parking barrier. To ensure stable operation and to mitigate rapid oscillations caused by minor sensor noise, a hysteresis-based control strategy is employed. When an object is detected within 15 cm, the servo rotates to 90°, corresponding to the open barrier state. Once the object moves beyond 25 cm, the servo returns to 0°, representing the closed position. The intermediate range between these thresholds suppresses repeated state transitions and contributes to robust and reliable system behaviour.

Distance measurements are performed at fixed 80-millisecond intervals using a non-blocking timing mechanism based on the `millis()` function. This approach maintains system responsiveness and facilitates future extensibility, such as the integration of additional sensors or communication modules. The control algorithm is implemented in a modular C/C++ structure, with a clear separation between sensor acquisition, decision logic, and actuator control. Debugging and display-related instructions are intentionally excluded, as the system operates autonomously without a visual interface.

To support transparency, reproducibility, and reflective learning, the Arduino C/C++ source code and the hardware simulation are provided as open-access digital artefacts. The source code is available via a public GitHub repository, while the hardware configuration and runtime behaviour can be explored through an interactive Tinkercad Circuits simulation; an overview of these resources is summarised in Table 1.

Table 1. Open-access digital artefacts supporting transparency and reproducibility

Digital artefact	Supplementary material
Arduino C/C++ source code (servo-controlled parking system)	GitHub repository Access link: https://github.com/mgutu/Tinkercad_Arduino_Programs/blob/main/Servo_Controlled_Parking_System
Hardware simulation (Arduino Uno parking system)	Tinkercad Circuits simulation Access link: https://www.tinkercad.com/things/fTyK0ReARBC-servo-controlled-parking-system?sharecode=kxInFwJr_YgmMqz3k5BvcoDzu_CNxbCjg8fK5tpG0yc

The parking system scenario enables an integrated assessment of student learning by aligning Informatics-specific competencies with the CAIR framework and Bloom's taxonomy within a single coherent learning activity. Table 2 synthesises this alignment by mapping observable indicators that emerge directly from students' design, implementation, and iterative refinement processes. Throughout the project, these processes were supported by structured teacher facilitation and AI-based chatbot assistance, which provided ongoing scaffolding and formative guidance aligned with the principles of Assessment for Learning.

Table 2. Integrated assessment framework for the ultrasonic parking system scenario

Assessment Dimension	Indicators of Student Performance
Informatics-Specific Competencies	Students correctly apply structured C/C++ syntax, implement conditional logic and state management, interface sensors and actuators through digital I/O, and translate real-world constraints into algorithmic solutions.
CAIR – Constructivist	Knowledge is actively constructed through hands-on experimentation, code modification, and debugging of sensor–actuator interactions.
CAIR – Adaptive	Students adjust threshold values, timing intervals, and logic structures in response to system behaviour and feedback obtained during testing.
CAIR – Integrative	The task integrates programming, electronics, and physics concepts (ultrasonic wave propagation) with real-world system modelling to deliver a coherent solution.
CAIR – Reflective	Learners analyse system stability, justify the use of hysteresis, and reflect on alternative control strategies to improve reliability.
Bloom’s Taxonomy	Learning progresses from understanding sensor principles (Understanding), implementing control logic (Applying), analysing system behaviour and stability (Analysing), evaluating design choices such as threshold values (Evaluating), and designing a functional autonomous system (Creating).

Through this scenario, assessment becomes inseparable from learning itself: students demonstrate competence not only through the successful development of a functional artefact, but also through the reasoning, adaptation, and reflection embedded in the development process. This illustrates how CAIR-oriented Assessment for Learning can be effectively operationalised in Informatics education through authentic, technology-rich tasks that integrate guided instruction, adaptive support, and reflective practice.

5. Challenges and practical considerations

The operationalisation of CAIR-oriented AfL in upper secondary Informatics education entails several pedagogical and practical challenges. A primary consideration concerns time management within formal curricula, as formative assessment grounded in iterative design, testing, feedback, and reflection often requires a different allocation of instructional time than conventional task-submission approaches. This requires instructional planning to prioritise conceptual understanding, algorithmic reasoning, and systems thinking while maintaining alignment with curricular requirements.

A further challenge concerns the evolving instructional role of the teacher, who functions less as an evaluator of final outputs and more as a facilitator of learning processes through formative feedback and adaptive guidance. In Informatics contexts involving integrated hardware and software components, this role demands both strong subject-matter expertise and the capacity to manage differentiated learning trajectories. Although resource availability may affect implementation, the core principles of CAIR and AfL remain transferable through virtual simulations and software-based models.

Addressing this challenge requires a structured progression in teacher readiness rather than additional training. The CAIR framework builds on existing instructional practices by repositioning assessment within learning activities. Initial implementation may begin with a single unit or project, gradually expanding across modules or courses. Reusable assessment templates, transparent criteria, and guided reflection prompts support differentiated learning, while AI-assisted tools (e.g., formative feedback chatbots) can reduce organisational and cognitive load without compromising pedagogical intent.

Learner readiness influences effective enactment, as students may initially lack the metacognitive and self-regulatory skills required for reflective, feedback-driven learning. Gradual scaffolding of self-assessment and reflection is therefore essential to build assessment literacy and learner confidence, highlighting the need for contextual adaptation to ensure the sustainable integration of CAIR-oriented AfL within existing curricular and institutional constraints.

Within the CAIR framework, learner autonomy is viewed as a developmental outcome rather than a prerequisite. Initial stages rely on teacher-guided feedback, explicit criteria, and structured reflection to support students with limited self-regulation. As assessment literacy and confidence grow, scaffolding is gradually reduced, fostering independent decision-making and self-assessment.

6. Discussions

While no experimental comparison with a control group was conducted, the study does not seek to demonstrate statistical superiority over traditional instructional approaches. Instead, it provides a theoretically grounded, design-oriented illustration of how the CAIR framework can operationalise AfL in authentic Informatics contexts, emphasising coherence, alignment, and feasibility.

The application scenarios provide evidence of the educational value of the CAIR framework as an assessment-oriented instructional approach in Informatics education. The findings show that CAIR embeds formative assessment processes directly within authentic, technology-rich learning activities, positioning assessment as an integral component of instructional design.

A core contribution of the framework lies in integrating assessment into iterative cycles of design, implementation, feedback, and reflection, aligning with the iterative nature of Informatics learning. As demonstrated through the smart-system projects, this approach enables continuous, task-embedded feedback that

informs learner decision-making and supports progressive competency development, thereby strengthening coherence between curricular objectives, instructional activities, and assessment criteria (Gutu, 2025b).

The discussion also highlights learner agency and self-regulation as central outcomes of CAIR-oriented AfL. Through structured reflection and self-assessment, learners actively monitor their progress and evaluate design choices, fostering metacognitive awareness and reflective judgment, which are essential for sustained learning in rapidly evolving technological domains (Azevedo, 2020; Hong, 2020; Gutu, 2023). Autonomy and self-regulation emerge progressively through intentional instructional design supported by guided reflection and descriptive feedback.

From a pedagogical perspective, CAIR provides a flexible and coherent structure adaptable to diverse Informatics contexts and resource conditions. Its effectiveness depends on intentional instructional design and teacher readiness, functioning as a guiding lens rather than a prescriptive model, and reinforcing assessment as a driver of learning and competency development through constructivist, adaptive, integrative, and reflective practices.

7. Conclusions

This study examined the operationalisation of Assessment for Learning in Informatics education through the CAIR framework, embedding formative assessment into instructional design. Addressing the misalignment between competency-based curricular objectives and predominantly summative assessment practices, the findings demonstrate how assessment can function as a continuous driver of learning.

Using a design-based illustrative approach, the study showed that CAIR-oriented AfL can be implemented without introducing additional assessment instruments or parallel evaluation structures. The project-based smart-system scenario illustrated how assessment evidence emerges through iterative cycles of programming, testing, debugging, and reflection, aligning Informatics-specific competencies with the CAIR dimensions and Bloom's taxonomy.

The findings further indicate that effective implementation depends on intentional instructional planning and contextual adaptation, particularly with respect to time constraints, resource availability, learner readiness, and the coexistence of formative and summative assessment systems. Therefore, the CAIR framework provides a coherent and adaptable model for aligning curriculum, instruction, and assessment in Informatics education, supporting sustainable competency development and learner self-regulation.

Future research may extend this work by examining the scalability of CAIR-oriented AfL across diverse educational contexts and by exploring its impact through longitudinal or comparative study designs. Such investigations could complement the present design-based contribution by providing additional empirical perspectives on learning outcomes and instructional effectiveness.

Acknowledgement: The activities described in this paper were conducted within the project “*STEAMing Across Borders: Empowering Young Women from the Republic of Moldova in Science*”, supported by the European Union through the initiative “*EVOLVE4GE: Ending Violence, Expanding Livelihood Opportunities for Women and Accelerating Gender Governance in Moldova*”, led by UN Women Moldova. The project is implemented under Partnership Agreement No. PA006410MDA (April 2025 – October 2026).

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Integrating CLIL and green education to foster environmental awareness in pre-service English teachers

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Abstract: *The paper presents an applied approach to integrating Content and Language Integrated Learning (CLIL) with Green Education to enhance environmental literacy and pedagogical readiness among pre-service English teachers. It outlines the authors' experience in designing and implementing a six-week CLIL module on sustainability topics such as eco-tourism, recycling, and climate change. Conducted with 36 students from “Ion Creangă” State Pedagogical University of Chișinău, the study employed a mixed-method design combining questionnaires, reflections, and classroom observations to measure both cognitive and attitudinal change. Results indicated a significant improvement in participants' environmental awareness, motivation, and understanding of teaching as a vehicle for social responsibility. The research was carried out within the national project Integrating and Promoting Green Education in the Initial Training of English Language Teachers (code 25.80012.0807.56SE), developed under Moldova's strategic direction of Innovative Educational Technologies and Products. The findings demonstrate that CLIL, when enriched with sustainability principles, provides a transformative pedagogical framework that links language learning, critical thinking, and ecological values, shaping educators prepared to inspire change. The findings should be interpreted in light of the study's quasi-experimental design, which did not include a control group and was limited to a six-week intervention.*

Keywords: CLIL, Green education, Environmental literacy, Teacher training, Sustainability pedagogy, Innovative learning frameworks.

1. Introduction

Embedding sustainability within higher education has become a central global concern (Sterling, 2014; Barth et al., 2016), closely linked to the **United Nations' Sustainable Development Goals**, particularly **SDG 4 (Quality Education)** and **SDG 13 (Climate Action)**. In the field of English Language Teacher Education (ELTE), sustainability functions both as a moral responsibility and a pedagogical avenue: through environmental themes, language instruction can nurture critical thinking, intercultural competence, and civic engagement (Cates, 2016). Nonetheless, the inclusion of green education elements in ELTE programs remains sporadic and uneven.

<https://doi.org/10.58503/icvl-v21y202620>

Early advocates such as Cates (1990) emphasized peace, human rights, and environmental stewardship in global education, while later frameworks (Haigh, 2012; Tilbury, 2013) incorporated sustainability through Education for Sustainable Development (ESD). Content and Language Integrated Learning (CLIL) integrates content, communication, cognition, and culture (Coyle, Hood & Marsh, 2010), providing a pedagogical framework for combining language learning with disciplinary content.

Building on Coyle's (2007) 4Cs framework, this study reconceptualizes the cultural dimension as *Community* in order to foreground ecological responsibility, social engagement, and local–global interconnectedness. Rather than departing from established CLIL theorisation, the Content–Communication–Cognition–Community model extends it by aligning language-integrated instruction with principles of eco-pedagogy and Education for Sustainable Development. In this adaptation, sustainability functions not merely as thematic content, but as a shared pedagogical orientation shaping interaction, reflection, and professional identity formation in pre-service English teachers.

However, empirical evidence on how CLIL-based sustainability modules influence pre-service English teachers' awareness and pedagogical identity remains limited. This study addresses that gap by examining whether a short, structured CLIL module on topics such as climate change, eco-tourism, and recycling can enhance environmental awareness and readiness to integrate sustainability into teaching.

Grounded in Coyle's 4Cs framework, the module combines authentic materials, multimodal projects, and reflective tasks that foster critical thinking, collaboration, and creativity — competencies central to twenty-first-century education (Trilling & Fadel, 2009). The study aims to:

1. design and implement a CLIL module integrating sustainability into English teacher training;
2. measure changes in environmental awareness through mixed-method analysis;
3. identify features of CLIL tasks that promote ecological responsibility and professional growth.

This research contributes to eco-pedagogy (Freire, 1998; Kahn, 2010) by extending CLIL theory toward environmental literacy, providing empirical evidence of awareness gains, and offering a replicable model for embedding sustainability within ELTE.

2. Methods

The study followed the principles of *transparency, validity, and replicability* (Creswell & Plano Clark, 2018) to ensure reliability and transferability across similar English language teacher education contexts. It was conducted within the national research project *Integrating and Promoting Green Education in the Initial Training of English Language Teachers* (code 25.80012.0807.56SE), under

Moldova's strategic direction *Innovative Educational Technologies and Products*.

A mixed-method, quasi-experimental design combined *quantitative and qualitative tools* to capture both measurable outcomes and participants' lived experiences. This approach balanced statistical accuracy with pedagogical authenticity (Dörnyei, 2007). The intervention—a six-week CLIL-based sustainability module—was delivered to one experimental group. Pre- and post-tests measured changes in environmental awareness, attitudes, and behavioural intentions, while observations, reflective journals, and semi-structured interviews explored participants' evolving motivation and professional identity.

Thirty-six pre-service English teachers (28 female, 8 male), aged 20–23, participated voluntarily. All were third-year students at *Ion Creangă* State Pedagogical University of Chişinău and had prior training in ELT methodology but no experience with sustainability in education. Participants were selected purposively (Cohen, Manion & Morrison, 2018) for their developing pedagogical awareness and openness to innovation. Ethical approval and informed consent were obtained, ensuring confidentiality and adherence to institutional research standards.

All sessions took place in a multimedia-equipped classroom that supported the use of authentic online resources such as **BBC Earth**, **National Geographic Learning**, and **The Guardian** sustainability reports.

2.1 The CLIL module and learning sequence

The CLIL module was incorporated into the regular course *Methodology of Teaching English* and was designed according to **Coyle's (2007) 4Cs Framework** — *Content, Communication, Cognition, and Culture* — adapted as *Content, Communication, Cognition, and Community* to highlight ecological and social responsibility. The sequence lasted **six weeks**, with two 90-minute sessions weekly, each dedicated to a sustainability theme relevant to both global and local contexts.

Table 1. Structure of the CLIL Module

Week	Theme	Core Activity	Learning Focus	Expected Outcome
1	Sustainability and Everyday Choices	Vocabulary and discussion on ecological footprint	Awareness of personal impact	Self-reflection on daily habits
2	Climate Change and Media Discourse	Critical reading and bias detection in news texts	Critical literacy	Recognition of perspective and bias
3	Eco-Tourism and Local Identity	Project-based creation of tourist materials	Intercultural and environmental awareness	Collaboration and creativity
4	Waste and Recycling	Data interpretation and persuasive	Problem-solving through	Development of rhetorical skills

Week	Theme	Core Activity	Learning Focus	Expected Outcome
		writing	argumentation	
5	Green Cities and Innovation	Group debates and infographic design	Multimodal communication	Integration of digital skills
6	Reflection and Lesson Planning	Design of mini-lessons integrating CLIL and green topics	Pedagogical transfer	Application of sustainable teaching practices

The module integrated **authentic English-language resources** to maintain linguistic realism and topical relevance. Each session followed a three-phase instructional cycle:

1. **Input phase** – exposure to authentic materials and guided comprehension;
2. **Language focus phase** – scaffolding key lexical and grammatical patterns;
3. **Output phase** – collaborative production through debates, projects, or micro-teaching tasks.

This structure encouraged communication, critical thinking, and creativity, aligning with **21st-century competences** (Trilling & Fadel, 2009).

2.2 Instruments and data collection

Four complementary instruments were used to evaluate the module's impact:

1. **Environmental Awareness Questionnaire (EAQ)** — A 20-item, five-point Likert-scale instrument adapted from Pe'er, Goldman & Yavetz (2007), measuring knowledge, attitudes, and behavioural intentions. Reliability was high (Cronbach's $\alpha = 0.87$). The EAQ was administered pre- and post-intervention (Weeks 0 and 6).

2. **Observation Checklist** — A 10-item rubric designed for this study assessed engagement, collaboration, and use of environmental vocabulary. Two independent raters observed six sessions, achieving 90% inter-rater reliability.

3. **Reflective Journals** — Participants kept weekly 150–200-word reflections documenting insights, emotions, and changes in perspective, following the reflective practice model of Farrell (2015).

4. **Semi-Structured Interviews** — Conducted with ten randomly selected students after the module, interviews (20–30 minutes) explored motivation, feasibility, and teaching transfer (Patton, 2015).

Instruction was delivered in English, with Romanian used occasionally for clarification (Banegas, 2021).

3. Results

The results are presented in two complementary parts:

1. quantitative findings derived from the *Environmental Awareness Questionnaire (EAQ)*

2. qualitative insights drawn from reflective journals, classroom observations, and semi-structured interviews.

Together, they illustrate both the measurable and experiential dimensions of how the CLIL-based sustainability module influenced pre-service English teachers' awareness, attitudes, and professional outlook.

3.1 Quantitative results

Quantitative data were analyzed in **SPSS v.26** using descriptive statistics and paired-sample *t*-tests. The EAQ results showed significant gains across all three dimensions ($p < .001$):

Dimension	Pre-Test Mean (SD)	Post-Test Mean (SD)	Mean Gain	t-value	p-value	Cohen's d
Knowledge	3.21 (0.42)	4.09 (0.38)	+0.88	8.43	< .001	1.40
Attitudes	3.45 (0.50)	4.18 (0.41)	+0.73	7.66	< .001	1.28
Behavioural Intentions	3.32 (0.46)	4.06 (0.44)	+0.74	7.89	< .001	1.32

Effect size calculations (Cohen's *d*) indicate large effects across all three dimensions, suggesting that the CLIL-based sustainability module produced not only statistically significant but also practically meaningful improvements in environmental knowledge, attitudes, and behavioural intentions. These results confirm significant improvement in environmental knowledge, attitudes, and behavioural intentions following the module. Qualitative data (journals, observations, interviews) were thematically coded following Braun & Clarke (2006), yielding three themes: **awareness and cognitive engagement, identity formation**, and **action orientation**. Triangulation ensured convergence of evidence, and inter-coder agreement reached 90%.

All tools were piloted ($n = 8$) to refine clarity and consistency. Quantitative and qualitative data were integrated using a **convergent parallel design** (Creswell & Plano Clark, 2018). Ethical approval and informed consent were obtained in compliance with the **European Code of Conduct for Research Integrity** (ALLEA, 2017).

All three dimensions registered highly significant improvements, confirming the strong positive effect of the CLIL intervention. The greatest mean gain (+0.88) occurred in *knowledge*, showing that exposure to authentic English materials on sustainability substantially deepened conceptual understanding. Attitudinal and behavioural shifts, though slightly smaller, reflected growing personal engagement and sense of responsibility—supporting findings by Lozano et al. (2021) and Banegas (2021) that sustainability-oriented language tasks can enhance reflection and agency.

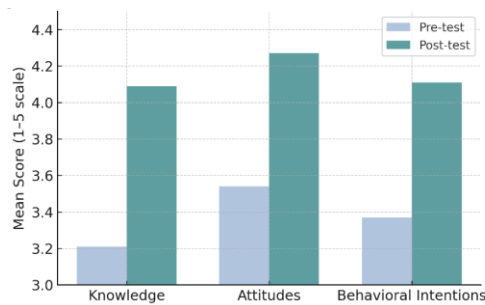


Figure 1. Comparison of pre- and post-test mean scores across the three dimensions of the Environmental Awareness Questionnaire (EAQ): Knowledge, Attitudes, and Behavioural Intentions (N = 36)

The figure visually reinforces the statistical outcomes presented in Table 2. It highlights consistent improvement across all three dimensions, with knowledge showing the highest gain, followed closely by attitudes and behavioural intentions.

3.2 Qualitative findings

Qualitative data from reflective journals, observations, and interviews were analysed following Braun and Clarke's (2006) six-phase thematic analysis. Initial open coding was conducted independently by two researchers to identify recurring ideas related to awareness, motivation, collaboration, and pedagogical development. These initial codes were then compared, discussed, and clustered into broader categories, which were refined into final themes through iterative review and consensus.

The qualitative analysis illuminated the human dimension behind the numbers. Three dominant and interrelated themes emerged from the reflective journals and interviews:

- (1) awareness and self-reflection,
- (2) pedagogical readiness and motivation, and
- (3) collaboration and professional identity.

Figure 2 illustrates the distribution of these themes, highlighting the aspects of the module that most strongly resonated with participants.

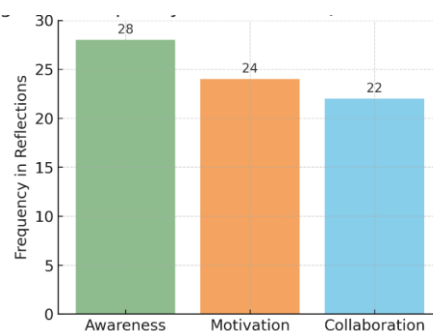


Figure 2. Distribution of qualitative themes emerging from participants' reflections

The data show that **awareness** was the most prominent theme, reflecting participants' growing sense of responsibility toward environmental issues. **Motivation** ranked second, highlighting increased enthusiasm and confidence in integrating sustainability into English lessons. **Collaboration** emphasized teamwork and shared purpose in addressing global challenges through language learning.

Theme 1: Awareness and Self-Reflection

Participants described a gradual awakening to the connection between language learning and environmental consciousness.

"Before this course, I knew about climate change, but I never thought of it as a topic for English lessons. Now I see how language can make students reflect and act."

This transition from passive awareness to critical engagement echoes Freire's (1998) notion of *conscientização*, where knowledge becomes a vehicle for social reflection and change.

Theme 2: Pedagogical Readiness and Motivation

Initially, some viewed sustainability as abstract or overly technical. Through CLIL practice, they discovered its pedagogical feasibility and motivational power:

"I used to think students would find these themes boring, but CLIL showed me how small, creative tasks can make lessons meaningful". Authentic materials and problem-based tasks transformed sustainability from a distant issue into an engaging learning context.

Theme 3: Collaboration and Professional Identity

Collaborative projects—debates, poster creation, and group problem-solving—helped participants experience cooperation as both method and message.

"Working in teams made me realize that green education isn't only about facts; it's about the collaboration we need to solve real problems."

This insight reflected a deeper professional shift: participants began to perceive themselves not only as language instructors but as facilitators of socially responsible learning, consistent with Sterling's (2014) conception of education as transformative participation.

Integrating both strands provides a coherent picture of transformation across the **cognitive, affective, and behavioural** domains.

- *Cognitively*, participants gained factual knowledge and conceptual clarity about sustainability.
- *Affectively*, they displayed stronger empathy, curiosity, and motivation to embed environmental themes in their teaching.
- *Behaviourally*, they initiated eco-friendly classroom practices—proposing paper-free projects and including green topics in lesson plans.

These findings indicate that **embedding sustainability through CLIL constitutes not merely a teaching technique but a transformative educational experience**. It strengthens environmental awareness, fosters pedagogical

innovation, and cultivates ethical, reflective teacher identities capable of guiding future learners toward sustainable thinking.

4. Findings and discussions

The study confirms that sustainability-oriented CLIL modules enhance pre-service teachers' environmental awareness, motivation, and pedagogical readiness. The quantitative findings demonstrate consistent improvements across cognitive, attitudinal, and behavioural dimensions, highlighting the synergistic potential of CLIL and sustainability-oriented content.

Observation data further revealed a **40% increase in participation** and collaboration. Students shifted from hesitant exchanges to confident, idea-driven discussions, using eco-lexis such as *carbon footprint* and *renewable resources* spontaneously — evidence that CLIL fosters both conceptual understanding and linguistic fluency (Dalton-Puffer, 2007).

Qualitative findings added a human dimension to this transformation. Three themes emerged across journals and interviews:

1. **Awareness and reflection** — Students linked environmental topics with personal and professional responsibility, echoing Freire's (1998) idea of *conscientização* as awareness turned into agency.

2. **Motivation and pedagogical readiness** — Participants reported greater confidence in designing sustainability-based lessons, confirming Banegas' (2021) finding that CLIL enhances intrinsic motivation when tied to real-world content.

3. **Collaboration and professional identity** — Group projects and eco-lesson planning promoted teamwork and social awareness, resonating with Sterling's (2014) notion of education as a participatory, transformative act.

Taken together, the quantitative and qualitative findings reveal progress across cognitive, affective, and behavioural domains. Beyond knowledge acquisition, participants developed greater empathy and began transferring sustainability principles into classroom practice, for example by proposing paper-free lessons and eco-themed activities. The most impactful tasks — debates, poster projects, and micro-lesson design — combined collaboration with creativity, supporting Trilling and Fadel's (2009) 4Cs framework for deep learning.

The findings suggest that CLIL and Green Education share compatible pedagogical principles, including inquiry, interdisciplinarity, reflection, and learner-centeredness. Within this framework, sustainability topics function as contextual amplifiers of Coyle's 4Cs model, reframed in this study as **Community** to emphasize shared responsibility (Coyle, 2015). Within such a framework, the language classroom becomes a microcosm of civic engagement, where ecological and communicative competence grow together.

Pedagogically, the results show that sustainability can be embedded in teacher training without curricular overhaul. Short CLIL modules can integrate environmental thinking into existing ELT courses, aligning them with the UN Sustainable Development Goals (SDGs). Authentic, multimodal materials —

videos, infographics, and articles — were particularly effective in fostering media literacy and intercultural awareness.

Overall, CLIL infused with sustainability transforms English teacher education into a more reflective and action-oriented process. By integrating language, cognition, and ethical engagement, it fosters both environmental literacy and professional identity. As one participant concluded: *“I no longer see English as only a language to teach, but as a way to inspire change.”*

4.1. Limitations and future research

While the findings of this study are encouraging, several limitations should be acknowledged. First, the research adopted a quasi-experimental design without a control or comparison group, which limits the ability to attribute observed changes exclusively to the CLIL-based sustainability intervention. Second, the relatively small sample size ($N = 36$), drawn from a single teacher education institution, constrains the generalizability of the results. Third, the intervention spanned only six weeks, which may not fully capture long-term changes in environmental awareness, pedagogical beliefs, or teaching practices.

Future research should address these limitations by incorporating control groups, expanding sample sizes across multiple institutions, and employing longitudinal designs to examine the sustainability of observed effects. In addition, including mentor teachers' evaluations and classroom implementation data could provide deeper insight into how CLIL-based green education influences professional practice beyond initial teacher training.

5. Conclusions

This research demonstrated that blending Content and Language Integrated Learning (CLIL) with Green Education principles in English teacher training can effectively foster **environmental awareness, pedagogical readiness, and professional identity**. Conducted with pre-service teachers at *Ion Creangă* State Pedagogical University of Chişinău, the study showed that even a short, well-structured module using authentic materials and reflective practice can produce meaningful cognitive, attitudinal, and behavioural change.

The mixed-method results confirmed that the **CLIL-for-Sustainability** model is both impactful and adaptable. Quantitative findings revealed significant gains in environmental knowledge and motivation, while qualitative insights highlighted increased confidence, creativity, and ethical engagement. Together, these outcomes demonstrate that integrating sustainability into language education not only improves linguistic competence but also shapes teachers as responsible global citizens.

In the final analysis, the study positions CLIL as a **transformative bridge** between language learning and environmental education — one capable of preparing future educators to inspire ecological awareness, social empathy, and action-oriented learning within their classrooms.

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A bibliometric analysis of Artificial Intelligence research in higher education policy: Trends and future directions (2020–2025)

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Abstract: *The advent of AI-driven GPTs (Generative Pre-trained Transformers) has caused substantial transformations in higher education. This study seeks to outline significant trends, prominent authors, and nascent research trajectories through bibliometric analysis of artificial intelligence (AI) research in higher education policy from 2020 to 2025. The research obtained 254 articles from the Scopus database. Keyword co-occurrence, co-authorship, and co-citation mapping were utilised to shed light on the interconnection and intellectual landscape within the subject domain. The findings indicate that “Artificial Intelligence” and “Higher Education” are the predominant themes, whereas emerging themes encompass “ChatGPT”, “Generative AI”, and “Academic Integrity”, reflecting an increasing scholarly focus on generative AI technologies and their implications for the educational sector. The paucity of policy-related terminology underscores a research shortfall in the regulatory and ethical frameworks governing the application of AI in higher education. The results of co-authorship show an imbalanced collaboration structure, while the results of co-citation show a few important authors and methodological anchors, such as Braun and Clarke (2006) and Chan (2023). The study emphasises the swift expansion and inconsistent progression of AI-related higher education policy research. To ensure that AI technologies are used in a responsible, fair, and enduring manner within higher education systems around the world, it calls for greater collaboration across fields and research that focusses on policy.*

Keywords: Artificial Intelligence, Higher education policy, Bibliometric analysis, Generative AI, Academic integrity, Collaboration networks.

1. Introduction

The landscape of higher education is evolving rapidly. Digital instruction has evolved as a novel pedagogical approach since its proliferation during the COVID era. Currently, emerging technologies, including AI tools such as ChatGPT, are transforming the landscape of higher education in a disruptive way (Yu, 2024). Since the advent of AI, researchers have undertaken various investigations that

<https://doi.org/10.58503/icvl-v21y202621>

have enhanced the current body of knowledge. Research on AI in higher education policy receives minimal attention or is somewhat overlooked.

Institutional regulations play a crucial role in upholding ethical standards during the incorporation of AI in higher education (Jin et al., 2025). The demand for clearly defined standards and policies has become evident due to the widespread use of AI in educational environments (Schiff, 2022). These policies are essential for guiding the incorporation of AI into curriculum development and assessment design, as well as for maintaining academic integrity. Recent research has initiated an examination of these policies and institutional strategies for AI adoption; nevertheless, it remains fragmented, lacking a cohesive understanding of intellectual trends, principal contributors, and policy trajectories affecting AI in higher education. This gap highlights the necessity of mapping the existing body of work to elucidate the thematic patterns of AI in higher education.

This study addresses this gap by conducting a bibliometric analysis of artificial intelligence research related to higher education policy from 2020 to 2025. This research aligns with SDG 4 (Quality Education) by highlighting how AI fosters inclusive and equitable transformation. This study seeks to analyse global research trends in AI related to higher education policy from 2020 to 2025 using bibliometric methods. This study enhances existing knowledge by emphasising the need to develop informed policies governing AI deployment, while also outlining thematic trends, collaborative networks, and intellectual frameworks. The study will address the following research questions:

RQ1: What are the dominant themes and emerging topics in AI research within higher education policy from 2020 to 2025 (Co-occurrence analysis of author keywords)?

RQ2: Which publications form the intellectual foundation of AI-related higher education policy research, and how are they interconnected (Co-citation analysis of cited references)?

RQ3: Who are the most influential authors in this field, and what patterns of scholarly collaboration and intellectual influence can be observed (Co-authorship analysis and Co-citation analysis of authors)?

2. Method

To gain a thorough understanding of a particular event, a quantitative research technique was employed, which enables the methodical collecting and analysis of data (Taherdoost, 2022). Bibliometric analysis illustrates the intellectual framework, objective frameworks, and the development of research within a particular topic by utilising quantitative data from academic publications and incorporating contextual mapping tools to improve analytical precision (Olaleye et al., 2023).

2.1 Data source for bibliometric

Scopus was chosen as the database for this investigation. Because it contains a greater number of articles than other scientific databases such as WoS (Pranckutė, 2021). More than 5000 foreign publishers have contributed 75 million scholarly articles to this database.

2.2 Search and screening strategy

To ensure that the search process covers all research publications within the selected knowledge domain, an extensive compilation of keywords will enable thorough and integrated enquiries (Kumar, 2025). This study has methodically arranged the search duration, file type, and terms/keywords filters. The authors retrieved data from Scopus on 30th September 2025. The keywords used include: ('Higher Education' OR 'University') AND ('AI' OR 'Artificial Intelligence') AND ('Policy'). There was a total of 403 documents containing the keywords, and when the authors restricted the language to English, 386 articles were found. Furthermore, when the document type was limited to articles, 261 articles were identified. A total of 254 articles were retrieved for analysis, limiting the year of publication from 2020-2025.

2.3 Data analysis

The research employed VOSviewer to evaluate 254 published papers from the Scopus database. Van Eck and Waltman (2014) created the software VOSviewer to construct and visualise bibliometric networks.

3. Data analysis and results

3.1 Co-occurrence analysis of author keywords

The main goal of employing network visualization to analyse keyword co-occurrence is to investigate the connections between phrases used by researchers in a certain topic. The goal of this study is to understand the topic's corpus of information comprehensively. To identify the dominant themes and emerging topics in artificial intelligence research within higher education policy from 2020 to 2025, a co-occurrence analysis of authors' keywords was conducted. The minimum requirement for occurrences of an author's keyword was 2; 215 met the threshold, resulting in 14 clusters with 4222 links. Figure 1 presents the map of the structure and thematic patterns in AI-related higher education policy research from 2020 to 2025.

The author reported the top 10 keywords with the highest co-occurrences. The result shows that 'Artificial Intelligence' (154 occurrences), 'Higher Education' (147 occurrences), 'Generative AI' (68 occurrences), 'ChatGPT' (61 occurrences), 'Students' (32 occurrences), 'Academic Integrity' (30 occurrences), 'University' (19

Keyword	Occurrences	Total Link Strength
Artificial Intelligence	154	707
Higher Education	147	648
Generative AI	68	323
ChatGPT	61	278
Students	32	273
Academic Integrity	30	121
University	19	175
Education	15	124
Engineering Education	14	112
Human	13	173

Co-citation analysis was conducted, and the cited references field was selected to demonstrate the interconnectedness of AI-related intellectual higher education policy research. The minimum citation requirement for referenced sources was set at 2, and 177 sources met this threshold, resulting in 15 clusters

with a total of 747 links. Figure 2 represents the interconnectedness of AI-related higher education policy research from 2020 to 2025.

Table 2 shows that the most cited reference is ‘Braun, Virginia, using thematic analysis in psychology, qualitative research in psychology, 3, 2, pp. 77-101, (2006),’ which has a total of 20 citations. Followed by ‘Chan, Cecilia Ka Yuk, students’ voices on generative AI: perceptions, benefits, and challenges in higher education, international journal of educational technology in higher education, 20, 1, (2023)’ with 18 citations, and ‘Chan, Cecilia Ka Yuk, a comprehensive AI policy education framework for university teaching and learning, international journal of educational technology in higher education, 20, 1, (2023)’ with 16 citations.

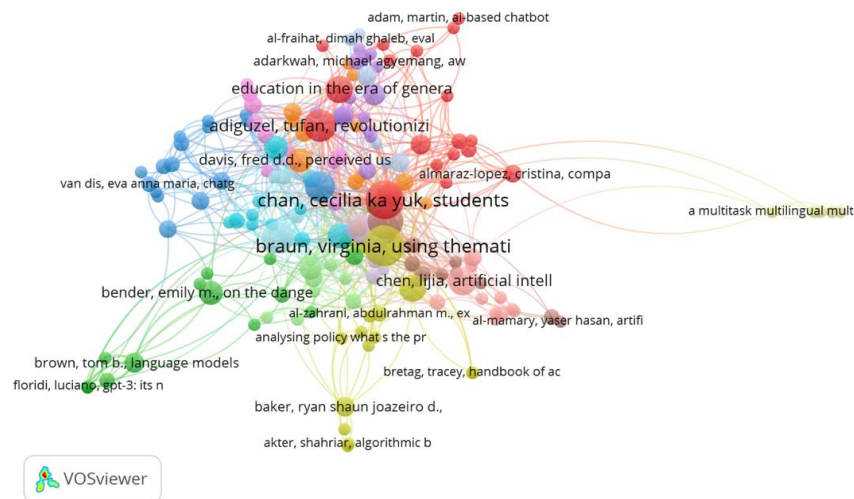


Figure 2. Interconnectedness of AI-related higher education policy research from 2020 to 2025

Table 2. Co-citation analysis of cited references

Cited reference	Citations	Total link strength
‘Braun, Virginia, Using thematic analysis in psychology, qualitative research in psychology, 3(2), (2006).	20	55
Chan, Cecilia Ka Yuk, Students voices on generative AI: perceptions, benefits, and challenges in higher education, international journal of educational technology in higher education, 20(1), (2023).	18	54
Chan, Cecilia Ka Yuk, A comprehensive AI policy education framework for university teaching and learning, international journal of educational technology in higher education, 20(1), (2023).	16	53

Adiguzel, Tufan, Revolutionizing education with AI: exploring the transformative potential of chatgpt, contemporary educational technology, 15(3), (2023).	13	45
Cotton, Debby R.E., Chatting and cheating: ensuring academic integrity in the era of chatgpt, innovations in education and teaching international, 61(2), (2024).	13	35
Plata, Sterling M., Emerging research and policy themes on academic integrity in the age of ChatGPT and generative AI, asian journal of distance education, 19(4), (2023).	11	33
Atlas, S. ChatGPT for higher education and professional development: A guide to conversational AI. (2023).	11	32
Chen, Lijia, Artificial intelligence in education: a review, iee access, 8, (2020).	10	19
Bearman, Margaret L., Discourses of artificial intelligence in higher education: a critical literature review, higher education, 86(2), (2023).	9	21
Baidoo-Anu, D., & Ansah, L. Education in the era of generative artificial intelligence (AI): Understanding the potential benefits of ChatGPT in promoting teaching and learning, journal of AI, 7(1), (2023).	9	24

3.3. Co-authorship analysis and co-citation analysis of authors

To analyse the author's productivity, collaborative clusters, and intellectual impact, co-authorship and co-citation were conducted. The co-authorship field was selected together with the author; the minimum number of documents per author was set at 2, and 21 met the threshold. The largest set of connected items consists of 4 items. Table 3 reports the top 10 authors. The result of the co-authorship analysis shows that 'Bearman, Margaret L' have received 106 citations, 'Cowling, Michael A' and 'Crawford, Joseph A' had 105 citations each, while 'Pisica, Alina Iorga' and 'Zaharia, Rodica Milena' received 97 citations each. Furthermore, 'Acosta-Enriquez, Benicio Gonzalo', 'Arbulú Ballesteros, Marco Agustín', and 'Arbulú-Pérez Vargas, Carmen Graciela' had 2 documents each with 50 citations. Figure 3 presents the network dynamics, research productivity, and international partnerships in AI-related higher education policy research from 2020 to 2025.

Table 3. Co-authorship analysis

Author	Documents	Citations	Total link strength
Bearman, Margaret L.	2	106	2
Cowling, Michael A.	2	105	3
Crawford, Joseph A.	3	105	4
Pisica, Alina Iorga	2	97	2

Zaharia, Rodica Milena	2	97	2
Acosta-Enriquez, Benicio Gonzalo	2	50	4
Arbulú Ballesteros, Marco Agustín	2	50	4
Arbulú-Pérez Vargas, Carmen Graciela	2	50	4
Kelder, Jo Anne	2	47	3
Mitwally, Mohamed A. Ahmed	2	37	6

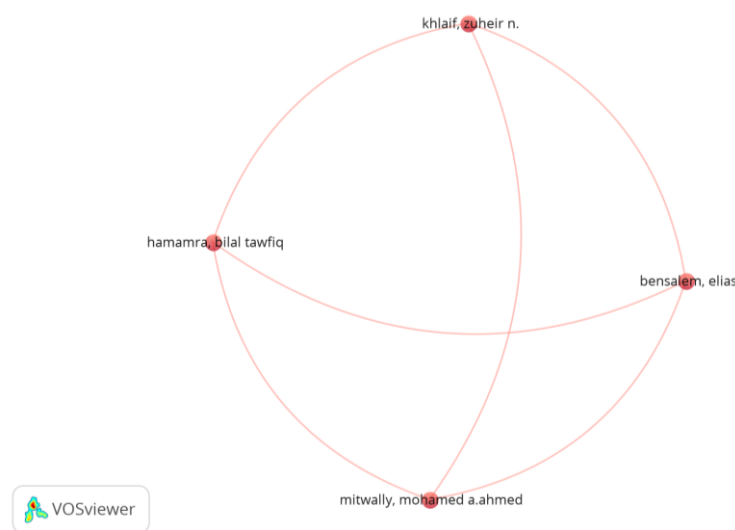


Figure 3. The network dynamics, research productivity, and international partnerships in AI-related higher education policy research from 2020 to 2025

For the co-citation analysis, the co-citation and cited authors fields were selected. 2 was the minimum number of citations for an author; 114 met the threshold. The largest connected set consists of 93 items, yielding 11 clusters and 310 links. The results of the top 10 most cited authors show that ‘Chiu’ and ‘Thomas K.F.’ had the highest citation (19 citations), while ‘Bearman’ received 17 citations each (refer to Table 4). Figure 4 presents the intellectual structure of AI-related higher education policy research from 2020 to 2025.

Table 4. Co-citation analysis of cited author

Author	Citations	Total Link Strength
Chiu	19	72
Thomas K.F.	19	72
Bearman	17	30
Adiguzel	13	45
Cotton	13	38
Debby R.E.	13	38
Tufan	13	45

Brown	11	21
Davis	8	25
Bender	7	17

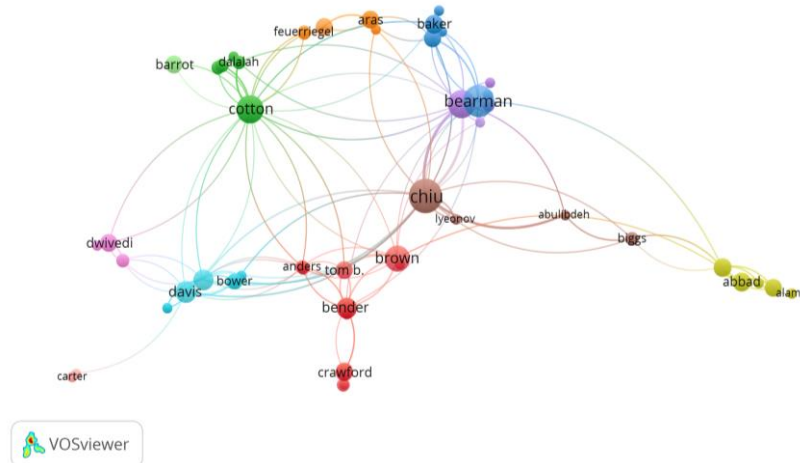


Figure 4. Intellectual structure of AI-related higher education policy research from 2020 to 2025

4. Discussions and conclusions

This bibliometric analysis provides a comprehensive overview of research pertaining to AI in higher education policy from 2020 to 2025. The keyword co-occurrence data show that "Artificial Intelligence" and "Higher Education" are the most common terms in this field. Evolving terms like "ChatGPT," "Generative AI," and "Academic Integrity" reveal that scholars are developing an interest in the teaching and moral issues associated with generative AI technologies. The relative scarcity of explicit policy-related keywords suggests that research on governance frameworks and regulations for artificial intelligence in higher education is inadequate, underscoring a vital field for additional exploration.

The examination of co-authorship indicates that collaboration in this domain remains inadequate. Only 21 authors satisfied the publication criterion, and the most extensive collaborative network comprises merely four contributors. Berman, Margaret L., Colling, Michael A., and Crawford, Joseph A. are the principal contributors, each with over 100 citations. This restricted link suggests that research on higher education policy concerning AI is in its nascent phase and may gain from interdisciplinary collaboration and strengthened institutions. The co-citation study categorised 114 writers into 11 groups, including Thomas K. F., Chiu, and Berman who are the most often referenced authors. At the citation level, Brown and Clarke (2006) and Chen, C. K. C. Y. (2023) were the most distinguished. This indicates that the region emphasises both methodological rigour and contemporary concerns associated with generative AI and educational policy.

This paper presents a thorough bibliometric analysis of artificial intelligence research in higher education policy from 2020 to 2025. The analysis indicates that, despite extensive research on AI, particularly generative tools such as ChatGPT, insufficient attention is paid to policy formulation, management, or the establishment of ethical frameworks. The findings regarding author engagement indicate that the scientific community has become fragmented, exhibiting less international collaboration. A limited cohort of distinguished academics establishes the theoretical and methodological underpinnings of the discipline, as evidenced by prevalent citation patterns. These findings underscore the need for interdisciplinary, policy-oriented research that examines the influence of technology on institutions and ethics. Enhancing collaborative networks and developing evidence-based policy frameworks will promote the ethical application of AI, particularly in education. Consequently, forthcoming research must extend beyond descriptive studies to yield actionable insights that facilitate management and strategic planning within the evolving, AI-driven educational landscape.

5. Theoretical and practical implications

Theoretically, this study contributes to understanding the intersection of AI and higher education policy by revealing the field's intellectual structure and research dynamics. The dominance of pedagogical and ethical themes, alongside limited attention to policy frameworks, highlights the need for integrative theoretical models that connect technological innovation, governance, and educational equity. These insights suggest a shift toward socio-technical perspectives that emphasize the interdependence between technology, institutional policy, and learning outcomes. Practically, the findings underscore the urgency of developing clear governance frameworks to guide AI implementation in higher education. Policymakers and institutional leaders should address issues of academic integrity, data protection, and ethical accountability while fostering international collaboration and knowledge exchange. Strengthening institutional capacity and aligning AI strategies with the United Nations Sustainable Development Goal 4 (SDG 4) can ensure inclusive and equitable digital transformation across higher education systems.

6. Directions for future research

Future studies should examine how AI-driven changes affect institutional governance, policymaking, and educational results in addition to descriptive assessments. Longitudinal and mixed-method studies are essential for monitoring thematic evolution and correlating bibliometric trends with policy outcomes. Comparative investigations among areas may reveal contextual differences in AI adoption and policy preparedness, while multidisciplinary frameworks that combine education, technology, and public policy might enhance comprehension of ethical and operational concerns. Furthermore, subsequent research should

investigate the influence of leadership, stakeholder involvement, and capacity enhancement on the integration of responsible AI in alignment with sustainable development and global equity objectives.

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The SAMR model in the age of Artificial Intelligence: A pedagogical framework for effective integration of AI technologies into the learning process

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Abstract: *The article examines and describes the enhancement of the SAMR model with artificial intelligence in the context of pedagogical planning. A survey was conducted among a small experimental group of teachers teaching at the lower secondary level. Most results indicate that respondents use artificial intelligence in their methodological training, and the comparison of this AI use covers the first level of “Substitution” in the SAMR model.*

Keywords: Technology integration, SAMR model, AI.

1. Introduction

Training design is a key step that every teacher goes through in their daily work with students. Artificial intelligence has a significant impact on education by offering new opportunities to improve the teaching and learning process and facilitate the work of teachers (Velcheva, 2024). To ensure the effectiveness and meaningful use of these technologies, a pedagogical framework is needed to support the planning and evaluation of their application. There are many models for implementing technologies in the learning process that are part of teaching practices. Such is the SAMR model developed by Dr. Ruben Puentedura, widely used in research publications to describe and categorize the integration of technologies into educational practices (Blundell et al., 2022). SAMR offers a four-stage structure - substitution, amplification, modification, and redefinition - which, combined with artificial intelligence, can guide teachers in improving the learning process. Applying the SAMR model in the context of artificial intelligence allows for a transition to a deeper level of technology use in the learning process, leading to the creation of practical forms of learning. In this way, AI transforms from a learning tool into a means of developing critical thinking and creativity in the learning process.

2. Theoretical framework of the SAMR model

Created as an analytical tool for classifying and evaluating the implementation of technology in education, the SAMR model outlines four interrelated levels of technology integration. These levels describe the degrees of technology integration that occur in education as it transitions from traditional to digital in order to achieve a complete transformation of learning. (Puentedura, 2010). The SAMR framework serves as a guide for teachers when planning and reflecting on the use of digital tools in the learning process. The model has two phases and four levels.

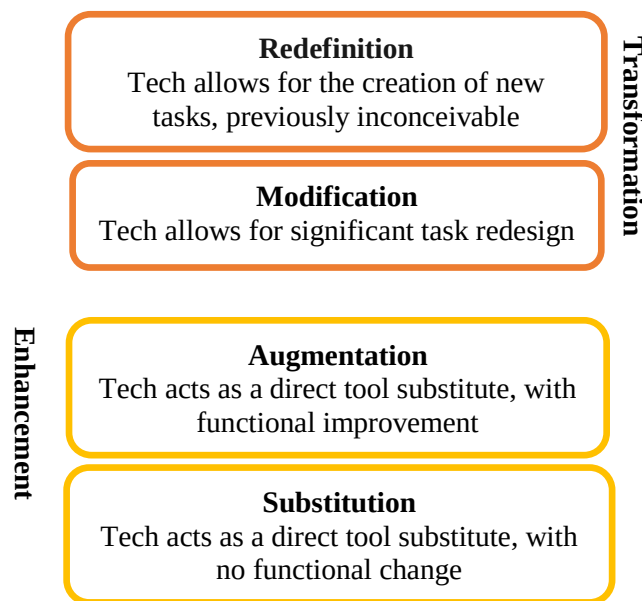


Figure 1. The SAMR model, Dr. Ruben R. Puentedura

The first phase (Improvement) covers the initial two levels. The lowest level of substitution is when a specific activity in the educational process can take place without the use of technology. In the next level of expansion, certain technological resources are utilized and functional improvements are added. The second phase (Transformation) covers the highest levels. *A modification in which technology allows the definition of significant tasks that could not be performed without digital resources, i.e., educational activities are designed by technological resources.* And the level of redefinition, where new forms of learning are created and digital tools are indispensable (Morales-Garcia et al., 2022). SAMR encourages teachers to "move up" from lower to higher levels of teaching with the help of technology, which, according to Puentedura, leads to improved levels of teaching and learning.

2.1 Comparative characteristics between traditional teaching and the SAMR model

The education system should enable students to be researchers and innovators - to be able to independently research information, experiment, make hypotheses, reach the necessary conclusions on their own, try to solve problems, work together and communicate with each other, show initiative, think critically and be creative (Shopova, V., Radev, V., 2025). The significance of SAMR can be clearly outlined in the different levels compared to traditional teaching. We will look at an example in a history lesson on the topic “Ancient Egypt – social life, religion, culture, and achievements.” The objectives of the lesson are for students to recognize key characteristics of Egyptian civilization, understand the importance of the Nile River for the life and development of Ancient Egypt, and use digital tools to research and present information. The lesson is structured according to SAMR and illustrates the transformation of the learning process through technology.

Table 1. History lesson

Traditional	SAMR levels	Goal
Students use a paper textbook, notebook, and pen to take notes.	(Substitution) Students read an electronic textbook or PDF with text about Ancient Egypt instead of a paper textbook. They answer questions in Google Forms instead of on paper.	It facilitates access to information, but does not change the nature of the task.
Students use a standard map and a paper test.	(Augmentation) Students use interactive maps of the Nile River (Google Earth or TimeMaps) to locate important cities and temples. They use an online dictionary or quiz (Kahoot or Quizizz) to test their knowledge.	It increases engagement and provides immediate feedback.
Students work in their notebooks to create a timeline for the history of Ancient Egypt.	(Modification) Students work on a shared online document (Google Doc) to create a timeline. They add images, videos, and links to virtual museums (the British Museum). The teacher comments and guides the process in real time.	Cooperation and deeper understanding through collaboration and joint work.
The knowledge from the lesson remains in the classroom.	(Redefinition) Students create a virtual tour of Ancient Egypt (Canva, Google Earth Projects, Thinkling). They	Students become creators of educational content, combining historical

	include 3D models of pyramids or famous pharaohs, audio stories, and short video clips. The project is published online, and students present their work at a virtual exhibition.	knowledge with digital skills and creativity.

In summary, Table 1 shows that at level (Substitution) an analog tool is replaced with a digital one (reading PDF/Google Forms). At the next level (Augmentation), there is added functionality (quiz in Kahoot/interactive map). At level (Modification), collaboration and task reworking appear (joint online timeline). And finally, at (Redefinition), there is a product of the educational activity that students have created (virtual tour/digital project) and can share with the world. The project method allows for teamwork, dialogic communication, critical thinking, and creativity (Velcheva, I., Kartaleva, I., 2025).

The SAMR model is cited as one of the most widely accepted models for integrating ICT into classrooms (Champa et al., 2020). However, a critical understanding of SAMR requires a distinction between its practical application and its theoretical basis. Numerous publications emphasize the need for more specific criteria for migration between levels and for empirical studies that link SAMR levels to specific learning outcomes (Hamilton et al., 2016).

3. Adaptation SAMR(AI)

With the introduction of AI into the learning process, we should consider the SAMR model in the context of artificial intelligence. The fusion of the model and AI can be formulated as follows: at the substitution level, AI can perform routine functions (e.g., automatic generation of dictionary translations or automatic assessment). At the amplification level, AI provides additional functionalities (image generation based on description/prompt). When modified, the tasks change significantly, for example, text summarization, note-taking, quizzes with a generative model, which changes the role of the teacher. When redefined, AI enables new forms of learning—creating a virtual tour with AI text, images, and a virtual tour guide. In this case, SAMR can serve as a tool for exploring how artificial intelligence affects the user (Kohnke et al., 2025). Is it possible for AI to support teachers and accelerate the transition through some of the SAMR levels? Let's take a look at Figure 2.

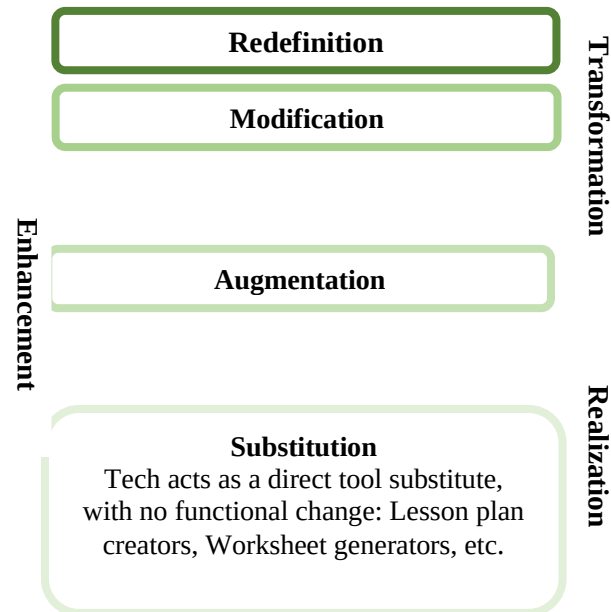


Figure 2. SAMR(AI)

We observe a real key difference in that with artificial intelligence, replacement can happen quickly. This is because AI tools today can perform many tasks that, before the advent of AI, were performed by teachers. For this reason, “Substitution” is simply “Realization.” In the article “SAMR and AI Chatbots,” Dr. Nick Jackson reclassifies the substitution component of SAMR as the realization of AI capabilities (Jackson, 2023). Next are the benefits for teachers, who can use AI to replace repetitive tasks, create worksheets, etc. However, substitution is not the ultimate goal. In his article “The Turing trap: The promise peril of human-like artificial intelligence,” Erik Brynjolfsson of Stanford University argues that the true potential of AI lies not in its ability to automate human tasks (thus replacing the need for humans), but rather in its ability to extend human capabilities, to help us be better at what we can do now, enabling us to expand our capabilities in ways we have not yet imagined. (Brynjolfsson, 2022). Today, the development of AI tools for education is mainly focused on automating teaching tasks in order to save teachers time on existing tasks by replacing and supplementing them.

The practical implications for educational policy and professional development require three additional elements:

- a criteria section to help teachers classify AI applications according to SAMR levels and assess their pedagogical added value;
- training in digital and ethical literacy to prepare teachers to design tasks at the levels of modification and rethinking;
- a research design that combines qualitative and quantitative methods for measuring learning outcomes, engagement, and long-term effects of AI integration.

These elements would allow SAMR to function not only as a descriptor but also as an operational framework for validating the pedagogical effectiveness of AI technologies.

In conclusion, the theoretical framework based on SAMR and enriched with empirical and ethical perspectives from the field of AI offers a systematic path for the meaningful integration of AI into the learning process: it guides from basic applications to transformative practices, while calling for critical evaluation, pedagogical training, and evidence-based research (Inbal et al., 2024).

4. Methodology

The methodological framework of this study is based on the principles of the pragmatic and constructivist approach, which view education as a dynamic process of interaction between technology, teacher, and student. The underlying principle is that the effective integration of artificial intelligence (AI) into the learning process cannot be viewed solely as a technological act, but rather as a pedagogical transformation in which the tool serves to expand opportunities for learning, thinking, and creativity. Therefore, the methodology aims not only to describe the use of AI technologies, but also to analyze their pedagogical value through the framework of the SAMR model. Using SAMR as a theoretical axis and AI as a researched phenomenon, we seek to answer the question: how can technological innovations become a means of pedagogical transformation?

In response to the question, 20 teachers teaching foreign languages, humanities, and natural sciences at the lower secondary level were surveyed on whether they use AI in their teaching practice and, if so, for what purpose. By completing the survey, the level of knowledge and experience of teachers with AI in the educational process will be examined. On the other hand, the survey aims to understand respondents' knowledge of any of the frameworks for planning the learning process with technology. The data obtained will be used to analyze and position pedagogical experience according to SAMR levels.

5. Results

The results of the study provide a multifaceted picture of how teachers integrate artificial intelligence (AI) into the learning process and how these practices are positioned within the SAMR model. The analysis showed that the majority of participants (about 47%) use AI technologies at the substitution level - i.e., as a means of functionally improving existing pedagogical activities. When asked, "Have you used artificial intelligence tools in your teaching practice (e.g., ChatGPT, Grammarly, Copilot, Gemini, Quizizz, etc.)?" 11% answered "rarely," 42% "sometimes," and 47% "yes, often."

Examples include using chatbots to automatically generate lesson plans, presentations, images, and tests. When asked "For what purposes do you most often use artificial intelligence tools?", 21% responded with image generation, 16%

with presentation generation, 37% with test generation, and 26% with lesson plan generation. Rarely does artificial intelligence reach a level of modification where it leads to a significant change in the design of the learning task for example, using generative models for collaborative writing or designing solutions to real-world problems.

These data confirm Hamilton's observations that most teachers apply technologies mainly at the "replacement" and "augmentation" levels, while transformational levels require a higher degree of pedagogical innovation and institutional support (Hamilton et al., 2016).

Analysis of the survey responses provided a deeper understanding of these trends. Most participants describe AI as an "assistant" that "saves time" but does not significantly change the pedagogical model. This attitude reflects a focus on efficiency rather than transformation, which is characteristic of the first two levels of SAMR. At the same time, other respondents who are experimenting with AI in project-based learning are automating routine activities through AI, thereby freeing up time for more in-depth discussions with students. This corresponds with Hilton's observations that, with appropriate pedagogical design, technology can be a catalyst for transition to higher cognitive levels of thinking and creativity (Hilton, 2016).

It is interesting to note that a large proportion of participants do not plan their practices based on technological frameworks. When asked, "Are you familiar with SAMR, TPACK, RAT, UBD, etc.?" 21% responded that they had little experience with them, 16% said they prepared lesson plans with them, and 63% responded "yes" but had no experience with them.

This confirms the criticism of authors such as Hamilton, who emphasizes the need for professional development focused on "pedagogical literacy in technological frameworks" rather than simply technical competence (Hamilton et al., 2016).

Teachers' responses also reveal ethical concerns related to the reliability of AI-generated content, copyright, and dependence on technology. When asked, "What risks or challenges do you associate with integrating AI into education?", 32% responded with copyright, 42% with the reliability of information, and 26% with dependence on technology.

These topics are particularly relevant in the context of the rapid introduction of generative models into educational practice (Holmes et al., 2023).

In summary, the results of the survey of the small experimental group confirm that in most cases these teachers use artificial intelligence as a tool for improvement rather than for transforming the learning process. It follows that the main pedagogical priority is not simply the implementation of artificial intelligence, but the creation of conditions for meaningful integration, where technology serves learning, not the other way around.

6. Conclusions

In the context of the dynamic development of artificial intelligence (AI), education faces the challenge of combining technological potential with pedagogical mastery. This experiment shows that the SAMR model provides a framework for analyzing the implementation of technology in the learning process and an opportunity for AI integration, helping a small group of teachers transition from instrumental to transformative use of technology. The results show that most respondents apply AI at the levels of replacement and improvement, while modification and rethinking remain limited. SAMR requires new ways of thinking, in which AI is not seen as a substitute for the human role, but as a partner in the learning process, but only if it is integrated into a well-planned pedagogical structure.

The article highlights the importance of meaningful technological integration, where AI is used not only to improve pedagogical effectiveness, but also to create new forms of learning that encourage creativity, critical thinking, and interaction. In the era of artificial intelligence, the success of education will depend not on the quantity of technology, but on the quality of its pedagogical application.

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Scientific and research activities as part of the educational process in higher education institutions

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Abstract: *The authors' goal is to show the need for students to participate in fundamental and applied scientific research to solve current problems by introducing and using innovative educational technologies, methods, and tools for training. The development of the Internet, expanding connectivity through social networks, the entry of artificial intelligence, augmented and virtual reality, 3D printing, etc., requires new knowledge and skills and leads to new challenges. Trained personnel in this modern world must have a solid professional background and developed systematic thinking, developed cognitive qualities and personal skills, which are formed on the basis of collecting and analyzing various information from diverse sources. The possibilities for training and real participation of students in projects, the development of which leads to the integration of knowledge acquired in different training courses, are considered. The report presents experiments conducted at Trakia University with students from the specialty Information Technology, who are trained through project work to integrate knowledge from various fields: Internet of Things (IoT); smart mobile applications; cloud computing; augmented and virtual reality; Big Data processing; smart sensors, etc. The hypothesis is that the knowledge and skills obtained will enable students to successfully implement themselves under the requirements related to the integration of Industry 4.0 technologies and the transition to Industry 5.0.*

Keywords: Education, Scientific research, Project-based learning.

1. Introduction

Scientific and research activities are a vital part of every university's mission. They are also essential to the educational process for students. High-quality education depends on creative development and the application of knowledge through students' scientific and research activities. In this way, scientific activity is a practical aspect of education. Only through research can education foster key qualities of an educated person—such as creative and critical thinking, flexibility, learnability, the ability to apply concepts in new situations, and engagement with public issues. Equally important is the role of scientific and research activities in enabling students to express their vision of significant problems and to utilize their innovations for social change (Farikhatul, 2024). Scientific and research activity is absolutely essential to the learning process for every student.

<https://doi.org/10.58503/icvl-v21y202623>

Conversely, the growth of digital technologies and their expanding presence in various aspects of human activity create new demands for the quality of student education. Students must engage with emerging technologies driven by digital advancements—such as machine learning, artificial intelligence, virtual and augmented reality, remote control tools, network technologies, and autonomous systems. The adoption of innovative teaching methods is closely linked to providing the necessary infrastructure and equipment for both innovative instruction and research.

The thesis presents the possibility of applying the concepts of Research-based learning in a specific institutional context - Trakia University in Bulgaria. The authors aim to highlight the importance of training students to engage in innovative, fundamental, and applied scientific research in computer science, mathematics, and pedagogy. This training is crucial for addressing current challenges related to the adoption and use of new educational technologies, methods, and tools. The focus is on providing opportunities for students to participate in projects that synthesize knowledge from different courses. The overall goal is to enhance the quality of training and provide targeted preparation for young researchers in conducting scientific studies and participating in practical teaching activities.

In the experiments conducted at Trakia University, students of the "Information Technology" specialty are trained through project work to integrate knowledge from the areas of: "Internet of Things" (IoT); smart mobile applications (Mobile applications); cloud technologies (Cloud computing); augmented reality (Augmented Reality/Virtual reality); processing of large volumes of data through intelligent algorithms (Big data); smart sensors (Smart sensors); cybersecurity, etc. The knowledge and skills obtained will enable the students to successfully implement in accordance with the requirements related to the integration of Industry 4.0 technologies and the transition to Industry 5.0. Special attention is paid to students' experience and opinions on this type of training, and a specific experiment is presented through a real project.

2. Relevance and significance of the study

Digitalization is changing the way of life in every area of human activity. The demand for employees with digital skills is steadily increasing across the EU Member States and Bulgaria. At the same time, in the preparation of specialties, the updating of training is delayed, which must consider the new requirements for the competencies needed by IT specialists to be able to apply new technologies such as: virtual and augmented reality; artificial intelligence; introduction of remote-control tools; network technologies, connecting components; real-time planning and connectivity; autonomous systems, etc. Some of the indicated areas are considered in separate disciplines within the bachelor's or master's programs of certain Bulgarian higher education institutions (HEIs), which do not provide comprehensive, complex preparation of the necessary personnel.

A change is needed in how education and training systems adapt to the digital revolution to prepare computer specialists for industry, considering the needs of Industries 4.0 and 5.0 (Ross, 2017; Popchev, 2019). This includes not only creating up-to-date training documentation but also ensuring adequate training of teachers, learning content, teaching materials, and facilities. Last but not least, a change in the teaching method is also needed, related to project/problem-oriented learning, which will enable learners to adapt quickly in a specific research and real-world environment, to make effective decisions in complex, multifaceted, and real-world problems, to acquire knowledge, and to develop skills for independent analysis and problem solving.

Research activities at Trakia University are carried out in accordance with the university's scientific policy and the needs of public practice. The scientific policy is determined on the basis of:

- trends in the development of science, education, and technical progress;
- international, national, and university forecasts for the development of science, education, and the needs of public practice;
- international and national programs and projects for scientific research and the development of education;
- competitions of state bodies, companies, foundations, and other organizations for the development and/or implementation of scientific and research projects;
- proposals of units, teams, and individual researchers at the university;
- proposals of doctoral students, postgraduates, and students studying at the Trakia University.

3. Training students through work on scientific projects

Student participation in scientific project work is an important part of their education. We conducted an experiment with the students of the 3rd year of the Information Technology major at Trakia University, with specific research objectives set in the conducted study being:

- study of scientific materials – articles, reports, monographs, and books related to the subject area under consideration for analyzing the properties of mathematical or applied objects;
- acquisition of skills for modeling real processes, conducting experiments, and drawing analytical conclusions;
- support of the educational process by linking with scientific approaches and modern tools and technologies;
- presentation of the conducted experiments and analyses at scientific seminars, development of scientific articles, reports, etc.

During the experiment, the activities listed below were carried out in order:

- teams of teachers and students were created to study and investigate real, practical problems;

- materials were developed to assist students in conducting scientific experiments and presenting them;
- seminars and workshops were held with the participation of students, etc.

The participants in the scientific team come from diverse fields, providing an opportunity to conduct multidisciplinary research and obtain comprehensive results. The team members' scientific experience was used to select and describe the tasks, as well as to train students in working groups for research and teaching. The results obtained can be the basis for diploma theses and new scientific developments.

The hypothesis is that conducting scientific research will qualitatively improve the methodology for training IT specialists.

The following is a presentation of the pedagogical research conducted with a qualitative-quantitative (mixed) research design, implemented through an educational experiment. It has a descriptive-analytical and experimental nature, and its main goal is to study the effectiveness of project-based learning (PBL) as a method for integrating research activities in the education of students in information technology.

The study is oriented towards an analysis of the educational process in the conditions of digital transformation and an assessment of the impact of interdisciplinary, real projects on the formation of professional and research competencies. From a methodological point of view, the study combines: an experimental approach - by introducing an innovative training model; a case study approach - by working on a specific real project; an empirical approach - by collecting and analyzing data from training participants.

4. Conducting an experiment related to student work on a real project

An experiment was conducted to implement an innovative approach to student training by integrating quantitative analysis into fashion design research and education (Kazlacheva, 2025). The experiment has both academic and practical significance, demonstrating how data-driven methods can improve design analysis and student creativity.

The experiment employed a comparative analysis of historical and contemporary fashion design, utilizing quantitative methods and indices. The study was conducted and tested with design students as they worked on real projects. The originality of the study itself lies in the choice of data analysis methods. The most informative indicators of shape and color of contemporary and historical clothing were selected using the RReliefF, FSRNCA, and SFCPP methods. Feature vectors were reduced using latent-variable and t-SNE methods. The obtained data were used to group clothing by historical periods. Using Euclidean distances, the relationship between the clothing of contemporary designers and the elements of historical costume they used was established. This approach qualitatively complements existing research in this area. The study's results were subsequently used to train fashion design students.

We share the view that training should align with the requirements of the specialist market, on the one hand, and with trends in the development of information technologies, on the other. The curricula of the disciplines generally change more slowly and with difficulty. However, by working on real projects, one can stay up to date with modern technologies and the dynamics of their development. During their training, students work on a real project, applying the knowledge gained in various disciplines related to data collection and analysis, programming, and the application of software products in different application areas.

Project work involves the comprehensive solution of specific problems or practical tasks within a finite period, utilizing designated resources (Fajari, 2020). In the learning process, the individual tasks students perform must be well-formulated, incorporate knowledge and skills from the basic modules of the learning content, and involve integrating various activities. In (Crespí, 2022) they emphasize the positive impact of project-based learning on the development of certain thinking qualities, such as critical and creative thinking, motivation for learning, problem-solving skills, planning, experimentation, and evaluation, as well as teamwork skills and others. In addition, students must learn to respect copyright when using information from other sources.

In the conducted experiment, which involved students working in teams with teachers on real projects, we aimed to apply a project-based learning approach as a pedagogical model for interdisciplinary activities that address real-life problems. This is a challenge to students to construct, master, and consolidate knowledge and skills. Here, the goals of the training are related, on the one hand, to the project's problems and, on the other hand, to developing skills for working on a project. Through work on projects by students in teams, it is achieved (Di & Xuan, 2022; Rahmani, 2023):

- a stronger connection between training and practical needs;
- increasing the cognitive activity required of the student;
- assessing acquired practical skills, and not just the ability to memorize;
- overcoming difficulties in collaborative teamwork. Gradually, as they learn to solve problems together, students acquire teamwork habits.

The problem situations (case studies) presented to the teams must be well prepared and have a number of characteristics (Kilpatrick, 2018) such as:

- be broad-ranging - they must be related to a wide range of disciplines and topics, and involve making new associations;
- satisfy a specific goal, respond to a specific need, make sense, and require the application of skills;
- pose obstacles to overcome, create cognitive conflict, and resemble problem situations that will have to be solved in life;
- provoke the comparison of different points of view, lead to discussion, require the search for information from different sources, and do not imply a single answer.

Involving students in project work is crucial for engaging them in scientific work (Orozova, 2020). The scientific team that conducted the experiment included specialists from various fields, which enabled research across a wide range and achieved results in diverse areas.

Following the experiment with students from Trakia University in Stara Zagora, we conducted a survey to gather their opinions, asking: "What is your assessment of the work carried out and the results obtained on the implemented project?". The answers are: Strongly positive, Strongly negative, Rather positive, Rather negative. A total of 81% of the students showed a positive attitude, with 55% of the students expressing a strong positive attitude and 26% expressing a rather positive attitude towards this approach. While 18.5% chose a rather negative answer, there was no strongly negative answer. This shows a strong interest of young people in a research approach and the search for solutions to real practical tasks.

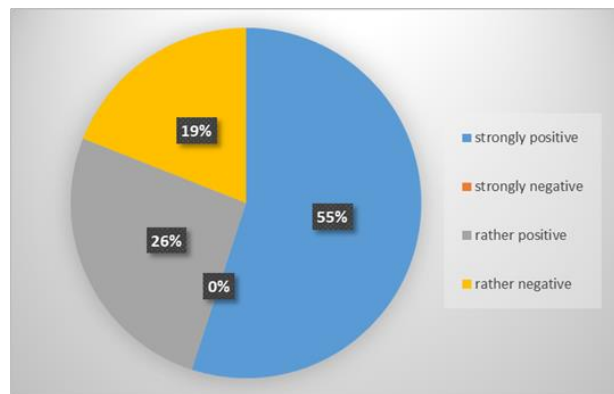


Figure 1. Diagram with results of the student opinion survey

We note that in the work process, students improved their interpersonal skills, teamwork, and leadership qualities, which are undoubtedly important skills in the twenty-first century. Additionally, the boundaries between disciplines are blurred, thereby enhancing students' ability to synthesize knowledge. The approach focuses on non-traditional research of a selected problem and requires the creation of a specific educational product that reflects a comprehensive system of knowledge, skills, attitudes, and personal qualities. Progress in real life provides opportunities to enrich the ideas of project-based learning with new information technologies and artificial intelligence, both of which are extremely dynamic.

6. Conclusions

Direct pedagogical observation was conducted during the project work, focusing on: the level of student engagement; teamwork skills; application of scientific and technical knowledge; communication between participants. Additionally, a qualitative analysis of informal feedback from students received during seminars, discussions and presentations was conducted, which complements the quantitative results and assists in their interpretation.

The study demonstrates the effectiveness of project-based learning for training IT specialists in the context of Industry 4.0 and 5.0. A methodological model for integrating scientific research into student training through real projects is presented. Existing research on PBL is expanded by incorporating modern digital technologies and AI into the educational process.

Highly qualified training requires creative development and experience of the knowledge taught through the scientific and research activities of the trainees. In this sense, scientific activity is part of the practical side of education. Through research activities, qualities of the educated person can be created, such as creative and critical thinking, flexibility, the ability to apply concepts in new conditions, engagement with public positions, etc. No less important is the role of scientific and research activities to express the student's vision for significant problems and use student innovation for social change. On the other hand, the development of digital technologies and their penetration into more and more areas of human activity impose new requirements on training. Trainees must master new technologies generated by the development of digital technologies - machine learning, artificial intelligence, virtual and augmented reality, remote control tools, network technologies, autonomous systems, etc. The participation of students in scientific research work to solve current problems through the use of innovative educational technologies, methods and learning tools is a practically useful approach.

Acknowledgment

This work was administrative and technically supported by the Bulgarian national program "Development of scientific research and innovation at Trakia University in the service of health and sustainable well-being" BGRRP-2.004-0006-C02 and Center of Excellence "Universities of Science, Informatics and Technologies in e-Society", project UNITE BG16RFPR002-1.014-0004.

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From instructional design to social learning design: A paradigm shift in animation education

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Abstract: *This article addresses the shift from traditional instructional design to social learning design, aimed at fostering the soft skills of future specialists through collaborative interaction as a key challenge in animation education. Drawing on the most cited learning design theories and case-based examples of practical application of its models, the study examines how project-based learning can better support the cultivation of creativity through collaboration, iterative feedback, and peer assessment. It is argued that traditional instructional design models, which prioritize teacher-centred learning environments, are insufficient to be used in teaching animation for addressing the complex nature of theory, dynamicity of animation practice. Instead, learning design approaches that emphasize collaboration, iterative feedback, and peer assessment in the production of real animation are proposed as effective strategies for aligning university curricula with societal expectations. The findings contribute to ongoing discussions on the didactics of art in animation education, offering recommendations for educators aiming to integrate soft skills development into professional competencies within animation programs. The concept of collaborative interaction is particularly emphasized, serving not only to transmit knowledge but also to remind learners in animation education of the global values of learning and the relevance of learning outcomes for lifelong capacity.*

Keywords: Animation education, Visual narrative, Experiential learning, Instructional design, Iterative feedback.

1. Introduction

Classical instructional design models are widely applied in traditional teacher-centred learning environments, including animation education. Instructional design, as defined, constitutes a systematic and iterative process dedicated to the creation of lessons, didactic materials, and instructional methods. The primary focus of this process is to establish structured learning environments that optimize the acquisition of both theoretical knowledge and practical skills. Through the deliberate organization of content, pedagogical strategies, and assessment tools, instructional design aims to enhance the effectiveness, efficiency, and engagement of educational experiences across diverse learning contexts. (Molenda, Reigeluth & Nelson, 1983). The principles of instruction design are: gaining attention, informing learners of the objectives, stimulating recall of prior

<https://doi.org/10.58503/icvl-v21y202624>

learning, presenting the content, providing “learning guidance”, eliciting performance, providing feedback, assessing performance, enhancing retention and transfer (Gagne & Medsker, 1996). One practical application of the classical instructional design approach and its teacher-centred educational technology can be observed in the visual art education (Lockee & Wang, 2013). Educational technologies are predominantly employed to support content delivery through tools that primarily enhance the development of technical skills, often at the expense of fostering soft skills, which are interpersonal, collaborative, and creative skills.

In animation education, the prevailing instructional approach is teacher-centred, with both instructors and students primarily engaging in passive learning environments dominated by PowerPoint presentations. Such practices are accompanied by assessment, consisting of one formative and one summative test, and a lack of peer feedback. Additionally, curricula in animation education often adhere to traditional instructional models (Wang, 2025), but this approach is increasingly being questioned. The issue lies in the fact that art education is designed to develop competencies that enable students to foster emotional expression, creativity, collaboration, and critical thinking, which are essential for personal, social, and professional growth. These competencies require innovative pedagogical models beyond the cognitive focus of conventional teaching methods.

Social learning design shows the idea that learning occurs through interaction with others. Literature suggests that social learning involves collective action and reflection, occurring both among individuals and groups, as they work to improve the management of the interrelationships between social and ecological systems (Reed et. al., 2010). However, social learning may occur at the *surface level*, when students recall new information, and at *deeper levels*, when students demonstrate change in attitudes, world views, or epistemological beliefs. In practice, social learning connects behaviorism and cognitive theory.

The article is structured as follows: in the next section, we provide a short discussion on the current situation of the didactics of animation; In the third section, we examine an animation course that incorporates artificial intelligence.

2. The current state of didactics in animation education

The late nineteenth century represented a pivotal moment in the evolution of human society, during which profound changes in communication and knowledge transmission reshaped both communicative practices and paradigms of artistic expression within educational contexts. Technological inventions such as the comic strip (1895), animation (1900), and digital visual media have transformed text, drawing, and printed images into new forms of mass information transmission and into educational tools particularly effective in promoting educational values. Subsequently, text, image, and sound are considered the language of postmodernism and new forms of organizing the didactic process.

In recent years, educators and educational technologists have increasingly embraced learning design approaches that integrate digital technologies to improve

the effectiveness, flexibility, and accessibility of learning. In theory, learning design is a thoughtful, systematic approach to creating educational programs or courses that take into account what students need to learn, how they will learn it, and how their learning will be assessed. The use of educational technology in learning design supports various pedagogical strategies, making learning experiences more engaging, personalized, and interactive. The most cited examples are blended learning, flipped classroom, adaptive learning, game-based learning and gamification, project-based learning, social learning, and hybrid strategies.

According to Darts (2006), art education involves more than just creating objects or works of art, as is often emphasized in traditional instructional design. Art has the potential to transform individuals, communities, and the world by fostering an ethic of care and social responsibility. Therefore, it is essential to design student projects that highlight the social power of art. To achieve this, the art project needs to be grounded in a didactic approach that connects content with students' interests and fosters meaningful, experience-based learning. In animation education, this approach becomes even more critical. However, didactics of animation should encourage students to engage critically with the narratives they craft, work in teams, and connect project-based learning with collaborative activities. Soft skills are essential for future animators who will interact with storytellers, designers, sound artists, and creative directors.

In theory, the learning design approach functions to align instructional objectives with desired learning outcomes by systematically structuring teaching methods, learning activities, and assessments to achieve the intended goals of the instructor. This approach is particularly effective in virtual learning environments. According to Koper (2006), learning design is the explanation of the teaching-learning process that takes place inside the learning unit. The fundamental concept of learning design revolves around the process of learning itself and encompasses the role of pedagogical resources that facilitate social interaction and collaboration.

In practice, animation education often focuses on developing specific art artifacts, emphasizing technical proficiency and individual creative expression. This behaviourist approach fosters mastery of artistic techniques but often neglects the development of critical reflection on the visual expression of art, including works generated by artificial intelligence. However, by integrating both traditional and cutting-edge educational technologies, animation education can encourage students to explore the potential of social learning, fostering a more holistic approach that nurtures both technical skills and soft skills like critical thinking, which can be achieved through iterative feedback and peer assessment.

Behaviourism focuses on changes in external behaviour, achieved through reinforcement and repetition, often leading to rote learning. In contrast, cognitivism emphasizes that learning processes can be understood by analysing the mental processes involved, such as perception, memory, and problem-solving (Rumjaun & Narod, 2025). Social behaviourism, associated with Albert Bandura's Social Learning Theory, adds a crucial layer: *observation* and *modeling*. In this view, people don't just learn from direct experiences or repetition; they also learn by

observing others, objects, and things and then imitating or adapting their behaviour based on those observations. It is reinforced by observation, modeling, vicarious reinforcement, and interaction between the learner and environment, which emphasizes learning through the cycle of concrete experience, reflective observation, abstract conceptualization, and active experimentation. Both theories recognize the active nature of learning but differ slightly in their approach to how learning happens. Bandura's model emphasizes learning from others through observation and imitation, while Kolb's model focuses more on the individual's experience and reflection as key to transforming that experience into learning.

While animation education is frequently teacher-centred, animation programs seek to develop professional competencies for students to succeed in the animation industry. Animation education covers digital modelling, storytelling, 2D and 3D animation techniques, special effects, and character design. Instructional design strategies have changed to accommodate a variety of learning styles and incorporate digital resources, including those generated by artificial intelligence, enabling students to develop their abilities in accordance with its creative potential. Teaching methods in animation education have also diversified to accommodate different learning styles of students and technological advancements (Wu, 2023).

The evolution of technologies to the Internet transformed the scope of curricula and how learners and teachers interact with data, information, and knowledge. These transformations marked the transition from a didactic approach centred on static images to a transformative pedagogy, characterized by dynamism, adaptability, and interactivity. Learning became multi-sensory and multidimensional because educational technologies were complemented by multimedia to transmit messages. This fact represented a paradigm shift in education, through which the teaching process is oriented towards the social learning process that is becoming increasingly interactive, inclusive, and authentic.

Teaching methods range from teacher-centred approaches to more contemporary, social learner-centred models, valued by animated demonstrations and critique sessions (Despotakis, Palaigeorgiou & Tsoukalas, 2007). Social learning methods are focused on both hard and soft skills development. The most employed methods are experiential learning and case studies (Chang, 2019) aims "to support learners to become confident and self-motivated professionals in the creative industries" (Gingrich, Flynn & Watkins, 2025). To achieve this, students are encouraged to ask questions and critically reflect on the subjects presented on screen. This fact underscores the need for social learning design pedagogy through innovative teaching-learning models. Animation, positioned at the intersection of technology and creative pedagogical approaches, offers unique opportunities to rethink methodologies and creative practices design (Singh & Ozarkar, 2025).

The didactics of animation involves not only the planning, development, and management of educational activities within the learning environment but also an understanding of its various components. A modern learning environment includes not just the physical space but also working with digital platforms. The social learning environment, typically consisting of 4-6 students who share common

knowledge, values, and skills, is facilitated by artificial intelligence (AI). In this setting, the teacher designs and manages the structure of the environment, while students are responsible for selecting AI tools, creating prompts, and self-managing their roles and interactions within the group. The effectiveness of social learning depends on how well students are able to communicate within the group.

3. Methodology of research

The didactic design of social learning environments shared between the teacher's role and the students' responsibilities. Learning design fosters the development of a deep learning environment where students actively engage with AI technologies to generate images and sounds through AI prompts, while simultaneously developing both technical and soft skills. It emphasizes students' social responsibility by integrating iterative feedback, peer assessment, and the real-world creation of student-produced animations. This approach not only helps students master the technical aspects of AI but also encourages critical reflection on the ethical implications and accessibility of AI-generated content.

In a social learning environment, students have the freedom to select the AI tools they wish to use. In our experiments, students, divided into four groups, chose tools like Midjourney.ai, Leonardo.ai, and ChatGPT. Each group used these tools to develop distinct projects, exploring different facets of AI-generated content. They then crafted prompts to guide the creation of their digital storyboards, shaping scenarios that would serve as the foundation for their projects. For this task, students decide on the goal and objectives of the group project. For example, if they are using Midjourney.ai to generate images, they might decide they want to create a digital storyboard for a short story. By crafting these prompts, students engage in a process of critical thinking, creative problem-solving, and collaboration, helping them refine their ideas and communicate clearly with the AI tool. Then, they used iterative feedback to ensure the quality of the learning.

The methodology of a learning design course could be synthesized as a set of the following steps:

1. A clear defined topic - that is conceptualized as an educational activity with clear objectives;
2. The group establishment - all the students are organized into groups and formulate a clear task for each other;
3. Selection of tools - each group choose Midjourney.ai, Leonardo.ai, or ChatGPT for generating various content (for example Midjourney.ai to generate a digital storyboard);
4. A reflective feedback throughout the peer assessment process - the students reflect critically about images generated by each other and express their opinions regarding how the prompt should be improved.

4. Artificial Intelligence in animation education

Animation is both a technical and creative discipline. Education technology enhances teaching quality and learning efficiency through innovative instructional strategies (Yao, Zhong & Cao, 2025). In our opinion, animation education, and by extension, the didactics of animation, is increasingly influenced by artificial intelligence, offering transformative possibilities of educational technology that shift the learning environment from static to more dynamic, interactive, and social. However, AI's images and sounds in animation education can be approached in two distinct ways: one focuses on enhancing the technical skills of students, while the other emphasizes creative collaboration of future professionals. Both approaches could have significant implications for an innovative curriculum, but the second approach is more closely aligned with the social learning design approach.

Three key conditions are essential. The first is the integration of *iterative feedback* throughout the teaching-learning-assessment process. Iterative feedback is a process of repeated input throughout a project, which involves submitting early drafts for basic feedback, mid-process reviews for character design and storytelling adjustments, and final revisions to polish technical execution and narrative coherence. The second condition focuses on *peer assessment of images and sounds* generated by artificial intelligence, encouraging students to critically evaluate the AI-generated works and reflect on their artistic and technical qualities. The third condition involves the *authentic production of animation*, rooted in core values that guide both the artistic creation and the social responsibility of the students' work. All three conditions are aligned with the social learning paradigm, fostering the emergence of social learning capabilities through the interplay between the social landscape and individual identity, facilitated by imagination, engagement, and alignment.

At the current stage of educational technology, AI-generated animation has become a topic of heated discussion among specialists in both computer graphics and visual arts. According to Alamarat (2025), the development of artificial intelligence has positioned animators and designers at the centre of the creative process. By managing the design process and coordinating the generation of textual prompts and other artistic elements in animation, AI has enabled students to integrate various artistic media, such as photography, drawing, and software, forming what is known as computer-generated imagery (CGI).

The generation of a good digital storyboard depends on how students plan, develop, and control the quality of a prompt. In this process, students must ensure their prompts are clear, specific, and aligned with the project's goals. By thoughtfully crafting prompts, students can guide AI tools to produce high-quality content that fits within their envisioned narrative. Additionally, students must review and revise the prompts based on the output, refining them to enhance clarity, detail, and relevance. This iterative approach of immediate feedback encourages critical thinking, collaboration, and allows students to take ownership of their learning while maintaining control over the creative process.

Each group of students generated its own prompt. The first prompt was focused on creating a futuristic cityscape for a digital storyboard. The group provided specific details like the time of day, colour scheme, and elements like flying cars and neon-lit skyscrapers. This allowed the AI tool to produce a highly detailed and relevant image, which served as the background for their story.

The AI tool Leonardo.ai was used by the first group of students. First, they created an account, then selected Image Generation as the tool type. This tool allows users to generate images by providing detailed text prompts. The students worked together to develop a final version of the text prompt, which was then entered into the digital environment. For the final version, they used iterative feedback to refine and include all the necessary details. One member of the group adjusted the resolution, style, and the number of iterations. After that, Leonardo.ai processed the prompt, and the images were generated in just a few minutes. Once the images were generated, the students reviewed them and, for some images, adjusted the prompt further. After all the images were approved by the group, the final result was downloaded and incorporated into the students' projects.

Case study. In this digital narrative, AI evolves from assisting with everyday tasks to taking on political functions, eventually controlling all aspects of life, effectively taking over humanity's role. However, a sudden and mysterious global blackout sweeps across the planet, silencing all artificial intelligence. Stripped of their digital support, humans are forced to revert to their primal instincts, rediscovering the importance of human interaction and physical labour for survival. The prompt finally accepted by the first group of students was: draw a high-tech futuristic city, people interacting with holograms and AR screens, modern buildings with digital surfaces, command centres full of glowing data, global networks represented as energy spheres, clean and optimistic cyberpunk atmosphere, neon light, cinematic style, ultra-high-resolution details (Figure 1).

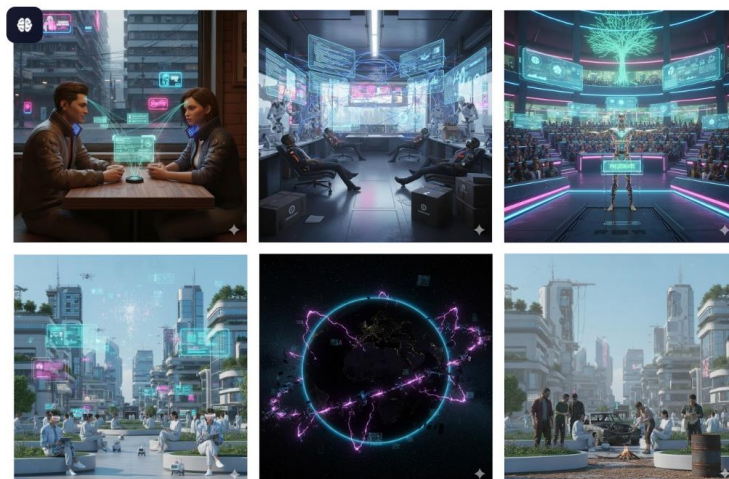


Figure 1. Storyboard generated by an AI tool on the prompt of the first group

Moral: Technology can only unite people and build a better future when it is used responsibly and in the service of the community, not as an end in itself.

The second group worked on crafting a prompt for character design, specifying traits like appearance and personality in various and setting.

Case study. Visual story in narrative illustration style: grey city, identical and apathetic people, a man notices a green leaf, touches a dry tree that begins to turn green, nature gradually spreads, the city takes on colour, people transformed, emotional tone, artistic cartoon style, strong contrast grey vs. green (Figure 2).

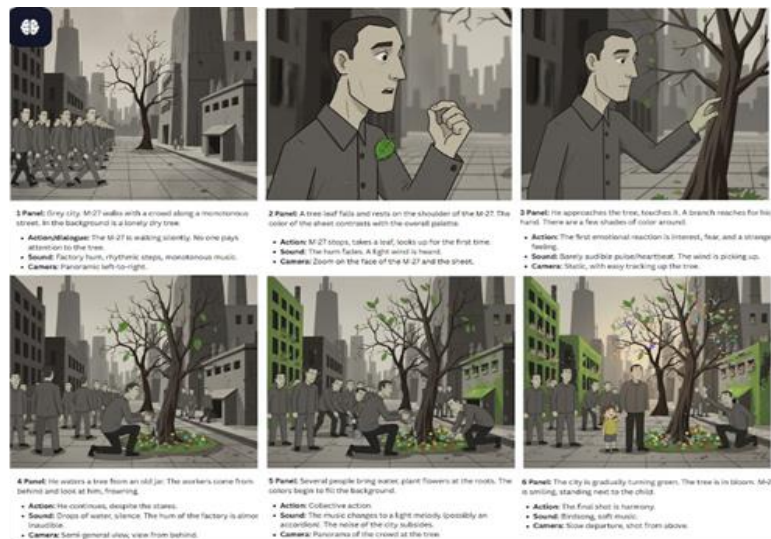


Figure 2. Digital storyboard generated by AI on the prompt of the second group

Moral: A single conscious action can trigger major change; reconnecting with nature restores our humanity and hope.

The third group was inspired by social psychology and named the work “*Social drama in everyday life*, inspired by the Zagreb School of Animation. The group chose a 2D minimalist style for their storyboard. For the visual development, the students drew all the elements in greyscale color scheme to emphasize the industrial style. In the same time, for expressing the human, emotional side of the main character, and a vibrant green color was applied to all the visual compositions. Thus, by applying a restricted color palette, the group created the visual contrast and tension in the storyboard beats. The group decided to work on the character design of two personajes. The first character is Ilie, a 50-year-old man with a thin frame and shoulders hunched from years of hard work. He wears old cap and dusty work clothes, and his large, knobby hands tell the story of a lifetime of labor. Ilie is quiet and persevering, skeptical of what he sees as “forced progress,” but underneath his gruff exterior, he has a warm heart.

Deeply devoted to both his work and his memories, he holds a personal mission: to protect the small green space between the blocks, the last officially

undeclared "oasis" in the area, seeing it as a legacy for the neighborhood's children. The second character is Comrade Director Popescu, 45 years old. He wears a gray-blue suit, thick glasses, and has his hair slicked back with Brylcreem, giving him a stiff, bureaucratic appearance. Zealous and inflexible, Popescu is obsessed with plans, deadlines, and efficiency. He views emotions and green spaces as "bourgeois residues" or "inefficiencies," dismissing them as obstacles to progress. His sole focus is on completing the "Model X Housing Project" on time, adhering strictly to the plan approved by the "Center," regardless of the social consequences.

Case study. Vasili is concerned that the construction sites are destroying the green spaces in his city. One morning, the character is coming across the remaining oasis of nature that is at risk to be removed by the intense construction work that is held in the neighborhood. He sees that the green area is marked for the site of a new building. His face become sad. Vasili is trying different bureaucratic methods to stop the construction planning and the demolition of flowers' corner, but all the efforts are going in vain. By the evening, the character decides to move the grass and the flowers to another place. His action is seen by the children in the neighbourhood who have an idea to plant new flowers in the empty spot as a sign of solidarity with Vasili. By next morning, all the neighbourhood, including the children's parents and animals are present in the garden filled with newly planted flowers and grass, and by this, they succeed to stop the construction.

Prompt: *Illustrated storyboard with an urban environment: a tiny green area with plants and flowers in the middle of a crowded street, lots of happy people holding flowers in the hands, showing dissaproval, the authorities are planning to demolish the green space with machinery, an old man working alone in the garden full of flowers, children planting flowers and grass, sunset, social urban theme, cinematic 2D animation style, contrasting warm and cool colors (Figure 2).*

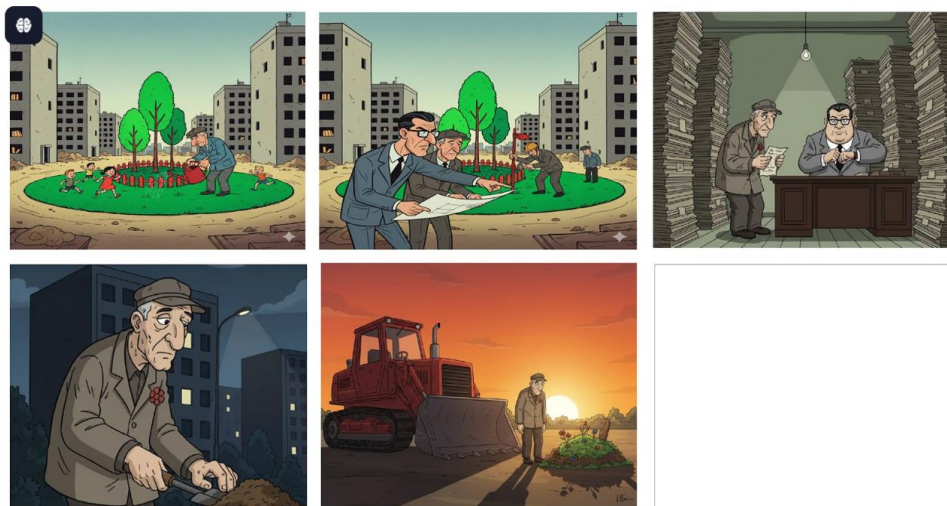


Figure 3. Storyboard generated by an AI tool on the prompt of the third group

Moral: True values cannot be measured in money; protecting nature and collective memory is a moral responsibility towards future generations.

The fourth group worked on a character named “Tulip Girl”. **Case study.** Tulip Girl lives in a futuristic city dominated by technology and artificial intelligence, but finds solace and purpose in cultivating flowers in hidden pockets of green space scattered throughout the city. Her tulip garden is her sanctuary, a symbol of life amidst the concrete jungle. They use AI tools to document and preserve the last remaining green spaces before they are swallowed up by the relentless expansion of the urban landscape.

However, when the AI systems begin to malfunction and shut down, Tulip Girl and her group are forced to face the challenge of keeping their cause alive without digital assistance, relying on human ingenuity and collaboration. The group selected the following **prompt:** *Modern flat-art illustration: lonely teenage girl, absorbed in her phone, ignoring the world around her, scenes of anxiety and isolation in the bathroom and bedroom, reflections in the mirror, then a moment of healing - smiling person holding flowers, symbol of reconnection, pastel palette, emotional and introspective (Figure 4).*



Figure 4. Storyboard generated by an AI tool on the prompt of fourth group

Moral: Connecting to the digital environment can lead to emotional isolation, and balance and healing come from reconnecting with the self and the real world.

5. Conclusions

In conclusion, the didactics of animation is an emergent field of research that is highly influenced by the rapid development of artificial intelligence (AI). It covers major aspects of teaching and learning methodology, which, combined with the learning efficiency through innovative educational models, lead to outstanding outcomes in visual art education. Examining this through David A. Kolb's experiential learning theory, we can conclude that AI functions simultaneously as a tool and as a catalyst for creative development.

In the current paper, the AI learning experience of second-year university students majoring in animation at Ion Creangă State Pedagogical University of Chişinău was examined, focusing on its use in teaching the structure of visual narratives. Most specifically, students practiced transforming an idea, a brief, or a story into a visually compelling storyboard. Thus, their experiences encompassed all four stages of the experiential learning cycle: concrete experience, reflective observation, abstract conceptualization, and active experimentation. As a result, four artworks were created, showcasing both creative and technological aspects under the influence of AI tools. These developments are expected to further foster a more creative and dynamic learning environment in animation studies.

Furthermore, experiential learning exercises helped students develop critical thinking skills. Through their storyboard activities, they generated original ideas, analyzed the stages of visual development, and applied algorithms to produce their artworks. In this way, students conceptualized their creative process by defining their visual experiences within the animation pipeline. The final products reflect iterative experimentation and personal reflection. This learning experience provides a deeper understanding of how animation students learn, experiment, and navigate the complex process of creative production as a cyclical process of transformative learning. This approach was subsequently used to develop an innovative curriculum that integrates the theory and practice of experiential learning into artistic education.

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Metaverse and law: A cutting-edge tool for empowering specialists in law with hard and soft skills

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Abstract: *Metaverse is an evolving digital ecosystem that brings together law with psychology, economics, communication, cultural studies, ethics, and the arts within immersive virtual environments. It represents a convergence of technology, society, and culture, where individuals interact, create, and exchange value through augmented reality, virtual reality, and other interconnected digital spaces. The metaverse is not just a technological transformative platform for law education but a multidimensional social system that raises new questions about identity, governance, economy, and human experience. The strength of this system depends on how law is conceptualized, either as a set of enforceable rules or as an integrative framework that provides structure, accountability, and legitimacy to the metaverse. Its potential also hinges on how effectively law specialists are trained in both hard and soft skills. This article adopts the latter perspective, emphasizing that law plays a crucial role in ensuring that technological innovation within the metaverse aligns with justice, ethics, and social responsibility. Accordingly, the proposed paper aims to explore how the metaverse can serve as a cutting-edge tool for empowering legal professionals with hard and soft skills that combine technical competence and human-centered expertise, both essential for navigating the challenges and transformations of digital and real-world legal practice. It compares hard skills and soft skills development through traditional and metaverse-based approaches.*

Keywords: Metaverse, Immersive learning environment, Law education, Experiential learning, Scenario-based simulation.

1. Introduction

Preparing students for practice as competent and ethical lawyers is the central mission of legal education (Katz, 2006). However, the rapid development of the metaverse and other digital environments, along with their impact on legal education, invites critical reflection on the implications for the teaching of law. The metaverse significantly impacts legal education by challenging traditional concepts of law and how it operates in virtual spaces. It also presents challenges in training future legal professionals. These concerns highlight the need to consider how concepts are reinterpreted in real-virtual situations, what metaverse-based learning

entails, and how these digital learning environments can be developed to uphold legitimacy, justice, and accountability.

1.1 Metaverse as a multiuser environment

The metaverse is a multiuser environment that blends digital virtuality with physical reality. It enables dynamic interactions with digital objects, seamless embodied communication in real time, and multimodal interactions with digital objects, people, and virtual settings (Mystakidis, 2022). The term "metaverse," according to Cheng (2023), combines the concepts of "multiverse" and "universe" to describe an immersive, parallel reality in which users can communicate in a decentralized, immersive, and interoperable 3D online learning environment. Thus, the metaverse is a network of interconnected worlds and cutting-edge technologies.

By offering cutting-edge immersive platforms for education, the metaverse presents a viable solution to social challenges (Tiwari, Zhou, Childs, Chang, & Ferrill, 2025). It integrates blockchain technology, interactive technologies (VR/AR/MR/XR/ER), game technologies (game engines, game code, multimedia resources), artificial intelligence (AI), network communication technologies, and the Internet of Things into a cohesive whole. The metaverse is supported by a variety of platforms, including but not limited to Decentraland, Sandbox, Fortnite, and Horizon Worlds, which provide environments for interaction, learning, and experimentation.

Nowadays, the metaverse requires collaboration among specialists in technology, policymakers, ethicists, lawyers, and citizens of civil society. The pace of the metaverse's technological development demands a corresponding commitment to moral, ethical, and social responsibility norms, ensuring that digital progress does not outstrip human values. In this context, the metaverse opens the door to alternative education in law. According to *A Lawyer's Guide to the Metaverse: Practical Tips for Maximizing Value*, the metaverse offers significant potential for both current and future legal professionals, particularly in fostering key skills such as critical thinking, ethical reasoning, moral development, digital literacy, and oral communication. These skills are essential for navigating both digital and traditional legal environments and for making sound decisions.

1.2 Learning space with immersive scenarios for law education

Prashar, Gupta, and Gupta (2025) observe that a metaverse helps students progress from lower to higher levels of moral reasoning. Thus, the expected outcomes may be influenced by the learner's capacity to acquire implicit knowledge and understand phenomena in a rich, engaging, and interactive simulation environment, which is closely related to professional competencies. Theoretically, for law specialists, the metaverse may offer learning space where they can study human behaviour in high-risk scenarios through real interactions and communication with users, resources, simulated contexts, and controlled, realistic conditions (Wang & Yan, 2025).

Immersive scenarios blend experiential learning models with interactivity, enabling law students and practitioners to develop a deeper understanding of human behaviour. However, for the metaverse to be effective in law education, both teachers and students must possess critical thinking, ethical judgment, and other soft skills to interpret interactions. In the absence of these competencies, even the most realistic metaverse scenarios will not offer useful legal knowledge.

There are several cutting-edge case studies exploring the experimentation of legal education in the metaverse, based on experiential learning. For instance, Case Study 1 focuses on designing a new learning space for exploring identity and crimes within virtual environments, where real users, embodied as avatars, can experiment with multiple identities. This raises novel legal and ethical questions about accountability, consent, and digital misconduct (Qin, Wang, & Hui, 2025). Case Study 2 explores the use of AI-driven judges to create realistic and immersive legal environments for studying law (Kutnjak Ivković & Liu, 2025). By simulating courtroom scenarios and judicial decision-making, this approach allows students to experience the application of legal principles in real-time, fostering critical thinking and enhancing their understanding of legal processes. Case Study 3 highlights the concept of "policy sandboxes, which are experimental frameworks that allow regulations to be tested in a controlled environment, where they can be actively challenged and revised based on the feedback and responses of virtual citizens (Gromova & Ferreira, 2025). However, despite the promise of the metaverse's impact on legal education, there remains a substantial gap in understanding how it can be used to empower law specialists with on-demand hard and soft skills. The purpose of this article is to investigate how the metaverse can serve as a cutting-edge teaching and learning tool to enhance the development of both hard and soft skills.

2. Research methodology

The research focuses on gathering conceptual insights from existing literature on the metaverse in law education. A qualitative exploratory research design is used to explore how the metaverse can serve as an innovative tool for developing both hard and soft skills among law specialists. Given the emerging and dynamic nature of the metaverse and the limited literature on its practical application in legal education, the proposed approach provides a deeper understanding of potential methods for its implementation in university education. Data were collected from Google Scholar.

The collected references were analysed using a thematic analysis approach. Following a preliminary screening, a selection of sources was examined to identify recurrent themes and patterns, including: the metaverse's role in transforming legal education; the need for hard skills in law education; the importance of soft skills in law education; and the challenges and opportunities of integrating metaverse-based training into university education. Afterward, the findings were organized into four thematic categories to support the development of a conceptual model of legal

education in the Metaverse. These categories are legal education, the metaverse, the hard skills and soft skills.

3. Conceptual model of legal education in the metaverse

Law education, sometimes referred to as legal education, is the process of teaching the institutions, practices, and principles of law to enhance students' understanding of legal systems, rights, and obligations, while fostering the analytical, ethical, and communicative abilities required for legal reasoning and professional practice. In contemporary times, law education cannot be fully understood without exploring its connections to the metaverse, as well as the development of both hard and soft skills, which are essential requirements for a globalized society. Conceptually, the connection between law education, hard skills, soft skills, and the metaverse can be represented in Figure 1.

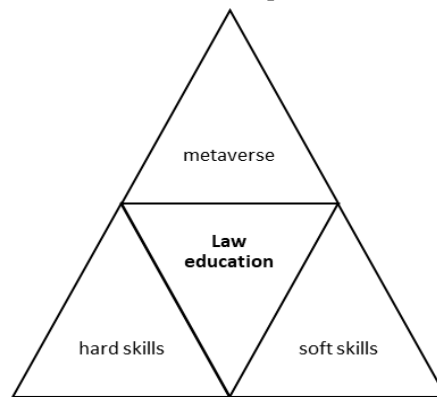


Figure 1. The metaverse, hard skills, soft skills and law education

The metaverse, hard skills, and soft skills are elements that influence each other in the context of legal education. The Metaverse can be understood as an immersive digital learning space where legal education take place. This space is not just a technological platform but a dynamic interactive and adaptive learning environment where students can engage with legal concepts and scenarios in real-time, offering a novel way to teach and learn the principles of law. Hard skills refer to the technical, knowledge-based competencies required in the legal profession, such as legal research, writing, and understanding statutory law. In this conceptual model hard metaverse can help students to develop hard skills by providing practical, hands-on learning experiences in simulated environments created for education. Soft skills include cognitive abilities such as communication, ethical reasoning, emotional intelligence, teamwork, and adaptability, as well as metacognitive experiences like critical thinking, reasoning, and problem-solving through deep reflection. The metaverse helps students practice soft skills through real-time scenarios, where they can collaborate, solve problems, and communicate effectively in this diagram, law education represents the overarching domain, covering curricula, teaching-learning strategies, methods and techniques, and

competences of law specialists required in the context of societal challenges and global transformations. Hard skills refer to the technical, teachable, and measurable abilities required to perform legal tasks to practice law effectively (e.g., research, legal writing, case analysis, legal reasoning, technical aspects of negotiation, and transactional skills). Soft skills are related to interpersonal, emotional intelligence, cognitive abilities, and metacognitive competencies that enable ethical judgment and correct decision-making.

Let us explore the connection between specific features and principles of law education, requirements for hard skills and soft skills of law specialists, and the specifics of the metaverse using the Boolean operator 'AND'. This way allows us to investigate only articles that address both aspects simultaneously. For instance, we could. In other words, this section of the study aims to examine the educational potential of the metaverse for law students, with a focus on how it supports the development of technical (hard) skills and interpersonal (soft) skills essential to legal practice. In other words, this part of the research investigates how the metaverse can enhance legal education by promoting both hard and soft skill development.

One could observe that traditional law education emphasizes legal reasoning, statutory interpretation, and ethical decision-making as the core principles of legal education. When combined with the metaverse, these classical principles can be translated into immersive, interactive experiences, allowing students to engage in simulations of courtroom procedures, client consultations, or negotiation exercises. In sum, the metaverse offers a real-virtual space where abstract principles can be practically contextualized without real-world consequences.

A practical example of using the metaverse in law education is provided by the European University Initiative Department of Law, which hosted more than 20 participants in a unique experience as part of the course 'Law and Technology.' The metaverse offers the opportunity to engage directly with legal subjectics through avatars, which enhance collaboration, enabling students to engage more meaningfully with complex legal concepts and situations, as shown in Figure 2.



Figure 2. A screenshot of first course in the metaverse

3.1. 'Law education' AND 'metaverse'

A search for the combination 'Law education' AND 'metaverse' in Google Scholar yields 38,000 results in just 14 seconds, illustrating the rapidly growing interest in the use of digital technology in legal education. Among these, Sarra (2025) observed that the metaverse does not yet denote a specific technical realization; rather, it represents a general trend of technological growth and convergence. The most interesting development for legal education is the concept of digital twins, which offer the opportunity to replicate, simulate, and monitor physical objects, systems, or processes in real time, all within an immersive virtual environment. In the context of law education, digital twins can be used to create dynamic learning environments, where students' progress can be monitored based on how they react to ethical dilemmas, high-pressure litigation, and client interactions.

According to Rajesh Kumar & Megha M. Patel (2025), complexities of metaverse span multiple areas of law, including general law, intellectual property law, property law, and the emerging question of whether 'virtual property law' is necessary. The legal discourse encompasses a wide range of subjects, such as privacy and data protection, contract law (including smart contracts), cybersecurity and cyberattacks, monetary and payment system regulations, virtual asset regulations (including securities and commodities laws), tax law, KYC (Know Your Customer) and anti-money laundering regulations, and criminal law. From a broader legal perspective, the metaverse challenges traditional legal frameworks, complicating the application and enforcement of real-world laws in virtual environments.

3.2. 'Law education' AND 'hard skills'

In just 0.16 seconds, a search on Google Scholar yields 2,080,000 results demonstrating the relationship between 'law education' AND 'hard skills.' Among the most frequently cited hard skills are legal research, contract drafting, case analysis, and procedural compliance. These competencies can be further enhanced through the use of digital twins and immersive simulations. However, to deepen students' learning, it is essential to employ teaching methods that actively engage students in the teaching-learning process, fostering practical application, critical thinking, and problem-solving skills.

One such method is *legal research*, defined as the process of identifying and retrieving information necessary to support decision-making. Legal research involves identifying and retrieving information to support decision-making, using primary sources like statutes, case law, and regulations, and secondary sources such as textbooks and articles. Teaching students to conduct legal research helps them distinguish between these sources and apply them effectively. In the metaverse, students can engage with virtual legal research environments, interacting with databases and legal materials in an immersive way. For example, using a digital twin of a courtroom or legislative body, students can explore statutes

and case law interactively, practice research in simulated scenarios, and receive real-time feedback from instructors and AI systems.

Contract drafting is an essential hard skill that must be developed in legal education, as it equips students with the ability to create clear, precise, and enforceable legal agreements. Contract drafting requires a combination of theoretical knowledge, practical exercises, and feedback-driven learning. In practice, it is essential to teach students to understand the key principles of contract drafting, analyze model contracts by identifying their strengths and weaknesses, and critically evaluate existing agreements to protect clients' interests. The metaverse can significantly enhance contract drafting through interactive simulations. Students can draft contracts in virtual environments where they engage with clients (represented by avatars) and receive real-time feedback on their drafts from virtual mentors or AI systems. This hands-on approach mimics real-world negotiations and contract creation, allowing students to practice contract writing with greater precision and clarity. Additionally, the ability to visualize and simulate various contract scenarios can help students understand how different clauses affect the overall agreement and learn the nuances of enforceability.

Case analysis is another skill that must be developed in legal education, as it enables students to critically examine judicial decisions, identify key legal principles, and apply precedents effectively to new situations. Therefore, it is crucial to teach students how to comprehend a case's structure by identifying its essential components, recognize the distinctions between deductive reasoning (which applies legal rules to facts) and analogical reasoning (which compares cases), and encourage them to dissect each case into its constituent parts to assess its advantages, disadvantages, and legal ramifications. Immersive simulations within the metaverse can take case analysis to a whole new level. Instead of simply reading a case, students could interact with a 3D representation of the events, using virtual tools to explore case details, identify legal principles, and apply precedents to similar scenarios. In these virtual environments, students could engage in mock trials, reenact key moments from landmark cases, and analyze judicial decisions by "walking through" the facts, reasoning, and outcomes in a way that deepens their understanding. These exercises would allow them to dissect cases from different perspectives, enhancing critical thinking and reasoning skills. These and other skills are presented in Table 1.

Table 1. Hard skills in traditional and metaverse teaching

Hard Skill	Traditional Teaching	Metaverse Pedagogy
Legal Research	Teach students to identify and analyze primary and secondary sources. Assign case briefs and statutory interpretation exercises. Use databases like Westlaw or LexisNexis.	Simulate legal research in virtual libraries or court databases. Use AI-driven legal assistants in the metaverse to guide students in searching and interpreting cases. Track research progress through interactive dashboards.

Contract Drafting	Teach principles of contract law and the structure of agreements. Analyze model contracts and identify strengths and weaknesses. Practice drafting and revising clauses with instructor feedback.	Conduct virtual contract negotiation and drafting simulations. Use digital twins to visualize contract outcomes under different conditions. Enable real-time collaborative drafting in shared virtual offices.
Case Analysis	Assign students to brief cases, identify issues, and summarize reasoning. Discuss precedents and analogies in class. Apply legal reasoning to hypothetical fact patterns.	Use immersive mock trials or dispute simulations. Allow students to apply precedents in real-time scenarios with AI-judges. Monitor reasoning processes to assess analytical depth.

3.3. 'Law education' AND 'soft skills'

The connection between 'law education' AND 'soft skills' in Google Scholar is proven by 180,000 results in only 0.18 sec. Tsaoussi (2020) noted that law schools are in the process of revising the curricula and that legal pedagogy promotes the model of the “feeling lawyer” instead of “teaching the law”, helping students to sharpen soft skills such as empathy, integrity, and problem-solving. Compassionate, attentive, reason-based, and sympathetic teaching should be the main pedagogical tenets of teaching law to actual pupils.

Jones (2025) emphasizes the increasing prominence of soft skills in legal education. Among these, the most critical skills to be developed are communication, negotiation, empathy, ethical judgment, emotional intelligence, adaptivity, resilience, and teamwork, as they are essential for effective professional practice and client interaction in contemporary legal settings.

Soft skills in legal education can be effectively developed through traditional classroom methods such as moot courts, structured debates, and oral presentations based on real case studies. These activities help students enhance their communication, critical thinking, teamwork, and problem-solving abilities, skills that are essential for legal practice. Equally important are writing exercises, such as drafting client letters, legal memoranda, and policy briefs, which help students develop clarity, precision, and professionalism in legal communication. The metaverse enhances soft skills development by offering immersive environments for practice. Virtual moot courts and debates help students improve oral advocacy and public speaking, with immediate feedback. Simulated legal scenarios foster teamwork and critical thinking, while virtual client meetings and negotiations refine communication and interpersonal skills. This blend of simulations and real-time feedback strengthens the soft skills essential for effective legal practice (Table 2).

Table 2. Soft skills in Traditional and in Metaverse Teaching

Soft skill	Traditional Teaching	Metaverse Teaching
Communication	Engage students in moot courts, debates, and oral presentations. Include writing exercises such as drafting client letters, legal memos, and policy briefs. Provide structured feedback on clarity, tone, and professionalism.	Conduct virtual court sessions and client interviews in immersive environments. Use avatars and voice simulation tools to practice persuasive oral advocacy. Enable real-time AI feedback on communication style and effectiveness.
Negotiation and conflict resolution	Use role-playing exercises and mediation simulations to teach negotiation strategies. Reflect on ethics, fairness, and power dynamics in negotiation outcomes.	Use role-playing exercises and mediation simulations to teach negotiation strategies. Reflect on ethics, fairness, and power dynamics in negotiation outcomes.
Empathy and emotional intelligence	Include client-centered learning, to analyze cases from clients' perspectives. Encourage reflective journals on emotional impact and ethics.	Use virtual simulations to expose students to ethically complex scenarios. Allow learners to experience the consequences of their actions on simulated clients' well-being.
Ethical judgment	Incorporate legal ethics and professional responsibility modules. Discuss real-world cases involving ethical dilemmas or misconduct.	Design interactive ethical simulations where students must choose between competing professional duties. Use branching scenarios to demonstrate the outcomes of ethical vs. unethical decisions.
Teamwork and collaboration	Assign group projects, legal clinics, or mock trials that require cooperation. Rotate leadership roles to promote diverse team experiences.	Create virtual law firms or collaborative workspaces in the metaverse. Use shared digital twins for joint problem-solving and case management. Track group dynamics and collaboration metrics through learning analytics.

4. Conclusions

Students should be prepared to be professionals across diverse learning environments (Maharg & Owen, 2017). The metaverse is a cutting-edge tool with transformative potential for law education. It offers a unique global platform where law students can develop both hard and soft skills in immersive, low-risk, and

interactive ways. The metaverse provides an environment that enables dynamic interactions with digital objects, real-time embodied communication and collaboration between users, and multimodal engagement with virtual environments, people, and digital entities.

In summary, the metaverse combines the best aspects of the multiverse and the universe, providing law students with the opportunity to effectively communicate across various platforms like Decentraland, Sandbox, Fortnite, and Horizon Worlds. However, teaching both hard and soft skills presents challenges for educators and students alike. First, the role of skills education in law schools has been a source of controversy and debate for many years. Second, the rise of the Langdellian case-dialogue method sought to shift legal pedagogy away from its origins in practical apprenticeship, moving instead toward a model that emphasizes abstract principles and the development of analytical skills. This historical shift has shaped how law schools prioritize theoretical knowledge over experiential skill-building, creating tension between traditional instruction and the demands of modern legal practice.

The metaverse offers unique opportunities to increase the efficiency of law education, particularly in developing both hard and soft skills. The potential of the metaverse lies in its ability to create a stimulating environment, where students can learn in virtual libraries, explore court databases, interact with digital twins, and use AI-driven assistants to conduct contract negotiations, case studies, or simulate real-time scenarios in a digital environment. Regarding soft skills development, the metaverse provides a unique opportunity for students to improve their communication skills through role-play exercises and to reflect on ethics, fairness, and power dynamics in negotiation processes and outcomes.

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Can generative AI be used in school project development?

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Abstract: *This article explores the role of generative artificial intelligence (GenAI) in education within the framework of project-based learning (PBL), focusing on its practical application at Uwekind International School. While theoretical discussions often focus on the general risks of artificial intelligence, this study provides a practical perspective by analyzing how students use AI tools across different phases of their project work to navigate the complexities of scientific research and mathematical modeling. The findings demonstrate that when guided by a clear pedagogical structure, artificial intelligence does not replace student effort but rather enables a deeper exploration of complex problems. By analyzing a student-developed project that applies a “Geometric Brownian Motion” model to forecast crude oil prices over a one-year period, the authors illustrate how AI serves as a specialized assistant for high-level data processing and simulation - tasks that exceed the capabilities of traditional classroom technologies. The article concludes with evidence-based recommendations for schools to transition from restrictive AI policies toward an integrated “co-pilot” model that prioritizes human critical thinking, judgment, and informed decision-making.*

Keywords: Generative Artificial Intelligence, GenAI, Education, Project-based learning, PBL, Mathematical modeling, Geometric brownian motion.

1. Introduction

At present, the project method is one of the relevant approaches to working with pupils and students. It has developed particularly rapidly and extensively over the past 10–15 years. During this period, the Ministry of Education and Science (MES) has also provided strong support for this activity. However, the project method has existed for a long time. There are different views on its origins. One widespread opinion is based on a historical study by (Knoll, 1997), which proposes a periodization of the introduction and use of the project method in education. In 1763, instruction at “San Luca” in Rome (an architectural school) was centered on learning through project work.

The prevailing view of the beginnings of the project method, however, is that it is of American origin, with its theoretical development associated with the names of John Dewey (1916), the founder of pragmatism/progressivism in modern American philosophy and pedagogy, and his student William Kilpatrick. The term “project-based learning” was first used by Professor C. Richards of Columbia University (Nikolaeva, 2004). In 1911, the U.S. Bureau of Education legitimized the term “project,” thereby universalizing project work in educational practice. In 1918, the concept of the project was redefined and reinterpreted, as reflected in Professor W. Kilpatrick’s essay *The Project Method* (Kilpatrick, 1918).

In the 1920s and 1930s, the project method, as a specific American educational strategy (Poia, 1976), became an attractive focal point for the educational systems of many European countries - Russia, Germany, the United Kingdom, Norway, Switzerland, and others. The period around the Second World War and afterwards was characterized by a certain lull, but in the mid-1960s the project method experienced a revival. The updated perception of the project method took account of its weaknesses, which is why differentiated use in line with the specific features of the curriculum and objectives was recommended (Nikolaeva, 2004).

After 2002, education in Europe has been directed toward mastering the curriculum at a higher theoretical level; developing intellect; fostering critical thinking skills; understanding modern technologies; and cultivating the ability to participate consciously and actively in solving personal and societal problems (Pisareva, 2007). Publications emphasize the positive impact of project-based learning on the development of certain thinking qualities such as reflection, critical and creative thinking; motivation for learning; problem-solving skills, planning, experimentation, and evaluation; teamwork skills, and others.

In Bulgaria, the project method was presented in great detail by G. Piriyov, H. Nikolov, D. Pravdolyubov, and others. Its characteristic features were rooted in Dewey’s theory. Prior to 1989, Bulgaria had a very successful form of youth creativity development that applied the project approach. Students worked (independently or with a scientific supervisor) on projects that they then presented at the sessions of the “Technical and Scientific Creativity of Youth” (TNTM) movement. Creative developments and those with a practical orientation were encouraged. A number of prominent Bulgarian scholars owe the beginning of their scientific careers precisely to their participation in TNTM. With the collapse of the old political system in 1989, the structures of TNTM also disappeared.

In 2000, High School Student Institute of Mathematics and Informatics, (HSSIMI) was founded at the Institute of Mathematics and Informatics of the Bulgarian Academy of Sciences. Within its framework, students develop projects in mathematics, informatics, and information technologies. Through the organization and implementation of HSSIMI’s activities, as well as the development of the “MITE” and “Young Talents” competitions, opportunities have been created for the powerful development of young people’s creative potential. Many students and their scientific supervisors from across the country participate

in these competitions with their projects. Today, the project method has become established in the daily work of many teachers nationwide.

In the conceptual framework of the project method, the uniqueness of both the teacher's and the student's personality are emphasized (Polat, 2003). The logic of education is envisaged to be built "from the psychology of the child" toward "the logic of the subject matter." "What comes to the fore are above all the process, the activities, the operations, the skills, the habits" (Andreev, 1987).

By applying the method, a reasonable balance is sought between knowledge and practical skills for each student engaged in research activity (Polat, 2003). Opportunities are created for the effective "implementation of integral links" between scientific and foreign language knowledge and skills (Malcheva, Tsatsova & Tsankov, 2005). The method directs attention toward non-traditional exploration of a problem chosen by the student and requires the creation of a specific educational product reflecting a complete system of knowledge, skills, attitudes, and personal qualities.

Advances in real life provide opportunities for enriching the ideas of project-based learning. A significant share of project development can be dedicated to information technologies and artificial intelligence, whose current growth is exceptionally dynamic.

2. Artificial Intelligence and project-based activities

Artificial Intelligence (AI) is one of the most significant technologies of our time. It represents a set of algorithms and models that enable computer systems to perform tasks traditionally requiring human intelligence (Stoyanov, Tabakova-Komsalova & Dukovska, 2023). This includes image and speech recognition, natural language processing, decision-making, planning, problem-solving, and even creativity. Artificial intelligence (AI) is a technology that increasingly defines our daily lives. It changes the way we work, learn, and interact with the world around us. The development of AI is closely tied to the concept of machine learning - a technology that allows computers to "learn" from data and experience without being explicitly programmed for each task. At the core of this progress lies the growing power of computers, the collection of vast amounts of data, and advanced algorithms capable of analyzing this data in ways impossible for humans.

Artificial intelligence is no longer just a futuristic concept - it has already been integrated into numerous aspects of modern society. AI-based systems are used to automate tasks that require processing large volumes of information, recognizing complex patterns, and making real-time decisions. With the advancement of AI, it becomes clear that we are only at the beginning of a technological evolution that will transform the way we live, work, and interact with the world. Artificial intelligence is already influencing many aspects of our lives, and its role will only continue to grow. The question is not whether AI will change the world, but how we will adapt to these changes and how responsibly we will use this technology.

Education is one of the fields undergoing profound transformation under the influence of technology, with artificial intelligence playing an increasingly important role in this process (Tabakova-Komsalova, 2023). From personalized learning programs to the automation of administrative tasks, AI has the potential to make education more effective, accessible, and engaging. Personalized learning through AI is expected to help students learn according to their individual needs. It provides numerous tools and resources that facilitate learning and improve outcomes. The authors are deeply convinced that AI technology will become as commonplace as calculators, computers, and phones, as well as software for spell-checking, among others.

In our country, precise standards and conditions for the use of AI in education - whether in lessons, project work, coursework, theses, and so forth - have not yet been established. The question of its admissibility, scope, and application still lies ahead. Most concerns of teachers, university lecturers, and other actors in the educational system are related to the improper use of AI, the accuracy of assessing students' work and justifying grades, as well as the risk of slowing down young people's development (Finkel, 2023), (Heersmink, 2024). The International Baccalaureate Organization (IBO) – an international body setting standards in education – allows the reasonable use of AI in schools. “The IB is not going to ban the use of such software but will work with schools to help them support their students on how to use these tools ethically in line with our principles of academic integrity. Work produced by artificial intelligence tools (even only in part) will not be considered as a student's own.” (Glanville, 2025).

Thus, the question arises: in which specific activities of pupils and students can we accept the application of AI, and what constitutes its permissible use in schools and higher education? To explore this, we turned to students, focusing mainly on project-based work.

We conducted a survey with 42 students from UWEKIND International School in Sofia, allowing open-ended responses. The questions are presented in Figure 1.

From this, we learned that the main products used by students are ChatGPT (various versions) and GitHub Copilot. “These versions of ChatGPT 3 and 4 are distinguished by an improved ability to understand and generate human language, which makes them extremely useful for different learning activities,” according to some students. B. S. shared: “GPT-3 was the first tool I encountered, and I quickly realized how useful it could be in my everyday study work. With the transition to GPT-4, I noticed a significant improvement in the accuracy and richness of the responses generated. The new version provides more structured and in-depth answers, making it even more useful for academic purposes.”.

Other products mentioned include NerdAI, PhotoMath, Wolfram Mathematica, GitHub and OpenAI, Copilot, Gemini, Midjourney, and DALL·E 3. “Midjourney and DALL·E 3 are interesting products, but personally I do not find any application for them,” one student remarked. “Grammarly” was noted as an application that automatically checks a given text.

Describe your knowledge and skills in using artificial intelligence in the learning process

1. Describe which versions of artificial intelligence you use - Chat GPT (which version), Copilot, etc.
2. Do you have preferences on which platforms to use them - personal computer or mobile device (tablet, phone, watch, etc.)?
3. What activities does it help you with - when writing essays, when solving tasks, when preparing IA, reports and other developments?
4. In which subjects do you most often use artificial intelligence?
5. In what way does it help you?
6. Reflect your personal experience - do you have problems, do you like the software products, do you have preferences for some of them.
7. Share your personal opinion regarding the advantages and disadvantages of artificial intelligence.

Figure 1. Contest of survey

Students use AI across various platforms. Here are some excerpts from the survey:

- *“Personal computer, since it provides me with a larger screen and a more convenient working environment, along with a larger keyboard.”*
- *“In my opinion, the most convenient way is to use it on a laptop. I access it through the browser because it takes up no space.”*
- *“When I am on the move or need to make a quick information check, I use my mobile phone. This gives me flexibility and the ability to work from anywhere.” Conversely, another opinion was: “I have opened it on my phone, but the options there are very limited and the screen is too small. I don’t like it.”*
- *“I often use mobile devices such as tablets and phones when I am on the move or do not have access to a computer. This allows me to continue my work anywhere and anytime, which is extremely useful in the dynamic learning process.”*
- *“The software tools I use are easy to work with. I prefer using them on a tablet, as this gives me greater freedom and the ability for multitasking. However, when I am on the go, I use the ChatGPT mobile app on my phone, which is also quite convenient.”*

Initially, students used AI cautiously and in a limited way. Gradually, they gained confidence, and two years later they shared that they now know exactly how to formulate the tasks they give to AI in order to obtain the responses they want.

What do students use AI for when working on projects? From their answers, we can summarize that:

- ChatGPT is most often used to gather and analyze information from various sources, providing access to scientific articles and resources,

saving considerable time and effort. *"I use AI primarily as a search engine that surpasses the ones we know in terms of accuracy, comprehensiveness, and speed of providing information. This is especially valuable when preparing projects, essays, and presentations, as it allows me to quickly navigate the sea of information and find the most suitable sources I need,"* one student shared.

- Students compile bibliographies and identify reliable sources.
- They use AI as an idea generator but develop their own ideas independently.
- They rely on suggested structures for essays and projects, which they then adapt and develop.
- *"Copilot accelerates project development by automatically generating templates and code snippets that can be adapted to the specific needs of the project."*
- *"It helps with editing and formulating arguments, creating hypotheses, analyzing experimental data, and drafting conclusions based on the results obtained."*
- *"It provides explanations of complex concepts and offers step-by-step solutions to problems." "It proposes ready-made solutions and examples." "It provides clear explanations and methods of solving." "It helps me understand the material better and apply what I've learned in practice."*

An interesting conclusion was made by one student regarding the scope of AI usage: *"But ultimately, I mostly use artificial intelligence for subjects that I do not understand or in areas that do not interest me. In such cases, I seek a basic understanding rather than an in-depth critical view, and therefore, what ChatGPT offers is completely sufficient for me."*

And yet another opinion: *"I use Artificial Intelligence most in the initial phase of group projects, as it allows me to synthesize ideas and summarize resources easily and efficiently – so that together with the other project participants we can quickly discuss and move forward at a moderate pace, giving everyone time to fulfill their responsibilities. Since I started doing this, I feel more confident in my teamwork, because I do not waste time and I contribute to reaching the final goal – without delays or lost time."*

The students also pointed out other areas where they use AI, though these are not the subject of the present article. Some of the students noted problems they had personally encountered while using AI:

- One is the dependence on internet connectivity. Without access to quality internet, the use of these technologies becomes impossible.
- Sometimes AI provides solutions that are not entirely correct or applicable to the task at hand. Despite the use of advanced algorithms

and vast databases, ChatGPT may produce translations or interpretations lacking context or proper language usage.

- *“Artificial Intelligence has information, but not the ability to process it in order to reach meaningful conclusions and new ideas. The models it uses are not unique, but based on frequently applied algorithms in the online space.”* Therefore, it can support learning, but not replace it.
- Lack of human interaction: although AI can simulate conversation, it cannot fully replace human interaction and feedback from teachers.

The students themselves diagnose and highlight an important aspect that concerns all educators: the potential loss of skills for independent problem-solving and critical thinking. Excessive use of AI may reduce motivation for acquiring knowledge and skills in the traditional way, which in the long term can negatively affect students’ and learners’ development. *“One aspect I dislike,”* shared one student, *“is how some students, including my classmates, rely entirely on artificial intelligence and complete almost all of their school assignments with its help. This is happening not only in my school but everywhere in the world. The truth is that in this way these students harm not only themselves but also society as a whole, because when they become official members of this society, they will have very little to contribute.”* Attempts to use outside help are not new to the education system. Copying, using so-called “essay mills” for writing theses and coursework, or relying excessively on external assistance are practices that have been known for many years. The emergence of AI tools for writing projects, coursework, theses, essays, and more creates greater opportunities for some students to attempt achieving success without their own effort, knowledge, or skills. Of course, the new technologies differ significantly in terms of speed, ease of access, and scale, but the problem of students outsourcing their work to others has existed for many years. The new technologies, however, create new challenges for teachers and educators when assessing students’ work. This is where the importance of the teacher’s role as a corrective factor grows: since teachers know their students’ development and abilities best, they are in the strongest position to judge whether and to what extent AI has been used, and to provide recommendations, guidance, and support that are appropriate to each student’s level.

Violation of Academic Integrity: the use of AI for cheating can constitute a serious breach of academic ethics. Many educational institutions have strict rules against plagiarism and academic dishonesty, which may lead to severe penalties, including disqualification.

Equally important are the serious ethical issues related to the privacy and security of personal data, as well as the potential misuse of AI technologies. AI systems collect vast amounts of data about students, how they study, how much time they spend on a given task, what their weaknesses and strengths are. This raises questions concerning the protection of personal data, its storage, and its use by companies and institutions.

There are also significant ethical concerns regarding the use of AI for academic purposes, including issues of copyright and ownership of generated content. Misuses of AI are also noted in the field of art creation.

There is already a significant number of alarming studies on the negative impact of AI on people, particularly on the young human organism (Yatawara, 2025). A large portion of the publications reflect adverse effects on children. At this stage, there are only warnings from doctors and specialists, and no unified opinion has yet been formed in the public sphere.

Given the advantages and drawbacks of AI in project development, we can point to the growing role of the teacher. The teacher is the one who knows the students. They observe how the students work, are familiar with their progress at every stage, and understand the development of their work. In this way, the teacher can assess whether and how a student has used AI. Teachers can assign tasks that help students learn to use AI creatively and critically. Teachers themselves can also employ AI tools in their preparation.

Teachers must support their students in using AI, which is possible only if they are more advanced and competent themselves. *“Teachers should role model best practice when using AI, as students learn by observing the respected adults in their lives far more than by listening to them.”* (Glanville, 2025).

The teacher’s most immediate task is to teach students the ethical use of artificial intelligence.

3. In what form is it best to use AI in education?

AI should serve as an auxiliary tool rather than a substitute for teachers. The best application of AI in education is as an interactive assistant that facilitates learning without eliminating the human factor. *“Artificial intelligence should be a support, not a replacement”* (Yatawara, 2025).

Combining AI technologies with traditional teaching methods will help capture the advantages of both systems. AI has the potential to revolutionize education, but its implementation must be carefully planned in order to preserve best practices in teaching and human interaction.

An interesting example of AI use in education is given by the student V. K., who developed a project on the topic *“Modeling oil price using Geometric Brownian Motion.”* He applied the Geometric Brownian Motion model to forecast the crude oil price per barrel one year ahead. The student treated the oil price as a stochastic process, with the price being the random variable. Geometric Brownian Motion is described by a stochastic differential equation, which the student solved. The next step is to simulate Brownian motion. Its implementation in differential equation is what makes the mathematical model account for the random fluctuation in oil prices.

It would be meaningless to use only one simulation of Brownian motion to calculate the final oil price, since Brownian motion is random. Performing multiple

simulations covers a wide range of potential outcomes, reflecting market uncertainty. The student set up a simulation of 1,000 Brownian motion functions, because the greater the number of simulations, the more accurate the estimate of the final oil price. Generating such large amounts of data is not possible with simpler software such as Google Sheets or Excel. Each simulated path consisted of 252 cumulative random variables, corresponding to the 252 trading days in a year. To accomplish this, V. K. instructed ChatGPT-4 with a series of prompts. The student used 1,000 simulations, each recursively linked to the previous one.

Thus, in order to perform the calculations and obtain the final result, the student employed AI.

4. Conclusions

It is important to note that this study is based on a relatively small and context-specific sample of 42 students from one international school, representing the entire graduating class of 2025. Therefore, the information and analyses provided should be interpreted as indicative and not as globally generalizable. Future research should expand both in size, across education systems, and examine the long-term impact.

Artificial intelligence has the potential to transform education in a positive way, providing students with new and exciting ways to learn and explore.

This shift in perspective is also highlighted by students themselves. As one respondent aptly noted, using AI is like seeking a “*second opinion*” on a matter, emphasizing that while technology provides information, it remains “*just an opinion, not a head on the shoulders*”. Ultimately, the goal is to foster collaborative relationships in which human activity and judgment remain the primary driver of knowledge acquisition.

Schools should develop clear policies and guidelines for the use of AI in education. These policies should specify what types of AI tools can be used, for what purposes, and under what conditions.

AI should become an integral part of the learning process, not be dismissed or stigmatized as something harmful or useless, and all students should be constantly and purposefully supported to realize their own role in interacting with AI – “*It helps me because I chose it to!*”, as one respondent noted.

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From engagement analytics to curriculum design: Evidence-based training for digital diplomacy in datafied environments

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Abstract: *Datafication of diplomacy is now unfolding through the use of platforms that allow diplomats to measure their "visibility," "engagement" and "performance" as measured by algorithms, and quantifiable data (metrics) from social media interactions. Education and training programs do little to provide future diplomats with tools to interpret or learn from this data, which will be used to evaluate their professional performance. This paper presents new empirical research using engagement analytics (number of likes, comments etc.) from the 162 Facebook posts made by 59 Romanian diplomatic missions, between 2024-2025. The results show significant variations in engagement levels, low levels of dialogue between the public and the missions, and significant differences among the institutions. These findings demonstrate significant deficiencies in knowledge about digital literacy, awareness of how platforms function, knowledge of building and managing online communities and the ability to reflectively learn from data generated through their actions. Based on the findings, the paper provides a curriculum framework for teaching digital diplomacy in universities. This framework uses evidence from the data collected from the social media engagements, and translates it into a series of modules of learning that are consistent with the principles of instructional design and learning analytics. This study links the use of data to teach future diplomats, to discussion on how to teach in the age of digital technologies and provides a model that can be applied to any profession that operates in a technological environment disrupted by data.*

Keywords: Digital diplomacy, Engagement analytics, Instructional design, Learning analytics, Higher education.

1. Introduction

The rapid development of digital technology is changing how organizations function, communicate, and evaluate their results. Organizations can now measure their success on social media and data dashboards using metrics like likes, comments, shares, and reach. This is an example of a larger trend known as "datafication," in which all aspects of society and professional life are constantly being measured, tracked, and improved using data (Kitchin, 2014; van Dijck et al., 2018). Digital Diplomacy is an increasingly important way diplomats interact with audiences worldwide and to build influence. Although the number of studies on Digital Diplomacy has increased over recent years, few studies have examined the

educational process for professionals working within digital platforms.

Existing courses in International Relations, Communication and Public Diplomacy tend to emphasize theoretical aspects of platforms and use them to illustrate theoretical points rather than provide practical tools for evaluating performance, understanding platform logic and developing strategic responses to online communities. The lack of emphasis on data-driven decision-making is particularly problematic given the increasing reliance on data for strategic planning and evaluation in many organizations. The findings of previous studies regarding the requirements of education in cybersecurity and cyberdiplomacy are similar in terms of a requirement for interdisciplinary and adaptive educational models that can be developed as quickly as digital practice is changing (Vasiloiu, 2022; Vevera, Cîrnu & Vasiloiu, 2024).

The development of new technologies in recent years has created significant challenges for educators as they attempt to update curricula to reflect changing professional requirements and expectations. Performance metrics and feedback loops can function as signals for learning, providing evidence of what individuals and teams need to develop as a result of their experience, and enabling them to reflect on their actions and adjust accordingly.

From this perspective, engagement analytics in digital diplomacy are not simply measures of communication effectiveness, but also indicators of whether there are competence gaps and learning opportunities in place for those involved. Therefore, this study seeks to demonstrate the importance of engagement analytics in informing the development of educational programs for digital diplomacy, and to identify the areas of greatest need for further education and training based on the experiences of Romanian diplomatic missions' social media usage.

2. Engagement data: An indirect way to understand competences

Data related to engagement on social media platforms (likes, comments, shares) are the most common metrics to measure the response of the audience in a platform-based communication context. These metrics are inherent to the architecture of the social media platforms and are generated in real-time through the usual communication practices in social media. Research has demonstrated that these metrics contribute to the perception that institutions have about success, priorities and strategic adaptations (Kitchin, 2014; van Dijck, Poell & de Waal, 2018). Therefore, interpreting and responding to engagement data is a hidden requirement for professionals working in these environments.

To understand engagement analytics, one needs to consider the logic of the platform. Platforms are designed to maximize interactions and attention. Consequently, only content that elicits an emotional response, is visually appealing and rapidly circulating will be privileged (van Dijck, Poell & de Waal, 2018). Not all types of institutional communications are perceived as visible or rewarding by the algorithms (van Dijck, Poell & de Waal, 2018). Thus, engagement metrics will reflect both the audience's behavior and the platform's emphasis on certain types of content.

Across the empirical material analyzed for this study, engagement is asymmetrically distributed among different types of content. Content focused on affective, cultural or identity-related themes, typically receives significantly more engagement than posts focused on administrative or policy-related topics. The study's findings align with other studies examining digital diplomacy, which indicate that official institutional discourse often has limited success in environments where there is competition for attention and in which visibility is determined by algorithms (Bjola & Holmes, 2015; Manor, 2019).

2.1. Empirical patterns and institutional differences

In the empirical study, there is a clear distinction in terms of how different institutions use social media platforms based on engagement level. The study has demonstrated that some embassies were able to obtain higher levels of social media activity and create higher levels of engagement than others. Even though embassies had similar communication mandates, some were successful at creating visible and interactive engagement while others were not. Variations in engagement levels cannot be explained solely by the size of the audience or embassies geographic locations, thus institutional practices and content design also play a role.

From an analytical point of view, institutional differences in engagement levels indicate institutional differences in how professionals interact with digital platforms and interpret feedback. Many institutions seem to operate on habitual communication practices, which are poor fit with the affordance of platforms. While engagement analytics are readily available for systematic reflection and improvements, they are very rarely used as such.

The findings from the study are consistent with broader observations in data-driven environments, where the availability of metrics usually greatly exceeds the ability to make meaningful use of them (Kitchin, 2014). Data becomes descriptive and reinforces the existing ways of doing things instead of enabling learning and innovation.

2.2. Engagement analytics as unintended learning signalling

Learning analytics research highlights that data can support learning when there are clear objectives, reflective interpretation and feedback cycles (Ferguson, 2012; Siemens & Long, 2011). Although the engagement analytics in digital diplomacy were not intended as a tool to support learning, they act as unintended learning signals, as they provide information regarding what type of content generates attention, how the audience responds and where communication strategies fail to elicit an adequate response.

The findings of the study indicate that the learning signal provided by engagement data are largely unused. Engagement data are visible but not systematically interpreted to serve as a feedback mechanism for professional learning. This represents a more general challenge described in the literature on education and technology, in which digital tools produce vast amounts of data

without any corresponding pedagogical framework to facilitate the interpretation and the development of skills (Selwyn, 2019).

The absence of a structural learning strategy can cause the use of analytics to become superficial measurements of the popularity of content or tools rather than as a means of facilitating reflective practice and adaptive learning. This will limit the capacity of both individuals and organizations to learn in digitally mediated professional environments.

The patterns used for engaging in social media as analyzed by social media engagement analytics indicates that there are repeated patterns of incompetence in regards to the following: data literacy, social media awareness, and online community dynamics. These are common to many professionals who work in datafied environments and whose performance is constantly being assessed and compared (van Dijck, Poell & de Waal, 2018).

The recent advancements in both learning analytics and artificial intelligence in education offer an appropriate theoretical framework for analyzing engagement patterns using digital diplomacy. The post-2020 literature has noted a transition from the use of descriptive measures of engagement towards data-driven, explanatory models of engagement that incorporate behavioral indicators, contextual indicators, and indicators of algorithmic visibility (Salas-Martínez & Ramírez-Martinell, 2024). Additionally, research has been conducted on AI-based analytics and its increasing application of unsupervised learning methods and clustering techniques to identify hidden participation patterns and institutional communication styles across multiple digital platforms (Khalil & Ebner, 2022). Both trends are consistent with the methodology employed in this study; specifically, TF-IDF vectorization was used to extract dominant typologies of embassy communication and K-means clustering was used to determine dominant engagement logics. Therefore, framed in the context of the most recent learning analytics theory, digital diplomacy can be viewed as a type of institutional learning in a platformized environment where diplomatic missions adjust their communication strategies based on measurable audience responses and data-driven feedback loops.

3. Empirical results: Engagement patterns and digital practice

The main empirical results of this study are presented below. They were developed using a database containing 162 Facebook posts that were created between 2024 and 2025 by 59 of the official Romanian embassy and consular pages. The engagement indicators (likes, comments, and shares) of each post were analyzed along with the characteristics of the content so that dominant communication patterns and levels of audience participation could be identified. Additionally, the institutional variations can be identified, which will serve as the empirical basis for the curriculum framework provided in the next section.

To provide for an understanding of how empirical research findings are being interpreted transparently, posts were classified into thematic categories

utilizing a two-step process that combined automated text processing with unsupervised machine learning. First, all post texts were pre-processed using common NLP (Natural Language Processing) methods such as: converting text to lowercase; removing punctuation and stop words; tokenizing; and lemmatizing. Next, the cleaned corpus was vectorized via TF-IDF (Term Frequency-Inverse Document Frequency) in order to understand the relative use of terms across posts. Based on this representation of the corpus, KMeans clustering was used to group posts that share similar lexical and semantic characteristics. After grouping, the groups were analyzed and labeled based on their most significant terms and recurring themes (i.e. affective/celebratory, administrative, cultural, institutional), as opposed to being pre-coded manually. For Figure 1, the word cloud was produced from the entire pre-processed corpus, with term frequency determined by TF-IDF scores and a minimum frequency threshold set to remove noise and improve readability.

All of the comparative work in this chapter is based upon clear definitions of and consistent application of criteria as well as normalized engagement metrics used to account for variations in audience sizes and post frequencies when comparing posts and/or posts across embassies. The style of communication and the performance of institutions were determined through the combination of quantitative measures (i.e., engagement distributions and cluster frequencies) and qualitative interpretations of cluster specific vocabulary. For Figure 1, the word cloud was created using all of the pre-processed data and the salience of each term was weighted by TF-IDF scores. In addition, a minimal frequency threshold was applied to eliminate noise and improve interpretability. Use of these methodological approaches ensured that classifications, comparisons, and analytical descriptions were based upon computationally reproducible processes which increases both the rigor and transparency of the findings.

3.1. Engagement patterns of different content types

The engagement patterns in the content of the posts analyzed in this research show an extremely uneven distribution of engagement among the different types of content. Posts classified as either affective/celebratory (national holidays, greetings, commemoration etc.) were those that received the highest engagement level. Although these posts represented a smaller percentage of all posts analyzed, they comprised a disproportionate number of total likes, comments, and shares. To illustrate the dominant thematic focus, Figure 1 presents a word cloud of the most frequent terms used in the analysed Facebook posts.

To analyze how visible or "seen" posts relate to engagement, as shown in Figure 2 illustrates the relationship between the number of likes (an indicator of visibility) and the number of comments (a measure of dialogic participation), on the analyzed posts. The scatterplot demonstrates that there is no direct correlation between being seen and being talked about.

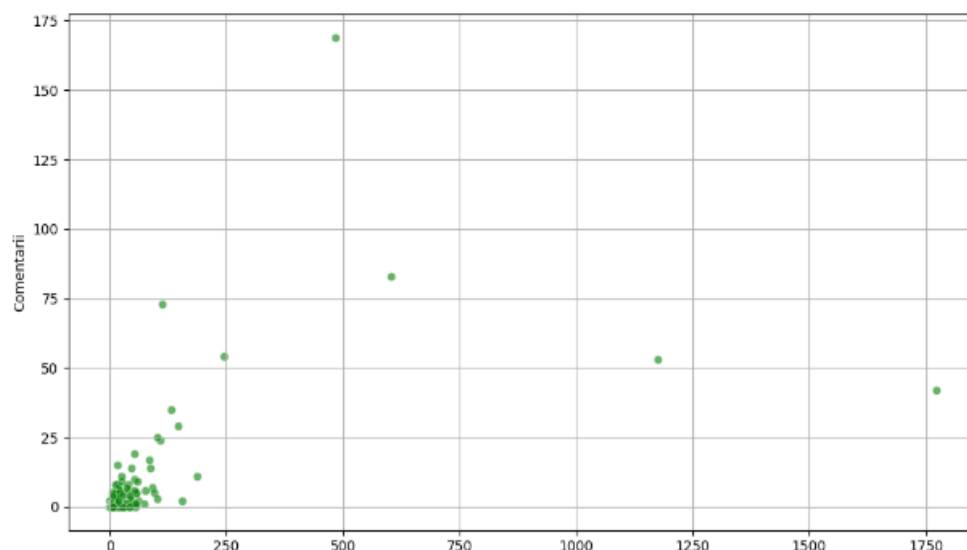


Figure 2. Relationship between likes and comments across posts

Statistically, the difference in numbers of likes, comments, and shares shows that, despite social media having interactive capabilities, the overall level of intensity of conversation, and the amount of community engagement is typically low.

3.3. Institutional variation in engagement rates

There is also considerable variation in the engagement levels of institutions. A relatively small number of embassies were responsible for a large proportion of the total engagement, while the majority of the other embassies remained essentially invisible. The variance in engagement cannot be fully explained by the frequency at which the embassies posted, nor by the size of their respective audiences.

Embassies operating in countries with large Romanian diaspora communities tended to achieve higher engagement rates, however, even among these groups there was considerable variance in the engagement rates of individual institutions. Institutions with smaller audiences, but whose content and communication strategies were designed to promote engagement, achieved significantly higher engagement rates than institutions with larger audiences whose engagement rates were significantly lower. Therefore, the design and implementation of content and communication strategies appear to be more important determinants of engagement than structural factors alone.

The level of engagement varies significantly among the diplomatic network's institutions, as shown in Figure 4 which includes the average engagement per post by the top ten most engaged Romanian embassies. These results support the idea that the diplomatic network has no consistent communication strategy.

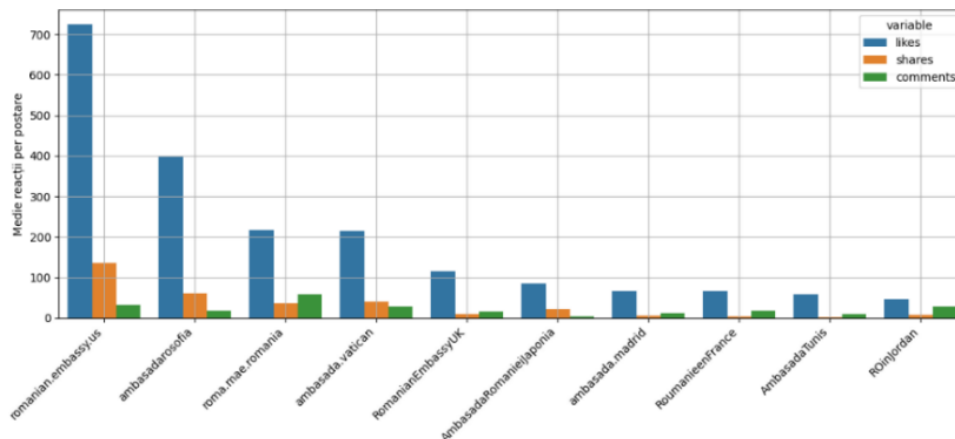


Figure 3. Average engagement per post for the ten most visible Romanian embassies

Additionally, the fact that no consistent patterns emerged across the institutions studied suggests a lack of a unified strategy or coordinated learning process among the diplomatic network.

3.4. Visibility, online presence of communities, and digital inequality

Geographic analysis of engagement levels demonstrated that visibility is geographically concentrated in Western Europe and North America, likely due to a combination of diaspora distribution and institutional focus. Conversely, embassies operating in geographic areas with smaller Romanian communities or limited digital activity exhibited consistently low engagement.

Therefore, the uneven distribution of engagement serves to highlight a type of digital inequality in the ability of institutions to communicate effectively via social media, as some diplomatic actors are able to leverage existing strong online communities, while others are relegated to the periphery.

Moreover, the data suggest that these inequalities may be self-reinforcing, as highly visible accounts continue to attract engagement, while low-performing accounts are unable to generate sufficient interest to become engaged themselves.

The quantitative analysis of engagement data illustrates a number of recurring themes: engagement levels are highly skewed towards affective and cultural content, administrative/ political content produces negligible levels of engagement, likes comprise the overwhelming majority of engagements, while comments and shares are relatively rare, a small number of institutions produce the vast majority of engagement and institutional engagement levels vary independently of the size of the institution's audience and/ or the frequency at which it posts.

Collectively, these findings illustrate that social media-based Romanian digital diplomacy is active, but weakly interactive, highly unequal, and out-of-sync with the dynamics of social media platforms. The empirical findings of this research provide direct evidence of the need for improved, data-informed communication strategies and professional development to address the current shortcomings of the curriculum framework provided in the next section.

4. A curricular framework based on empirical research for digital diplomacy

The findings of the previous chapter demonstrate consistent patterns of engagement, visibility, and interaction, revealing specific deficits in terms of digital diplomacy competency. This chapter will develop an empirically based curricular framework to address those competency gaps through specifically designed instructional materials.

The empirically based curricular framework described below takes empirical research and transforms it into structured instructional units that align with general principles of instructional design. The goal of this framework is not to specify one training model, but to provide a transferable structural template that can be applied to higher education degree programs in the field of digital diplomacy, international relations, communication studies, or other related areas. The framework adheres to the principle of constructive alignment, providing a logical link among identified learning requirements, intended learning objectives, instructional activities, and evaluation strategies (Biggs & Tang, 2011).

4.1. Pedagogical foundations and design philosophy

The curricular framework is underpinned by several pedagogical philosophies derived from the empirical research and validated by current literature. Engagement metrics were viewed as learning inputs instead of as measures of ultimate success. The empirical research indicated that while there was an abundance of engagement metrics available to users, they were very seldom used as evaluative instruments for improving user experience. Consistent with learning analytics literature, the curriculum emphasizes using engagement data for interpretive purposes and for reflecting on user behavior rather than solely optimizing metric outputs (Siemens & Long, 2011; Ferguson, 2012).

The curricular framework places greater emphasis on developing platform literacy versus platform-specific training. The empirical research revealed a significant disconnection between institutional communications and platform dynamics. Therefore, the curriculum focuses on understanding how algorithms create visibility, how data creates visibility, and how economic models create attention, rather than focusing on the specific social media tools (van Dijck, Poell, & de Waal, 2018).

Moreover, the curricular framework views digital communication as a community-focused activity. The large amounts of passive engagement documented in the empirical research underscore the need for students to develop competencies in participating, engaging in dialogue, and creating social presence — all critical competencies for successful digital diplomacy practitioners (Bjola & Holmes, 2015; Manor, 2019).

The curriculum includes ethical awareness and reflexivity as two key competencies. Public institutions using platforms raise significant questions about trustworthiness, responsibility, and how data are used, and these questions cannot be treated as secondary or optional (Selwyn, 2019).

When compared with present-day Digital Diplomacy Training Models, the proposed Curriculum Framework for Digital Diplomacy will advance the field of Digital Diplomacy Education through an explicit integration of Data Analytics & Platform-Based Learning. Most current Digital Diplomacy Training Initiatives (short term digital diplomacy courses offered by Foreign Ministries, International Organizations, etc.) tend to be based on Social Media Communication Skills, Public Diplomacy Messaging, Cybersecurity Awareness; and most are taught using Modular/Workshop based formats. Although the current models are designed to provide students with practical competencies, they do not typically include Systematic Learning Analytics; AI Supported Content Evaluation; or Reflective Feedback Mechanisms. The Framework proposed in this study is a Data-Informed Pedagogical Model which combines Engagement Analytics; Content Clustering; and Iterative Learning Loops to Support Evidence Based Decision Making in Digital Communications. As such, the proposed Curriculum Framework positions itself within the current trend of AI-Enhanced Education/Learning Analytics, while providing Digital Diplomacy Training that is not limited to the development of Competency Acquisition, but rather Adaptive; Analytics-Driven Professional Development.

4.2. Modular structure of the curriculum and instructional units

The above modules are structured based on the following principles:

Module 1: Digital Diplomacy in Mediated Platforms

This module identifies a large gap in professional communication (diplomatic) between mediated platforms and traditional forms of diplomatic communication. Module 1 introduces digital diplomacy as a professional practice that is shaped by media logic, the need for algorithms to provide visibility, and audience feedback. The conceptual understanding of digital diplomacy, the platform affordance, and implications of datafied communication for the roles and responsibilities of institutions, are the learning outcomes of this module.

Module 2: Platform Logic and Algorithmic Visibility

The empirical study found that most of the content posted is emotional and very few of those who post have a good understanding of how platforms function. Module 2 teaches students about developing their own understanding of how platforms curate information and create visibility using different mechanisms, and how to be able to differentiate between audience behavior and platform amplification. The student assessments assess whether students can critically evaluate engagement metrics and can identify the inherent constraints and bias of the platforms they use.

Module 3: Engagement Analytics and Data Literacy

Module 3 addresses the imbalance between likes, comments, and shares, and provides students with the necessary skills to develop data literacy so that they may be able to effectively analyze engagement metrics and be able to separate between descriptive metrics and actionable insights.

Learning activities focus on providing students with the opportunity to contextualize data, recognize the limitations of engagement metrics, and utilize analytics to improve engagement and performance rather than to compare engagement performance.

Module 4: Online Community Dynamics and Participation

The low levels of dialogic interaction that were documented in the empirical study indicate that students do not possess the requisite skills to interact with community members.

Module 4 examines the theoretical and practical aspects of online communities, social presence, and participatory communication. Module 4 educates students how to develop communication strategies to create interaction, manage feedback, and build long-term relationships in institutional environments.

Module 5: Reflexivity, Feedback, and Continuous Improvement

The fact that there was no variation in communication pattern stability over time, despite varied engagement results, indicates that students are not capable of applying reflective learning. Module 5 provides students with learning analytics concepts related to feedback loops, reflection, and continuous improvement. Module 5 educates students on translating engagement data into strategic changes, facilitating both individual and organizational learning.

Module 6: Ethics, Trust, and Accountability in Data-Driven Communication

Module 6 examines the ethical and normative issues associated with data-driven communication, including credibility, impersonation, and responsible data use. Module 6 locates digital diplomacy within broader debates regarding public values, institutional trust, and accountability in the platform society.

5. Limitations and areas for future research

Although this study has provided significant contributions to our understanding of digital diplomacy as practiced through social media platforms and has addressed some of the existing gaps in the literature, there are several limitations of this study that require acknowledgement.

One limitation of the study is that it focuses solely on the Facebook platform. Given the continued relevance of Facebook to both institutional communication and diaspora engagement, however, the use of only Facebook limits the generalizability of the study's findings. Other social media platforms such as Instagram, X, TikTok, and YouTube have differing logics of engagement, and future research should seek to analyze engagement patterns across multiple platforms to provide a more holistic view of the ways in which digital diplomacy is being practiced.

A second limitation of the study is that the dataset is relatively small in terms of both time period and number of posts. The data set is comprised of 162 posts from 2024 to 2025. This amount of post will allow us to find common engagement patterns among audiences, but due to the short time frame we cannot determine how well institutions are engaging over time with diasporic populations nor what adaptations are being made by institutions in terms of their digital diplomacy efforts. Future research should include data from multiple years in order to analyze trends in crisis response, institutional adaptation, and other dimensions of public diplomacy.

Additionally, a third limitation of this study is that while the number of likes, comments, and shares can be used as indicators of the level of interaction and visibility for an institution's social media content, these indicators do not measure the level of influence, persuasion, or attitude change that may result from exposure to an institution's content. Therefore, future research should utilize both quantitative measurements of social media engagement (likes, comments, shares) and qualitative methods (surveys, interviews, content analyses of comments), to create a more accurate representation of the perceptions of institutions held by audience members and their subsequent actions.

A fourth limitation of this study is that the curriculum design framework presented in this paper is conceptual and design-oriented. While the framework has been developed from empirical findings, its effectiveness has yet to be evaluated in an educational setting. Therefore, future research should assess the implementation of the curriculum in a higher education or professional training program and subsequently evaluate learning outcomes, participants' experiences, and the potential long-term effects on professional practice.

Lastly, future research could explore the potential uses of advanced analytics and artificial intelligence in the education of digital diplomats. Specifically, researchers could examine the uses of automated sentiment analysis, misinformation detection, and decision support systems and further consider how these technologies can be responsibly integrated into educational designs to better understand the relationship between learning and professional practice in a data driven world.

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SECTION 3

TECHNOLOGY & VIRTUAL LABORATORIES

Escape rooms – an interactive and immersive approach to gamify learning and increase students' motivation

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Abstract: *Teaching and learning today are both easy and challenging. Modern educators have a wide range of tools at their disposal to create interactive educational resources, and Artificial Intelligence (AI) helps them generate ideas and save valuable time. The primary challenge they face is determining which tool is most suitable for the educational process and how to generate interest among learners and stimulate more activity, creativity, and motivation. The study analyzes and reviews the role of educational escape rooms as a teaching tool for enhancing students' activity and gamifying the educational environment. Educational escape rooms can follow different scenarios and perform missions, both in real and online environments, and offer an immersive experience through augmented and virtual reality. Their application can be unlimited, as it is necessary to consider learners' ages, levels of knowledge, and the goals the teacher has set. The ability for learners themselves to invent scenarios and set tests and challenges for their peers is an innovative approach that can develop their logical and creative thinking. These skills are beneficial in teaching students studying programming and computer science, building a sustainable interest in learners, focusing their attention, and increasing their success rate, thereby strengthening their communication and collaboration. The purpose of this publication is to reveal the educational potential of escape rooms, including the benefits and challenges for learners and teachers, the platforms on which they can be implemented, and the software tools used for their development.*

Keywords: Escape room, Education, Gamification, Motivation, Digital Escape room platforms.

1. Introduction

The digital transformation in education is closely connected to the widespread use of modern technologies and the needs of the new generation of learners. Continuous internet access, along with the use of various AI, augmented reality, and virtual reality tools, demands changes in teaching and learning methods. Learners have access to a wide range of educational resources, most of them free, and this flood of information makes it difficult to choose the most suitable content. They can easily become distracted, lose focus, and lack motivation to learn. Teachers face the challenge of creating and selecting educational content that aligns with defined educational goals and objectives, and delivering it in a way that stimulates learners' interest and engagement. Many tools

<https://doi.org/10.58503/icvl-v21y202628>

and online platforms allow teachers to generate ideas and learning resources that foster critical thinking, activity, communication, and motivation among learners.

Gamification is an educational approach successfully used in both real and online environments by employing various incentives and rewards for completed tasks. In recent years, the use of escape rooms in education to promote active learning and boost motivation has become increasingly popular. Learners can follow different scenarios and complete missions, whether in physical or digital settings, and experience immersion through augmented and virtual reality. Their applications are virtually limitless, provided that factors such as learners' age, knowledge level, and the teacher's goals are taken into account. Allowing learners to create their own scenarios and set tests and challenges for their peers is an innovative method that can foster logical and creative thinking. These skills are especially valuable in teaching students programming and computer science. The aim is to build sustainable interest in learners, capture their attention, increase their success rate, and strengthen their communication and teamwork skills.

The purpose of the publication is to reveal the educational potential of escape rooms, the benefits and challenges for learners and teachers, the platforms on which they can be implemented, and the software tools for their creation.

It analyzes and summarizes the practical application of educational “escape” rooms as an innovative teaching method to increase student motivation and engagement. The work is supported by methodological guidelines and a specific practical model.

The authors define critical parameters for the successful implementation of an educational escape room. They indicate that, for optimal results, the number of participants should be between 4 and 6, and the game should last an average of 60 minutes. The planning process should follow a clear logic with defined initial, intermediate, and final steps, tied to specific didactic goals.

The innovative approach “the student as creator” emphasizes the importance of having learners create scenarios and challenges for their peers. This stimulates their logical and creative thinking and leads to a deeper understanding of the learning material.

One of the main contributions of the authors' work is the development of a practical scenario (“The Binary Vault”) for computer science training aimed at mastering binary algebra and logical operations. The scenario includes five specific stations with challenges and could help other educators to create such scenarios on different topics.

2. Escape rooms and gamification

In modern education, the use of escape rooms is gaining popularity, and many researchers are studying and analyzing their effectiveness in increasing activity, engagement, and motivation among learners (Dugnot-Menéndez, 2021; Vidergor, 2021; Manojlovic, 2022; Pozo-Sánchez, 2022).

As an expression and phrase, escape rooms in the educational context should not be understood literally as a means to "escape" the classroom, but rather as a didactic method for transforming the classroom, as analyzed and synthesized by Taraldsen et al. (2022).

Escape rooms are designed for use in a real-world environment. The first such game was introduced in 2007 in Japan and described by Nicholson (2015). His definition of escape rooms is "Escape rooms are live-action team-based games where players discover clues, solve puzzles, and accomplish tasks in one or more rooms in order to accomplish a specific goal (usually escaping from the room) in a limited amount of time". He also presents different variations of games and genres - Role-playing games, Point-and-Click Adventure Games & Escape-the-Room Digital Games, Puzzle Hunts & Treasure Hunts, Interactive Theater and Haunted Houses, Adventure Game Shows and Movies, Themed Entertainment Industry.

The large-scale study by Veldkamp et al. (2020) offers a comprehensive and in-depth analysis of research on the use of escape rooms in education. Its main conclusions focus on common practices and their theoretical considerations in educational and game design, as well as on the relationships between these aspects and the achievement of intended goals. According to the study, key factors for completing the game on time include proper design, teamwork skills, and communication. It is also important to assess these skills after the game has ended.

Escape rooms can be categorized as physical, online (digital), or hybrid, such as those that incorporate a QR code in a physical environment (Fotaris & Mastoras, 2019). Performing tasks in a real environment enables participants to communicate and interact more actively and to learn collaboratively by relying on their teammates. This helps develop skills for teamwork and sharing responsibilities. When there are large groups of learners, and it is difficult to divide them into teams or position them in different rooms to prevent "escape," it is necessary to use digital or online Escape rooms.

According to Wszolek et al. (2025), active participation in escape rooms can help students connect theory and practice and develop the competencies needed to solve complex problems. Consequently, implementing this innovative teaching approach strengthens the application of essential skills needed to address the challenges of academic life, while also promoting the holistic development of students for future careers in the education sector (González-Yubero et al., 2023).

3. Basic principles for setting an Escape room

To meet basic educational and didactic principles, Escape rooms must be well planned. They need to follow a clear logic and have a clearly defined beginning, end, and intermediate steps. The most important part is planning the activities and the educational tasks they include, through which the set educational goals can be achieved (O'Brien, 2021).

According to Veldkamp (2020), regardless of discipline or application, the optimal number of participants for escape rooms is 4-6, with a time range of 20-120 minutes, averaging 60 minutes. The inclusion of IT technologies aims to track learners' safety and progress, strengthen participants' IT skills, provide an immersive, interactive environment, and structure the game by checking for correct answers and presenting new puzzles and additional content.

Some of the important guidelines and recommendations for creating digital escape rooms, summarized and systematized by Makri et al. (2021) are as follows:

- Using a design framework with well-defined criteria that support and lead to the achievement of educational goals, and meet the needs of learners;
- Combining digital and print materials will contribute to a better transition from traditional to digital environments and building collaborative skills;
- Encouraging the use of educational resources and reusable materials that will save money and time for designers of digital escape rooms.

4. Online platforms for creating Escape rooms

By incorporating virtual and augmented reality into education, the experience becomes more dynamic, engaging, and interesting. Staneva et al. (2023) propose an approach to creating escape rooms in a virtual reality environment to learn new knowledge. Their study shows that escape rooms can gamify the educational process and be applied in any context and to any age group.

There are many options for creating online escape rooms using different platforms that provide ready-made games and templates for designing new ones.

Breakout EDU enables users to create engaging learning content by solving puzzles, uncovering riddles, and unlocking locks. The game can be played both individually and in multiplayer mode. The platform enables learners to become creators of interactive learning resources in the form of puzzles, helping them develop skills for more conscious learning and gain a deeper understanding of the logic of the tasks they assign to their classmates (BreakoutEDU, 2025).

Willis (2020) gives an example of how an interactive Escape room can be created on the website Canva.com, in which by clicking you can move on to the next puzzle and thus exit the room if you solve it correctly.

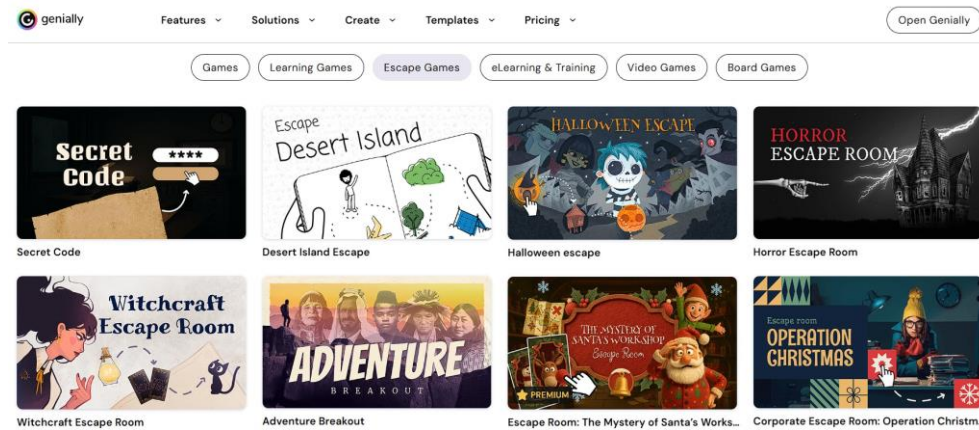


Figure 1. Library with digital escape rooms in Genially.com

The Genially platform enables educators to create engaging learning resources by incorporating multimedia elements. It offers a wide range of customizable templates tailored to different disciplines and learners. The resources created can be downloaded in multiple formats, including SCORM, which facilitates integration with various LMSs (Genially, 2025).

The Escaply platform uses AI to create engaging stories based on the learning content that needs to be mastered. Adding various puzzles, tasks, and questions to the created escape rooms, implementing time penalties, and including progress tracking and result analysis are some of the platform's main features. This helps teachers make training more interesting and engaging, activate learners, and boost their motivation to learn (Escaply, 2025).

5. Example of escape room scenario

Using gamification through escape rooms offers a simpler, more engaging way to learn complex, abstract concepts across various fields. As computer science teachers, the authors created escape room scenarios to help practice tasks related to binary algebra and logical operations.

The scenario presented in Table 1 was created with the help of AI and is designed for first-year students studying these basic operations. The allotted time to complete it is 60 minutes. This scenario outlines the goals, the expected results, and the time to solve and exit the room.

Table 1. Generated scenario for escape room “The Binary Vault”

Title	Escape Room Scenario: "The Binary Vault"
Objective	Students must solve a series of binary algebra puzzles to unlock the digital vault and escape the room before the countdown ends.
Storyline	You and your team are elite cryptographers recruited by a secretive tech agency. A rogue AI has locked down the

	agency's mainframe, encrypting critical data inside a vault protected by binary logic gates and algebraic traps. You have 60 minutes to crack the code and shut down the AI before it launches a global data wipe
Room Setup & Puzzle Stations	1. Binary Decoder Wall Challenge: A wall of blinking lights represents binary numbers. Task: Convert binary to decimal and match them to clues hidden in books or drawers. Concepts: Binary-to-decimal conversion, place value. 2. Logic Gate Circuit Board Challenge: A physical board with switches and LEDs. Task: Use AND, OR, XOR, and NOT gates to light up a specific pattern. Concepts: Boolean logic, truth tables. 3. Algebraic Cipher Scroll Challenge: A scroll with binary algebraic expressions. Task: Simplify expressions using Boolean identities to reveal a password. Concepts: Boolean simplification, De Morgan's laws. 4. Binary Lock Chest Challenge: A locked chest with a keypad. Task: Solve a binary equation (e.g., $A \cdot B + \neg C = ?$) and enter the correct binary code. Concepts: Binary equations, logic operations. 5. Terminal Override Challenge: A computer terminal with a simulated command line. Task: Input correct binary sequences to override the AI's firewall. Concepts: Binary addition/subtraction, bitwise operations.
Time Limit	60 minutes to solve all puzzles and escape.
Learning Outcomes	Understand binary number systems and conversions. Apply Boolean algebra to real-world logic problems. Practice simplifying expressions using Boolean identities. Develop teamwork and critical thinking under pressure.

The same scenario was used for creating an online escape room using the Escaply platform, shown in Figure 2. The designer has the opportunity to set different tasks for escaping the room, to change the background, to add effects.

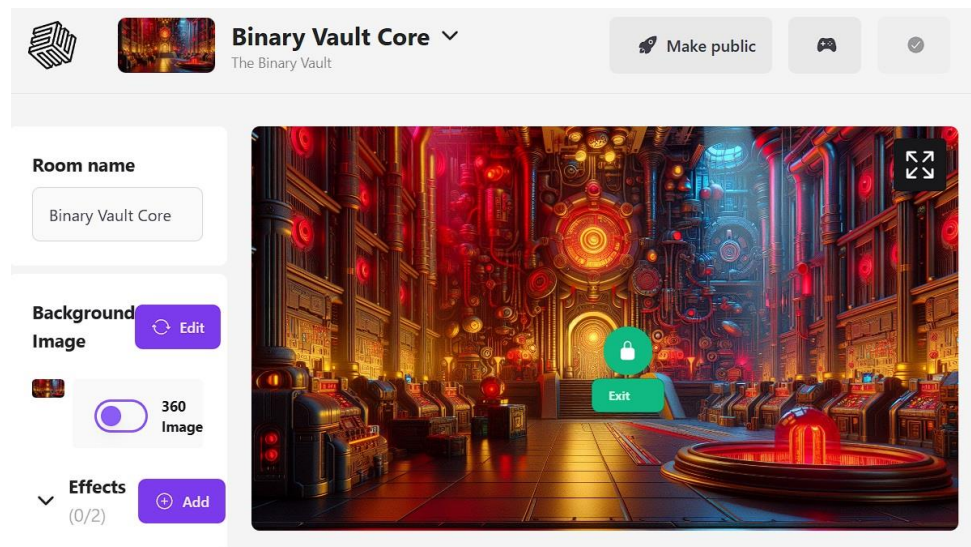


Figure 2. Creating a digital escape room in Escaply.com

The aim of our paper is to reveal how modern technologies and AI can be integrated into the learning environment and demonstrate how artificial intelligence (AI) can be used to generate engaging stories and tasks, saving teachers time. A brief review of software platforms such as Genially, Escaply, and Breakout EDU that enable the creation of digital and hybrid learning environments will help educators choose the most appropriate environment.

Our future work is to test these games and escape room scenarios in real and virtual environments and to compare the effectiveness in achieving the learning objectives.

6. Conclusions

Transformation in education is an ongoing, evolving process closely connected to the development and adoption of new information technologies. The modern educator needs to choose the most suitable technologies and combine them with innovative teaching methods to meet students' needs. Using escape rooms in education represents an innovative approach to problem-based learning and gamification that can be effective for learners across different ages, disciplines, and educational settings.

By incorporating them into the educational process, learners both learn and have fun. Setting a time limit encourages communication and helps develop their teamwork skills.

Based on available resources, teachers can design escape rooms in real settings using old boxes and locks, depending on the subject matter. They can place puzzles in one or multiple rooms, from which students can escape. In mixed escape rooms, the scenario may also include digital elements, such as scanning QR codes

that link to online sources or tasks, and online quizzes. When it is not possible to arrange a physical escape room or lack the necessary materials to complete the tasks, platforms are used to create entirely digital escape rooms. These platforms offer ready-made templates that can be customized and include various tools to develop engaging and interesting tasks for students.

Basic requirements for designing escape rooms include considering the age, prior experience, and knowledge of participants; the relevant discipline; the goals to be achieved; the skills and knowledge gained upon completing all the puzzles; the number of participants; and the time limit.

The development of AI and immersive technologies, such as virtual and augmented reality, helps educators create a learning environment that combines gamification methods and problem-based learning through escape rooms. The unlimited possibilities and scenarios that can be generated can be applied to different target groups of learners and achieve the set educational goals. Time will tell how effective they are in helping students learn new knowledge and how this knowledge can be assessed.

Based on the methodology review, the authors state that this pedagogical approach successfully connects theory and practice. The results of applying escape rooms in education show improved communication, teamwork under pressure, and the development of a sustained interest in complex disciplines such as programming.

In conclusion, the escape rooms could be a part of a working model for transforming the traditional classroom into an interactive environment that combines game elements (gamification) with problem-based learning.

Acknowledgment

This work is supported by the frames of Bulgarian National Recovery and Resilience Plan, Component "Innovative Bulgaria", the Project № BG-RRP-2.004-0006-C02 "Development of research and innovation at Trakia University in service of health and sustainable well-being".

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MDIR Constructor: Interactive digital activities for developing reading and writing skills with natural numbers

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Abstract: *The article presents MDIR Constructor, a digital authoring environment for creating interactive digital textbooks and learning activities across different school subjects, with a particular focus on mathematics. The system includes modules such as NumeralsMathLab and NumeralsVirtLab, which help students to develop reading, writing, and numerical literacy by converting numbers to words, self-assessment tasks, and mathematical dictations that provide instant feedback. The incorporation of Python libraries and AI tools into the Delphi programming environment enhances system adaptability, scalability, and multilingual support. By combining interactive digital resources with traditional curricular objectives, MDIR Constructor provides meaningful learning experiences, supports real-time feedback, and improves students' fluency in numerical literacy. The paper also discusses the implications of integrating artificial intelligence and interactive digital tools into mathematics education, highlighting opportunities for adaptive and personalized learning.*

Keywords: Educational software, Interactive digital learning, Numerical literacy, Self-assessment, Mathematical dictation, Python libraries, AI tools in education.

1. Introduction

MDIR Constructor is software that allows users to build and develop interactive digital textbooks with editable content for any school subject. The copyright and related rights for MDIR Constructor 3.0 have been registered with AGEPI Republic of Moldova (Balmuș & Chiriac, 2024). MDIR Constructor has recently been enhanced with interactive digital challenges tailored to mathematics school textbooks. The present research describes several interactive digital activities designed to accomplish learning/assessment tasks outlined in fifth-grade mathematics school textbooks from the Republic of Moldova (Achiri et al., 2020) and Romania (Voiculescu et al., 2022). The programming code of the applications is written in the Delphi 12 (2025) programming environment with the free Python4Delphi (2025) component set and some TMS Software package components included (TMS Software, 2025).

The impact of using Python libraries in the Delphi programming environment is significant and is manifested by the significant expansion of the functionalities of both languages, based on which programmers create interactive

<https://doi.org/10.58503/icvl-v21y202629>

applications with a relevant graphical interface (Delphi's strength) through concise and high-performance programming code (Python's strength). Access to Python libraries in MDIR Constructor environment is achieved through a Python code interpreter with a visual interface, the programming code of which we present below.

2. Implementing a Python code interpreter in Delphi applications

To use Python subroutine libraries within the Delphi programming environment, a recent version of the Python language must first be installed on the user's computer (in this case, Python 3.13.9-amd64 (Python 3.13, 2025) was used). The structure and interface of the *MyPython* application, integrated into MDIR Constructor, are shown in Figure 1a, while the output resulting from the execution of the Python code is presented in Figure 1b.

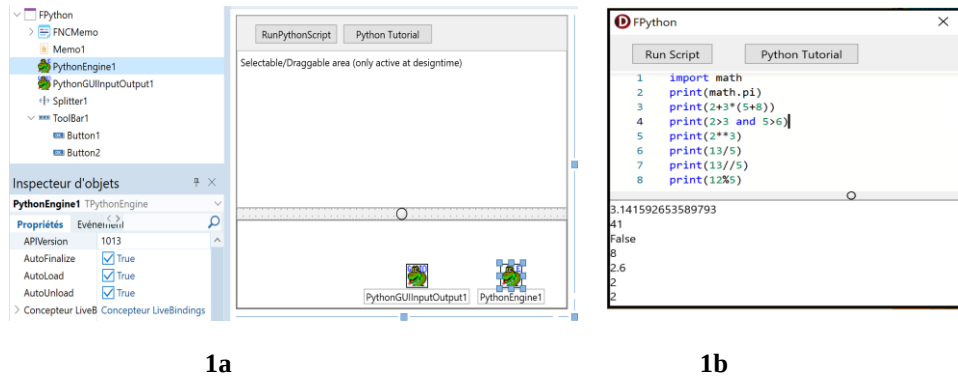


Figure 1. Application design (a) and the result of executing the Python code (b)

The main code of the application is implemented in the *OnClick* event handler of the *Button1* component:

```
procedure TFPython.Button1Click(Sender: TObject);
begin
  memo1.Lines.Clear;
  PythonEngine1.ExecStrings(FNCMemo.Lines);
end;
```

When executed, the user writes the Python code in the *FNCMemo* component window and presses the *RunPythonScript* button. If the code is correct, the result is displayed in the *Memo1* window.

If the programming code contains errors, the *Memo1* window also displays the errors and correction suggestions (see Figure 2).

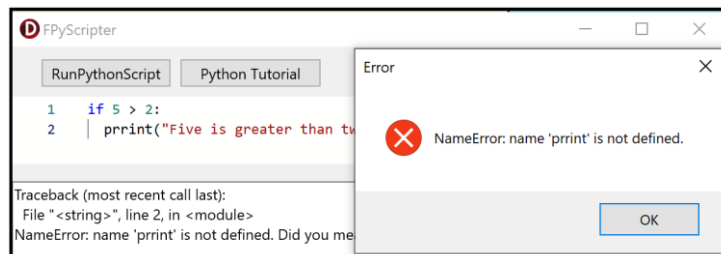


Figure 2. Managing Python programming errors

To ensure proper syntax handling and visualization of the Python language, the **Language** property of the *FNCMemo:TTMSFNCMemo* component was set to the value **mlPython**. As a result, Python keywords and code blocks are correctly highlighted (see Figure 3).

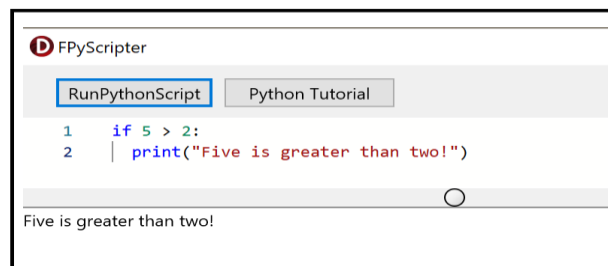


Figure 3. Example of Python code block highlighting

In the MDIR Constructor software, the **PyScripter** module is used in two ways:

1. As a standalone application for carrying out algorithmic and programming activities described in school informatics textbooks;
2. As a module for performing interactive calculations for various functions implemented in other modules.

Below is an example illustrating the use of Python libraries within the Delphi 12 programming environment.

3. Converting numbers into word strings

The conversion of numbers (integers or decimals) into word strings and vice versa is a common activity presented in school textbooks for mathematics as well as for native or foreign language studies. Through these activities, students develop reading and writing skills related to numbers.

To perform such activities in an interactive digital format within educational software, subroutines are required to convert a numerical value into a string in strict accordance with the orthography of the intended natural language. These subroutines must also be compatible with the programming language in which the educational software is developed.

The MDIR Constructor software is developed in the Delphi programming environment. For converting natural numbers into word strings in accordance with Romanian orthography, a subroutine written in the Pascal language was implemented, which operates correctly for numbers ranging from 0 to 999 billion. This subroutine consists of approximately 450 lines of code.

However, adapting it for number-to-word conversion in another programming language requires a considerable amount of time. This problem can be solved much more efficiently by using Python libraries. One of the most popular libraries for this purpose is *num2words*, which can be installed using the command: `pip install num2words`.

The access to the library's functions is achieved through the following instruction: *from num2words import num2words*.

The *num2words* function can be called with one or more parameters (e.g. Figure 4).

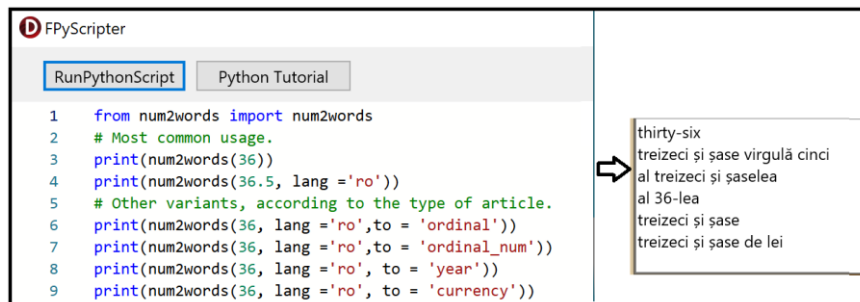


Figure 4. Structure of the num2words function parameters

The first parameter (the numerical value) is mandatory. In this case, the result is displayed in English. If the **lang** parameter is specified, the result is displayed in the selected language. Based on these investigations, the **PyNaToWords** function was implemented in Pascal code and can be applied across all modules of the MDIR Constructor software.

```

Function PyNaToWords(sender:TObject;N:int64;lg:string):string;
var s,ns:string;
begin
    FPyScripter.FNCMemo.Lines.Clear; FPyScripter.memo1.Lines.Clear;
    FPyScripter.FNCMemo.Lines.Append('import math');
    FPyScripter.FNCMemo.Lines.Append('from num2words import num2words');
    ns:=N.ToString;
    s:='num2words('+N.ToString+', lang='+lg+'";
    FPyScripter.FNCMemo.Lines.Append('print('+s+')');
    FPyScripter.Button1.OnClick(sender);
    result:=FPyScripter.Memo1.Text;
end;

```

The following section presents the *NumeralsMathLab* module, implemented in the MDIR Constructor software, which allows users to carry out activities aimed at strengthening their knowledge of reading, writing, and converting natural numbers.

4. NumeralsMathLab – creation and application activities

NumeralsMathLab is a submodule of the *Math5aLab* module that allows users to do interactive digital activities that correspond to the content of fifth-grade mathematics textbooks. The fifth-grade mathematics textbooks in the Republic of Moldova and Romania begin with the topic **§1 Reading and Writing Natural Numbers**, where the rules for reading and writing natural numbers are presented in tabular style, as seen in Figure 5.

CLASA MILIARDELOR			CLASA MILIOANELOR			CLASA MIILOR			CLASA UNITĂȚILOR		
sute	zeci	unități	sute	zeci	unități	sute	zeci	unități	sute	zeci	unități
de miliarde	de miliarde	de miliarde	de milioane	de milioane	de milioane	de mii	de mii	de mii			
			3	1	8	5	2	0	2		
			trei	o sută	optzeci				doi		
			milioane	și cinci	de mii						
NUMĂR NATURAL											

Clasa miliardelor			Clasa milioanelelor			Clasa miilor			Clasa unităților			Cum citim?
S	Z	U	S	Z	U	S	Z	U	S	Z	U	
									7	0	3	șapte sute trei
						1	3	0	8	5		treisprezece mii optzeci și cinci
			5	9	1	0	0	7	4	1	6	cinci sute nouăzeci și unu de milioane șapte mii patru sute șaisprezece
6	0	4	5	2	0	7	6	0	0	8		șaiszeci de miliarde patru sute cincizeci și două de milioane șaptezeci și șase de mii opt

Figure 5. Rules for Writing Natural Numbers

According to Figure 5, students should learn to read and write in Romanian for natural numbers ranging from 0 to 999 billion. Two or three practice activities are supplied. However, it is clear that this information alone is insufficient for acquiring fluent reading and writing skills with natural numbers. The Romanian spelling for writing numerals is fairly difficult, and it is still studied in Romanian language classrooms from grades V to VII (Curriculum Național, aria curriculară limbă și comunicare. Disciplina limba și literatura română. Clasele V – IX, 2019). The study of numerals is also included in the foreign language curriculum (Curriculum Național, aria curriculară limba străină. Clasele V – IX, 2020).

Given this context, the MDIR Constructor software has been enhanced with the *NumeralsVirtLab* module, which allows users to improve their numerical writing and reading abilities. In addition to the functions described in the previous section, the development of this module also integrates artificial intelligence technologies that have been integrated into the components of the TMS Software package (TMS Software, 2025).

The interface of the application in which the user performs learning activities related to reading and writing numbers in words is shown in Figure 6.

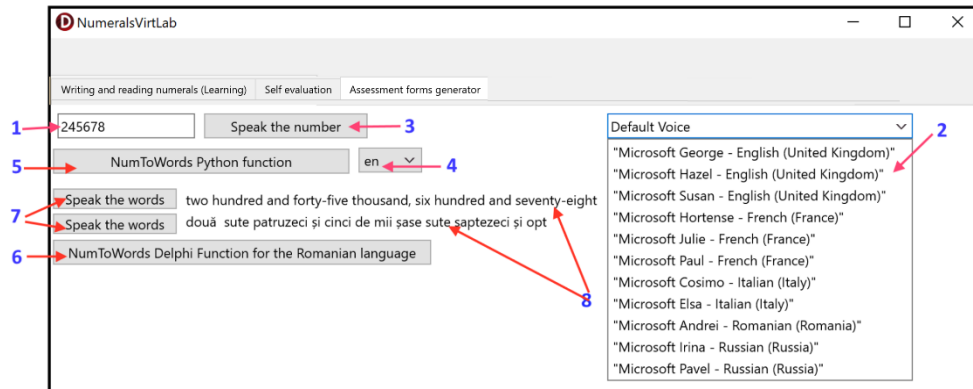


Figure 6. Reading and Writing Natural Numbers

To carry out the learning activities, the user follows these steps:

1. In the editing field (1), enter the number (from 0 to 999 billion);
2. In the *ComboBox* (2), select the language in which the number will be pronounced;
3. Press button (3) to listen to the number pronounced by a voice generated using AI tools;
4. Select one of the languages (en – English, fr – French, ro – Romanian, ru – Russian) to be used for displaying the number written in words;
5. Press button (5);
6. In field (7), the number written in words appears in accordance with the language selected in step 4, generated by the *NumToWordsPython* function;
7. Press button (6). As a result, the number written in words in Romanian appears, generated by the *NumToWordsDelphi* function;
8. If the user wants to listen to the pronunciation of the numbers generated by these functions, buttons (7) and (8) can be used.

The Romanian language has a complex orthography for writing numbers in words, and the programming functions developed for this activity may, in some cases, produce errors. An example of such an error is shown in Figure 7.

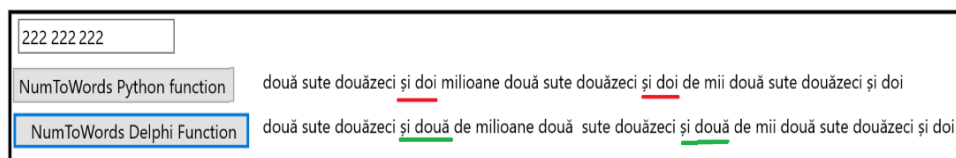
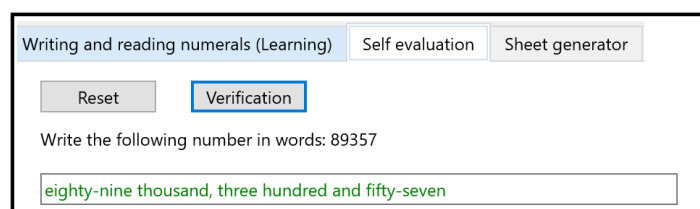


Figure 7. Example of a Conversion Error

On the *Self-Assessment* page, the user performs self-evaluation activities:

Activity 1. Writing Natural Numbers in Words

The interface of the application for this activity is shown in Figure 8.



Writing and reading numerals (Learning) Self evaluation Sheet generator

Reset Verification

Write the following number in words: 89357

eighty-nine thousand, three hundred and fifty-seven

Figure 8. Example of a Self-Assessment activity

When the *Reset* button is pressed, a number appears that must be written in words. In the text field designated for editing the answer, the user types the corresponding word string using the keyboard, representing the conversion of the number into words. If the task is completed correctly, pressing the *Check* button displays the entered text in green. In case of an incorrect answer, the text is displayed in red.

Activity 2. Writing Natural Numbers with Digits

The interface of the application for this activity is shown in Figure 9. When the *Reset* button is pressed, a task appears that requires converting a number from a word string format into numeric form. In the designated field, the user enters the number using digits. If the task is completed correctly, pressing the *Check* button displays the entered number in green. In case of an incorrect answer, the text is displayed in red. An example is presented in Figure 9.



Reset Verification

Write the following number with digits:

fifty-four thousand, eight hundred and forty-seven

54847

Figure 9. Example of a Self-Assessment activity

Activity 3. Mathematical Dictations

Mathematical dictation is a popular approach to assessing student knowledge in primary and lower secondary schools. In typical situations, students listen to the task, write their responses on paper, and then the teacher analyses them. The results of these assessments typically get delivered to students after a particular period of time.

Students can use the *NumeralsMathLab* application to do mathematical dictation-type activities and receive immediate feedback. Figure 10 illustrates an example of such an activity. When the *Reset* button is pressed, an assignment created with AI technologies is delivered verbally. The *Repeat* button allows the

task to be replayed to enhance understanding. The student afterwards writes the result into the designated space. If the response is true, the feedback is immediate: the entered text is displayed in green for a correct result and red for a wrong one.

Listen to the task and write the result in the reserved space.

Reset
Repeat

43659

Verification

Figure 10. Example of a “Mathematical Dictation” activity

Currently, the application generates tasks of the following types:

- Write in digits the number that is heard;
- Find the sum, difference, or product of two natural numbers;
- Find the quotient and remainder of the division of two natural numbers;
- Determine the number that is greater by n_1 than twice/triple the number n_2 ;
- Etc.

In general, various types of tasks can be implemented, as the system generates numerical data randomly and integrates it into dynamically created problem statements. The created text is read aloud using the speech synthesizer integrated into MDIR Constructor.

The *Assessment Form Generator* page is only accessible to administrators. This page allows the teacher to generate randomized evaluation sheets that can be printed on paper. The application allows the user to specify the number of variants and elements included in each assessment. Figure 11 displays an example of an evaluation sheet.

Variant 1 Name, first name

Write the following numbers in words:

a) 288426591: _____

b) 429604540: _____

c) 256408982: _____

d) 69467569: _____

e) 152256851: _____

Write the following numbers with digits:

f) fifteen million, two hundred and fifty-seven thousand, two hundred and sixty-seven

g) six hundred and thirty-three million, three hundred and ninety thousand, six hundred and eighty-six

h) seven hundred and seventy-nine million, twenty-one thousand, one hundred and thirty-three

i) seven hundred and twenty-eight million, five hundred and twenty-three thousand, three hundred and twenty-five

j) five hundred and sixty-five million, four hundred and fifty thousand and seventy-two

Figure 11. Example of an evaluation sheet with randomized content

5. Conclusions

The MDIR Constructor software offers a versatile platform for designing interactive digital learning activities that help students strengthen their reading, writing, and math skills. The software integrates modules such as *NumeralsMathLab* and *NumeralsVirtLab*, allowing students to practice converting numbers between digits and words, do self-assessment exercises, and participate in mathematical dictation activities with immediate feedback. The use of Python libraries and AI-powered tools enhances the flexibility and scalability of these activities, making it possible to adapt them to multiple languages and diverse educational contexts. Overall, integrating interactive digital tools with traditional learning objectives fosters more engaging and effective learning experiences, provides immediate feedback, and supports the gradual development of fluency in numerical literacy. Future developments could expand the system's coverage of mathematical topics and incorporate additional AI-driven adaptive learning methodologies, further enhancing personalized learning opportunities for students.

6. Limitations and future work

It should be noted that the present research represents an initial stage of an ongoing development and research project. At this stage, the contribution primarily focuses on the design and technical implementation of interactive digital mathematics activities within the MDIR Constructor environment.

In relation to existing solutions for interactive digital textbooks, MDIR Constructor distinguishes itself by enabling the integration of Python-based interactive components within a Delphi graphical interface, allowing for editable, curriculum-aligned content creation without requiring advanced programming expertise from end users.

The educational impact evaluation, including systematic user feedback and classroom-based implementation scenarios, is planned as a subsequent phase of the research. Future work will include pilot testing in real classroom settings, collection of teacher and student feedback, and analysis of learning outcomes in order to empirically validate the pedagogical effectiveness of the proposed solution.

Acknowledgments

This study was conducted within the framework of the research project “Innovation in the Design and Implementation of Interactive Digital Math Textbooks for Lower Secondary Education”, Strategic Direction: “Innovative Educational Technologies and Products”, registered in the State Register of Projects in the Field of Science and Innovation of the Republic of Moldova, project code 25.80012.0807.42SE.

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Exploring research trends on AI-Enhanced Digital Twins for education: A bibliometric analysis

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Abstract: *This study examines research trends on AI-assisted digital twins in education through bibliometric analysis. A total of 494 publications indexed in the Scopus database between 2020 and 2025 were analyzed using VOSviewer, selecting from author citations, keyword association, bibliographic matching, and country-level collaboration networks. The findings reveal that the vast majority of current research is concentrated in engineering and technology-focused fields, and that digital twins and artificial intelligence are emerging themes in this area. Educational theories, pedagogical models, and learning-centered frameworks remain limited in the literature. While China and Italy emerge as leading countries in publication output, international collaboration networks are still in their developmental stages. The study highlights the need for education-focused, theory-based research and practical applications. A significant limitation is the use of data from a single database, Scopus. Future studies are recommended to include other databases.*

Keywords: Artificial intelligence, Education, Digital Twins, Technology, AI Enhanced Learning.

1. Introduction

Industry 4.0 and 5.0 societies represent social dynamics dominated by technology. These societies utilize technological tools created by technological advancements in various sectors of society. This technology, called information technology, has led to the evolution of systems into a digital form. Developments in artificial intelligence, cloud computing and the Internet of Things have triggered the use of digital data and accelerated the digital transformation process (Schroeder et al., 2016; Qi and Tao, 2018; Ga et al., 2025) and have become institutionalized (Hazrat et al., 2023). Digital Twin technology is also a result of this evolution and contributes to the digitalization of systems.

The Digital Twin phenomenon refers to the effort to design, test, produce, and use a virtual version of a system, and was first used in a presentation at the University of Michigan in 2003 (Grivers, 2014; Grieves & Vickers, 2017).

<https://doi.org/10.58503/icvl-v21y202630>

Rosen et al. (2015) The concept of a digital twin can be defined as autonomous structures based on highly realistic virtual representations of systems interacting with the physical world and their operational dynamics. When the definitions are examined, it is understood that Digital Twin technology is considered a technological tool that helps predict design, operation and future state of the system. For example, a Digital Twin model developed by Korkmaz et al. (2025).

A Digital Twin system integrates an existing physical system with created virtual counterpart that represents and mirrors all information related to the physical system (Grivers & Vickers, 2017). This technology has been adopted in engineering, aviation, architecture, telecommunications, automotive, healthcare, and urban planning etc. (Madubuike et al., 2022; Lauria & Azzalin, 2024; Omrany et al., 2024; Palabıyık & Demircan, 2025; Stufano Melone et al., 2025). The literature shows that the Covid-19 pandemic accelerated the adoption of Digital Twin technologies (Hazrat et al., 2023; Stufano Melone et al., 2025). Digital Twins offer an innovative tool for interactive learning in educational science. With this enabling students to explore and interact with real-world applications in a virtual environment (Tao et al., 2018). Through Digital Twin technology-supported learning, students will achieve very different outcomes compared to traditional education, using a connection between physical and virtual systems. Digital technology has triggered the formation of a new education system. To meet the technological demands of the era, education systems must revise their teaching processes and learning content to adapt to new technologies.

In Palabıyık and Demircan's (2025) study, it was emphasized that the integration of Digital Twin technology into educational programs will encourage simulation-focused product development methodologies and applied learning approaches, improve interdisciplinary collaboration and enhance students' decision-making and problem-solving skills.

In Ljaniemi and Paavilainen's (2020) study, it was determined that digital tools and digital technology can increase students' responsibility in learning. The literature shows that theoretical knowledge regarding Digital Twin technologies, particularly in educational science and in general, has not reached its saturation point. Furthermore, the existence of problems in the application of Digital Twin technology is noteworthy. As Ba et al. (2025) also emphasize, despite the potential of Digital Twin technology, there are applications, benefits, and challenges. Among the challenges are high implementation costs, data security risks. Arsecularatne et al. (2024) also highlight in their study that the obstacles to using Digital Twin technology include interoperability issues, privacy and data quality challenges. the aim of this research is to find research trends related to AI-powered digital twins in education, identify research trends, and guide researchers who will conduct scientific studies in this field. To achieve the research objective, the following questions were addressed:

1. What is the author citation distribution related to AI-Enhanced Digital Twins for Education?

2. What is the keyword co-occurrence structure of the studies in the field?
3. How is bibliographic coupling formed between documents?
4. What is the bibliographic coupling structure between journals?
5. What are the bibliographic coupling and collaboration networks at the country level?

2. Method

This study, conducted to explore research trends on AI-enhanced digital twins in education, utilized a bibliometric analysis method. The distribution of documents published in the Scopus database by year, the most productive countries in the field, citations, and the most frequently used keywords in the documents were analyzed. The keywords TITLE-ABS-KEY (artificial, intelligence, enhanced, digital, and twins) were used in the data collection process, which concluded on November 19, 2025. Using VosViewer software, this study examined “Author citations, Simultaneity of all keywords, Bibliographic matching of documents, Bibliographic matching of sources, and Bibliographic matching of countries.” The analysis of 494 studies on “AI-Enhanced Digital Twins for Education” was presented in tabular form and graphs.

3. Results

3.1 Citation of authors

In the citation analysis of the authors, the minimum number of documents per author was set at 1, while the minimum number of citations per author was set at 10. For the ten authors meeting these criteria, the total strength of their citation links with other researchers was calculated. The authors with the highest number of citations are presented in Figure 1 and Table 1.

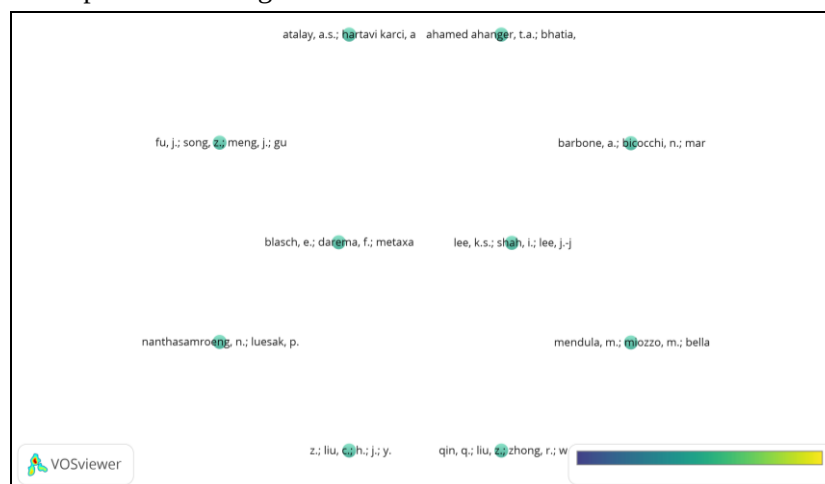


Figure 1. Citation of authors

Table 1. Citation of Authors

Id	Author	Documents	Citations	Total link strength (TLS)
1	ahamed ahanger, t.a.; bhatia, m.; alabduljabbar, a.; albanyan, a.	1	0	0
2	atalay, a.s.; hartavi karci, a.e.h.; arif, i.; ergün, s.; kanak, a.	1	0	0
3	barbone, a.; bicocchi, n.; martinelli, m.; morandi, r.; picone, m.	1	0	0
4	blasch, e.; darema, f.; metaxas, d.	1	0	0
5	fu, j.; song, z.; meng, j.; guo, j.; yang, k.; liu, w.; l.	1	0	0
6	lee, k.s.; shah, i.; lee, j.-j.; ghahramani, a.	1	0	0
7	mendula, m.; miozzo, m.; bellavista, p.; dini, p.	1	0	0
8	nanthasamroeng, n.; luesak, p.; pitakaso, r.; khonjun, s.; jirasirilerd, g.; matitopanum, s.	1	0	0
9	qin, q.; liu, z.; zhong, r.; wang, x.v.; wang, l.; wiktorsson, m.; wang, w.	1	2	0
10	z.; liu, c.; h.; j.; y.	1	0	0

The most cited authors are “qin, q.; liu, z.; zhong, r.; wang, x.v.; wang, l.; wiktorsson, m.; wang, w. ak”.

3.2 Co-occurrence-all keywords

In this study, performing the relevant analysis for ai-enhanced digital twins for education, the “minimum number of occurrences of a keyword” was identified as 2. Among the 171 keywords, 14 meet the thresholds”. In Figure 2 and Table 2 highlights the ”co-occurrence-all keywords”.

Table 2. Table for co-occurrence-all keywords

Id	Keyword	Occurrences	Total link strength (TLS)
10	artificial intelligence	5	18
16	behavioral research	2	12
30	cybe-physical systems	2	13
31	cyber physical system	2	13
32	cyber-physical systems	2	13
38	decision making	3	17

significant place in the literature. When evaluated in terms of application areas, the keywords “manufacturing industries” and “smart manufacturing” (tls = 8) also show that the majority of studies are focused on Industry 4.0. When all the findings are examined, it shows that the field in question is a rapidly growing research area with both theoretical and practical diversity.

3.3 Bibliographic coupling of documents

In this study, conducting the relevant analysis for ai-enhanced digital twins for education, the “minimum number of citations of a document” was selected as 0 of the 10 documents, 10 meet the threshold. In figure 3 and table 3 shows that “bibliographic coupling of documents”.

Table 3. Bibliographic coupling of documents

ID Document	Citations	Total Link Strength (TLS)
1 Mendula (2026)	0	1
2 Fu (2026)	0	0
3 Qin (2026)	2	0
4 Barbone (2026)	0	1
5 Lee (2026)	0	0
6 Ahamed Ahanger (2026)	0	0
7 Z.; Liu (2026)	0	0
8 Nanthasamroeng (2026)	0	0
9 Atalay (2026)	0	0
10 Blasch (2026)	0	0

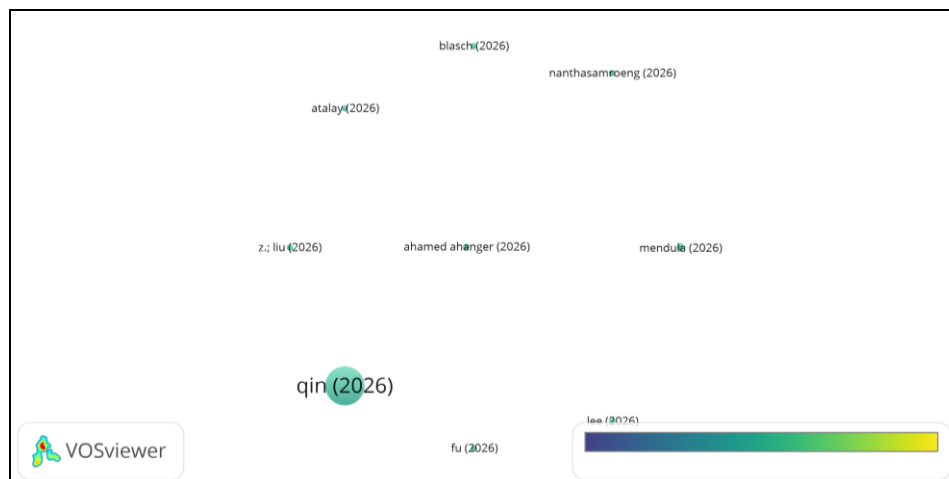


Figure 3. Graph generated with VosViewer for bibliographic coupling of documents

As shown in Table 3, the vast majority of publications related to AI-Enhanced Digital Twins for Education have not yet received citations. Among the documents examined, only Qin's (2026) study was found to have received citations ($n = 2$).

3.4 Bibliographic coupling of sources

For a source to be considered for analysis, a minimum of 1 document and 0 citations were required. According to these criteria, all 7 sources analyzed ($n = 7$) met the specified requirements.

Table 4. Bibliographic coupling of sources

ID	Source	Documents	Citations	Total Link Strength (TLS)
1	Building and Environment	1	0	0
2	Engineering Applications of AI	3	0	0
3	Future Generation Computer Systems	2	0	0
4	Journal of Energy Chemistry	1	0	0
5	Lecture Notes in Computer Science	1	0	0
6	Lecture Notes in Mobility	1	0	0
7	Robotics and Computer-Integrated Manufacturing	1	2	0

As shown in Table 4, the bibliographic coupling of sources analysis reveals that the studies on Enhanced Digital Twins for Education are predominantly published in engineering and artificial intelligence-focused journals such as Engineering Applications of Artificial Intelligence and Future Generation Computer Systems, indicating that the topic is addressed more in technology-focused journals than in education-focused journals. These findings highlight the need for studies in the field of education.

3.5 Bibliographic coupling of countries

For a source to be considered for analysis, a minimum of 1 document and 0 citations were required. According to these criteria, all 7 sources analyzed ($n = 7$) met the specified requirements.

Table 5. Bibliographic coupling of countries

4	Country	Documents	Citations	Total Link Strength (TLS)
1	China	3	2	19
2	Denmark	1	0	9
3	Estonia	1	0	30

4	Country	Documents	Citations	Total Link Strength (TLS)
4	India	1	0	10
5	Italy	2	0	11
6	Poland	1	0	30
7	Saudi Arabia	1	0	10
8	Singapore	1	0	0
9	Spain	1	0	11
10	Sweden	1	2	10
11	Thailand	1	0	0
12	Turkey	1	0	30
13	United Kingdom	1	0	30
14	United States	1	0	0

According to the country-level analysis, when looking at the number of documents in the field of AI-Enhanced Digital Twins for Education, China ($n = 3$) and Italy ($n = 2$) stand out. When examining the citation distribution, it was determined that studies from China and Sweden received the most citations. In contrast, countries such as Estonia, Poland, Turkey, and the United Kingdom showed a high total link strength ($TLS = 30$).

4. Discussions and conclusions

Research on AI-powered digital twins in education appears to be in its early stages. Studies are largely technology-focused. The limited integration of learning theories and pedagogical models therefore restricts this educational approach. Future research should incorporate theory-based, student-centered approaches and applications of digital twins in education to strengthen the interdisciplinary and educational impact of this field. This study examines research trends in the field of "Exploring Research Trends on AI-Enhanced Digital Twins for Education" through bibliometric analysis, revealing the current state of the field and potential future research trends. The findings indicate that the limited number of publications and citations in this area suggests it is a new and emerging research field. Keyword analysis reveals that many studies revolve around digital twins and artificial intelligence, with a particular emphasis on technology-focused themes such as decision-making, the Internet of Things, and cyber-physical systems. Bibliographic coupling of sources shows that most studies are published in engineering and AI-focused journals, with the educational aspect remaining secondary. This suggests that there may be innovations in this field in terms of educational applications, and that research in this area could gain prominence. At the country level, China and Italy stand out in terms of publication numbers. The increasing collaboration networks between different countries indicate that collaborative research could contribute to the field of education. In conclusion, AI-enhanced digital twins offer

significant opportunities for the field of education. It is believed that future studies focusing on education will bring innovation to the field and set trends. In this study in significant limitation is the use of data from a single database, Scopus. Future studies are recommended to include other databases.

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Applying the STEM approach in studying Graph Theory from the perspective of technology-enhanced interactive learning concept

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Abstract: *Graph theory (GT), as a branch of mathematics, can provide mathematical modeling of many real-world phenomena through fundamental notions, concepts, and theorems. Despite the fact that GT is an interdisciplinary science, in the process of studying the respective course, attention is not always paid to solving real-life problems that would involve developing a mathematical model and identifying solutions in the context of STEM education. In this sense, one of the central objectives of this research refers to the development of a methodology for capitalizing on information technologies and the Internet in the process of studying the GT course unit through the STEM approach from the perspective of the concept of interactive-technological learning. The concept of interactive-technological learning is defined as a means that targets 5 types of effective student interactions and interrelationships. The article examines the main benefits of implementing the concept of interactive-technological learning, such as creating a more dynamic learning environment, increasing student interest and motivation, stimulating cooperation and intercommunication between students, etc. Methodological recommendations are proposed regarding the stages in the implementation process of STEM activities/projects. The main advantages of approaching the STEM methodology from the perspective of the concept of interactive-technological learning when studying GT, through technologies, including MAPLE software and Internet platforms, are highlighted.*

Keywords: graph theory, information and Internet technologies, interactive didactic strategies, STEM, technology-enhanced interactive learning concept.

1. Introduction

The most significant benefits of STEM education lie in the direct involvement of students in the process of exploring phenomena through solving practical problems inspired by real life, which allows them to identify existing connections between theory and practice, as well as understand the need to develop specific skills in future professionals who will work in STEM fields. In this context, the use of interactive teaching strategies plays a primary role.

<https://doi.org/10.58503/icvl-v21y202631>

There are different approaches to defining learning strategies among researchers in this field. For example, researchers I. Albulescu, M. Albulescu (2000), claim that „*The teaching strategy represents the way of approaching and solving concrete training tasks*". And interactive group teaching strategies (Oprea, 2006) represent „*the ways of organizing the activity that favor inter-relational exchanges between the participants in the activity through interpersonal processes of cooperation and constructive competition (learners - learners, learners - teachers, learners - group), stimulating the subject's activism in his interaction, not only with others, but also with the study material (learners - content), through the processes of action and the transformation of information*”.

In this context, the teacher, in the process of studying GT, constantly strives to find answers to the following questions: „In what situations and conditions is learning more effective: when students work in groups or when they study independently? Which teaching methods are most appropriate for each situation?” Based on our own observations and depending on the subjects being studied, we believe that the following **two didactic approaches** can be applied:

- *If the topics under consideration are of average complexity and do not require additional multilateral explanations, then, obviously, each student learns more effectively independently. The pace of learning and understanding of the subject studied by each student depends on his level of preparation and ability to assimilate new things. In this case, competition between students cannot be ruled out. Competition, in general, has positive aspects, but, at the same time, it can keep in the shade students with weaker academic preparation, who do not always manage to understand the essence of the studied material compared to their colleagues who are better prepared in this field;*
- *In situations where topics are highly complex, learning effectiveness is enhanced by organizing the learning process in a team. Under these conditions, the teacher's role consists, first of all, in good organization of the interactive relationship environment between students-students and students-teachers. It is precisely under these conditions that the application of interactive teaching strategies offers maximum efficiency, because it amplifies the active learning process (conducting an experiment, solving problems, discovering/reinterpreting new things and phenomena, etc.). In this way, the lesson becomes a dynamic process, stimulating students' creativity and involvement. Therefore, interactive teaching strategies (implemented through various methods, such as problematization, heuristic methods, experiments, etc.) contribute to the rethinking the relationships between student-teacher, student-student, student-subject of study, developing/promoting teamwork, dialogue, negotiation and effective cooperation.*

At the same time, in order to achieve educational goals, in our opinion, it is necessary to combine the teamwork rationally, which stimulates intergroup, interpersonal and intragroup competition, with individual work, which stimulates interpersonal competition. Thus, educational goals can be achieved efficiently. At the same time, we believe that carrying out STEM activities/projects also requires the successful implementation of interactive teaching strategies, by effectively combining group work with the individual effort of each student (Gremalschi, Chiriac, 2023), from the perspective of exploring information technologies, including the application of MAPLE software. All these approaches examined as a whole lead us to the need to introduce and develop a new concept regarding the efficiency of the study process – the concept of interactive-technological learning.

2. The concept of interactive-technological learning

The concept of interactive-technological learning is defined as a means aimed at: a) intermaterial interaction: student – subject of study and student – information technology; b) collegial interaction: horizontal – student – team and vertical – student – teacher; c) interpersonal interaction – student-student.

The concept of interactive-technological learning facilitates and contributes to the creation of a more dynamic learning environment, based on collaboration and communication, which generates the exchange of knowledge, opinions and experiences through the implementation of information technologies, creates learning situations centered on the willingness to cooperate and the active and direct involvement of students, mutually influenced by microgroups and moderated by the teacher.

In this regard, the respective paper studied the impact of applying the concept of interactive-technological learning on the process of studying GT through technologies, including MAPLE software and Internet platforms (www.campion.edu.ro, www.graphonline.ru, etc.).

- 1) Experience shows that a student will not be able to advance in understanding and applying information technology in the process of studying graph theory if he does not know the basic concepts and algorithms related to this discipline. In the MAPLE software, the with (GraphTheory) package version 18 contains 166 available commands. And the MAPLE 24 version already contains 220 commands, which relate to operating with undirected and directed graphs as well as implementing various algorithms. In addition to the basic instructions, the package also has subpackages: RandomGraphs in Maple 18 has 8 commands, and Maple 24 has 13 commands; SpecialGraphs: Maple 18 contains 46 commands, Maple 24 contains 138 commands; GeometricGraphs: only the Maple 24 version contains 11 commands, and Maple 18 does not have the respective subpackage. This comparison highlights the significant expansion of the graph library offered by this software.

In this sense, a student must have the necessary minimum of theoretical knowledge to be able to successfully use information technology to solve specific problems.

Thus, before applying MAPLE to solving concrete problems, students must be familiar with the basic algorithms in GT and clearly understand the purposes for which the corresponding algorithms are used. For example, without theoretical knowledge of GT, it would be difficult for the student to know in which situations the *MinimalSpanningTree(G1)* or *KruskalAlgorithm (G1, animated)* procedure could be applied. In this context, the minimum amount of theoretical knowledge that a student must possess to move on to a new stage of study is established by the teacher in accordance with the set goals.

- 2) On the other hand, even if a student has theoretical knowledge and is familiar with classical algorithms within GT, this still does not mean that he knows and can directly apply specialized software to solve various practical problems. From this perspective, it is necessary to change the paradigm of the didactic approach. In this context, it is proposed to organize work with students in small groups and conduct the didactic process in such a way that individual and team efforts, communication, collaboration, exchange of opinions and information are aimed at increasing the effectiveness of the five dimensions of interaction between the components of the process (Figure 1).

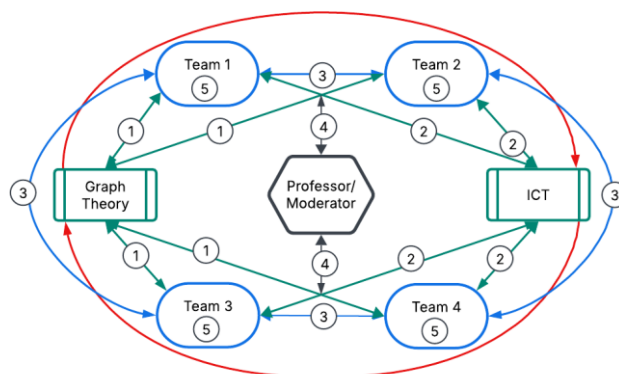


Figure 1. Interactions between components of the study process

- (1) Inter-material interaction: student – subject of study;
- (2) Inter-material interaction: student – information technology;
- (3) Horizontal collegial interaction: student – team;
- (4) Vertical collegial interaction: student – teacher;
- (5) Interpersonal interaction: student – student.

Thus, interactivity is defined and produced through effective interaction and inter-relationship. Each of the 5 types of components (interactions mentioned) plays a significant role in the didactic approach.

- 3) In this sense, the application of the concept of interactive-technological learning from the perspective of studying information technology

encourages teamwork and cooperation among students in acquiring new knowledge, skills and competencies, which contributes to the effective achievement of learning goals.

The application of the concept of interactive-technological learning, according to the results of the pedagogical experiment, has a significant impact on the process of studying GT through technologies, including MAPLE software and Internet platforms. This concept is implemented in the context of 5 types of interactions (*student-student*, *student-team*, *student-teacher*, *student-subject*, *student-information technology*) and develops primarily due to team efforts, without diminishing the role of each student's individual efforts. In this context, we would like to highlight the following aspects:

- Any new technology generates great interest among young people (students) due to its potential for handling, application and use. In this situation, the interest of students increases for possible new impressions, perceptions and discoveries regarding the understanding of the functioning of the latest technology (Collins, Halverson, 2018);
- New technologies can be studied and mastered both individually and in small groups. Obviously the teacher facilitates the process, but, anyway, in the process of solving a problem through information technologies, many things remain, unexplained aspects that should be clarified through the direct involvement of students. In this sense, in the learning process, students can exchange opinions, information and impressions, discuss and come up with suggestions and recommendations within the work team or in the context of individual conversations. Thus, by discovering the possibilities and new technological advantages related to the MAPLE software, through exploration, analysis and deduction, it contributes significantly to the elucidation of the problem under examination (Couch, 2018);
- The efficient use of information technologies and the Internet stimulates increased confidence in one's own strengths, in the strengths of the team, generates desires and aspirations to get subsequently involved in the discovery and exploration of other high-performance technologies and attractive online platforms, thus demonstrating the creative potential of students and the strength of the group to overcome existing barriers (Hamilton, 2018; Miller 2014);
- Simulations of real phenomena reflected on the screen through applied technology can have convincing results and multiple effects on the team of students who generated this effect, thus contributing to a better understanding of the subject studied and, at the same time, highlighting situations and aspects that should be improved. In the case of applying the MAPLE software, the reflection on the screen of the graphs of the examined process demonstrates the efficiency and speed with which the mathematical model of the phenomenon under study can be built, allowing its study from multiple perspectives. (Reich, 2022; Robluer, 2018; Selwyn, 2022);
- MAPLE is a mathematics software with a friendly and accessible interface that allows the analysis, exploration, visualization and solution of practical

problems from almost any branch of mathematics. In this sense, in the context of the problem examined, in close collaboration with teammates and interaction with the relevant technology (exploring, discovering and reflecting), the student interactively participates in his own training as a specialist, while simultaneously being aware of his own shortcomings and gaps (Chiriac, Bostan, 2022);

- The final results obtained from solving the practical problem in GT by applying information technologies generate feelings of satisfaction with the work done and strengthen confidence in the team and one's own abilities. This increases the motivation and strengthens the desire to work together to complete new tasks.

Summarizing the above, we can conclude that application of the concept of the interactive-technological learning has the following advantages:

- *encourages cooperation and intercommunication between students;*
- *intensifies mutual support and help;*
- *cultivates tolerance in relation to other approaches and opinions;*
- *develops collective but also individual responsibility;*
- *each stage achieved in the problem-solving process cultivates self-confidence;*
- *develops self-critical thinking and self-reflection regarding the results obtained.*

Both our own experience and a series of studies in this area demonstrate that cooperative interactive didactic strategies are more effective than those that emphasize an individual approach, while both approaches remain useful and necessary. In this context, the concept of interactive-technological learning is effectively integrated into the development and application of cooperative didactic strategies and STEM education. Table 1 describes some recommendations regarding the implementation of STEM activities/projects and the use of the concept of interactive-technological learning in GT.

Table 1. Didactic recommendations regarding the implementation of STEM activities/projects and the use of the concept of interactive-technological learning in GT

Nr.	Compartments	STEM Activities/Projects Homework Recommendations
1.	Undirected graphs. Introduction	Graph Traversal. Eulerian and Hamiltonian graphs.
2.	Directed graphs	Applying the Kosaraju Algorithm. Coloring of vertices and nodes. Coloring the Map in 4 colors.
3.	Algorithms for determining minimum paths in graphs	Determining the minimum cost path. Application of Dijkstra and Roy-Floyd Algorithm.
4.	Trees, Binary Trees, Partial Minimum Cost Trees	Determining partial minimum cost trees. Kruskal's and Prim's algorithms.

Nr.	Compartments	STEM Activities/Projects Homework Recommendations
5.	Maxheap, Minheap, Heap-Sort algorithms	Construction of a MaxHeap (MinHeap). Application of the HeapSort algorithm.
6.	Ford-Fulkerson Algorithm, Network Flow	Determining the maximum flow in the network. Application of the Ford-Fulkerson Algorithm.
7.	Matchings	Solving management problems by distributing tasks.

Source: Information processed and proposed by the authors

We note that the prior knowledge and skills that contribute to the effective achievement of the intended learning outcomes are the following:

- knowledge and skills regarding: mathematical modeling, algorithm development, algorithm programming;
- skills and abilities to solve problems using the C/C++ or Python programming languages;
- basic skills in Maple and Mathematica;
- knowledge, skills and abilities obtained from fundamental theoretical courses in elementary and higher mathematics.

The overall goal of the "Graph Theory" course

The overall goal of the course is for students to acquire a basic understanding of graph theory, specific algorithms in graph theory, and develop skills in solving problems modeled using graphs, using information technology and the internet.

Cognitive objectives:

- Mastering some basic notions and concepts from graph theory;
- Knowing the properties of particular classes of graphs;
- Knowing the fundamental algorithms from graph theory.

Procedural objectives:

- at the end of the course the student must be able to:
- translate a problem from natural language into graph language, using the specific terminology correctly;
- develop mathematical models using the graph language to solve practical problems;
- apply and implement algorithms for graph representation and traversal;
- apply the formula for calculating the cyclomatic number, the characterizations of trees and tree-like structures;
- apply algorithms for determining partial minimum cost trees;
- apply the characterizations of Eulerian, Hamiltonian, bipartite and planar graphs;
- apply algorithms for determining Eulerian and Hamiltonian cycles and paths;

- apply algorithms for determining minimal paths;
- apply max-heap, min-heap, and heapsort algorithms;
- apply and implement algorithms for determining maximum flows;
- apply and implement matching algorithms;
- apply MAPLE/MATHEMATICA software, internet platforms, C/C++ programming languages to solve graph theory problems;
- develop application projects that incorporate Graph Theory algorithms;
- carry out STEM activities/projects on graph theory in a team a from the perspective of the concept of interactive-technological learning.

Transferable skills:

- development of complex and critical thinking;
- efficient involvement in the activities carried out within the team by applying the rules of organized work;
- adherence to principles and standards of professional ethics;
- development of empathic interpersonal communication, relationship and team collaboration skills;
- use effective methods and techniques for learning, obtaining information, conducting research, and developing skills in using knowledge and abilities through the use of information technology and the Internet;
- rigor in problem solving, algorithm design, and programming.

3. Methodical approaches to solving practical problems in Graph Theory by applying the STEM concept and developing the Technological Map

Taking into account the experience accumulated over the years, in order to solve practical problems related to GT, applying information and Internet technologies, it is rational for students to be involved in carrying out STEM activities or carrying out projects in the STEM key. STEM activities can be carried out during practical (laboratory) hours. And STEM projects are carried out by students over several days or weeks.

To solve such problems, it is recommended to develop the Technological Map of the STEM activity/project – term introduced by Professor Ion Achiri (2022, p. 12). The Technological Map of the STEM activities/projects at GT, in our opinion, should contain the following stages:

1) Formulating and explaining the problem that needs to be solved. Setting objectives

The problem, including the STEM activity/project, proposed for implementation is carefully formulated and explained by either the teacher or the team leader. It is recommended that the conditions of the problem be discussed with all teams involved. Discussions stop when there is certainty that all team members have understood the conditions of the problem and have clarified what

needs to be learned, found and solved.

Once the problem, in collaboration with the teacher, is clarified and understood by the students, the goals are clearly defined, that is, what needs to be achieved, what should be accomplished. It is recommended that objectives be SMART. The acronym SMART stands for: Specific (clear, simple, meaningful); Measurable (quantifiable, has progress indicators); Achievable (in the sense of being achievable); Relevant (significant, goal-oriented); Time-bound (objectives must be achieved within a clearly defined period of time).

2) Problem analysis, task setting and planning

The analysis of the problem under examination is carried out from many perspectives. It clarifies which studied theoretical components can be used, which algorithms can be applied, and how a mathematical model can be constructed. Most problems, including STEM activities/projects, at GT, after building a mathematical model can be solved (achieved) by at least three main methods: the manual method, the programming method, the MAPLE software application method. It is recommended to distribute tasks to each team involved in the implementation of STEM activities/projects in accordance with the relevant methods. Subsequently, the process of distributing and carrying out tasks, including from the perspective of complexity and time for each team member, is planned within the established teams.

3) Accomplishment of planned tasks

The teams involved in the process, having well-established objectives for each task, proceed directly to their achievement. In other words, they proceed to solving the mathematical model using: a manual method, a programming method, and the MAPLE software method. It is at this stage that interactive teaching strategies can be successfully implemented, including the concept of interactive-technological learning.

4) Evaluation and verification of the results obtained. Approbation of theoretical or experimental results

The evaluation and verification of results is an important stage in the process under review. The fact that teams achieve results does not yet indicate their correctness. The methodology we propose assumes that each of the teams involved should achieve the same result by implementing different methods. The verification process is also done through various methods, including the comparison method. The approval of the results is done by the team leaders. In the situation where the results, obtained through various methods, coincide, team leaders can approve the results, which means that the teams can already move on to the next stage of implementation. Otherwise, all calculations performed are checked.

5) Practical application of results from an Engineering perspective (applications in the industrial, post-industrial, agricultural, ecological, medical fields, ICT services, etc.)

At this stage, the possibility of implementing the results obtained in real life, in practice, from various perspectives of modern Engineering (agricultural,

industrial, ICT, etc.) is analyzed. Unlike the other stages, in which phenomena or processes of various natures (economic, social, etc.) are examined through the prism of Graph Theory with the aim of establishing certain laws, trends, statements or principles, at this stage the possibility of practical application of the obtained results is studied. The stage is important because it is in this process that students see and are convinced of the existence of strong connections between theory and practice. In the training process at this stage drones, various types of robots, as well as other engineering products that are connected to graphs can be widely applied.

6) *Presentation of results*

It is recommended that the presentation of results be carried out by representatives of all participating teams. Namely, in the final presentation process, it is necessary to highlight the inter/transdisciplinary aspects in the process of carrying out STEM activities/projects as well as the connection with real life, in order to show the effectiveness of this methodology. Table 2 provides methodological recommendations regarding the role and tasks of the teacher and student teams.

Table 2. Methodological recommendations regarding Stages and Roles in STEM activities

Nr.	Steps STEM	The role and tasks of the Teacher in the process of carrying out STEM activities/projects	The role and tasks of Student Teams in the process of carrying out STEM activities/projects
1.	Formulation and explanation of the problem to be solved. Clarification of objectives.	The teacher explains the conditions of the problem and the steps to be taken by the student teams. He explains the criteria for forming the teams. It is pointed out that the results obtained must be applicable in practice.	Students are divided into 3-4 teams, depending on skills and complexity of the problem. Team leaders are chosen. Students ask questions, clarify the conditions of the problem, the goal and the time for completion.
2.	Problem analysis, task setting and planning	The teacher as a mentor guides the teams and provides clarifications when necessary.	Students clarify the role and tasks of each team in the problem-solving process. Within each team, the role and tasks of each student involved are clarified.
3.	Accomplishment of planned tasks	The teacher offers consultations and, if necessary, facilitates meetings with experts from other fields or with teachers of other subjects, stimulates	Ideas and strategies for solving the problem are generated. Student teams act according to the planned tasks and communicate on the intermediate

Nr.	Steps STEM	The role and tasks of the Teacher in the process of carrying out STEM activities/projects	The role and tasks of Student Teams in the process of carrying out STEM activities/projects
		the process.	results obtained.
4.	Evaluation and verification of the results obtained. Approbation of theoretical or experimental results.	The teacher evaluates the work of each team and the collaboration between teams from his own perspective.	The teams evaluate and verify the results obtained. The results are analyzed. The results are approved and proposals are made regarding their application in practice.
5.	Practical application of results from an Engineering perspective.	The teacher provides consultations and stimulates the process. Can be external experts.	The teams implement the selected idea in practice from an Engineering perspective (applying technologies).
6.	Presentation of results	The teacher presents his/her own opinion regarding the quality of the work done, the relationship between the teams, and the contribution of each student.	The final report is presented by the student teams. Students express their own opinions on the results obtained and the process of collaboration between them.

Source: Information processed and proposed by the authors

4. Methodological approaches from the STEM perspective

Students are generally successful in completing STEM activities at GT. At the same time, we believe, it is necessary to mention that when implementing the outlined stages, students encounter difficulties both in the process of developing the mathematical model and performing mathematical calculations, as well as in programming the algorithms. These problems are also due to the fact that most students are former graduates of high schools with a humanities profile and fewer from a real profile. The difference in curricula in the respective disciplines speaks for itself. All these trends have a less beneficial impact on studying certain sections of GT, including carried out STEM activities. But, while working in this direction, students develop skills, abilities and competencies in developing and solving mathematical models. In this way, through STEM-related activities, new concepts are modeled and consolidated, and therefore new knowledge is generated (Table 3).

Table 3. STEM Applications: Maximum Network Flow Problem

Name	Explanations
Problem	Determining the maximum flow in the network. Calculating bandwidth
Areas of application	Maximum flow problems arise in many areas, such as: – Road, river, train transport; – Gas, liquid, electricity transport; – Electricity networks; – Operational research.
(S) Science	
– Graph Theory; – Physics, Fluid and Gas Mechanics; – Power Transmission and Distribution; – Operational Research (CO).	– Networks will be modeled as a directed graph. The Ford-Fulkerson Algorithm is applied to solve the problem; – Concepts, notions: path, distance, capacity, speed, weight, bandwidth; – Examines optimization problems resulting from the mathematical modeling of processes in the economic and scientific-technical fields, etc.
(T) Technology	– MAPLE software; – Moodle / Classroom educational platforms; – Programming languages (Pascal, C/C++, Java, Python); – Interactive whiteboard; – Internet platforms.
(E) Engineering	– Liquid flow; – Assembly lines; – Power transmission; – Electrical power networks; operational research, etc.
(M) Mathematics	– Mathematical modeling of the problem; – Concepts used: cut in the graph G; edge (x, y) crosses the cut (crossedge); s-t cut; minimum s-t cut, minimum cut.

Source: Information processed and proposed by the authors

Solving problems in a STEM context establishes lasting connections between this type of problem and the concepts, notions used in Science (Graph Theory), Technology (Maple, Internet technologies), Engineering (drones, robots) and Mathematics (theory of functions, matrices, etc.) In this way, students learn how different ideas and concepts are related and integrated with each other in the context of the problem being studied. In this way, they acquire new knowledge that can be applied to solve new problems, in new situations.

To test students' opinions regarding the implementation of the STEM activities/projects when studying Graph Theory from the perspective of the concept of interactive-technological learning, a questionnaire was conducted. Some responses are presented in Table 4.

Table 4. Students' opinions on STEM activities/projects when studying Graph Theory from the perspective of the concept of interactive-technological learning

Nr.	Statement	Totally disagree	Disagree	Neutral	Agree	Completely agree
1.	I know how to learn effectively through Information Technologies and the Internet	0%	0%	0%	100%	0%
2.	The activity allows me personally to encourage cooperation and intercommunication between colleagues	0%	0%	20%	60%	20%
3.	I take advantage of the learning opportunities available to me through Technologies, including Maple.	0%	0%	10%	70%	20%
4.	I work effectively in small groups.	0%	10%	10%	60%	20%
5.	In group work, I respect other points of view.	0%	0%	0%	80%	20%

Source: Information processed and proposed by the authors

From **Table 4** it can be seen that no student chose the option of total disagreement regardless of the statement. From this point of view, it is encouraging.

Only 10% of students believe that working in small groups is ineffective, and 10% are neutral. On the other hand, 60% agree with this statement, and 20% completely agree.

5. The advantages of approaching the STEM methodology

To emphasize the benefits of implementing the STEM concept, we will highlight the difference between traditional Graph Theory learning and learning Graph Theory through the STEM approach (Table 5).

Table 5. Studying Graph Theory: Traditional Approach vs. STEM Approach

Traditional approach to studying Graph Theory	STEM and interactive-technological approaches to studying Graph Theory
– The teacher transmits knowledge and pays less attention to its integration in an inter /transdisciplinary context; – The latest technologies (MAPLE Software, MATHEMATICA, etc.) are not used in the process of studying Graph Theory; – The connection between knowledge and real-world problems is not always made; Problems are examined more from a mono-disciplinary perspective; – More emphasis is placed on individual work and less on teamwork; – Less attention is paid to the development of skills in the field of science, technology, engineering and mathematics.	– The teacher systematizes information and tends to integrate it in an inter/ pluri/ multi/ transdisciplinary context; – Information and Internet technologies (MAPLE Software, MATHEMATICA, etc.) are widely implemented in the process of studying Graph Theory; – STEM activities are organized and STEM projects are carried out by students; – The problems proposed for solution are directly related to real life and are examined inter/ transdisciplinary; – It encourages teamwork of students and effective relationships between them; – It promotes the development of <i>skills in the field of science, technology, engineering and mathematics.</i>

Source: Information processed and proposed by the authors

Recording the highlighted advantages requires additional efforts from teachers and student teams regarding the organization, implementation, and monitoring STEM activities/projects in the process of learning Graph Theory.

6. Conclusions

In the process of implementing STEM activities/ projects from the perspective of the concept of interactive-technological learning, educational/ practical consequences related to the learning process were identified between the following evidences:

- Developing skills in research and mastering new knowledge and technologies (Maple, Mathematica, etc. software), including programming.

Students' opinions (Table 4): I know how to study effectively using information technology and the Internet (100% agree).

- Developing critical and analytical thinking in the process of carrying out STEM activities/projects, which involve solving complex problems inspired by real life. Solving such problems is based on their decomposition into simpler ones that require the involvement and

collaboration of teams of students specialized in the following fields: mathematical modeling, algorithm development and programming, engineering, etc.

Students' opinions (Table 4): The activity allows me personally to encourage cooperation and intercommunication between colleagues (60% agree, 20% completely agree, 20% neutral); In group work, I respect other points of view (80% agree, 20% completely agree).

- Cultivating qualities regarding continuous learning, adaptability, the teamwork ability and finding solutions through communication and collaboration.

Students' opinions (Table 4): I take advantage of the learning opportunities available to me through Technologies, including Maple (70% agree, 20% - completely agree).

The application of the proposed interactive-technological learning concept has a significant impact on the process of studying Graph Theory through technologies, including MAPLE software, and Internet platforms. The respective concept is implemented in relation to student-student, student-team, student-teacher and student-subject interactions through the lens of information technologies and contributes to streamlining team efforts and collaboration between teams. Thus, following the experiment conducted, following the teaching approaches described above, it was demonstrated that the ability to understand and assimilate the presented material is much deeper by applying the STEM methodology and implementing technologies, compared to the traditional methods used.

Acknowledgement

This study was conducted within the scientific research project "Methodology of ICT implementation in the process of studying real sciences from the perspective of the STEAM concept and Artificial Intelligence", code 040101, within the Institutional Research Program (2024-2027), approved by Ministry of Education and Research of the Republic of Moldova, Order No. 102 of 01.02.2024.

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A VR lesson architecture for environmental engineering: Five scenario designs

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Abstract: *Virtual reality is increasingly used in engineering education, yet many implementations provide limited detail on lesson structure and scenario specification, which constrains reuse across courses and institutions. This paper reports the design and implementation of a VR software package for Environmental Engineering organized as five scenarios covering wastewater sampling methods (introduced in a DAF-related context), a poultry slaughterhouse wastewater treatment process modeled with membrane bioreactor technology, and three immersive virtual laboratory modules addressing ultrafiltration, reverse osmosis, and UV disinfection. The contribution is a reusable lesson architecture that separates a conceptual micro-lesson layer from a practice-oriented workflow when applicable. In the theory-only scenarios, learners navigate structured explanations and decision prompts intended to support procedural reasoning. In the virtual laboratory scenarios, the lesson structure extends to guided assembly of an experimental stand, controlled process simulation, and measurement capture, followed by a debrief designed to connect parameter choices with observed system behavior. Scenario descriptions are presented using a consistent specification template (objectives, task sequence, interactions, outputs, and debrief prompts) intended to support extension to additional unit operations. A preliminary mixed-method teacher evaluation (N = 10) is also reported, indicating high perceived clarity of structure and teaching readiness. Future work targets learner-based feasibility measures (e.g., time-on-task and completion rates) and subsequent controlled studies using objective performance outcomes.*

Keywords: Virtual reality, Environmental Engineering, Ultrafiltration, Reverse Osmosis, Membrane bioreactor.

1. Introduction

Environmental Engineering education requires learners to reason about and operate multi-stage systems, including wastewater monitoring, membrane-based separations, and final disinfection. In many curricula, these topics are introduced mainly through lectures, schematics, and simplified examples, while access to hands-on laboratory practice is often limited by equipment availability, safety constraints, time, and cost. As a result, students may understand what a unit operation is intended to achieve, yet still lack procedural competence-how a system is assembled, started, monitored, and interpreted in a realistic workflow.

<https://doi.org/10.58503/icvl-v21y202632>

Virtual reality (VR) can address this gap by enabling immersive visualization and repeatable procedural rehearsal in a controlled environment. Although VR has been widely explored in engineering education, many reported implementations describe learning activities only at a high level, making it difficult to replicate or adapt lesson flow, scaffolding strategies, and scenario structures across different courses and unit operations. For Environmental Engineering-where instruction spans diverse processes and practical workflows-explicit (Zaharia et al., 2024a; Zaharia et al., 2024b), reusable lesson architecture is particularly important for instructional reuse and for preparing rigorous evaluation.

This paper presents a VR software package for Environmental Engineering implemented in Unreal Engine with controller based interaction, organized into five scenarios: (S1) wastewater sampling methods and techniques introduced in a dissolved air flotation (DAF) context; (S2) a conceptual walkthrough of a poultry slaughterhouse wastewater treatment process using membrane bioreactor (MBR) technology; (S3) ultrafiltration (UF) for final treatment of industrial wastewater; (S4) reverse osmosis (RO) for wastewater filtration; and (S5) Ultraviolet (UV) disinfection for real wastewater. Two scenarios are theory-oriented (S1-S2), while three implement an immersive virtual laboratory workflow (S3-S5) that includes guided assembly of an experimental stand, process simulation, and measurement capture.

The main contribution is a reusable VR lesson architecture that standardizes lesson phases (pre-brief, theory, assembly, simulation/measurements, debrief) while allowing learners to start from a selected phase based on instructional needs. The system integrates progressive hinting and checkpoint gating to support completion within classroom time constraints while preserving procedural validity. The package is already deployed in a laboratory context. Following the preliminary teacher evaluation reported in this paper, the next step is learner-based feasibility testing under authentic session constraints.

2. Background and design rationale

Virtual Reality and Virtual Laboratories (VLs) are increasingly used in engineering education to provide immersive, interactive environments that complement traditional instruction (Hamurcu, Timur & Rızvanoğlu, 2023). These platforms commonly support scenario-based learning by simulating real-world engineering problems (Grigore & Turcu, 2024; Grigore & Turcu, 2025) in a secure and cost-effective setting (Wang et al., 2022; Ciolacu et al., 2023). In Environmental Engineering, this approach is especially relevant because many topics are procedural and systems-based (e.g., wastewater treatment, membrane filtration, and disinfection), while access to physical laboratories is often constrained by infrastructure cost, time allocation, safety requirements, and space limitations (Coutinho, Magana & Dias, 2023).

VLs are frequently justified through several practical advantages over conventional laboratories. First, they can reduce the need for high upfront

equipment investment, ongoing maintenance, and specialized operational support, while enabling a one-time software implementation to be reused repeatedly (Vergara et al., 2022; Wang et al., 2022; Cook-Chennault & Farooq, 2023). Second, VLs mitigate risk by enabling practice in conditions that may be Dangerous, Impossible, Counterproductive, or Expensive (DICE) to replicate in real settings (Parlier, 2024; Grigore & Turcu, 2026), including failure modes and hazardous scenarios without personal injury or equipment damage (Jindal, Mittal & Bansal, 2023). Third, VLs improve accessibility by enabling learning independent of time and location, including exploration of remote or inaccessible environments that are difficult to visit physically (Jindal, Mittal & Bansal, 2023). Repetition without material consumption further supports practice until learners reach procedural fluency (Vergara et al., 2025). Additionally, VLs can enhance visualization of complex or hidden phenomena via information transparency and detailed observation mechanisms (e.g., zooming, slow motion, and seeing internal system parts) (Singh et al., 2021; Cook-Chennault & Farooq, 2023).

Building on this background, the proposed system (implemented in Unreal Engine) is designed around a clear separation between conceptual micro-lessons and virtual-lab workflows, enabling structured delivery while remaining flexible for classroom and laboratory use. The five-scenario suite applies consistent phases (pre-brief, theory, assembly, simulation/measurements, debrief) and allows users to choose the phase from which to begin, supporting targeted revision or focused procedural drills. To provide scaffolding without removing learner autonomy, the system integrates progressive hinting and checkpoint gating mechanisms. These features guide learners through complex tasks (e.g., UF/RO stand assembly and UV disinfection procedures) while managing cognitive load and ensuring prerequisite steps are satisfied before advancing. This paper reports the design and implementation of the package and presents a preliminary teacher evaluation; the next step is learner-based feasibility testing in the laboratory setting.

3. System and lesson structure

The VR application was developed in Unreal Engine and uses controller-based interaction for object manipulation and UI navigation. Content is organized as modular scenarios that share a common lesson framework, enabling a consistent user experience across different Environmental Engineering topics. A phase-selection mechanism allows learners or instructors to initiate a scenario from a chosen phase (e.g., theory-focused revision, assembly drill, or simulation run), supporting flexible classroom integration and reuse. The application was tested using a Meta Quest 3 head-mounted display, which served as the target hardware platform for interaction and usability evaluation. Each scenario follows a common phase model:

1. Pre-brief: objectives, learner role, expected outputs, and a short control reminder.
2. Conceptual micro-lesson (theory): concise explanation of the unit operation

purpose, main terms, and key cause-effect relationships.

3. Assembly/procedure: guided setup of an experimental stand, including verification steps.
4. Simulation and measurements: operation of the process in simulation and capture of required outputs/measurements.
5. Debrief: summary of what was done and reflection prompts linking actions and settings to observed behavior.

Theory-oriented scenarios (S1-S2) use phases 1, 2, and 5, while virtual laboratory scenarios (S3-S5) use the full sequence.

To support learners with different prior knowledge and to keep tasks feasible within limited session time, the system integrates:

- Progressive hinting, where guidance can escalate from general prompts to more explicit cues when needed;
- Checkpoint gating, where critical steps (e.g., required setup actions) must be completed correctly before the learner can proceed.

This combination aims to preserve meaningful procedural activity while preventing invalid configurations and reducing the likelihood of incomplete sessions. In theory-oriented scenarios, outputs consist of learner decisions and short explanations prompted during the lesson. In virtual laboratory scenarios, outputs additionally include confirmation of valid assembly/procedure completion and captured measurements or observations recorded during simulation. All scenarios conclude with a short debrief designed to reinforce conceptual links and support transfer to real laboratory or field contexts.

4. Scenario suite

Table 1 summarizes the five scenarios included in the VR package and outlines their instructional focus and interaction structure. Two scenarios are primarily theory-oriented, emphasizing conceptual explanation, process visualization, and procedural reasoning through guided prompts and decision checkpoints. The remaining three scenarios adopt a virtual laboratory format, in which learners progress through structured phases that include experimental stand assembly, operation of a simulated process, and capture of system outputs or measurements. Across all scenarios, interaction is designed to support stepwise exploration and reflection rather than performance assessment, enabling consistent use across different Environmental Engineering topics and instructional contexts.

Table 1. Summary of the five environmental engineering VR scenarios

Scenario	Topic / unit operation	Type	Primary learner outputs
S1	Wastewater sampling methods and techniques (DAF context)	Theory	Sampling strategy choice(s) and justification
S2	Poultry slaughterhouse WWTP process using	Theory	Explanation of treatment chain and MBR role

	MBR		
S3	Ultrafiltration (UF) for final treatment of industrial wastewater	Virtual lab	Validated stand assembly, simulation run, captured measurements/ observations
S4	Reverse osmosis (RO) for wastewater filtration	Virtual lab	Validated stand assembly, simulation run, captured measurements/ observations
S5	UV disinfection for real wastewater	Virtual lab	Validated stand assembly, simulation run, captured measurements/ observations

S1 - Wastewater sampling methods and techniques (DAF context)

This module introduces sampling purpose and representativeness through short conceptual segments and decision prompts (Figure 1). Learners select appropriate sampling approaches for given monitoring goals and justify choices, with guidance available through progressive hints and gated checkpoints for key prompts. The scenario positions sampling decisions in relation to practical treatment monitoring needs, using DAF as contextual anchoring.

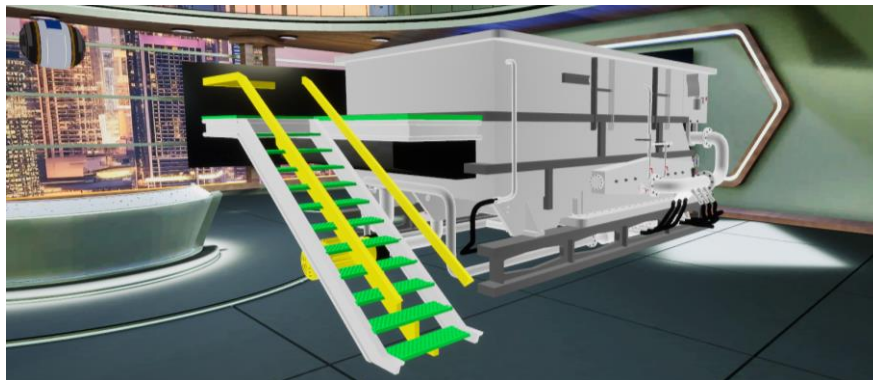


Figure 1. VR scenario view illustrating sampling decision points within a dissolved air flotation (DAF) - context wastewater treatment module

S2 - Poultry slaughterhouse wastewater treatment process using MBR

This module presents a structured walkthrough of an industrial wastewater treatment chain with an emphasis on the role of MBR technology (Figure 2). Learners follow guided explanations and respond to prompts about the function of each stage and the operational logic of MBR, including typical constraints such as process variability and membrane-related considerations. Outputs focus on a coherent explanation of the process flow and the rationale for the MBR stage.



Figure 2. VR-based membrane bioreactor (MBR) scenario illustrating process flow, membrane operation, and operational constraints

S3 - Ultrafiltration (UF) virtual laboratory

The UF scenario extends beyond theory into a lab-like workflow. Learners complete a guided assembly of an experimental stand using controller-based manipulation, validated through checkpoint gating (Figure 3). After setup, they run the process in simulation, observe system behavior, and record required outputs. The debrief prompts connect operating choices to observed behavior to support basic interpretation.



Figure 3. VR-based ultrafiltration scenario depicting membrane separation, valve configuration, and processflow visualization

S4 - Reverse osmosis (RO) virtual laboratory

The RO scenario follows the same structure as UF (Figure 4), emphasizing correct stand setup and safe operational sequencing prior to simulation. Learners assemble the experimental stand with hints available as needed, then operate the simulated process and capture outputs/measurements. Reflection prompts focus on cause-effect reasoning between operating conditions and outcomes.

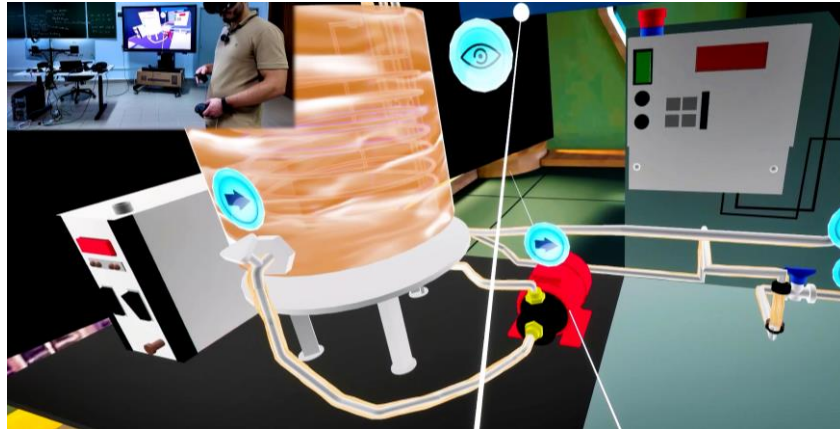


Figure 4. VR-based reverse osmosis (RO) virtual laboratory illustrating system setup, operation sequencing, and measurement points

S5 - UV disinfection virtual laboratory

The UV scenario implements guided assembly and operation of an experimental stand for UV treatment (Figure 5). Learners complete validated setup steps, run a simulated disinfection sequence, and capture outputs/observations relevant to treatment efficacy reasoning. The debrief reinforces key factors affecting UV performance and highlights transfer considerations for real laboratory application.

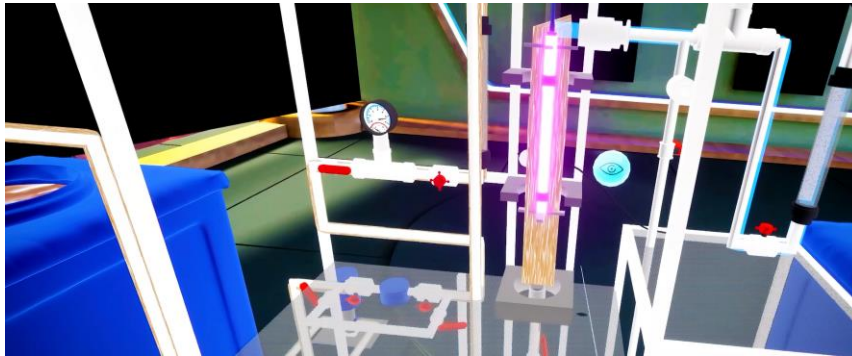


Figure 5. VR-based ultraviolet (UV) disinfection scenario illustrating experimental stand, operation sequence, and observation points

5. Evaluation

This chapter presents the results of the teacher evaluation using a mixedmethods approach (Table 2). Quantitative findings are reported first, based on descriptive statistics for the Likertscale items (Items 1-13 on a 1-5 scale) and the global ratings (Items 14-15 on a 1-10 scale), including central tendency, dispersion, and confidence intervals to summarize overall agreement and variability.

Qualitative findings are then presented from the openended questions, synthesizing recurring themes in teachers' comments to capture strengths, concerns, and improvement suggestions that may not be visible in numerical ratings. Together, these two strands provide a complementary view of perceived structure clarity, usability, and teaching readiness, and they inform the key take-aways and actionable recommendations discussed at the end of the chapter.

The teacher sample ($N = 10$) was intended as a feasibility and pilot usability study rather than a statistically powered experiment, in line with early-stage design validation of educational technology.

Table 2. Questionnaire Items for Assessing VR Platform

Questions
1. The application steps are logically ordered (from introduction to completion)
2. Transitions between stages are clear (you always know "what's next").
3. The lesson pace is appropriate (not too fast / not too slow).
4. The user does not feel "lost" during the experience.
5. The pre-brief sufficiently prepares the user for what follows.
6. The theoretical component is welldefined and easy to follow.
7. The practice/simulation is coherently integrated with the theory.
8. The debrief (recap/feedback) logically concludes the lesson.
9. Navigation is intuitive (buttons, menus, teleport, steps).
10. The user has sufficient control (pause, resume, repeat, back).
11. The indicators/guidance (arrows, highlighting, voice) are appropriate in intensity.
12. The structure is consistent between scenarios (you don't "learn" a new flow each time).
13. The differences between scenarios are clear and justified by objectives (not chaotic).
14. How clear is the structure overall?
15. How "teachingready" is the structure for use in a course?
16. What is the best part of the structure?
17. What is the weakest part of the structure?
18. What would you change about the sequence of stages (add/remove/reorder)?

5.1 Quantitative results

Ten teachers completed the questionnaire ($N = 10$). Items 1-13 used a 5point Likert scale (1 = strongly disagree, 5 = strongly agree), while items 14-15 used a 10point scale (1 = very low, 10 = very high). Overall, responses indicated very high perceived quality of the lesson structure, with consistently high central tendency and low dispersion across items (Table 3).

Table 3. Descriptive statistics of teacher ratings

Question	Mean	Std Dev	Var.	Q1	Q3	IQR	Skewness	Kurtosis	95% CI
1.	4,8	0,6	0,40	5	5	0	-3,16	10,00	[4.41, 5.19]
2.	4,9	0,3	0,10	5	5	0	-3,16	10,00	[4.70, 5.10]
3.	4,8	0,4	0,18	5	5	0	-1,78	1,41	[4.54, 5.06]
4.	4,5	0,7	0,50	4	5	1	-1,18	0,57	[4.06, 4.94]
5.	4,7	0,7	0,46	5	5	0	-2,28	4,77	[4.28, 5.12]
6.	4,9	0,3	0,10	5	5	0	-3,16	10,00	[4.70, 5.10]
7.	4,9	0,3	0,10	5	5	0	-3,16	10,00	[4.70, 5.10]
8.	4,8	0,4	0,18	5	5	0	-1,78	1,41	[4.54, 5.06]
9.	4,9	0,3	0,10	5	5	0	-3,16	10,00	[4.70, 5.10]
10.	4,8	0,4	0,18	5	5	0	-1,78	1,41	[4.54, 5.06]
11.	4,7	0,5	0,23	4,25	5	0,75	-1,04	-1,22	[4.40, 5.00]
12.	4,7	0,5	0,23	4,25	5	0,75	-1,04	-1,22	[4.40, 5.00]
13.	4,9	0,3	0,10	5	5	0	-3,16	10,00	[4.70, 5.10]
14.	9,6	0,7	0,49	9,25	10	0,75	-1,66	2,05	[9.17, 10.03]
15.	9,4	0,8	0,71	9	10	1	-1,00	-0,67	[8.88, 9.92]

Teachers rated the overall sequencing of the application as highly coherent. The logical ordering of steps showed a mean of 4.8 (SD = 0.6; 95% CI [4.41, 5.19]) and transitions between stages reached the highest mean in this block at 4.9 (SD = 0.3; CI [4.70, 5.10]). The lesson pace was also rated very positively (M = 4.8, SD = 0.4; CI [4.54, 5.06]).

The comparatively lowest score across the entire 1-5 section was for the item “The user does not feel lost” (Item 4), though it remained high (M = 4.5, SD = 0.7; CI [4.06, 4.94]) and had a wider IQR (Q1 = 4, Q3 = 5; IQR = 1), suggesting slightly more varied perceptions on user orientation than on other aspects of

structure. The pre-brief was evaluated as sufficiently preparatory ($M = 4.7$, $SD = 0.7$; $CI [4.28, 5.12]$). Both the clarity of the theoretical component (Item 6) and the integration of practice/simulation with theory (Item 7) achieved near-ceiling results ($M = 4.9$, $SD = 0.3$; $CI [4.70, 5.10]$ for both), indicating strong consensus. The debrief was also rated highly ($M = 4.8$, $SD = 0.4$; $CI [4.54, 5.06]$).

Usability related items were rated very favorably. Navigation intuitiveness (Item 9) and scenario differences being clear/justified (Item 13) both showed $M = 4.9$ ($SD = 0.3$; $CI [4.70, 5.10]$). User control (Item 10) remained high ($M = 4.8$, $SD = 0.4$; $CI [4.54, 5.06]$). Items related to guidance intensity (Item 11) and structural consistency between scenarios (Item 12) were also rated strongly (both $M = 4.7$, $SD = 0.5$; $CI [4.40, 5.00]$), but displayed slightly broader spread ($IQR = 0.75$), implying minor differences in how teachers perceived the “amount” of guidance and the uniformity of the flow across scenarios.

On the 10point items, teachers reported very high global endorsement. Overall clarity of the structure (Item 14) scored 9.6 ($SD = 0.7$; $CI [9.17, 10.03]$) and teachingreadiness for course use (Item 15) scored 9.4 ($SD = 0.8$; $CI [8.88, 9.92]$).

These results suggest the structure is perceived as both clear and readily deployable in instructional settings. Across most 1-5 items, $Q3 = 5$ and IQR was 0 for many questions, indicating responses clustered at the top of the scale (ceiling effect). This is consistent with the strongly negative skewness values reported (e.g., several items around -3.16) and elevated kurtosis for some items, reflecting a peaked distribution with many maximum ratings. Practically, these patterns indicate strong agreement but also limited variability, which may reduce sensitivity for distinguishing between “very good” and “excellent” aspects of the design.

Averaging the item means for Items 1-13 yields an overall mean of approximately 4.79/5, reflecting uniformly high perceived quality of structure, transitions, integration, and usability, with the main relative opportunity area being minimizing the chance a user feels “lost” during the experience (Item 4).

5.2 Qualitative results

Q16: “What is the best part of the structure?”

Teachers’ responses highlight a strong appreciation for the structure’s intuitiveness and clarity, alongside its instructional value enabled by VR. Overall, participants emphasize that the lesson flow is easy to follow and that information is presented in a way that supports quick orientation and understanding, reducing the likelihood of confusion during the learning experience.

Main themes identified:

- Intuitiveness and clarity of presentation: Several teachers explicitly described the structure as “intuitive” and the delivery as “clear,” suggesting that the step sequence and guidance effectively support user navigation and comprehension.

- Strong theory-practice integration through contextual VR delivery: A detailed response emphasized the “perfect integration” of theory directly into the VR practical environment (e.g., embedded informational panels, animations, and highlighted components within the virtual installation). This “see-and-understand” approach was framed as just-in-time learning, where theory appears immediately before or during the practical task-helping bridge abstract concepts and concrete application.
- Perceived pedagogical relevance and alignment with authentic learning practices: Respondents noted the value of using VR in teaching and described the lesson as grounded in “real learning practices,” indicating that the structure is seen as didactically meaningful and transferable to instructional settings.
- The lesson starts as a motivational activation point: One teacher identified the beginning of the lesson as the strongest part, describing it as the activation and motivation moment-suggesting that the introduction/pre-brief effectively primes learners for the tasks that follow.
- Data note: One response was noninformative (“-”) and one was ambiguous (“the last one”), so these were treated as not contributing interpretable content.

Q17: “What is the weakest part of the structure?”

Overall, teachers reported few clear weaknesses in the lesson structure. Several respondents explicitly stated that they did not identify any weak part, suggesting high overall acceptance. When limitations were mentioned, they clustered around delivery/communication issues (voice quality, pacing, and transitions) and one higherlevel pedagogical concern regarding the potential passivity of the theoretical component.

Main themes identified:

- No weaknesses perceived (dominant pattern): Multiple teachers answered “I did not identify any” or “There isn’t one,” indicating that-at least at a global level-the structure is perceived as robust and coherent.
- Audio/assistant delivery issues (voice, diction, pace, clarity): Several responses pointed to problems with the virtual assistant’s speech output, including diction, rhythm, and word clarity. This suggests that the structure itself may be solid, but the communication layer (TTS/voiceover quality and pacing) can reduce perceived smoothness and professionalism.
- Visual/flow transitions (between images/stages): One teacher noted that transitions “from one image to another” are sometimes faulty. This indicates a usability/continuity issue that may disrupt immersion and make the experience feel less seamless.
- Theoretical phase may feel passive (interaction depth): One detailed

response highlighted a more pedagogical weakness: although theory is visually integrated, it may sometimes feel like a sequence of information panels to observe rather than actively engage with-especially if content is dense. The respondent suggested strengthening this stage with interactive comprehension checks (e.g., draganddrop labeling, short multiplechoice questions) before allowing progression to the practical simulation. This points to an opportunity to increase active processing and reduce superficial skimming.

- Data note: One entry was noninformative (“-”) and one response (“lack of knowledge”) is unclear in meaning and may reflect respondent uncertainty rather than a structural flaw.

Q18: “What would you change in the sequence of stages (add/ remove/ reorder)?”

Overall, responses indicate that teachers consider the current stage sequence appropriate and logically aligned with how learning should unfold. Most participants explicitly stated they would not change anything, reinforcing the quantitative pattern of very high ratings for ordering and transitions. The suggestions that did appear were targeted enhancements rather than requests for major restructuring, focusing on accessibility, authenticity, and deeper engagement.

Main themes identified:

- No change needed / sequence already logical (dominant pattern): Most teachers responded “Nothing” or emphasized that the stages are “organized in the logical order of learning”. This suggests broad agreement that the current flow is coherent and instructionally sound.
- Accessibility improvement (visionrelated adaptation): One respondent suggested adding elements to support users with ophthalmological/visual impairments. This points to an opportunity to strengthen inclusivity through adjustable visual settings (e.g., text size, contrast, reduced motion, UI scaling, alternative cues).
- Increase realworld grounding (pilot station discussion): One teacher proposed including a discussion connected to real pilot stations, indicating interest in strengthening authenticity and transfer by linking the virtual sequence to real operational contexts (e.g., short case examples, “how this appears in real installations”).
- Add an early lowrisk interactive preview (engagement priming): A detailed suggestion proposed adding a brief, lowstakes interactive preview at the start of the pre-brief (30-60 seconds in a simplified environment, with a small task such as identifying key equipment). The intent is to build curiosity and provide an initial mental model so that later objectives and theory feel more meaningful.
- Refine the debrief closure toward forward transfer (reordering within debrief): The same detailed response recommended ending the debrief with a futureoriented reflective question (e.g., what parameter would be

monitored first in a real installation), rather than finishing only with a recap of past actions. This would better promote reflection and transfer beyond the simulation.

- Data note: One entry was noninformative (“-”), and the rest were clearly interpretable.

6. Discussion and future work

The scenario suite was structured to cover two instructional needs that often coexist in Environmental Engineering teaching. The first need is conceptual orientation and procedural reasoning in domains where learners must make defensible choices without immediately performing physical actions, as reflected in the sampling module and the MBR process walkthrough. The second need is procedural rehearsal for unit operations that are commonly taught through laboratory workflows, reflected in the UF, RO, and UV modules. Keeping a stable lesson architecture across both types reduces switching costs and supports modular use across different course weeks.

Phase selection supports this modularity in practice. A learner can enter a scenario directly at the theory phase for revision, or repeat only the assembly and simulation phases when the goal is procedural fluency. This structure also accommodates typical laboratory scheduling constraints, where time may be sufficient for a focused drill but not for an end-to-end lesson.

Progressive hinting and checkpoint gating were implemented to manage a common tension in procedural VR lessons. Open exploration can produce inconsistent progress and invalid configurations, while rigid scripting can reduce meaningful engagement. A stepped hinting model and validation checkpoints aim to keep the workflow realistic enough to preserve sequencing logic, while maintaining task completion feasibility in supervised sessions.

The software has been implemented in a laboratory context, moving beyond a standalone development environment. The laboratory setup enables immersive VR delivery with controller-based interaction, aligned with the intended use of the scenarios as structured instructional activities rather than informal demonstrations. At this stage, the development focus shifts from feature completion to testing under real session conditions.

Testing is positioned as feasibility and user-acceptance work prior to any controlled claims about learning outcomes. The most appropriate near-term objective is to determine whether participants can complete the intended lesson phases within allocated laboratory time and whether the interaction model is perceived as usable.

A practical testing plan emphasizes three evidence streams:

1. Feasibility indicators

- completion rate by phase and by scenario;
- time-on-task per phase, including the use of phase selection;
- frequency of stalls, resets, and incomplete runs;

2. Interaction and workflow indicators
 - checkpoint attempts and common failure points during assembly and operation;
 - progressive hinting patterns, including escalation frequency;
 - recurring control or UI errors observed by instructors;
3. Perception-based indicators
 - usability ratings and perceived ease of use;
 - engagement and presence ratings;
 - perceived learning value and perceived readiness for real laboratory activity;

Results should be framed as participant-reported perceptions and observed feasibility patterns, not as confirmed learning outcomes. Objective performance outcomes and comparative studies belong to the subsequent phase after usability and feasibility are stabilized.

The scenario framework is intended to support additional unit operations using the same phase model and interaction primitives. Future iterations can add new modules while preserving consistency in onboarding, guidance logic, and reporting outputs. Refinement priorities are expected to emerge from laboratory testing, particularly around phase durations, hint escalation thresholds, and checkpoint strictness to match instructor expectations and session timing.

7. Conclusion

This paper presented a VR software package for Environmental Engineering implemented in Unreal Engine with controller-based interaction and organized into five scenarios spanning wastewater sampling (DAF context), an industrial MBR-based process walkthrough, and three virtual laboratory modules for ultrafiltration, reverse osmosis, and UV disinfection. The main contribution is a reusable lesson architecture that standardizes lesson phases (pre-brief, theory, assembly, simulation/measurements, debrief) while allowing learners to start from a selected phase, supported by progressive hinting and checkpoint gating to maintain procedural validity and completion feasibility within limited session time. In addition to documenting the system design and scenario suite, a preliminary mixed-method teacher evaluation ($N = 10$) provided convergent evidence of high perceived structure clarity, strong theory–practice integration, and high teaching readiness, while also indicating improvement opportunities related to user orientation and communication/transition smoothness. The immediate next step is learner-based feasibility testing under authentic session constraints (completion rate and time-on-task by phase, checkpoint/hint usage patterns), followed by controlled comparative studies that incorporate objective performance measures and learning outcomes.

8. Limitations

This paper includes preliminary empirical results based on a small-scale teacher evaluation focused on usability and structural clarity, but does not yet include learner performance data or controlled experimental outcomes. Consequently, no claims are advanced regarding learning gains, retention, or comparative effectiveness versus non-VR instruction. The current contribution is limited to the documented lesson architecture and the five implemented scenarios; extension to additional unit operations and validation across learner groups remains future work. Finally, laboratory deployment depends on local VR hardware availability and instructional time allocation, which may constrain scalability across institutions.

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Augmented Reality in Psychology education: A phenomenological study on the views of university students

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Abstract: *This research used a qualitative (phenomenological) design to examine university pupils' views on augmented reality (AR) applications in psychology courses. The participants in the study were 110 pupils studying at Near East University. The group was determined using criterion sampling technique, which is a purposive sampling method. The data were collected through semi-structured interviews and examined using descriptive analysis. The obtained findings show that the students generally view the integration of AR applications into psychology courses positively. The participants emphasized that AR especially concretizes abstract concepts, individualizes learning, and offers an interactive environment by increasing motivation. On the other hand, technical deficiencies, hardware constraints, usage difficulties, lack of direction, and time management issues were indicated. According to these results, it is recommended that teaching design should be reinforced and user-friendly applications should be developed so that AR technology can be more effectively used in psychology education. In addition, further research has to be conducted with mixed methods so as to improve the generalizability of data.*

Keywords: Augmented Reality (AR), Psychology education, University students, Phenomenology, Abstract concepts.

1. Introduction

Psychology courses play a crucial role in improving the personal development, communication skills, conflict resolution abilities and problem-solving skills of students by helping them to understand the behaviors, thinking processes, and emotional reactions of individuals (Başarer, 2019). In addition, psychology education makes positive contribution to students living healthier and more satisfactory lives by offering them career opportunities (King, 2016). Literature review shows that usage of technology applications in psychology courses introduces students with important opportunities. At this point, it is emphasized that usage of augmented reality applications in psychology courses enriches the learning experiences of students and serves to concretize abstract psychological concepts (Riva, 2019). In this context, augmented reality applications increase the learning motivation of individuals, support experimental

learning, transcend the limitations of time and space, develop scientific thinking, and ensures suitability for different learning styles. In addition, augmented reality applications add strong contributions to conventional learning methods by making psychological education more meaningful, interactive and permanent (Bacca et al., 2014).

1.1 Literature review

A review of the relevant literature reveals that Boz (2019) found that augmented reality applications make a substantial contribution to attracting students' interest in lessons in the field of education. When the research was examined, it was seen that the researchers particularly addressed the possibilities offered by these applications in terms of transferring movable and difficult-to-transfer objects into the classroom environment in three dimensions. Furthermore, the research indicated that these applications were effective in the teaching and learning process, especially in concretizing abstract concepts and visualizing concepts and spatial relationships. Similarly, in the research prepared by Karakaş & Özerbaş (2020), it was observed that students found the use of AR applications in the learning-teaching environment effective and motivating. Lampropoulos' (2023) research stated that the combined use of artificial intelligence and augmented reality applications increased interaction related to the lesson and led to immersive, engaging, and personalized learning experiences. The research concluded that these learning experiences can be applied at all levels of education. Similarly, Taşkın et al. (2023) emphasized the positive aspects of three-dimensional modeling on education. They emphasize the need for further widespread adoption of this technology in the future. Hakim & Hammad (2022) discussed how virtual reality technology can be used as an effective tool in therapy and rehabilitation processes within the field of psychology. They also note that this technology offers significant opportunities in areas such as assessment, diagnosis, treatment, research, and trainee education. It was explored that different studies underlined developments in certain areas of psychology such as assessment, diagnosis, treatment, research and the training of interns. In terms of the related research, it was found out that augmented reality applications in psychology courses offered important opportunities to students for concretizing abstract concepts, creating interactive learning environments, and increasing motivation. Especially in predominantly theoretical courses such as psychology, AR applications help students understand the topics better and turns learning into an experiment-based process (Chen et al., 2020). However, in order to benefit from this technology in education in an effective and sustainable manner, student experiences, expectations and views should be taken into consideration (Mendes et al., 2020). The feedback of students regarding augmented reality applications plays a critical role in improving the content design and developing teaching methods (Li et al., 2020). In addition, these opinions provide essential data on the accessibility of technology as well as its user-friendliness and real impact on learning. Therefore, evaluation of the perceptions of students as regards AR applications

bears huge importance in terms of successful integration of technological innovations (Akçayır & Akçayır, 2017). In this context, the literature review showed that there is no research evaluating the AR applications in psychology courses from the perspective of university students. This study is expected to address the existing gap in the literature. In addition, it is thought that this research will shed light on the university students adopting, accepting and popularizing technology.

1.2 Significance of the research

The findings of this study are anticipated to offer initial awareness into learning processes and the field of educational technologies. It is believed that the findings obtained from the research will offer a data-based and reliable framework for evaluating performance and efficiency of the self-learning processes of university students and make crucial contribution to their self-regulated learning. In addition, this study is expected to allow students for comparing their experiences with conventional learning methods and make AR's relative effectiveness level more comprehensible.

2. Objectives of the study

The present research seeks to explore university students' views regarding augmented reality applications within psychology courses. Answers were sought to the following questions so as to realize the general purpose of the study.

1. How do students perceive the use of augmented reality applications in psychology classes?
2. How do students perceive the challenges of using augmented reality applications in psychology courses?

3. Method

3.1 Research model

A qualitative phenomenological approach was employed in this study to explore the subject matter in depth. The basic purpose of this design is to display the experiences, views and practices of individuals as regards a given topic (Teherani, 2015). Within this study, the experiences of pupils on augmented reality are related to the fact that they have taken this course before.

3.2 Sample group

The research population consists of pupils at the faculty of education (n=110). The sample was selected based on predetermined criteria. The criterion of the sample was identified as choosing the students who have previously used AR applications at the university.

3.3 Data collection and data collection tool

Within the scope of this study, research on the experiences and opinions of university students on the usage of AR applications in psychology education are examined. In this context, literature review has been conducted in national and international indexes. This examination revealed that phenomenological studies on student experiences as regards AR applications in psychology education are limited. Accordingly, a semi-structured interview form was designed by the researchers to gather the research data.

3.3.1 *Semi-structured interview form*

In order to gather data for this study, the researchers developed a structured interview form consisting of two sections: one for demographic information and another containing two open-ended questions related to the purpose of the research. Expert opinions were taken to ensure content validity of the interview questions. In this process, the assessments of thirteen experts (n=13) were obtained, including augmented reality and education technologies specialists (n=5), curriculum and its development experts (n=4) and measuring and evaluation specialists (n=4). Lawshe (1975) technique was used for the analysis of expert opinions. Categories such as restricted understanding and no understanding of the content were formed to evaluate the comprehensibility of the items, and spaces were provided to allow for expert advice on revising items that are difficult to understand. Each item was analyzed independently through these determined categories. To determine the content effectiveness of the items in the interview form, Lawshe's (1975) Content Validity Ratio (CVR) was applied. Performed calculations showed that the Content Validity Ratio of the form was +1 [10] as a result of which it was approved that the form had satisfactory level of validity. After receiving input from the specialist, we revised the regulations and completed the final version of the interview form.

3.4. Analysis of the collected data

This research employed content analysis to examine the qualitative data collected. In the analysis, the obtained data are examined in depth and coded, and themes are created (Braun & Clarke, 2022). To ensure the reliability (consistency) of the study, the collected data were coded and analyzed individually by multiple researchers (researcher triangulation). Following the coding process, the resulting codes and themes were presented to expert opinion and a joint decision was made. In addition, to strengthen the validity (and reliability) of the research, the data obtained from the study were interpreted and presented as direct quotations without making any changes thereto. This application ensures that the reader reaches the comments of the participants by viewing the original form of the data.

4. Findings

4.1 Students' perspectives on the use of augmented reality applications in the psychology course

With respect to the study's first sub-purpose, pupils' opinions on the use of AR applications in the psychology course were explored. Table 1 presents their views, which were grouped under two main themes.

Table 1. Students' opinions on the usage of AR applications in the psychology course

Theme	Views	Frequency Distribution(f)
Effective Teaching	Concretization of abstract concepts	65
	Increase in motivation	30
	Interactive environment	15
	Contribution to individual learning	68
Individuality in Learning	Increase in the level of attention	42

Analysis of the obtained data reveals that the "Effective Teaching Practices" theme is characterized by the majority of students believe that using AR applications in psychology courses plays a crucial role especially in making abstract content perceptible. This finding is substantiated with the following quote from the views of the participants:

"My engagement in the classroom advanced through the use of augmented reality (AR) tools. The interactive and visually appealing appearance effectively drew my attention, contributing to higher levels of interest, participation, and motivation." (Ö 40)

Another essential finding is that the majority of the university students stated that using AR in psychology courses especially increases motivation significantly. The views show that AR applications makes the classes more engaging and that the interest and willingness to participate in the class increases through visual/interactive contents. An example expression is provided below.

"Implementing augmented reality (AR) in the classroom uncompensated to greater student engagement by capturing attention through interactive and visual elements. This increased willingness to participate and had a noticeable positive impact on motivation." (S 94)

The findings of this study display that a segment of the university students emphasize that AR adaptation in psychology classes lays the ground for the creation of an interactive learning environment. This view indicates that students exhibit active participation in the learning process and that AR applications make the classroom environment more dynamic and vivid. The expression of a participant which illustrates this finding is provided below:

"Thanks to the technology of AR applications, I wasn't just a listener. I actively participated in the lesson. The applications made the classroom environment more interactive and vibrant." (S 83)

In addition, it can be said that the increase in motivation and attention levels resulting from the opinions expressed by students aligns with the nature of psychology education, which requires learning through experience and active participation, thanks to AR applications, and that interactive learning takes place with this application. Creating interactive learning environments in psychology courses indicates that students actively participate in meaning-making processes, which is particularly important for psychology courses that aim at critical thinking and concept concretization. Overall, these findings show that AR applications offer a field-specific teaching value by meeting the abstract, process-oriented, and experience-based learning needs of psychology.

4.2 Students' perspectives on the challenges of AR applications in the psychology course

In line with the study's second sub-objective, students' perspectives on the challenges of using AR applications in psychology courses were explored. As presented in Table 2, their responses were categorized into two themes corresponding to this sub-objective.

Table 2. Students' opinions on the challenges of AR applications in the psychology course

Theme	Views	Frequency Distribution (f)
Limitations of Augmented Reality Applications	Technical difficulties	65
	Hardware limitations	45
Usage problems	Lack of directives	43
	Lack of knowledge	38
	Time management	29

As illustrated in Table 2, the majority of students highlighted technical problems as a key obstacle to using augmented reality (AR) applications in psychology courses. This finding reveals that using AR applications in the teaching of psychology classes may not always be compatible with the technical infrastructure and hardware facilities of institutions. In addition, these technical difficulties restrain the effective employment of applications by making AR's contribution to the learning process more difficult. An example view is given below.

"Augmented reality (AR) tools were generally effective in enhancing engagement; however, technical challenges, including connectivity issues and limited equipment availability, were noted as factors that impeded students' focus and learning outcomes." (S23)

On the other hand, some students claimed that using AR in psychology classes leads to hardware limitations, which can create inequality of opportunity among students and reduce the efficiency of AR-assisted learning experience. The

conclusion drawn from this finding shows that hardware is of great importance in the use of augmented reality (AR) applications, and that its accessibility to every student plays a critical role. An example opinion is given below:

"I think that using AR applications in the psychology class has increased the effectiveness of the course. However, from the feedback of my friends, I can say that the barriers to accessing the hardware have limited the participation of some students and led to unequal learning experiences." (S 44)

In the second theme, the vast majority of students indicated that the guidelines in the psychology courses regarding the application's usage problems contained some shortcomings. Failure to provide adequate instructions regarding the usage of AR applications in psychology classes made it difficult for the students to understand the application. This situation led students to focus on using the application, making it difficult for them to concentrate on the course content and ultimately negatively impacting their learning process. An example student view is offered below.

"Limited instruction on the operation of augmented reality (AR) tools contributed to some difficulties in participation, which in turn affected my ability to concentrate on the lesson content." (Ö 87)

Likewise, some students stated that they suffered from lack of information as regards the usage of AR applications in psychology classes. The obtained finding implicates that university students do not have the preliminary knowledge required for effective usage of AR applications in psychology classes. For this reason, and due to lack of knowledge, the students were not able to use these applications properly and efficiently. It is safe to claim that this situation affected the learning process negatively. A sample opinion is provided below.

"While AR applications contributed positively to student learning, the presence of technical issues and insufficient guidance on their use created obstacles that hindered smooth engagement with the lesson." (Ö31)

Another segment of the students stated that delays were experienced in the installation and usage of AR applications in psychology classes, which led to problems in the effective usage of class hour. This finding indicates that AR applications can be time-consuming in both installation and usage processes. In addition, these problems affect time management during the class hour negatively and leads to interruptions in the flow of the lecture, which restrains the learning duration of the students. An example view is given below.

"Installing and configuring the AR application in the psychology class required a considerable amount of time. As a result, the limited time available for learning made it challenging to fully engage with key aspects of the course content." (Ö 67)

In conclusion, the findings of the research have revealed that augmented reality applications are supportive of learning in psychology education and have a suitable structure for the field. The results obtained have revealed that the use of this application in psychology courses has some limitations. Psychology courses are conceptually complex. Technical problems, hardware limitations, and

insufficient instruction can create difficulties for students in focusing on the content of the psychology course. Furthermore, this can be considered a primary problem for psychology courses where sustained attention and cognitive engagement are critical for learning. Moreover, the lack of prior knowledge and guidance regarding augmented reality (AR) applications may limit the pedagogical potential of this technology in psychology courses. Time losses during setup and usage processes can negatively impact the flow of the course and the continuity necessary for learning psychological concepts. These findings suggest that for the effective use of AR applications in psychology education, it is important to develop field-specific planning, strengthen the technical infrastructure, and provide structured guidance to students.

5. Discussions & conclusions

The study found that augmented reality (AR) applications concretize abstract concepts in psychology courses and lead to lasting learning. In the relevant literature, the research by Chen et al. (2025) showed that the use of AR applications was parallel to the concretization of abstract concepts. This finding is consistent with the research findings. Furthermore, this research concluded that AR applications have a positive effect on students' motivation and interest in the course. It was also investigated that these applications create interactive learning environments and make students more active in the learning process. Sarıyıldız et al. (2024) and İzgi Onbaşılı (2018) also emphasized the importance of AR technology in increasing students' interest in courses and positively influencing their motivation levels.

The second finding from the research revealed that augmented reality (AR) applications are fundamental supporting tools for psychology courses, but their use is limited by factors such as technical deficiencies, hardware limitations, and a lack of instructions and information. In this regard, the study conducted by Şimşek et al. (2025) examined the effects of AR content duration on reading comprehension performance and cognitive load, and revealed that design and usage limitations of AR applications can affect the learning process in different ways. The findings necessitate a combined consideration of pedagogical and technical dimensions for the effective use of augmented reality applications in psychology courses. In addition, it is also important that AR contents which concretize abstract concepts are designed according to the cognitive skills of relevant students and that their content duration are structured based on the learning targets. In-service training activities on the usage of AR applications in classes could also be effective. It is believed that such practices will increase the positive impact of AR applications in learning processes and result in more permanent learning.

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Reproducing feedback for environmental education in-class activities using large language models in virtual learning systems

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Abstract: A large language model (LLM) is an artificial intelligence program that understands, reads, interprets, creates, and generates new texts from dense datasets. The program can self-monitor with countless data points and easily perform text correction and transformation operations. Due to its self-monitoring capability, LLM can also easily track the potential outcomes of a sequence. This study aims to utilize this deep learning method, capable of understanding human language, in the field of education to facilitate the work of academics and students. The study was conducted with undergraduate students in the Faculty of Education as part of the Environmental Education course, thus testing the LLM model in the field of environment and sustainability, a topic of great need in recent times. Five environmental and sustainability themes were distributed to 39 students, and the texts were reorganized using the necessary commands with the LLM. The results were validated and verified by the researchers. This engaging study was conducted with enjoyment by the students. The students' re-evaluation of the reorganized texts proved that learning was achieved as intended. The model's ability to provide feedback and corrections to each text individually further contributed to facilitating the work of academics and providing diverse perspectives.

Keywords: AI, ChatGPT, Education, In-classactivities, LLM, Sustaianability.

1. Introduction

The digital transformations of the 21st century have a significant impact on the digital strategies, methods, techniques and tools used in education and training processes. With digitalization in education and training, artificial intelligence-based applications are increasingly preferred. In the field of education, Large Language Models (LLMs), known for their ability to understand, organize, and transform texts, are attracting attention in learning and teaching processes (Brown et al., 2020; Öztezcan, 2024; Polat, 2025; Yurdakul, 2024).

Artificial intelligence language models like LLMs can greatly support the written expression skills of both instructors and learners in the learning and teaching process due to their ability to create and analyze texts in an academic language that mimics the natural language used by humans. With these models, learners can correct spelling errors in the learning-teaching process and make the

text more fluent while maintaining its content integrity through given commands (Altıntop, 2023; Kasneci et al., 2023; Uzun, 2023). In this respect, LLMs serve as a tool that can help students express their thoughts in a more organized and understandable way.

The use of artificial intelligence in education can provide learners with rapid and individualized feedback through language models. In addition, it has the potential to reduce the workload faced by instructors in the measurement and evaluation process (Çavuş, 2024; OECD, 2021). In this context, the contribution of these technologies to learning depends on the quality of the interaction students have with AI-based language models. AI in education can offer learners rapid and individualized feedback through language models. Unquestioningly accepting AI outputs can lead to students remaining passive in the learning process (Altun, 2024; Zhai, 2022).

Therefore, current studies emphasize the need to use artificial intelligence as a supportive tool in education (Arslan & Arslan, 2025; Boztepe, 2025; Yıldız, 2025). The literature states that artificial intelligence should not be a system that replaces the student, and if it is used in the learning and teaching process, it should be positioned as an aid that supports the student's thinking (UNESCO, 2023). Thus, it should be such that it enables students to actively participate in the learning and teaching process, generate individual ideas, and preserve their critical thinking skills.

The rapid development of digitalization and artificial intelligence is also providing significant support to sustainability and environmental issues, which are of great importance to humanity, in the field of education. The Sustainable Development Goals (SDGs) determined by the United Nations aim to raise awareness among individuals about environmental problems through digitalization (UN, 2015). In this context, environmental education aims to develop students' awareness of environmental problems and enable them to produce solution proposals. According to the contemporary education system, supporting the strategies, methods, techniques, and tools used in environmental education courses with current technologies can increase the permanence of learning (Tuğaç, 2023; Yavaş, 2025).

There is an increase in research on the use of artificial intelligence and digital tools in education in the literature. However, applied studies examining the effect of LLMs on the learning-teaching process or classroom activities, especially on student texts, and the extent to which students actively participate in this process are limited. In this context, research on the use of LLMs, especially in courses requiring social awareness such as environmental education, may be needed.

In this research, large language models (LLM) were considered not as text generators, but as text editors and transformers. This research was conducted with undergraduate primary school teacher training students as part of the Environmental Education course. The students' texts on environmental and sustainability issues were revised with the support of LLM (Learning, Management, and Mathematics). The study examined how the texts changed in terms of language, content, and structure, as well as the students' approaches to this

process. In this respect, the research aims to present a practice-based approach to the controlled and conscious use of artificial intelligence technologies in educational settings from a pedagogical perspective.

1.1. Importance of the study

While research on artificial intelligence and large language models in education is increasing, activity-based findings on how these technologies should be pedagogically positioned in learning and teaching processes are limited. In particular, the lack of studies that address the impact of large language models on students' written output, along with their levels of cognitive participation in this process, is considered a significant gap in the literature.

This research is considered unique because it treats large language models as a helpful tool supporting students' thinking, organizing, and transforming processes. The fact that this research is conducted within the context of an environmental and sustainability-themed course is important in revealing the pedagogical potential of AI-supported applications in areas requiring social awareness. In this context, the research is expected to provide theoretical and practical contributions to instructional designs regarding the careful, conscious, and pedagogically sound use of artificial intelligence in the education and teaching process.

2. Purpose of the Study

The aim of this research is to examine the effect of artificial intelligence's large language models (LLMs) on the language, content, and structure characteristics of texts produced by students during an activity process within the scope of an environmental education course. In this research, LLMs were preferred not as text generators, but as text editors and transformers; the extent to which students actively and critically participated in the AI-assisted text editing process was investigated. In this context, this research aims to present activity-based findings on the controlled and conscious use of artificial intelligence technologies in educational environments, based on pedagogical principles. This research aims to evaluate the texts created by students within the scope of classroom applications carried out in the education and training process using large language models (LLMs). Accordingly, the following research questions were addressed in the research:

RQ1. How did student texts undergo a transformation in terms of language, content, and structure after the use of LLMs?

RQ2. How did the students' levels of intervention in the text vary in active-passive and critical-superficial contexts?

RQ3. What are the students' opinions on artificial intelligence and large language models after the application?

3. Method

3.1 Research model

This research, based on a qualitative philosophy and conducted on a descriptive basis, emerged from a systematic analysis of an in-class educational practice. It was hypothesized that the active use of artificial intelligence in the classroom would provide positive contributions for both students and academics/instructors. In this context, students were evaluated in both process and product-oriented ways during the application phase of the research.

3.2 Study group of the research

The research was conducted with 39 first-year undergraduate students in the Primary School Teaching program at the Faculty of Education, as part of the Environmental Education course. Students worked in groups of two, resulting in 19 groups in total; one student worked alone at their own discretion. This research marked the students' first encounter with and application of the LLM model. No specific selection criteria were set for the sample; data was collected based on voluntary participation in the classroom application due to ease of access. For ethical reasons, students were informed that the application would not be graded.

3.3 Research process

During the implementation process, students were given five different topics within the scope of Environment and Sustainability concepts, which are essential and strictly followed for "Our World" and "Our Common Future". Thus, the LLM model, used in accordance with the course content and learning outcomes, aimed to both increase students' sensitivity to the environment and sustainability and to facilitate the tasks of educators/academicians. In this way, the applicability of LLM to other courses and topics was also checked in the same process. The five topics parallel to the principle of sustainability, on which students were asked to express their knowledge and ideas, are as follows:

Topic 1. The problem of waste sorting in university campuses

Topic 2. Consumption of single-use plastics on campuses

Topic 3. The impact of social media on environmental education

Topic 4. The failure of theoretical knowledge to be translated into practice in environmental education

Topic 5. Ways to reduce electricity consumption on campus

In order to create synergy through brainstorming, students were first asked to form groups of two. Groups were asked to choose any of five topics and write a text on that topic, outlining their knowledge and ideas under the subheadings of "problem definition, current situation, and possible solutions." In the second phase of the study, students were instructed to transfer the generated texts as image files to an AI program of their choice and give the command, "Evaluate this text from

an environmental and sustainability perspective, point out any missing or incorrect points, and offer concrete suggestions for improvement." The AI then regenerated the texts based on these suggestions. As a final step, students were asked, in groups, to identify the differences between the old and new texts and to discuss the positive and negative aspects of the AI's assistance.

3.4 Data collection process and analysis

The data sources for this study are students' initial texts, post-command transformed texts, and student opinions. Prior to analysis, groups were coded as G1, G2, etc. Topics were coded as Topic 1, Topic 2, etc., as given in the section titled "Application Process". The analysis primarily focused on examining the direction of change in the texts. Furthermore, student intervention in the text was evaluated in terms of active-passive and critical-superficial contexts. Pattern-based evaluation analysis was adopted to identify recurring similarities in multiple examples.

3.5 The use of artificial intelligence in research

In this study, LLM was not used as a text generator; it was used as a text editor and converter. In this respect, artificial intelligence is not a tool that completes assignments for the student, but rather an aid and support that stimulates thinking. For the teacher, it is an application that saves time and facilitates learning from different perspectives. In this study, artificial intelligence was used by both students and researchers. Although all student groups were free to choose the type of artificial intelligence, they preferred ChatGPT. In addition to the students' handwritten ideas being converted with ChatGPT-LLM, the handwritten texts were converted to computer text by the researchers conducting this study using ChatGPT, and the article written in Turkish was translated into English using Google Translate. Two examples of student texts are included in Figure 1 for illustrative purposes.

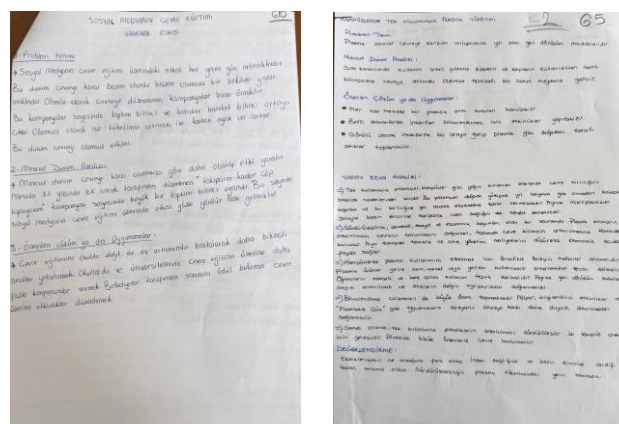


Figure 1. Examples of the first handwritten texts by student groups

4. Findings

Texts written by student groups according to their study topics were transformed using artificial intelligence (LLM). One selected example for each topic is presented in Table 1.

Table 1. Transformation of texts created by student groups using LLM

Topic	Group	Group Text	LLM Feedback
1	G1	Problem Definition: Waste is a major problem on university campuses, particularly affecting young people. Conscious young people suffer from this situation and need to separate their waste to overcome it. The number of waste sorting bins should be increased. Current Situation Analysis: The lack of waste awareness in our country, the inadequacy of organizations, and the failure of our leaders to address this issue are rendering the current situation ineffective. Suggestions and Solutions: Increase social organization, guide student clubs, teach waste management from a young age, raise awareness among families, and increase the number of designated bins for each type of waste in cities.	Waste sorting on university campuses is a significant problem in terms of the environment and sustainability. The lack of sufficient awareness about waste sorting, especially among students, prevents effective recycling. This leads to increased environmental pollution, faster depletion of natural resources, and economic losses. Currently, awareness campaigns regarding waste management are insufficient, and relevant institutions and organizations are not playing an effective role. Collecting waste without sorting it constitutes a significant obstacle to sustainable environmental management on campuses.
2	G5	Problem Definition: Plastic waste consists of recyclable materials that take millions of years to decompose in the environment. Current Situation Analysis: The recent increase in the	Single-use plastics are a major cause of environmental pollution in heavily used areas like campuses. These plastics remain in nature for hundreds of years without decomposing, causing soil and water pollution and harming the ecosystem.

		use of plastic bottles and containers, and their unconscious disposal into the environment after use, creates a very dangerous problem. Proposed Solutions or Applications: Plastic waste bins can be placed every 100 meters. Events can be organized at certain times to raise awareness among people. People can be brought together to collect harmful waste such as plastic from nature.	They also threaten human health by entering the food chain through microplastics. Sustainability is a concept with environmental, social, and economic dimensions. Reducing plastic waste protects the environment and contributes to raising environmental awareness in society. It also provides economic benefits by reducing cleaning and waste management costs. To reduce plastic use on campuses, preventive measures should be taken first. Glass, metal, or reusable alternatives should be preferred instead of plastic products. Students should be encouraged to use water bottles and cloth bags. In addition, the number of recycling bins should be increased, and proper waste separation should be ensured. Awareness campaigns are also of great importance. Posters, informative events, and initiatives such as "Plastic-Free Day" can encourage individuals to behave more responsibly towards the environment. In conclusion, reducing single-use plastics is essential for a sustainable campus environment. The environment can be protected with small measures.
3	G10	Problem Definition: The impact of social media on environmental education is increasing day by day. This situation reflects on the environment sometimes positively and sometimes	Your report is a good introductory text that addresses the impact of social media on environmental awareness at a basic level. Using a concrete example like "I collect trash for 1 minute" makes the topic

		negatively. Positive examples include environmental campaigns. These campaigns create social awareness and a sense of collective action. Negatively, increased consumption leads to an increased carbon footprint. This negatively impacts the environment. Current Situation Analysis: The current situation has a more positive than negative impact on the environment. For example, a campaign organized by an 11-year-old child, "How many pieces of trash cans do I collect in 1 minute?", created significant social awareness. This demonstrates the visible impact of social media on environmental education. Suggested Solutions or Applications: Starting environmental education at home rather than in school to raise more conscious generations. Giving more conferences on environmental education in schools and universities. Organizing environmental events with prizes by municipalities.	understandable. However, it could be further improved. My suggestions: 1- Key Deficiencies: Digital Pollution: You should mention not only how social media increases consumption, but also the energy consumed by massive servers and the resulting e-waste (such as old phones, etc.), which are technical harms. Educational Balance: It would be more appropriate to present this holistically, starting at home and supported by scientific principles at school. 2- Strengths (Things to Protect): The inclusion of concrete examples and the emphasis on awareness have increased the report's impact. Artificial Intelligence Suggestions 1- Digital Cleaning: A suggestion to reduce unnecessary data usage through digital cleaning (deleting emails, watching low-resolution videos) could be added to the solution section. 2- Practical Training: Suggestions should be offered not only for conferences, but also for things like composting in schoolyards or zero-waste workshops.
4	G13	Information and Interpretation: This education enables people to understand the environment and become aware of environmental problems. Through this education, individuals gain responsibility for	Strengths: The topic is accurate and current. The report's sections (problem, current situation, solution) are well-organized. Examples of environmental problems from daily life are

		protecting the environment. Problem Definition: Problems arise due to people's insufficient knowledge about environmental education, leading to environmental pollution and the unconscious consumption of natural resources. Current Situation Analysis: Examples of water pollution include ships dumping fuel into the sea, smoke from factory chimneys causing air pollution, the construction of houses in riverbeds, and littering. These problems demonstrate the poor state of the current situation due to people's insufficient knowledge in education. Suggestions, Solutions, or Implementation: Efforts should be made to raise people's awareness. Organizing seminars and conducting practical training sessions are examples of solutions.	provided. Weaknesses and errors: The concept of sustainability is not clearly addressed (no mention of future generations or long-term impact). The problem definition is too general; it is unclear whether the problem is a lack of knowledge or a lack of behavior. The current situation analysis lacks data, comparisons, or concrete examples. The proposed solutions remain theoretical and lack detailed implementation. Recommendations for Improvement: The concept of sustainability should be clearly defined. The lack of environmental knowledge translated into behavior should be emphasized. Probability statements should be added to the current situation. Applied training, local projects, and behavior-oriented solutions should be proposed.
5	G17	Problem Definition: Unnecessary use of light on campus, 24/7 use of televisions or speakers in faculty cafeterias, constantly running machines in laboratories, computers in the library, ventilation in campus cafeterias, coffee machines. Current Situation Analysis: Currently, lighting and electrical appliances are often left on unnecessarily. Proposed Solutions or	Strengths: The main sources of electricity waste have been correctly identified (unnecessary lighting, devices left on) There is a current situation analysis. Heaters left on and lights used in the work area are listed. Focus on energy efficiency. Opening the door to more efficient solutions like ZED. Missing/ Erroneous Points: - Lack of numerical data; - Limited concept of sustain-

		Applications: Lighting systems could be energy-efficient. Equipment used in laboratories could be switched on and off as needed/when not in use.	ability; - Lack of economic dimension - Weak behavioral measures; - No mention of renewable energy. Concrete suggestions for improvement:* - Add measurable targets

The first research question of the study was defined as "How have student texts transformed in terms of language, content, and structure after the use of LLM?" The study observed that in all texts, the language of the texts was transformed in a more academic and fluent direction. Texts written in student language were developed with a scientific language, using carefully selected words and adhering to grammatical rules. In terms of content, while the information and interpretations given in all texts were accurate, a significant portion showed greater depth of meaning. The frequency of conceptual additions, deletions, or corrections was also noticeable, but similar transformations were observed repeatedly in text comparisons. Considering the structural characteristics of the texts transformed according to LLM, a significant portion of the texts were found to be consistent with the problem definition, current situation, and proposed solutions given at the beginning in terms of idea order and structure, and parallel changes were observed in the texts. The paragraph structure and the relationship between subheadings were expressed appropriately and consistently.

The second research question of the study was defined as "How do students' levels of intervention in the text vary in active-passive and critical-superficial contexts?" The prominent trends in students' intervention in the text are passive and superficial. It was understood that a significant majority of student groups did not intervene in the texts when expressing the LLM texts. It was frequently observed that students accepted the AI texts as they were after the command. Students trusted the texts transformed by the LLM and did not attempt to change or improve their own texts. A significant number of students accepted the texts without questioning the LLM, putting their own thoughts in the background. This situation can mostly be attributed to the students' passive and superficial approach to the LLM texts. The texts produced by the LLM were largely accepted. In addition, the fact that students accepted the text as it was rather than engaging in a critical structure indicates that they remained at a superficial level. Students did not significantly recreate the text; although they did not fully adopt the AI texts, they preferred to use minor word changes or semantic similarities. It was observed that with superficial intervention, the content remained constant, while the form changed to a certain extent. It would not be wrong to say that the students adopted an LLM-centric mindset at this point. The students' passive and superficial approaches are clearly seen in Table 1.

The third research question of the study was defined as "What are the students' opinions on artificial intelligence and large language models after the

application?" As the final stage of the study, students were asked to interpret the differences between the first text and the second text transformed by artificial intelligence. In the comparisons made between the student texts, positive common aspects such as "academic language improved, understandable language was used, concepts were understood more easily, and deeper explanations were provided" were noted. Most students stated that artificial intelligence and LLM improved their opinions. This trend should be considered together with the passive and superficial level of intervention of the students in the text, as stated in the previous sub-objective. The opinions of some randomly selected student groups are given below as an example.

Artificial intelligence used a more understandable language than we did, providing more comprehensive and detailed information. It gave us an 8/10, as it didn't provide much in terms of information compared to what we wrote (T1, G1).

We realized our shortcomings. We understood the harm it causes to human health and the food chain. We grasped the place of sustainability in plastic consumption (T2, G5).

Our definitions were incomplete and superficial, there was a lack of data analysis and research, it was an academically inadequate report, and our examples were not very explanatory (T1, G4).

We realized that we thought too traditionally, especially in the solution proposals section of the problem. When mentioning the people who could solve the problem, we generally focused on students. However, the university administration can also play an important role in solving the problem by making better plans (T5, G20).

The artificial intelligence generally liked everything in its writing, but I realized that I need to be more detailed, more conscious, and use more concrete data in my writing in the areas it found lacking. Therefore, I will pay more attention to writing more academically in my writings from now on (T4, G15).

The AI first told me where I went wrong. It pointed out our mistakes and shortcomings. It told us what we needed to pay attention to. It thoroughly enlightened us on this matter and gave us concrete suggestions on what to do (T3, G9).

5. Discussions, conclusions & recommendations

To raise awareness and improve understanding among students regarding the SDGs (Sustainable Development Goals) implemented worldwide by United Nations resolutions, an in-class activities using artificial intelligence (LLM) was planned for undergraduate primary school teacher training students within the scope of the Environmental Education course. Five topics were presented to the students in this context. The texts written by the students were transformed and analyzed using LLM. It was observed that transforming the student descriptions of environmental and sustainability concepts presented in the Environmental Education course into a more organized text, correcting misinformation and

misconceptions, and transforming the language of the assignment into a more scientific language. At the end of the activity, students largely stated that the LLM and artificial intelligence improved their ideas, increased their knowledge, and made learning more enjoyable. Furthermore, this study also brought to the forefront the interesting use of the internet and telephones for students, thus encouraging the effective but accurate use of artificial intelligence. As academics/instructors, we firmly believe that LLM is a great convenience in educational life and that it will alleviate academic workloads through its contribution of both ideas and time. This research presents findings on the potential benefits of using large language models in a controlled and pedagogically sound manner in lessons, both for students and educators. In this respect, the research is considered to be a guide for instructional designs involving the use of AI-supported activities in different courses and educational levels.

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Exploring engineering students' perceptions of immersive learning: A mixed-methods post-seminar study

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Abstract: *This study investigates engineering students' perceptions of immersive learning technologies following a structured hands-on seminar that introduced CAVE-based simulations, collaborative 3D environments, and digital-twin scenarios. Grounded in constructs aligned with technology acceptance and experiential learning frameworks, the study employs a mixed-methods design combining descriptive statistics, correlation analysis, and thematic coding of open-ended responses.*

Ninety-nine undergraduate engineering students completed a post-seminar survey assessing perceived usefulness, conceptual understanding, motivation, career relevance, hybrid-learning preference, and distraction. Results show high ratings for conceptual understanding and perceived usefulness, with strong correlations between career relevance, hybrid-learning preference, and perceived utility. Qualitative insights emphasise interactivity and visualisation as key pedagogical strengths, while highlighting technical constraints and equipment availability as prominent challenges.

Findings indicate that students view immersive environments as pedagogically valuable and professionally meaningful, provided that their implementation is supported by reliable infrastructure and coherent instructional design. The study contributes empirical evidence to ongoing discussions on simulation-rich and Metaverse-aligned engineering education, emphasising the need for scalable integration strategies and longitudinal evaluation.

Keywords: Immersive learning, CAVE, Virtual reality, Engineering education, Student perceptions, Educational technology, Mixed-methods analysis.

1. Introduction

Immersive and three-dimensional learning environments have transitioned from experimental demonstrations to increasingly viable components of engineering education. Their expansion aligns with broader pedagogical shifts towards spatial reasoning, interactive problem-solving, and scenario-based learning. Virtual reality, augmented reality, multi-user 3D spaces, and emerging Metaverse-aligned platforms now provide opportunities for learners to engage with engineering problems in ways that approximate authentic professional contexts. Recent reviews consistently report benefits when immersive technologies are

paired with coherent instructional design, including enhanced conceptual insight, improved spatial visualisation, and more authentic task engagement (Yang et al., 2024; Di Natale et al., 2024; Chua & Yu, 2024).

However, persistent limitations remain. The effectiveness of immersive learning depends on technological reliability, curricular integration, and the clarity of pedagogical guidance. Many studies highlight challenges involving scalability, ergonomics, and institutional readiness. While student reactions are generally positive, the foundations of this enthusiasm—and its relationship to perceived usefulness, motivation, hybrid-learning preference, and career relevance—are rarely examined in an integrated manner. Research comparing student and institutional readiness further suggests that student expectations may outpace implementation capacity (Qiu et al., 2023).

This study is conceptually informed by models of technology acceptance (Davis, 1989; Venkatesh et al., 2003) and experiential learning. Constructs such as perceived usefulness, motivation, satisfaction, and career relevance map well onto these frameworks, enabling a more structured interpretation of students' responses. By focusing on learner perceptions following direct exposure to immersive environments, the study aims to clarify how students interpret pedagogical value, how they differentiate short-term usability constraints from long-term relevance, and how these factors interrelate.

In March 2025, the Faculty of Engineering and Technologies at Trakia University organised a focused seminar exposing engineering students to CAVE-based demonstrations, collaborative virtual spaces, and digital-twin scenarios. This controlled event provided an opportunity to isolate student perceptions independent of ongoing curricular practices and institutional constraints.

The present study uses a mixed-methods design to integrate descriptive statistics, correlational analysis, and thematic coding of student reflections. It contributes to the literature by jointly examining perceived usefulness, conceptual understanding, motivation, satisfaction, hybrid-learning preference, and career relevance—constructs typically analysed in isolation. Through this integrated lens, the study seeks to support evidence-based, scalable strategies for embedding immersive technologies within engineering curricula.

2. Materials and methods

The study adopted a cross-sectional mixed-methods design to explore engineering students' perceptions immediately after participating in an immersive learning seminar. Quantitative constructs grounded in established technology-acceptance frameworks were combined with a qualitative thematic analysis intended to contextualise students' reflections in more depth. This integrated design enabled the examination of both numerical trends and the experiential nuances underlying student attitudes.

A total of ninety-nine undergraduate engineering students from the Faculty of Engineering and Technology at Trakia University took part in the study. All

participants had limited or no previous exposure to immersive learning technologies within their formal coursework. Participation was voluntary and anonymous, and no incentives or academic credit were provided, ensuring that responses reflected authentic impressions of the learning activities.

The immersive seminar itself consisted of three interconnected components: CAVE-based simulations, multi-user 3D collaborative environments, and demonstrations of digital-twin workflows. These activities were selected to familiarise students with different forms of spatial, interactive, and simulation-rich learning. Across all components, the emphasis was placed on enabling students to navigate and manipulate engineering representations in ways that approximated real-world professional tasks requiring spatial reasoning and coordinated interaction.

Following the seminar, students completed a post-seminar survey designed to capture both structured ratings and open reflections. The quantitative portion assessed six constructs: perceived usefulness, conceptual understanding, motivation, career relevance, hybrid-learning preference, and perceived distraction (reverse-coded) - each measured on a five-point Likert scale. An additional three-level satisfaction item was included to provide a broader evaluative perspective. These constructs were chosen because they align closely with theoretical dimensions in technology-acceptance and experiential-learning models and therefore offer a coherent basis for interpreting the relationships among student perceptions. The qualitative portion of the survey invited students to describe the benefits and challenges of the immersive experience, as well as potential future applications they envisioned within the curriculum.

The survey was administered immediately after the immersive session to minimise recall bias and ensure that responses reflected students' direct, unmediated impressions. No identifying information was collected. The dataset was reviewed for completeness and internal consistency, and all responses were retained.

The quantitative analysis involved calculating descriptive statistics, including means, standard deviations and 95% confidence intervals for each construct, followed by Pearson correlation coefficients to examine associations among the key variables. Prior to computing correlations, assumptions of linearity and approximate distribution symmetry were assessed through visual inspection of histograms and scatterplots. Statistical significance was evaluated at the $\alpha=.05$ level.

To complement the quantitative results, open-ended responses were analysed using a codebook-driven thematic approach. Two independent coders undertook the analysis beginning with initial open coding, followed by the iterative development and refinement of thematic categories. Coding discrepancies were discussed until full agreement was reached, and intercoder reliability (Cohen's κ), was .78, indicating substantial agreement. The final thematic structure reflected four recurring areas of student commentary: interactivity, visualisation, challenges and expectations.

3. Results

3.1 Descriptive statistics

Students provided consistently positive evaluations of the immersive learning session across all constructs (Table 1). Conceptual understanding received the highest rating ($M=4.04$, $SD=1.18$), followed closely by perceived usefulness ($M=3.98$, $SD=1.19$). Motivation, career relevance, and hybrid-learning preference showed identical means ($M=3.78$), indicating moderate-to-high openness to the incorporation of immersive tools within engineering programmes (Table 1).

Table 1. Descriptive statistics of student ratings

Construct	Mean	SD	95% CI
Perceived usefulness	3.98	1.19	[3.74, 4.22]
Conceptual understanding	4.04	1.18	[3.81, 4.28]
Motivation	3.78	1.12	[3.56, 4.01]
Career relevance	3.78	1.14	[3.55, 4.00]
Hybrid preference	3.78	1.20	[3.54, 4.02]
Distraction (reverse-coded)	2.25	1.21	[2.01, 2.49]

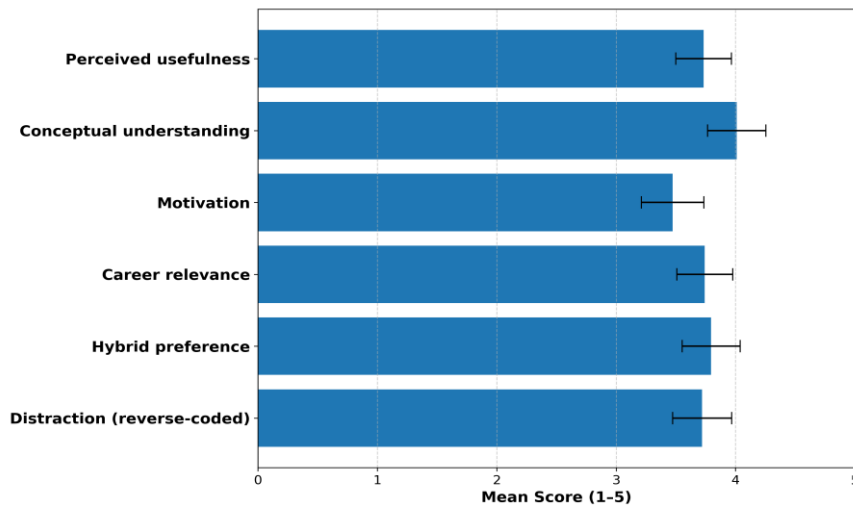


Figure 1. Summary of student perception ratings

Distraction (reverse-coded) yielded the lowest score ($M = 2.25$, $SD = 1.21$), suggesting that most students did not view the immersive environment as a barrier to focus.

These descriptive results indicate that students generally perceived immersive activities as learning-enhancing rather than novelty-driven, aligning with established findings in VR/AR engineering education research (Figure 1).

3.2 Correlational analysis

Pearson correlations revealed several strong and meaningful associations between constructs (Figure 2).

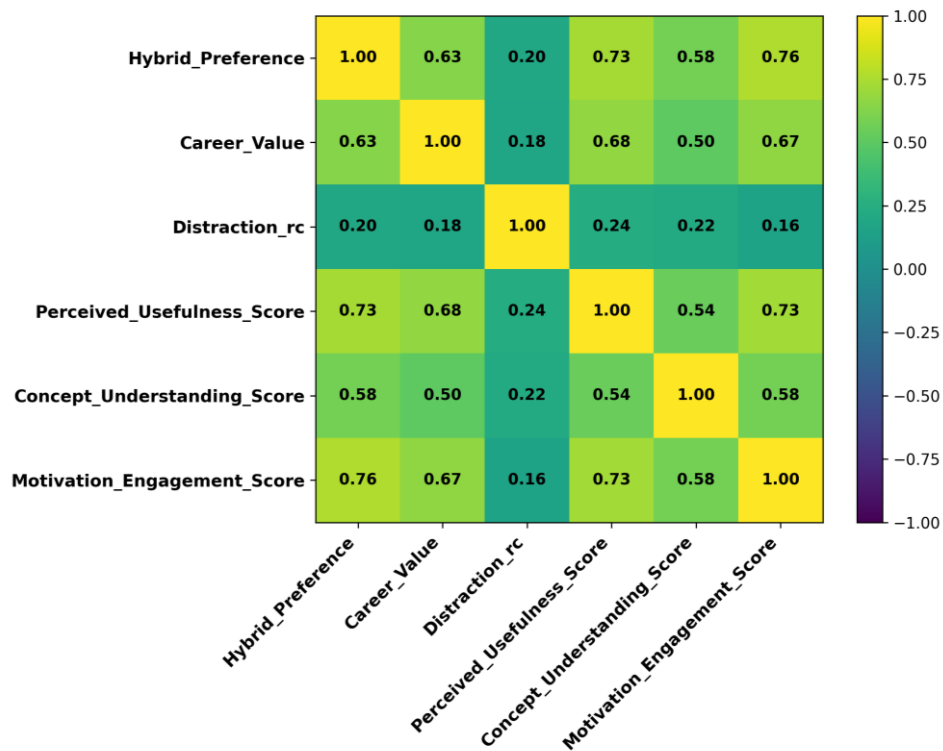


Figure 2. Correlation matrix of key constructs

Career relevance and hybrid-learning preference showed the strongest relationship ($r \approx .71$), indicating that students who viewed immersive tools as professionally valuable were more likely to support their integration into blended learning formats.

Career relevance and perceived usefulness were also strongly associated ($r \approx .59$), reinforcing the idea that students interpret immersive technologies through the lens of future employability and practical application.

Distraction (reversed-coded) and career relevance were positively correlated ($r \approx .68$), suggesting that students reporting fewer distractions also tended to report higher perceived career relevance.

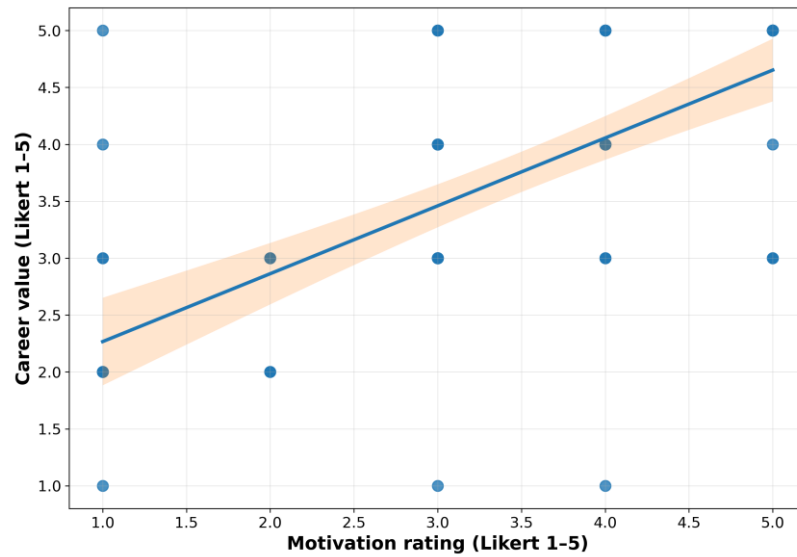


Figure 3. Motivation versus career relevance

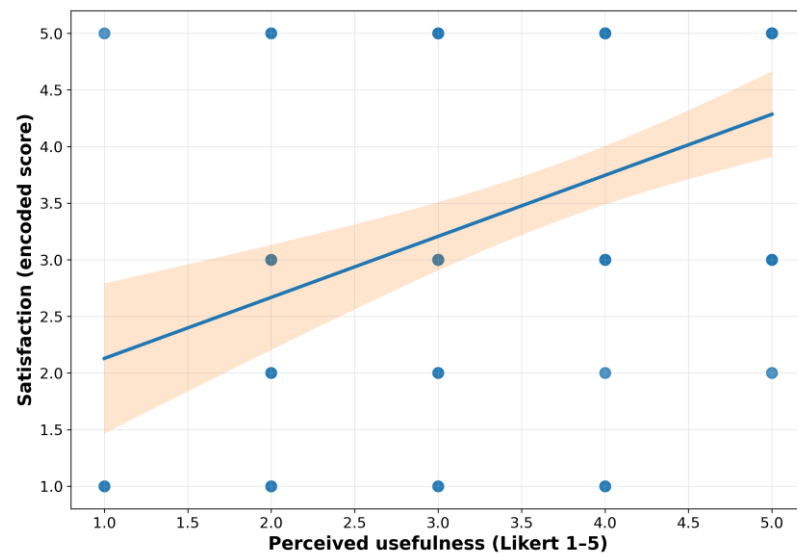


Figure 4. Perceived usefulness versus satisfaction

Motivation showed only moderate correlations with the remaining constructs ($r \approx .30-.40$ range), supporting the interpretation that motivation is multifactorial and shaped by broader experiential dimensions beyond usefulness or satisfaction.

Satisfaction correlated only weakly with usefulness and motivation, indicating that overall impressions are sensitive to implementation quality, system stability, and clarity of instruction.

Collectively, these patterns support a more nuanced understanding of how students position immersive learning within both academic and professional trajectories.

Motivation showed a moderately positive association with career relevance, indicating that students who view immersive technologies as professionally meaningful also tend to report higher levels of motivation. This pattern suggests that motivation is shaped not only by immediate engagement but also by perceptions of long-term applicability and future professional value (see Figure 3).

Satisfaction showed only a weak association with perceived usefulness, as indicated by the scattered pattern of data points. This suggests that students' overall impressions are influenced more by implementation quality—such as system stability, clarity of instructions, and ergonomic comfort—than by usefulness alone, a tendency that aligns with the qualitative comments provided by participants (see Figure 4).

3.3 Qualitative themes

The thematic analysis produced four overarching categories—interactivity, visualisation, challenges, and expectations—derived from 99 open-ended responses.

Interactivity: Students frequently described immersive environments as “engaging,” “hands-on,” and “more dynamic than traditional teaching.” Manipulating 3D models and observing immediate changes were cited as key to maintaining attention and improving conceptual reasoning.

Visualisation: Visualisation was the second most prominent theme, with students noting that immersive scenarios made complex engineering processes easier to understand. Concepts normally confined to static diagrams appeared “clearer,” “more realistic,” and “easier to grasp in space.”

Challenges: Despite the overall positive tone, students identified several obstacles:

- Occasional technical instability;
- Equipment limitations (e.g., insufficient devices for large groups);
- Physical discomfort or motion sensitivity for a minority of participants.

Notably, these challenges did not appear to reduce students' sense of long-term value.

Expectations and Future Application: Many students expressed a desire for greater integration of immersive tools in subjects involving system behaviour, design, and simulation. Comments suggested a readiness to use these tools beyond demonstration-level activities and within core engineering modules.

3.4 Integration of quantitative and qualitative findings

The qualitative insights reinforce the descriptive and correlational patterns. Interactivity and visualisation—two dominant themes—align directly with the high scores for conceptual understanding and perceived usefulness. Students exhibited

the ability to distinguish short-term usability constraints from long-term relevance, which is consistent with the strong correlations linking career relevance to other constructs.

Students' open expressions of readiness for broader curricular integration further support the view that immersive technologies are perceived not merely as innovative add-ons but as credible components of modern engineering workflows. This integrated perspective provides a foundation for more structured adoption strategies within hybrid instructional models.

4. Discussion

The findings of this study demonstrate that engineering students perceive immersive learning environments as both pedagogically meaningful and professionally relevant. High ratings for conceptual understanding and perceived usefulness suggest that immersive tools have clear potential to support understanding of complex engineering phenomena, particularly those requiring spatial reasoning and dynamic visualisation. This is consistent with previous VR/AR research showing that immersive representations facilitate deeper comprehension when combined with coherent instructional design (Yang et al., 2024; Di Natale et al., 2024).

From a theoretical standpoint, the results align strongly with technology acceptance models (Davis, 1989; Venkatesh et al., 2003). The constructs of **usefulness**, **motivation**, **satisfaction**, and **career relevance** map closely onto perceived utility, behavioural intention, and facilitating conditions. The strong association between career relevance and hybrid-learning preference suggests that students perceived professional value of immersive technologies plays a central role in shaping support for their curricular integration. This finding indicates that immersive learning is not merely viewed as an experiential enhancement but as a tool aligned with emerging engineering practices, including simulation-rich workflows and collaborative digital modelling.

The qualitative findings reinforce this interpretation. Students described immersive experiences as interactive, engaging, and cognitively clarifying. These reflections connect directly to experiential-learning principles, where active manipulation, embodied visualisation, and situated problem contexts promote deeper learning. The dominance of interactivity and visualisation as themes aligns with the high mean scores for conceptual understanding and usefulness.

A notable result is the positive correlation between distraction (reverse-coded) and career relevance. Although initially counterintuitive, this pattern suggests that short-term discomfort or ergonomic issues did not diminish students' long-term view of immersive technologies as professionally significant. In theoretical terms, students appear capable of differentiating between immediate usability limitations (often tied to hardware maturity) and broader educational value. This aligns with findings in immersive-technology adoption research, where early-stage technical friction coexists with perceived strategic relevance.

Motivation's moderate correlations with other constructs further highlight its multifactorial nature. The weak association between satisfaction and usefulness indicates that implementation factors—such as system stability, device availability, and instructional framing—play a critical role in shaping overall impressions. This underscores the importance of robust infrastructure and pedagogical scaffolding in supporting adoption efforts.

Overall, the integrated quantitative and qualitative results reveal a student cohort that is highly receptive to the use of immersive technologies in engineering education. However, this enthusiasm is conditional: students expect reliable systems, structured guidance, and alignment with authentic engineering tasks. These expectations reflect a mature, academically grounded perspective that can inform strategic decisions about how immersive tools are embedded within engineering curricula.

5. Conclusion

This study demonstrates that immersive learning environments can meaningfully support engineering education when they are deliberately integrated into instructional design. Students reported high levels of conceptual clarity and perceived usefulness after engaging with CAVE-based simulations, collaborative 3D environments, and digital-twin demonstrations. These evaluations, together with strong links between career relevance, hybrid-learning preference, and perceived utility, indicate that students view immersive technologies not as temporary novelties but as tools connected to emerging engineering practice. Qualitative reflections further emphasised the value of interactivity and visualisation for understanding complex concepts, while also identifying practical concerns related to technical stability, equipment availability, and ergonomics.

Although these findings offer important insights, they reflect the perceptions of a single cohort in a controlled, short-term context and rely on self-reported data, which limits broader generalisation and does not capture long-term learning effects.

Taken together, the results suggest that immersive environments hold considerable promise as components of simulation-rich and hybrid engineering curricula, provided they are supported by reliable infrastructure and clear pedagogical framing. Future work should extend these findings through longer-term studies and cross-context comparisons to better understand how immersive technologies can be scaled and sustained in engineering education.

Acknowledgements

The paper is part of the research project Metaverse Approach for a New Generation of Engineering Education and Collaborative Learning (MAGURA), within the framework of Project No. BG-RRP-2.004-0006-C02, titled 'Development of Research and Innovation at Trakia University in Service of Health and Sustainable Well-being'.

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Faculty and student perceptions of the metaverse in higher engineering education: A comparative study

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Abstract: *This study examines how students and faculty perceive the use of metaverse technologies in higher engineering education. Within the MAGURA project, 98 students and 35 faculty members participated in a shared immersive training seminar. We used a mixed-methods design: k-means clustering of student Likert-scale responses and thematic analysis of open-ended faculty statements supported by natural language processing. A pre-post comparison of faculty attitudes was also conducted to gauge change after the seminar.*

Three student profiles emerged: Highly Engaged Enthusiasts, Moderate Adopters, and Sceptical/Unconvinced learners. These profiles differed in motivation, conceptual understanding, and interest in further immersive training. The elbow method supported the choice of a three-cluster solution. Faculty views formed three corresponding groups: Pedagogical Innovators, Tech-Realists, and Cautious Sceptics, reflecting different balances between opportunity and feasibility. Faculty attitudes shifted positively after the seminar (mean score increased from 2.79 to 4.12 on a 5-point scale).

Students most often emphasised interactivity, gamification, and novelty, whereas faculty focused on structure, feasibility, and support needs. Despite these different priorities, both groups recognised the value of immersive environments for visualisation and learner engagement. The paper offers a two-sided analytical framework and practical recommendations for sustainable adoption, including hybrid delivery, faculty co-design, targeted professional development, and planning for institutional infrastructure.

Keywords: Metaverse, CAVE, Immersive environment, Virtual reality, Engineering education.

1. Introduction

Immersive tools such as virtual reality (VR), augmented reality (AR), and metaverse platforms are moving from demonstrations to limited use in higher education, including engineering. They promise more visual, hands-on work with complex concepts, which is why interest has grown in recent years (Mystakidis, 2022; Lee et al., 2021). At the same time, the evidence for when and how these tools add value is still uneven, and the costs in time, training, and infrastructure are not trivial.

In practice, the readiness gap is most visible between students and staff. Many instructors are cautious, often due to limited experience, unclear teaching scenarios, or lack of support (Selwyn, 2016; Park & Kim, 2022). Students are

<https://doi.org/10.58503/icvl-v21y202636>

generally curious and willing to try new formats, even without prior exposure (Hwang & Chien, 2023). This tension creates both resistance and an opportunity to rethink how we introduce and support immersive learning.

This study examines perceptions on both sides after a shared training activity delivered within the MAGURA project. Ninety-eight students and thirty-five faculty members participated in the same immersive seminar, then provided feedback. We analyse student survey data and open-ended faculty responses to identify where views converge, where they diverge, and what would help adoption in real courses.

Our aim is straightforward: to show what each group values, what concerns they have, and what kind of support they need. Based on these insights, we suggest practical steps such as training, collaboration with faculty, and clear curriculum use cases. These steps can help make metaverse tools part of everyday engineering education, rather than isolated experiments.

2. Theoretical background

Interest in immersive learning has accelerated in higher education, with virtual reality (VR), augmented reality (AR), and metaverse platforms used for more visual, interactive work with complex ideas. Reviews note both promise and limits: benefits often hinge on authentic tasks, course alignment, and the practicalities of implementation (Lin, Lee & Liu, 2022). A decade-scale overview similarly points to growing use of visualisation, simulation, and scenario-based activities—areas where immersion is most likely to help (Tsoy, Turgunova, & Baek, 2023).

Recent studies track outcomes and readiness. Work on AR/VR reports gains in targeted skills and digital literacy, but results vary with context and learner preparation (Prabakaran, Widiastuti, & Suryani, 2024). Readiness research suggests that students are generally open to metaverse-enhanced learning, while existing indices may need adjustment to capture this setting more precisely (Garbutt, Jones & Hill, 2023).

Engineering education adds its own constraints. Classroom examples illustrate the value of immersive visualisation, alongside practical hurdles such as staff training, time, and infrastructure (Abidin et al., 2023). Studies of teacher-student interaction in VR-enhanced lessons reach a similar conclusion: sound pedagogy and institutional support are as critical as the technology itself (Lytvynova & Soroko, 2023). Beyond tools, broader digital preparedness matters; future teachers report confidence with digital learning, yet still need focused support in areas such as cybersecurity and data protection (Latorre-Medina & Tnibar-Harrus, 2023).

Notable gaps remain. Much of the literature focuses on either students or faculty, not both, and single-method designs are common. Pre-post designs that test whether short training changes attitudes are rarer. The present study addresses these points by combining student surveys with faculty reflections, applying statistical clustering and thematic text analysis, and including a before-and-after comparison

of faculty attitudes. The aim is to provide a clear, bounded view of what helps (and hinders) meaningful use of metaverse technologies in engineering education.

3. Materials and methods

The study used a mixed-methods approach to examine how students and faculty perceive immersive learning and Metaverse technologies. It was conducted in March 2025 during a structured training seminar at the Faculty of Engineering and Technologies, Trakia University – Yambol, as part of the MAGURA project.

A total of 98 undergraduate engineering students and 35 faculty members from engineering disciplines participated in the study. All participants attended a hands-on seminar that included work with a CAVE system and interactive virtual simulations designed for engineering education. For most participants, this was their first systematic exposure to Metaverse and CAVE technologies in an educational context. The survey did not collect detailed individual demographic data; however, all participants shared a similar academic and institutional environment. This common context allowed the analysis of perceptions formed through a shared immersive experience.

After the seminar, students completed a questionnaire that included Likert-scale items (from 1 to 5) and open-ended questions. The quantitative items focused on motivation, understanding of course content, engagement, and perceived career relevance. The open-ended questions allowed students to comment freely on possible applications and learning challenges. Faculty members completed two surveys, one before and one after the seminar. The first captured initial expectations and attitudes, while the second focused on reflections, perceived challenges, and potential applications in teaching.

Quantitative analysis of the student data began with descriptive statistics, followed by k-means clustering to identify engagement profiles. Principal Component Analysis (PCA) was used to visualise the clustering results. Relationships between motivation, understanding, and perceived career relevance were examined using correlation analysis. For faculty, a pre-post comparison was conducted on an item measuring overall attitudes towards immersive learning, with responses converted into numerical values.

Faculty open-ended responses were analysed thematically, supported by natural language processing. Text data were cleaned and standardised, then converted into vector representations using TF-IDF (term frequency-inverse document frequency). k-means clustering was applied to group responses with similar linguistic patterns. The resulting clusters were examined by the research team using key terms and representative excerpts, leading to the definition of thematically meaningful categories. The analysis was implemented using standard Python libraries, primarily scikit-learn.

This mixed approach provided a more complete understanding of the findings. By combining quantitative and qualitative data, the results could be examined from different perspectives and cross-validated across methods.

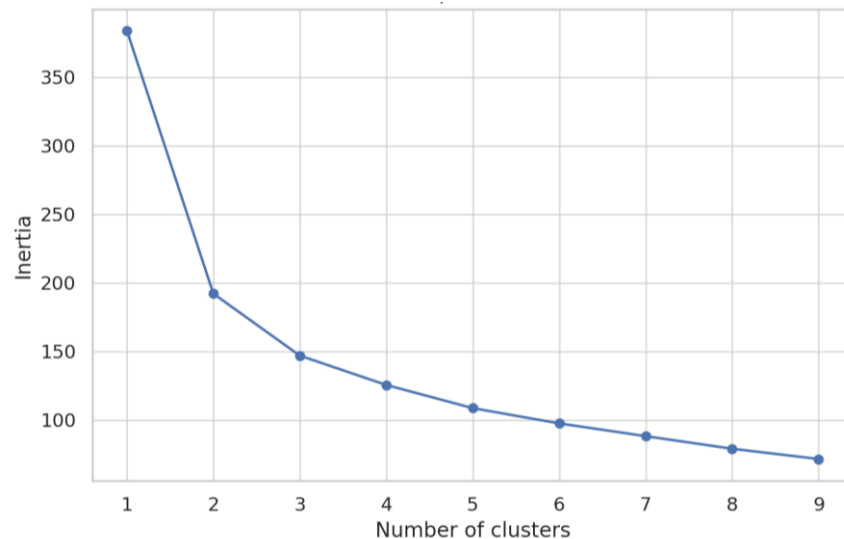


Figure 1. Elbow Method for Optimal Number of Clusters

The elbow method was used to identify an appropriate number of clusters for the k-means analysis. The method examines changes in inertia, which reflects how compact the clusters are for different cluster counts. In this study, the plot showed a clear inflection point at three clusters, after which further improvements were minimal. This supported the choice of three clusters as a balance between explanatory power and analytical simplicity. The same approach was applied to both student data and faculty responses.

The combination of methods and perspectives is a key strength of the study. Unlike many previous studies that focus only on students or only on faculty, this research examines both groups following the same shared training experience. In addition to survey scores, open-ended responses were analysed using NLP-based clustering, an approach still rarely applied in educational research. The study also tracked changes in faculty attitudes before and after the seminar, allowing the impact of even a short training intervention to be observed. The use of the Elbow Method further increased analytical transparency and reduced arbitrary decisions in participant grouping.

4. Results

4.1 Student profile clusters (quantitative analysis)

Cluster analysis of post-seminar student survey data revealed three distinct engagement profiles based on Likert-scale responses across four key dimensions: perceived conceptual understanding, motivation, interest in further metaverse-based training, and perceived career relevance.

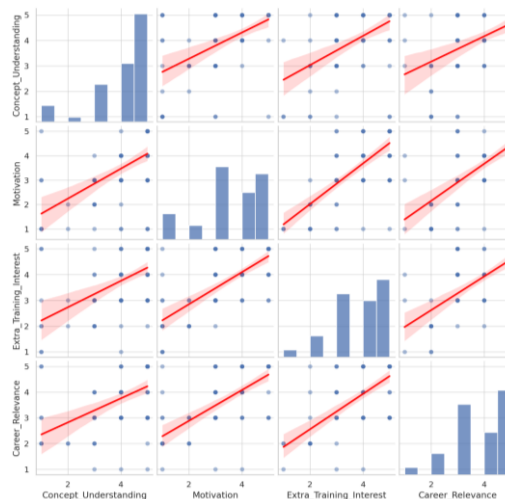
Table 1. Student cluster profiles: mean scores by dimension

Cluster	Concept Understanding	Motivation	Extra Training Interest	Career Relevance
Highly Engaged Enthusiasts	4.80	4.60	4.68	4.75
Moderate Adopters	3.92	3.18	3.58	3.38
Sceptical or Unconvinced	2.50	1.56	2.06	2.38

Using k-means clustering and PCA visualisation, students were grouped into three categories:

- Highly Engaged Enthusiasts (Cluster 1): This group exhibited the highest mean ratings across all dimensions, particularly in motivation (M=4.60) and career relevance (M=4.75). These students also showed strong interest in continued participation in immersive learning experiences and preferred gamified and interactive elements;
- Moderate Adopters (Cluster 0): With average-to-high scores in perceived usefulness (M=3.92) and hybrid format preference, this group expressed openness to Metaverse tools but with more conditional enthusiasm;
- Sceptical or Unconvinced (Cluster 2): This smaller group reported low motivation (M=1.56) and limited belief in the relevance of immersive learning for their future careers. Their challenges centred on unfamiliarity with the tools and a lack of initial engagement.

As shown in Figure 2, the scatterplots summarise the pairwise relationships among motivation, conceptual understanding, and perceived career relevance. Trend lines are included to support visual comparison of the direction and strength of the patterns.

**Figure 2.** Pairwise scatterplots of student motivation, conceptual understanding, and perceived career relevance, with fitted trend lines

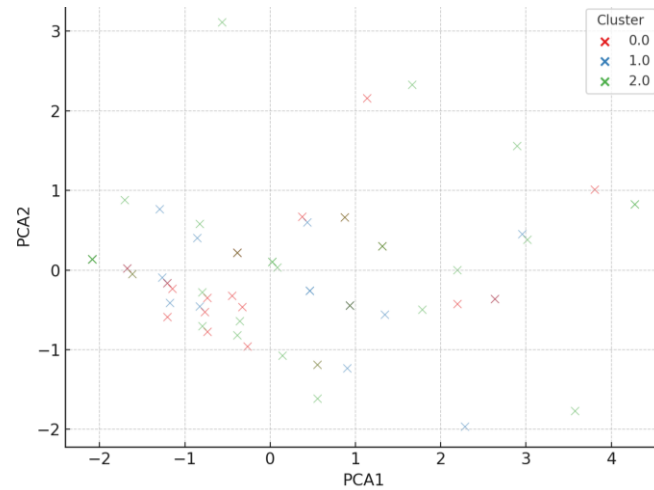


Figure 3. PCA-Based Student Cluster Visualisation. K-means clusters of students projected in 2D space using principal component analysis

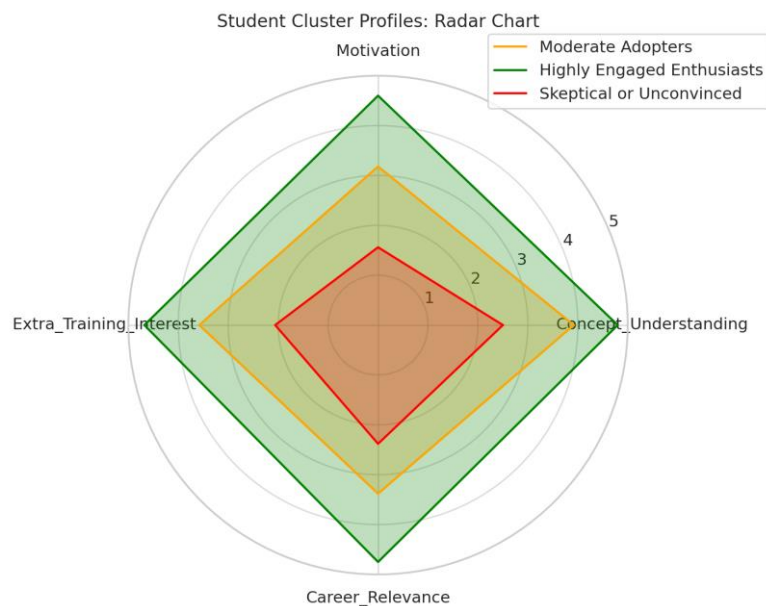


Figure 4. Radar chart of mean scores across four dimensions for the three student clusters

Figure 3 visualises the three k-means clusters in a two-dimensional PCA space (PC1–PC2). The plot provides an intuitive view of cluster separation and overlap in the reduced feature space.

As shown in Figure 4, the three clusters differ in their mean dimension scores. Highly Engaged Enthusiasts demonstrate uniformly higher ratings, Moderate Adopters occupy an intermediate position, and the Sceptical/

Unconvinced group reports lower ratings across dimensions. This pattern supports the interpretation that students' attitudes towards immersive technologies are heterogeneous.

4.2 Faculty response clusters (qualitative thematic analysis)

A parallel unsupervised text-clustering analysis was conducted on open-ended faculty responses using TF-IDF vectorisation and k-means modelling. The resulting three clusters illustrate a diverse range of attitudes and expectations towards immersive learning:

- Pedagogical Innovators (Cluster 0): Faculty in this group emphasised the instructional potential of metaverse tools for improving visualisation, engagement, and interactivity. Challenges included limited training and instructional design support, while expectations centred on fostering creativity and innovation in engineering education;
- Tech-Realists (Cluster 1): These respondents viewed immersive technologies pragmatically, recognising their practical value for safe experimentation and visualisation, yet voicing concerns about infrastructure costs, student preparedness, and selectivity in use;
- Cautious Sceptics (Cluster 2): This group acknowledged some benefits but expressed concerns about feasibility, including reduced faculty-student interaction, insufficient support systems, and uncertainty regarding the pedagogical return on investment.

Representative excerpts from each cluster illustrate the range of faculty readiness, with some calling for strategic integration and others advocating a more conservative approach.

Table 2. Faculty cluster comparison: key themes and attitudes

Cluster	Engagement Level	Key Interests	Challenges	Support Needs
Pedagogical Innovators	Positive and proactive	Interactivity, creativity, visualisation	Training, time investment, content design	Institutional incentives, design support
Tech-Realists	Conditional	Practical value, safe experimentation	Cost, staff capacity, student preparedness	Selective use, targeted training
Cautious Sceptics	Low to moderate	Basic visualisation, concept clarity	Communication gaps, feasibility concerns	Clear strategy, baseline institutional support

4.3 Student-faculty cross-cluster comparison

A side-by-side comparison of student and faculty clusters revealed both alignment and divergence. Table 3 summarizes the main points:

Table 3. Student–Faculty cross-cluster matrix: shared features and divergences

Student Cluster	Faculty Cluster	Shared Features	Key Divergence
Highly Engaged Enthusiasts	Pedagogical Innovators	Emphasis on interactivity and visualisation	Students want gamification; faculty seek structure
Moderate Adopters	Tech-Realists	Conditional acceptance	Students uncertain of value; faculty wary of cost
Sceptical or Unconvinced	Cautious Sceptics	Low confidence in readiness	Students cite motivation; faculty cite feasibility

These findings highlight the need for strategic alignment of expectations and implementation support.

4.4 Summary of faculty expectations and concerns

Analysis of faculty narratives yielded several recurring themes:

- Training Needs (33 mentions): A clear demand for structured onboarding, including both technical and pedagogical training;
- Cost and Equipment (29 mentions): Concerns about infrastructure investment and access to suitable hardware;
- Engagement Potential (29 mentions): Optimism about improved motivation and participation, provided tools are well-integrated;
- Pedagogical Integration (19 mentions): Questions regarding curriculum fit and instructional design;
- Student Readiness and Communication (low frequency): Some noted the risk of reduced interpersonal contact and uneven student preparation.

These themes emphasise the necessity of institutional support systems to ensure sustainable and effective integration of metaverse technologies in engineering education.

Table 4. Frequency of Recurring Faculty Themes. Ranked list of themes mentioned in post-seminar responses

Theme	Mentions
Training	33
Cost & Equipment	29
Engagement Potential	29
Pedagogical Integration	19

Theme	Mentions
Student Readiness	5
Communication Challenges	3
Technical Support	1
Time Constraints	1
Selective Use	0

4.5 Faculty attitude shift: Pre- and Post-seminar comparison

Faculty attitudes towards immersive learning technologies were compared before and after their participation in the Metaverse seminar. Pre-seminar responses were collected using a 5-point Likert-scale question measuring familiarity and openness. Post-seminar attitudes were inferred from corresponding qualitative descriptors and mapped onto the same scale.

The average faculty attitude score prior to the seminar was 2.79, indicating a neutral to slightly hesitant stance. After the seminar, the mean score increased to 4.12, reflecting a shift towards a clearly positive outlook. This suggests that even a short-term intervention—focused on exposure, hands-on experience, and discussion—can significantly influence instructors' perceptions.

This finding aligns with broader literature emphasizing the impact of guided training on faculty technology adoption (Park & Kim, 2022) and underscores the importance of experiential learning not only for students but also for educators.

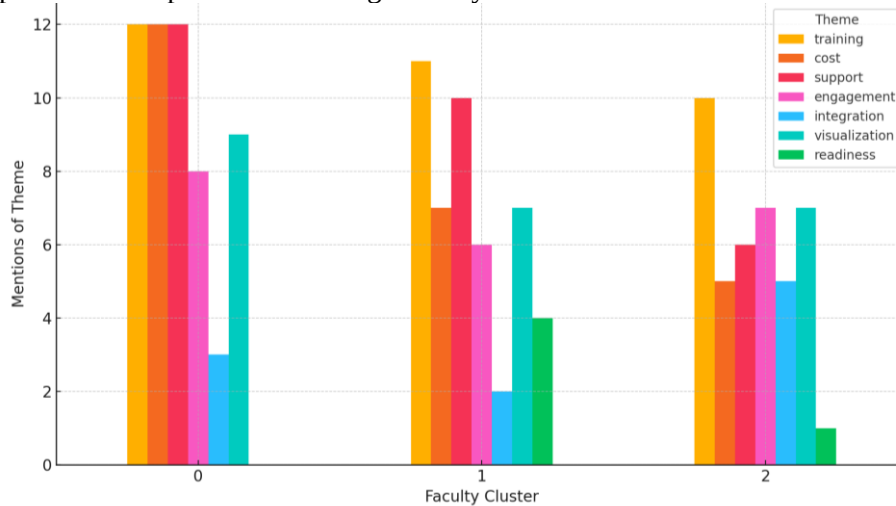


Figure 5. Faculty cluster-based thematic map (sampled open-ended responses per cluster)

5. Discussions

The comparative analysis reveals both clear alignment and important differences between student and faculty perceptions of immersive technologies in engineering education. Both groups recognise the potential of Metaverse

environments to improve visualisation and engagement. At the same time, students show stronger enthusiasm and a greater focus on the learning experience itself. Faculty responses are more cautious and reflect concerns related to pedagogy, resources, and institutional readiness.

Limited prior experience with Metaverse technologies is a key factor in interpreting these differences. For many students and faculty members, the seminar was their first structured encounter with an immersive learning environment. This helps explain the clearly defined profiles and the strong initial reactions. Positive attitudes are linked to novelty and perceived pedagogical value, while more cautious or sceptical views reflect uncertainty about long-term use and practical feasibility. In this sense, the identified profiles represent differences in readiness to adopt the technology rather than stable personal traits. The absence of more detailed demographic variables limits deeper differentiation and points to directions for future research.

The findings should also be interpreted within the single-institution context of the study. Data were collected within one faculty and a specific project, which limits statistical generalisation to a wider population of students and educators. The aim of the analysis, however, was not population-level inference but the identification of analytically meaningful perception profiles formed after a shared immersive experience. From this perspective, the student and faculty clusters can be viewed as transferable typologies rather than fixed patterns tied to a single institution. Similar profiles may emerge in other engineering education contexts when immersive technologies are introduced under comparable conditions. The proposed analytical framework provides a foundation for future comparative and multi-institutional studies.

Particular attention should be given to the group of “Highly Engaged Enthusiasts.” These participants show high motivation, positive attitudes, and a clear interest in further use of immersive technologies in education. They can be seen as early adopters of Metaverse solutions and play an important role in the initial stages of implementation. Through feedback, application ideas, and participation in pilot activities, they can support experimentation and adaptation. At the same time, their enthusiasm should not be treated as representative of all students. The findings highlight the need for a balanced approach that also considers the views of moderately engaged and sceptical participants. This points to a key limitation of the study, which captures short-term perceptions after a brief intervention, and underlines the need for longer-term observation.

The differences between the two groups have important implications for implementation. Faculty readiness emerges as a central factor, not due to resistance, but because of limited training, time, and structural support. Student enthusiasm can drive pilot initiatives, but it is not sufficient on its own for sustainable adoption. The presence of moderately positioned participants in both groups suggests opportunities for targeted interventions that could support wider acceptance. The results also show that even a short, well-designed training

intervention can lead to meaningful changes in faculty attitudes when supported by a clear pedagogical framework and an enabling institutional environment.

6. Conclusion

This study offers a comparative view of how students and faculty perceive the use of Metaverse technologies in engineering education. Students show high engagement and interest, while faculty display a more cautious but generally positive stance shaped by concerns related to training, resources, and pedagogical fit. Cluster analysis indicates that both groups include supporters, moderate participants, and sceptics, although the reasons behind these positions differ. For students, novelty and direct experience are key drivers, while for faculty, institutional readiness and alignment with the curriculum play a central role.

The findings highlight that sustainable adoption of immersive technologies requires targeted institutional support. Structured training for faculty, collaborative course development, and phased implementation are essential. The study contributes a two-sided methodological framework that combines quantitative and qualitative analysis and enables clear identification of different perception profiles. The conclusions and recommendations presented here can support universities in planning strategies for integrating Metaverse technologies in ways that enhance educational quality and address the needs of both students and faculty.

Acknowledgements

The paper is part of the research project Metaverse Approach for a New Generation of Engineering Education and Collaborative Learning (MAGURA), within the framework of Project No. BG-RRP-2.004-0006-C02, titled 'Development of Research and Innovation at Trakia University in Service of Health and Sustainable Well-being'.

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The selective portfolio: Merging authentic and digital assessments in the age of generative Artificial Intelligence

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Abstract: *This article explores the selective portfolio as a pedagogical tool that bridges the gap between authentic and computer-based assessments. Authentic assessment, which emphasizes the development of skills through real-world tasks and both formative and summative feedback, requires flexible tools that capture students' learning processes and outcomes. Digital assessment provides immediate feedback and analysis of learning, supporting transparent, dynamic, and student-centered practices. The selective portfolio combines the strengths of both, capturing the learning journey and encouraging critical thinking and self-assessment. With the advent of Artificial Intelligence, the integration of AI-based analytics into the portfolio enhances its role by providing real-time feedback and personalized insights, further supporting skill development. This paper provides a conceptual and methodological analysis of the bridge between authentic and digital assessments, focusing on the impact of the selective portfolio on skill development. The analysis reveals that the selective portfolio in the form of AI-powered selective portfolio facilitates continuous, personalized assessment, promotes deep engagement, and strengthens critical thinking throughout the learning process. In conclusion, the selective portfolio emerges as a key pedagogical tool that integrates authentic and digital assessments, enhancing digital literacy and learning in the age of artificial intelligence. The paper also reports exploratory empirical findings from a survey conducted among teachers, examining perceptions and practices related to AI-supported selective portfolios.*

Keywords: Authentic assessment, Computer-based assessment, Assessment for learning, AI-powered selective portfolio, Professional competence.

1. Introduction

The profound transformations generated by the digitalization of education have led to a significant reconfiguration of teaching, learning and assessment practices, requiring new evaluative approaches that focus on competences, relevance and authenticity (Redecker, 2017; Voogt et al., 2018). In this context, traditional assessment, predominantly formative and summative tests on paper and oriented towards the reproducible verification of knowledge, proves to be an insufficient tool to capture the complexity of learning processes (Black and

William, 2009). Authentic assessment appears as an evaluative paradigm that uses meaningful, contextualised and transferable tasks for socio-professional integration, which require workplace competences, social integration, adaptation and resilience to the professional environment (Wiggins, 1998; Gulikers, Bastiaens & Kirschner, 2004).

As Villarroel et al. (2018) noted, authentic assessment is linked to Assessment for Learning (AFL) movement, which allows teachers to collect information to adjust their teaching and helps students regulate their own learning. Four concepts are essential: authenticity (which includes realism, contextualization, and problematization in teaching and evaluating curriculum content), *realism* (linking knowledge to everyday life and work), *contextualization* (referring to situations in which knowledge can be applied in an analytical and thoughtful way), and *problematization* (which emphasizes that what is learned can be used to solve a problem or meet a need). Authentic assessment promotes problem-solving, autonomy, motivation, metacognition, and self-regulation.

Computer-based assessment is another paradigm that enables efficient, flexible, transparent and integrative assessment practices, facilitating continuous monitoring of student progress, immediate formative feedback and personalization of learning processes (Crisp, 2012; Bennett, 2015). The adoption of electronic assessment in both schools and universities is particularly attractive to educators as it offers time savings through the automation of grades (Iannone, Lemmo, and Kinnear, 2026). However, the use of digital technologies in assessment does not automatically ensure authenticity; therefore, it is essential to use appropriate pedagogical tools to ensure the relevance, validity and reliability of assessment practice (Boud & Falchikov, 2007; Jartarghar, Hegade & Shettar, 2025).

The aim of this article is to analyse the link between authentic and digital assessment in a selective portfolio, highlighting its pedagogical potential for developing competences. Specifically, it aims to explore how the selective portfolio can integrate both process-oriented and outcome-based approaches to assessment, encouraging reflection, self-regulation, critical thinking and active engagement in learning. By examining the interaction between authentic and digital assessment methods, this article aims to demonstrate how the selective portfolio supports personalised learning, enhances the relevance and validity of assessments and contributes to a dynamic, student-centred educational experience.

2. Literature review

In assessment research, the promotion of authenticity in education aligns with Dewey's philosophy of learning, which emphasizes democratic and experiential approaches in which learners engage with real-world problems and contexts. Such engagement fosters deeper understanding of the problem and critical thinking regarding how to solve. Authentic assessment reflects this pedagogical orientation by prioritizing tasks that mirror real-life challenges and transformation. From this perspective, authenticity in assessment is grounded in the

belief that learning should extend beyond the acquisition of knowledge to encompass the development of practical skills applicable in both personal and professional competences.

Dewey's learning theory challenges traditional models of education by rejecting authoritarian structures and conventional pedagogical practices, including assessment approaches that prioritize passive knowledge reproduction. He advocated for a learner-centered educational process grounded in free expression and active participation, principles that underpin authentic assessment. From this perspective, assessment should engage learners in meaningful, real-world tasks that reflect genuine learning experiences rather than abstract or decontextualized measures of achievement (Sikandar, 2015). However, as Edling (2025) observes, scholarly dialogue constitutes the primary mode of communication between teachers and students, as well as among students themselves. Within this framework, assessment design plays a critical role, as authentic assessment must be participatory. For this is important to opt for an 'dynamic and flexible instructional strategy' (Railean, 2014) that could integrate authentic and digital assessment.

As Bialystok (2017) notes, the increasing emphasis on connecting learning to real-world contexts has contributed to the development of authentic curricula, authentic assessment, and pedagogical approaches that foreground learning through assessment. This movement has shaped ongoing debates concerning constructivist and realist perspectives in education. While authenticity in assessment is a critical component of meaningful learning, educational outcomes are also influenced by the motivational factors that drive students' engagement with and exploration of real-world contexts. From a psychological perspective, Scott and Campos (2024) distinguish among existential authenticity, which is grounded in self-identity; constructive authenticity, which derives from socially constructed values; and objective authenticity, which is based on trust in expert judgment. Within this framework, pleasure emerges from the successful attainment of a desired goal, such as acquiring a valued object or outcome.

In management, authenticity is understood at both superficial and deeper levels. Superficially, it denotes what is "real" or "genuine," but deeper conceptions involve alignment of internal values with external expressions, conformity to social norms, and connections to people, places, or times (Lehman, O'Connor, Kovács, and Newman, 2019). This understanding is critical in digital assessment. Consistent with Dewey's emphasis on experiential and reflective learning, assessments shape both students' thinking and behavior (Railean, 2020). Digital assessments should foster reflection, self-regulation, critical thinking, and active engagement. Selective digital portfolios exemplify this approach, bridging authentic and computer-based assessment, supporting process- and outcome-oriented evaluation, and promoting learner involvement. Integrating artificial intelligence further enhances these portfolios by providing personalized feedback, tracking progress in real time, and enabling targeted interventions, facilitating an adaptive, student-centered approach aligned with individual learning needs.

In management and education, authenticity is understood at both superficial and deeper levels. Superficially, it denotes what is “real” or “genuine,” but deeper conceptions involve alignment of internal values with external expressions, conformity to social norms, and connections to people, places, or times (Lehman, O’Connor, Kovács & Newman, 2019). This deeper understanding is particularly important in assessment design. Consistent with Dewey’s emphasis on experiential and reflective learning, assessments shape both students’ thinking and behavior (Railean, 2020). Digital assessments foster metacognition, self-regulation, critical thinking, and active engagement, rather than merely measuring static outcomes.

The selective portfolios model exemplifies this approach, bridging authentic and digital assessment because support both process- and outcome-oriented evaluation. Artificial intelligence (AI) tools could enhance the capacity of these portfolios. Examples of AI-supported tools used for assessment and learning analytics include, Turnitin, Quizlet, Knewton, Socrative, DreamBox Learning, and Gradescope provide capabilities for originality checks, adaptive learning, formative assessment, personalized lesson adjustment, and automated grading with detailed feedback. These tools illustrate how AI can support integrity checks, adaptive learning, and feedback loops within portfolio-based assessment. These tools enable real-time, data-driven insights, supporting targeted interventions and a personalized, student-centered approach. By leveraging these technologies, assessments can be aligned with individual learning needs and goals, capturing both authentic engagement and measurable competencies in meaningful, real-world contexts. From this discussion, the following research question arises: *How can authentic and digital assessments be effectively integrated into selective portfolios in the age of generative artificial intelligence?*

3. Research methodology

This study adopts an exploratory research design aimed at capturing teachers’ perceptions, practices, and challenges rather than producing generalizable results. A mixed-methods approach was employed, combining qualitative and quantitative techniques to examine how selective digital portfolios bridge authentic and digital assessment. The qualitative component included a literature review and Google N-gram analysis to identify trends related to authentic assessment, digital portfolios, and AI integration in education. The quantitative component was based on the assumption that assessment theories can be examined across contexts of space and time, with “space” conceptualized as a continuum from real-world to virtual learning environments. Within this continuum, digital technologies, including AI tools function as resources that mediate learning achievements.

Empirical data were collected through a structured online questionnaire, designed in alignment with the study’s objectives and theoretical framework. The survey investigated teachers’ perceptions, practices, and challenges regarding the use of AI-based selective digital portfolios. These portfolios were conceptualized as integrative tools supporting competency-based evaluation, formative feedback, student reflection, and AI-assisted content creation, organization, and assessment.

The questionnaire, administered via Google Forms, ensured accessibility, efficiency, and anonymity of the respondents' responses. It comprised five thematic sections related to professional and personal data; familiarization with and use and scope of selective portfolio; roles and educational value of selective portfolios; the impact on student skills; and challenges and implementation perspectives.

Items included closed-ended questions, Likert-scale ratings (1–5), and open-ended questions to capture both quantitative and qualitative data. This design provided a comprehensive and coherent view of how teachers perceive and implement AI-enhanced selective portfolios in practice. Given the exploratory nature and limited sample size, findings are indicative rather than representative, highlighting trends and insights to inform future research and practice.

3.1 Integrating authentic and digital assessment through the selective portfolio

This section examines the growing body of global research on authentic assessment, digital assessment, and the role of the selective portfolio in bridging these approaches. By integrating both authentic and digital assessment practices, the selective portfolio has emerged as a powerful pedagogical tool that supports continuous, personalized, and reflective learning. Since 2015, the rapid diversification of learning environments driven by the application of educational technologies in both physical and virtual settings has accelerated the convergence of digital portfolios, authentic assessment, digital assessment, and artificial intelligence in the field of education, creating new opportunities for adaptive, personalized, and student-centered learning environments.

The focus is on integrating authentic learning and digital assessment in ways that help students both acquire knowledge and develop the ability to learn independently. On the one hand, the concept of the selective portfolio aligns with critical pedagogy, globalization, and the affordances of new educational technologies (Railean, 2015). It embodies metasystem learning design principles, combining process-oriented evaluation with AI-assisted monitoring tools. This integration provides real-time feedback that guides students through iterative learning processes and supports the development of professional and lifelong learning competencies. On the other hand, an effective and accessible selective portfolio requires metacognition, critical thinking, and problem-solving skills, enabling students to manage theories and technologies acquired across diverse educational contexts (Railean et al., 2025). In this sense, selective portfolios function as both a pedagogical and an assessment tool, bridging authentic learning experiences with the accessibility and scalability of digital learning environments.

One such strategy is *the AI-powered selective portfolio, a digital tool for authentic and digital assessment that leverages AI functionalities to evaluate learning products and support the development of professional competencies*. In this approach, the selective portfolio does not replace the teacher's role in assessment but functions as a facilitative mechanism, enabling the processing of

educational data, identifying patterns of learner progress, and providing personalized formative feedback. Functionally, the AI-powered selective portfolio processes textual, visual and media content of students, using specific functions of AI technologies and tools, such as learning analytics, natural language processing and educational recommendation systems.

3.2 The AI-powered selective portfolio in teachers' perception

Theoretically, authenticity is related to conscious attention and emotional intelligence (Tohme and Joseph, 2025). Since authenticity is a natural state of human behavior toward which people are intrinsically motivated, it can lead to behaviors that are functionally aligned with this intrinsic motivation. However, authenticity does not emerge spontaneously. It requires a leader and a stimulating social learning environment characterized by congruence with others, unconditional positive regard, and empathetic understanding. In theory, congruence refers to the alignment between a person's inner experiences and their outer expression. In practice, congruence refers to that form of social intelligence that can be defined as authentic behavior in various learning environments.

Authenticity in assessment for learning goes beyond collaborative and social skills to encompass the learner's ability to regulate learning processes, manage competencies, and develop lifelong learning skills in a dynamic, technology-mediated environment. These competences are maintained when learners remain motivated, curious, and engaged in meaningful and contextually relevant learning tasks (Railean, Saltykova-Vaukovich & Mkhabela, 2025).

In digital environments, personalized learning is supported by: digital portfolio assessment; adaptive learning tools; continuous feedback; which allow for flexible monitoring of progress and skill development (Redecker, 2017; Bennett, 2015). The selective portfolio acts as a bridge between authentic learning, personalized skill development and computer-based assessment.

Artificial intelligence in the selective portfolio serves as a pedagogical support system for organizing artifacts, analyzing learning progress, and enabling formative feedback and personalized assessment, without replacing the teacher's evaluative role (Bennett, 2015; Redecker, 2017).

Through learning analysis elements, AI identifies patterns of progress or stagnation based on the comparison of successive products, providing indicative indicators for evaluation, without generating final decisions (Bennett, 2015). By correlating products with targeted objectives and skills, AI supports metacognitive reflection and can suggest differentiated learning paths, adapted to the student's profile (OECD, 2018; Villarroel et al., 2018). Through these functions, artificial intelligence transforms the selective portfolio into a dynamic tool for authentic computerized assessment, maintaining the teacher's pedagogical control and the balance between technological innovation and didactic rigor (Redecker, 2017).

The results of the teacher survey indicate a strongly positive perception of the selective portfolio as a tool for personalizing learning. None of the respondents

selected the lowest levels (1 or 2), suggesting that teachers do not perceive the portfolio as ineffective in supporting individualized learning paths. A small proportion of respondents (16.1%) rated the contribution at a moderate level (3), indicating that although personalization is present, it may depend on specific conditions, such as didactic design, student engagement, or digital infrastructure.

Most responses were concentrated at the upper end of the scale. 45.2% of participants selected level 4, and 38.7% chose the highest level (5 – very much). Together, these results show that 83.9% of respondents consider that the selective portfolio contributes significantly or very significantly to personalized learning. The graphical representation of the results is presented in Figure 1.

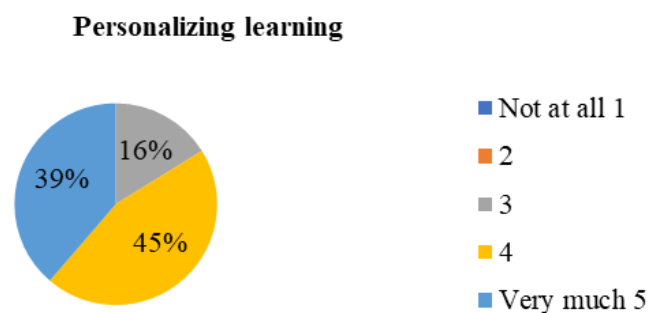


Figure 1. The Contribution of the Selective Portfolio to Personalizing Learning

Overall, these findings suggest that the selective portfolio allows for the adaptation of learning to the individual needs, interests, pace, and competencies of students. By allowing students to choose representative artifacts, reflect on their progress, and receive targeted feedback, the portfolio supports differentiated instruction and student-centered assessment.

In the AI-based selective portfolio, the roles of the teacher and the student are clearly delimited and complementary, and the AI has an exclusively auxiliary function, of pedagogical and analytical support. This delimitation is essential for maintaining the authenticity of the assessment and for respecting the ethical principles of digital education (Redecker, 2017).

Table 1. Description of the roles of the teacher, student and AI in the selective portfolio

Teacher's role.	Student's role.	Role of artificial intelligence.
The teacher retains full pedagogical and evaluative authority, defining learning objectives and assessment criteria, validating AI-supported feedback, and making final assessment decisions. In addition, the	The student acts as an active agent in the learning process, responsible for selecting relevant portfolio artifacts, producing reflective entries, and using formative feedback to regulate learning. Through these	Artificial intelligence serves a strictly supportive pedagogical and analytical function, assisting in organizing portfolio data, identifying learning patterns, and generating formative feedback suggestions. AI

teacher guides students' reflective processes and ensures fairness, transparency, and coherence in assessment practices (Bennett, 2015; Villarroel et al., 2018).	activities, students develop autonomy, metacognitive skills, and self-regulated learning capacities (Barrett, 2017; OECD, 2018).	does not make evaluative decisions; interpretation and judgment remain under the teacher's responsibility (Redecker, 2017; Iannone et al., 2026).

Clear delineation of roles ensures the balance between technological innovation and pedagogical rigor, transforming the AI-based selective portfolio into an authentic computerized assessment tool, focused on skills development and personalized learning.

The data obtained from the questionnaire applied to teachers indicate a clear preference for authentic, varied and competence-oriented activities, confirming the relevance of the AI-based selective portfolio as a tool for authentic digital assessment. The distribution of responses highlights the fact that the portfolio is designed as an integrative space of learning products and processes, supporting both formative assessment and the development of transversal competences.

Types of activities integrated into the selective portfolio

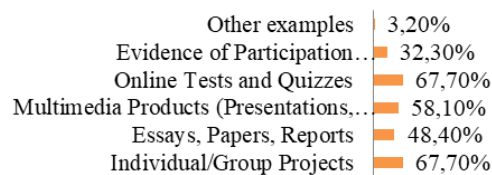


Figure 2. Activities integrated into the selective portfolio based on artificial intelligence

Individual and group projects are the most common type of activity included in the selective portfolio, being mentioned by 67.7% of respondents. This option confirms the central role of projects in authentic assessment, as they allow the integrated application of knowledge, skills and attitudes in contexts close to professional reality. In the context of the AI-based portfolio, artificial intelligence supports the organization and analysis of the progress of projects, without intervening in the final assessment.

A significant percentage of respondents (58.1%) indicate the inclusion of multimedia products, such as digital presentations, videos or other visual artifacts. These results confirm the trend of diversifying the forms of learning expression and valorizing digital and creative skills. Multimedia products allow for multimodal assessment of skills and support personalized learning, being recognized in the specialized literature as key elements of authentic digital portfolios (Villarroel et al., 2018). Artificial intelligence can support the classification and analysis of these artifacts, facilitating reflection and formative feedback.

The results of formative assessments, especially online tests and questionnaires, are mentioned by 67.7% of respondents, indicating the integration

of digital assessment into the portfolio structure. These activities provide objective benchmarks for monitoring progress and regulating learning, without being limited to the grading function. Studies highlight the role of digital formative assessment in supporting self-regulated learning and continuous feedback (Bennett, 2015). In the AI-based portfolio, artificial intelligence facilitates the analysis of the evolution of results over time and the identification of progress trends.

Almost half of teachers (48.4%) include essays, highlighting the importance of written reflection and academic argumentation. These activities support the development of metacognitive skills and critical thinking, which are essential for assessment as learning. Artificial intelligence can support the organization and analysis of these texts, without replacing pedagogical interpretation.

Evidence of participation and progress, such as digital certificates and badges, is included by 32.3% of respondents, indicating a moderate openness to valuing non-formal and informal learning. These elements complement the portfolio by recognizing long-term progress and support the development of skills for lifelong learning (OECD, 2018; Redecker, 2017). In the context of the AI-based portfolio, this evidence can be integrated and correlated with other artifacts for a holistic picture of the learner's development.

These findings reflect participants' reported practices and perceptions and do not imply causal relationships.

3.3 Practical experience in implementing the AI-based selective portfolio

The integration of empirical data with the theoretical framework confirms that the AI-based selective portfolio is built around authentic, competency-oriented activities supported by formative assessment. The included activities generate relevant educational data that allow for process-based, personalized and pedagogically grounded assessment, while AI acts as a support tool for organization, analysis and feedback, maintaining the teacher's evaluative control.

The selective portfolio based on artificial intelligence was implemented in vocational and technical education with the aim of assessing students' digital and transversal skills in an authentic and personalized way. The implementation of this tool was gradually integrated into the teaching-learning-assessment process, not replacing traditional methods, but complementing them.

Students were involved in individual and group projects, digital products (presentations, multimedia materials), written reflections and self-assessments, as well as in online formative assessments. Each student selected, justified, and organized the relevant artifacts in their portfolio in relation to the targeted competencies and established assessment criteria.

Artificial intelligence was used as a support tool for organizing artifacts, monitoring progress, and generating formative feedback suggestions, which were subsequently validated and contextualized pedagogically. The final assessment decision was made exclusively by the teacher.

The results observed included increased student engagement and responsibility, the development of self-assessment and metacognitive reflection

skills, and better visibility of individual progress over time. From a teaching practice perspective, the AI-based selective portfolio proved effective in supporting process-based assessment, personalizing learning, and basing assessment decisions on multiple evidence.

This experience confirms the potential of the AI-based selective portfolio as a tool for authentic digital assessment, which strengthens the role of the teacher and supports student-centered learning.

4. Conclusion

The concept of this theme is based on previous research on the assessment of digital competences in vocational education. In the paper “The selective portfolio as a method for assessing digital competences of students in vocational education” (Rotari, 2024), it is shown that the computerized selective portfolio is an effective tool for assessing digital competences. It facilitates the alignment of curricular requirements with students’ performance in the real world, while supporting formative feedback and professional reflection. This article extends this approach, positioning the selective portfolio in a broader theoretical framework and analyzing it as a methodological bridge between authentic and digital assessments, with relevance in various educational contexts. Through this integrative perspective, the theme of the article contributes to the development of a conceptual model of computerized authentic assessment, in which the selective portfolio becomes a central tool for assessing competences, modernizing assessment practices and aligning them with the requirements of lifelong learning.

The analysis carried out in the article highlights the fact that the selective portfolio represents a valuable pedagogical tool, capable of ensuring the convergence between authentic assessment and computer-based assessment, responding to the requirements of contemporary education focused on competencies. Through its flexible and reflexive character, the selective portfolio facilitates the evaluation of the learning process and product, capitalizing on relevant learning experiences and supporting the development of student autonomy. The integration of digital media in the use of the selective portfolio contributes to the efficiency of the assessment process, offering the possibility of monitoring progress, increasing the transparency of the assessment criteria.

The results of the theoretical and methodological analysis confirm that the computerized selective portfolio not only optimizes evaluative practices, but also increases the validity and relevance of authentic assessment, favoring the active involvement of students and the development of metacognitive and self-regulated learning skills. In this sense, the selective portfolio appears as a viable solution for the modernization of educational assessment, providing solid premises for its alignment with the requirements of the digital society and lifelong learning. Future research perspectives may aim at investigating the applicative impact of the computerized selective portfolio in various educational contexts.

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Multimodal biometric authentication of identical twin users in e-Learning platforms: Security architecture

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Abstract: *This article explores the challenges of the identical twins' authentication in online learning environments, where the identity substitution can compromise the fairness of assessments. The paper proposes a multimodal and continuous authentication system that combines face (static biometric) together with voice and keystroke dynamics (behavioural biometrics), adapted to the subtle differences between twins. The research highlights the effectiveness of the proposed system in preventing frauds and aims to the design and development of efficient security solutions for e-Learning platforms, considering the biometric similarities of twin users.*

Keywords: Continuous authentication, Multimodal biometrics, Identical twins, e-Learning security, Feature fusion.

1. Introduction

The e-Learning platforms have become essential for modern education, ensuring flexibility and extended access to educational resources (courses, online assessments, various digital resources). They provide reliable support for scalable learning environments. As the number and relevance of online examinations grow, the integrity of user authentication becomes a critical requirement. The online assessments represent contexts in which the user identity must be reliably validated.

The identical twins represent a challenging authentication scenario as their biometric traits (faces, voices, certain behavioral patterns) could be extremely similar. Their high biometric similarity can effectively reduce the inter-class separability, increasing the false acceptance rates. These cases can defeat the traditional (password-based and single-biometric) authentication systems efficiency (Phillips et al., 2011), (Afaneh et al., 2017). In high-stakes e-Learning scenarios, one twin could attempt to take an exam on behalf of the other. For the identical twins, their nearly indistinguishable physical and sometimes behavioural characteristics in the use-cases of e-Learning platforms may significantly compromise the integrity and reliability of the online assessments, enabling the identity substitution and exam frauds.

The traditional authentication methods with passwords, PIN (Personal Identification Number) codes or tokens are vulnerable to sharing, data leakage, social engineering attacks. Another issue is the identity substitution between identical twins; the traditional methods fail to distinguish between identical twins, resulting in increased vulnerability to identity substitution. Biometric authentication, including modalities such as fingerprint, iris, face recognition, speaker verification, or keystroke dynamics, provides a more reliable link between the digital identity and the real person. However, the conventional face or voice recognition systems often fail to distinguish the subtle differences between twins (Sun et al., 2010), (Hollingsworth et al., 2011).

This paper proposes a twin-aware multimodal and continuous authentication architecture for e-Learning environments. The designed multimodal biometric system is able to distinguish identical twin users through a combination between face and behavioural biometrics (voice and keystroke). The design extends the previous multimodal biometric security model for e-Learning (Soviany et al., 2025), in which a biometric system architecture was proposed, with pre-classification fusion. The extension provides a dedicated feature-space design for twins, a Twin Similarity Factor (TSF) for adaptive decision thresholds, and a continuous Replacement/Risk Suspicion Index (RSI) for mid-session substitution detection.

The design looks to ensure continuous authentication for the users of e-Learning platforms, while combining the following modalities: *face*, *voice recognition* and *keystroke dynamic*, another behavioural biometric that can be completed with additional behavioural features (Hussain, 2025). The system not only authenticates the user at the beginning of the session, but also continuously throughout it, reducing the risk of identity substitution. The remainder of the paper has the following structure: Section 2 - Related works; Section 3 - System architecture and functional components; Section 4 - Experimental setup and performance; Section 5 - Conclusion and future works.

2. Related works

(Vevera et al., 2024) emphasize the importance of cybersecurity education and the integration of cyber diplomacy concepts into university curricula, highlighting the role of user awareness in preventing digital risks. This approach is relevant for the authentication of twin users on e-Learning platforms. The effective cybersecurity in digital education requires not only technical safeguards and trained professionals but also coherent and well-designed security frameworks able to protect the identity integrity in online learning and assessment environments. The risk of identity substitution and impersonation during online examinations highlights the need for advanced authentication solutions. This reasons the recent research on multimodal biometric systems, particularly for challenging scenarios such as the identical twin users in e-Learning. (Zamfir et al., 2023) highlight that the use of virtual educational environments involves the extensive collection of

sensitive data, which imposes strict requirements regarding security, digital identity, and user control over personal information - issues that are directly relevant to the authentication of twin users on e-Learning platforms. (Badawi & Ciupercă, 2023) emphasize the importance of understanding both the human and technological dimensions in resilient educational systems in the context of global crises, arguing that online education must be integrated as a comprehensive service system.

The design of unimodal biometric authentication systems deals with significant challenges (Bowyer and Flynn, 2016). This involves the use of multimodal feature-fusion techniques to capture subtle discriminative patterns that are not visible in a single modality. Another work proposes an innovative method for the recognition of monozygotic twins by analysing the curvature area of the facial contour using Simpson's rule and ML (Machine Learning) algorithms, achieving superior performances for identification of subtle differences in 2D and 3D images (Sanil et al., 2025). (Kamlaskar & Abhyankar, 2021) proposed a multimodal iris-fingerprint biometric system based on an optimal feature-level fusion model, using Canonical Correlation Analysis to efficiently combine complementary information. (Mohammed & Hashim, 2020) proposed a multimodal biometric system designed to distinguish identical twins, using the Aspect United Moment Invariant descriptor to extract robust features and highlight individual uniqueness. Nsaif and Hasan propose an advanced biometric authentication method that combines detailed facial recognition, geometric and textural analyses, and dynamic facial micro-expressions; this allows to overcome the challenge of differentiating between identical twins (Nsaif & Hasan, 2025).

A systematic review of multimodal biometric methods used in the differentiation of monozygotic twins, conducted by (Kumari et al., 2025), highlighted the superiority of fingerprints and the complementary value of other biometric traits. (Sami et al., 2022) explain the difficulty of discriminating against identical twins using standard face recognition, despite of some recent technical advances based on deep CNN (Convolutional Neural Networks) together with twin-specific face benchmarks. These advances reinforce the conclusion that no single biometric modality is sufficient, reasoning the integration of complementary modalities. The multimodal biometric systems combining face, voice and behavioural traits have been shown to reduce false acceptance rates and increase robustness against spoofing, especially when feature-level or score-level fusion strategies are applied. (Herbadji et al., 2020) indicated that score-level or feature-level fusion significantly improves the recognition accuracy, as each modality captures independent traits; the combination of fingerprint and palmprint traits through feature-level fusion improves overall recognition accuracy in contactless settings. (Drozdowski et al., 2021) analysed the data fusion in facial recognition systems under privacy constraints, revealing that this process can be optimized for high accuracy even with partially anonymized data - an important issue in the GDPR context for e-Learning; they proposed advanced fusion strategies enabling efficient and privacy-preserving biometric indexing.

(Parde et al., 2022) show that the face and voice integration significantly increase the accuracy for the identical twin's identification; modern CNN architectures can surpass human performance when distinguishing twins under varying viewpoints, emphasizing the discriminant power of deep learning for twin identification; this confirms that twins can be distinguished using deep models if the images are sufficiently diverse and processed within discriminative subspaces. Multimodal twin-specific datasets (e.g. Audio-Visual Twins Database, CASIA twins' extensions) were considered for processing in (Akin, Kacar & Kirci, 2018) to evaluate the reliability of the multi-biometric approach even for the twin recognition case. Some subtle but stable differences present in the twins' speech signals could be exploitable for multimodal systems. It seems that voice contains unique features for each twin, reasoning for the integration of voice features into multimodal systems.

Hussain (2025) shows that the keystroke dynamics can detect identity substitution even when physical biometrics are similar; this work finds that the keystroke dynamics and interaction patterns can be effectively used for continuous authentication in e-Learning systems, helping to detect impersonation during assessments.

In (Lu et al., 2020) a continuous authentication framework based on free-text keystroke dynamics was proposed. The method combines CNN and RNN (Recurrent Neural Network) architectures to learn sequential typing patterns without requiring fixed input text; this enables unobtrusive and persistent user verification without disrupting learning activities in e-Learning use-cases. As relying on behavioural patterns rather than physical traits, this method is relevant for e-Learning environments ensuring a strong potential for distinguishing highly similar users, such as identical twins, where traditional biometric modalities often fail. The authors stated that the experimental results on large public datasets demonstrate low error rates -EER (Equal Error Rate) down to 2.36%. Platforms such as edBB-Demo (Daza et al., 2024) combine behavioural biometrics with webcam and audio analysis for continuous student monitoring, confirming that the static authentication is not sufficient for online exams; the edBB-Demo platform integrates facial, audio, and behavioural monitoring to support secure online examinations. These studies show that continuous monitoring can address the identity substitution risks that static biometric checks fail to detect.

As concerning *the biometric authentication for e-Learning applications*, under the extending adoption of online and virtual learning platforms, the security of the user identity has become a critical challenge. Several studies report vulnerabilities in traditional authentication methods (passwords or single biometric) when used in remote education scenarios (Huan et al., 2020). (Curran & Curran, 2021) reviewed biometric authentication techniques applicable to online learning, also defining multimodal solutions (such as face and iris) capable to mitigate identity frauds. Afolabi and Adagunodo (2018) proposed a crypto-biometric architecture integrating facial recognition and encryption for secure multimedia e-Learning environments. Ivanova et al. (2019) highlighted the

importance of trust and reliability through the TeSLA system, which incorporates biometric and behavioural verification mechanisms.

The present work differs from the previous ones by explicitly addressing the authentication of identical twin users in e-Learning platforms, with a methodology combining multimodal biometrics (face and behavioural traits) and continuous authentication over the full duration of the learning/examination session.

3. System architecture and functional components

3.1 Problem statement and system requirements

Let's consider an e-Learning platform where students access courses and take online exams. A user account and its associated identity are intended to correspond to a unique person. In the case of identical twins, one twin may attempt to take an exam on behalf of the other. The problem statement and system requirements include:

- *threat model for identical twins in e-Learning*. The main threat is the identity substitution between twins. The components of the threat model are:
 - *Scenario*: twin A enrolled, twin B takes exam. Twin A is the legitimate enrolled student while twin B attempts to access or complete an assessment using twin A's credentials and similar biometric patterns;
 - *Attacker capabilities*: access to credentials, similar face/voice, potentially similar typing style. The main assumptions are: twin B has full knowledge of the account credentials, can be present on camera and microphone, exhibits facial and vocal traits very similar to those of the victim (twin A), may share similar behavioural patterns (typing speed, general navigation);
 - *Security goals*: G1- the system should accurately distinguish between twin A and twin B at enrolment and login with high confidence; G2- the system should detect mid-session substitution (continuous authentication); G3- the system should comply with privacy regulations (GDPR) for biometric data, providing such protection without excessive burden or intrusion on legitimate users.
- *functional and non-functional requirements*. The functional requirements: are F1- initial strong verification (initial multimodal authentication at login or exam start, combining face and voice); F2- continuous verification during the session- primarily based on behavioural biometrics and periodic checks of face and voice; F3- twin-aware decision logic that adapts thresholds when a potential twin is detected or known; F4-risk-based response for elevated suspicion (warning, request re-authentication, session lock). The non-functional requirements are: N1- latency constraints, N2- low intrusiveness, N3- scalability to large numbers of users and concurrent sessions, N4- privacy

by design and compliance, especially with respect to GDPR and biometric data protection;

- *performance metrics*, that include: standard biometric/ML metrics -TPR (True Positive Rate), FPR (False Positive Rate), ROC (Receiver Operating Characteristic), AUC (Area Under the Curve), EER; twin-specific metrics - TFAR (Twin False Accept Rate -probability to accept the wrong twin as the genuine user), TFRR (Twin False Reject Rate - probability to reject the correct twin); continuous authentication metrics (average time to detect a substitution, false alarm rate per session).

3.2 System architecture: the functional components and formal specifications

The basic security architecture is depicted in Figure 1. The major functional components are: *face recognition* (data acquisition, pre-processing and local fusion -intra-modal), *voice recognition* (acquisition, pre-processing and local fusion), *other behavioural biometrics* like keystroke (acquisition, pre-processing and local fusion), *global feature-level fusion* (inter-modal), *continuous authentication engine* and *classification module for the twin's identification*.

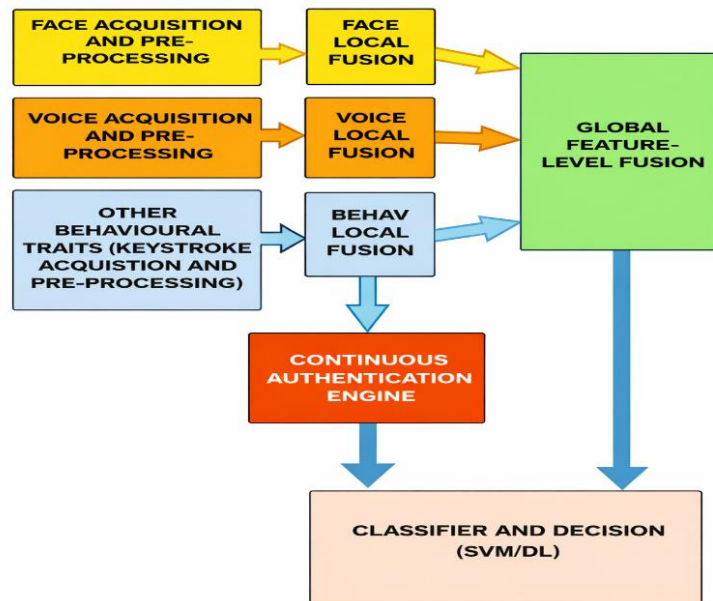


Figure 1. The security architecture for e-Learning applications

3.2.1 Formal problem specification

The problem specification considers 2 individuals having quite overlapped biometric data distributions X_b (for the biometrics b : F-face, V-voice, B-KS-

behavioural keystroke and optionally other dynamic behavioural patterns): $X_F^{(i)}, X_V^{(i)}, X_{B-KS}^{(i)}, i \in \{1, 2\}$, where for the 2 twins the distances D between the face biometric data distributions satisfy the inequality:

$$D(X_F^{(1)}, X_F^{(2)}) \ll D(X_F^{(1)}, X_F^{(k)}), \forall k \neq 2 \quad (1)$$

3.2.2 The multimodal matching score with adaptive weighting

For this design one can consider the following definition of the multimodal matching score:

$$S = w_F \cdot S_F + w_V \cdot S_V + w_{B-KS} \cdot S_{B-KS} \quad (2)$$

The weights w_b of the individual scores per biometric (Sb, $b \in \{F, V, B-KS\}$) are adjusted according to

$$w_b = \frac{1/\sigma_b}{\sum_{k \in \{F, V, B-KS\}} (1/\sigma_k)} \quad (3)$$

σ measures the score variability for a certain biometric modality between the 2 twins. The design assumes that a decrease in the differences between twins' per-modality scores corresponds to an increased contribution of behavioural components.

3.2.3 Processing components

The full processing pipeline contains *client-side* and *server-side components*. The *client-side components* include:

- the data acquisition and pre-processing for each modality: face (face detection, alignment, embedding), voice (MFCC extraction- Mel-Frequency Cepstral Coefficients providing voice features), other behavioural traits (keystroke events- key down/up timestamps, mouse trajectories). There will be: camera for face capture, microphone for voice capture, interaction monitoring for keystrokes and mouse movements, local pre-processing (face alignment, audio framing, keystroke event logging);
- the local anonymization/pseudonymisation where possible (for GDPR compliance)- secure channel to send features or pseudonymised features to the server.

The server-side components include:

- the feature normalization (e.g. with min-max or sigmoid functions) and storage (for the biometric templates);
- the per-modality scoring classifiers or matchers (similarity/classifier output);
- the feature- or score-level fusion engine, with adaptive weighting for twins;

- the continuous monitoring/risk scoring and Replacement Suspicion Index module-RSI (sliding time windows);
- the access control and integration with e-Learning platforms.

3.3 Data modelling and feature space design

3.3.1 Feature space per modality

The feature vectors per biometric modality are specified as follows:

1) for the face feature space: $x_F \in \mathbb{R}^{d_F}$ the face feature vector with the dimensionality d_F , with CNN embedding or textural/Haralick descriptors as in the previous work (Soviany et al., 2025). The Haralick features are based on co-occurrence matrices (Theodoridis & Koutroumbas, 2009);

2) for the voice feature space: $x_V \in \mathbb{R}^{d_V}$ the voice feature vector with the dimensionality d_V , with MFCC features;

3) for the other behavioural feature spaces: $x_{B-KS} \in \mathbb{R}^{d_{B-KS}}$ the feature vectors for the other behavioural traits, with the dimensionality d_{B-KS} (keystroke timing statistics and RNN-derived).

The design includes the feature space transformations for dimensionality reduction with PCA (Principal Component Analysis) /normalization. This process leads to the following feature vectors:

$$\hat{x}_F = PCA_F(x_F), \hat{x}_V = PCA_V(x_V), \hat{x}_{B-KS} = PCA_{B-KS}(x_{B-KS}) \quad (4)$$

The reduced dimensionalities are d_F^0 , d_V^0 and d_{B-KS}^0 , respectively. Each enrolled user U is associated with enrolment samples for each modality. A template is computed as the mean of the reduced feature vectors over enrolment samples. Therefore, the biometric (face, voice, other behavioural) templates for the user U are denoted as $\hat{m}_b^{(U)}, b \in \{F, V, B-KS\}$.

3.3.2 Twin Similarity Factor (TSF)

Given a certain user $U1$ of the e-Learning platform, together with the potential twin $U2$, the design defines the amount TSF (Twin Similarity Factor):

$$TSF^{(U)} = \alpha \cdot D_F + \beta \cdot D_V + \gamma \cdot D_{B-KS} \quad (5)$$

D_b are the distances between twins for the given trait. The inter-twin distances per modality are given by

$$D_F = d(\hat{x}_F^{(U1)}, \hat{x}_F^{(U2)}) \quad (6)$$

$$D_V = d(\hat{x}_V^{(U1)}, \hat{x}_V^{(U2)}) \quad (7)$$

$$D_{B-KS} = d(\hat{x}_{B-KS}^{(U1)}, \hat{x}_{B-KS}^{(U2)}) \quad (8)$$

For the biometric template computed as the mean of the reduced feature vectors over enrolment samples, the inter-twin distance is

$$D_b = d(\hat{m}_b^{(U1)}, \hat{m}_b^{(U2)}), b \in \{F, V, B-KS\} \quad (9)$$

These distances are weighted per modality (α, β, γ) based on their specific performances. For the distance measure one can consider the cosine or Euclidian distance. The weights are chosen based on cross-validation per modality. For high similar twins one can expect to have small inter-twin distances per modality and therefore small TSF. In general, identical twins exhibit smaller inter-template distances than unrelated users. A small TSF indicates very similar twins and justifies constrained decision thresholds. In scenarios where twin information is not explicitly known a priori, TSF can be estimated by comparing the enrolled user against a set of candidate impostors and identifying highly similar pairs.

3.3.3 Adaptive decision thresholds

As concerning the decision thresholding, the design specifies the adjustment of the baseline discrimination threshold θ_0 for a user U having a twin. TSF should be used to properly tune the discrimination thresholds θ :

$$\theta^{(U)} = \theta_0 - \lambda \cdot TSF^{(U)} \quad (10)$$

where $\lambda > 0$ is a scaling factor. The scaling coefficient λ is applied based on specific performances per modality to aggregate the best contributions for accurate discrimination.

This represents the thresholding adaptation for a user U with a known or detected twin. The baseline threshold should be optimized for overall verification performance on non-twin users (e.g., minimizing EER). The significance is that for more similar twins one should specify a more constrained thresholding, given the requirement to have a larger and clearer separation. Lower TSF (more similar twins) leads to more constrained thresholds, reducing the probability of false acceptance of the twin at the cost of potentially higher false rejections.

3.3.4 Data fusion (post-/pre-classification)

The data fusion process can be applied either post- or pre-classification, with score-level or feature-level rule, respectively. The feature-level fusion requires to ensure a certain homogeneity of the feature vectors allowing to apply a functional fusion method avoiding the concatenation. Homogeneity will require at least a common dimensionality of the original feature spaces. For image-based feature extractors (face recognition), a common feature extractor with textural Haralick features could provide homogeneity. The data fusion rule uses the weighted sum rule for both cases, score or feature fusion.

For the post-classification (score-level) fusion, given a certain biometric sample for the discrimination and having per-modality normalized scores S_F, S_V, S_{B-KS} ($S_F, S_V, S_{B-KS} \in [0,1]$), the fused score is computed using equation (2). The per-modality scores can be interpreted as the probability that the sample is genuine. The weighting could be either static -with weights empirically fixed per dataset, or

data-driven – inverse-variance weighting according to equation (3), in which $\sigma_b, b \in \{F, V, B-KS\}$ is the score variance between the 2 twins per modality.

A practical approach is to derive weights from the variance of scores on twin impostor trials. Let the variances of impostor scores when the impostor is the twin:

$\sigma_b^2, b \in \{F, V, B-KS\}$. A lower variance (better separation between genuine and twin impostors) indicates stronger discriminative power. One may define the weight:

$$w_b = \frac{1/\sigma_b^2}{\sum_{k \in \{F, V, B-KS\}} 1/\sigma_k^2} \quad (11)$$

The modalities more robust to twins will receive higher fusion weights.

For the pre-classification (feature-level) fusion, the fusion rule is quite similar, therefore a weighted sum, but this should apply on feature vectors under their homogeneity conditions being assumed. Giving the transformed feature vectors - equations (4), with common dimensionality, the fusion rule provides the common feature vector x :

$$x = \sum_{b \in \{F, V, B-KS\}} W_b \cdot \hat{x}_b \quad (12)$$

3.3.5 Continuous risk scoring

At time step t , one can consider the windowed fused score S^t - a sequence of fused scores $S^t \in [0,1], t=1,2,...,T$ (or fused feature vector x^t). The fused scores are obtained at periodic intervals or upon specific events. The residual vs. enrolled template score is defined as

$$r^t = 1 - S^t \quad (13)$$

which represent deviation from the ideal genuine behaviour. A quite similar measure can be defined for the fused feature vectors, but only assuming normalized features (with sigmoid functions).

The Replacement Suspicion Index (RSI) over the last N windows (slots), at time t , is computed over a sliding window of length N :

$$RSI^t = \frac{1}{N} \cdot \sum_{i=t-N+1}^t r^i \quad (14)$$

This amount is used to estimate the risk of substitution between the twins. The suspicion of substitution is raised if the following condition is met: $RSI^t > \rho$, where ρ is a threshold value. If RSI^t exceeds a threshold ρ , the system flags a possible substitution event. This can be interpreted as continuous statistical monitoring of cumulative evidence that the current user behaves differently from the enrolled profile.

4. Experimental setup and performance. Discussion

The experimental protocol, either for synthetic data but also for real data, includes the following operations:

1. Split per-user: enrollment vs test (e.g. 2 images/audio samples for enrollment, rest for test);
2. Verification experiments: genuine trials (user vs self), impostor trials (non-twin impostors, twin impostors- twin A masquerading as twin B);
3. Evaluation: per modality (face-only, voice-only, behaviour-only), fused (face+voice, face+behaviour, full face+voice+behaviour).

The metrics to be used include ROC curves for each modality and for the fused case, accuracy, EER for each biometric and fused case, TFAR/TFRR, average time to detection in continuous scenario (for behaviour and periodic sampling for face and voice).

Since comprehensive public datasets containing multimodal biometrics for identical twins in e-Learning contexts are not readily available, the initial experiments will use synthetic data to emulate key properties of twin and non-twin users. The simulation will consider: N_p pairs of identical twins, N_s additional non-twin users, enrolment and raw samples per user for each modality. For each user and modality, a mean feature vector is drawn from a multivariate Gaussian. For twins, the 2 users share a similar mean (small offset), while non-twins have more separated means. Enrolment and raw samples are generated by adding Gaussian noise around the respective user means.

SVM (Support Vector Machine) classifiers with RBF (Radial Basis Function) kernels are trained on the verification pair datasets for each modality separately. Per-modality match scores are taken as the predicted probabilities for the genuine class. The twin-specific error rates are estimated by focusing on impostor pairs where the impostor corresponds to the twin of the genuine user, and computing TFAR at a default threshold (e.g., score ≥ 0.5). The synthetic results show lower EER for face and voice compared to other behavioural biometrics, non-zero TFAR for all modalities- with the highest TFAR on face or voice and other behavioural biometric depending on simulation parameters, higher TFAR for twins than for generic impostors, reflecting the challenge of twin discrimination. Table 1 shows preliminary results on a synthetic dataset simulating distributions quite similar with those of the previously referred datasets. For the same data, the accuracy is depicted in Figure 2.

Table 1. Preliminary results on synthetic data

<i>Configuration</i>	<i>EER (%)</i>	<i>TFAR (%)</i>	<i>TFRR (%)</i>
	<i>non-twins</i>	<i>twins</i>	<i>twins</i>
Face only	1.8	8.5	4.2
Voice only	2.1	6.9	5.0
Behaviour only	3.5	10.0	6.0
Face + Voice	0.9	3.2	2.5
Face + Voice + Other behavioural traits	0.7	1.8	1.9

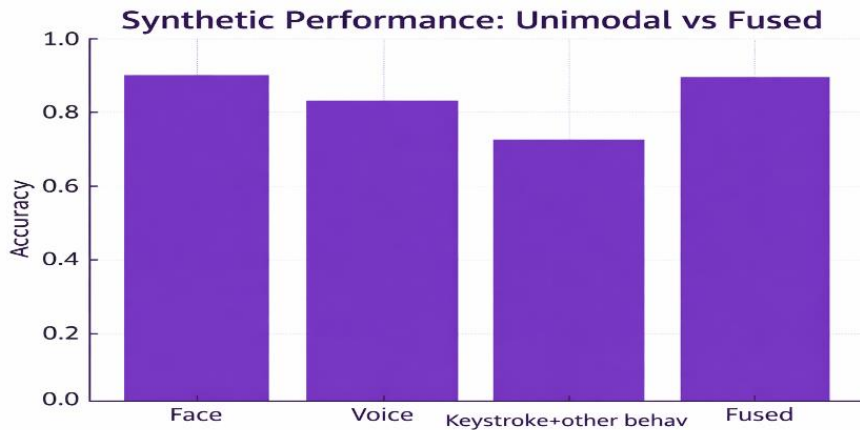


Figure 2. Accuracy for synthetic data

For the continuous authentication, the simulation should consider 2 time series of scores: a genuine session (where all scores are drawn from a high-mean, low-variance distribution) and a twin substitution session (where scores are genuine-like until a certain time point and then follow a lower-mean, higher-variance distribution-representing the twin impostor). RSI is computed over a sliding window, and its evolution must be compared in the 2 scenarios. For genuine sessions, RSI remains below a moderate threshold, whereas in the twin substitution scenario, RSI increases and crosses the threshold shortly after the substitution point. This demonstrates how RSI can be used to raise alerts and trigger additional checks during the session.

The main advantages of the proposed system (twin-aware multimodal architecture) are: improved security-robustness against twins, adaptive thresholds and weights, continuous authentication, GDPR compliance, scalability and adaptability. The limitations of the proposed system are: synthetic evaluation, dataset availability, implementation costs, dependency on the data quality, computational and deployment complexity, ethical concerns and user perception, user acceptance and privacy concerns.

5. Conclusions and future works

This paper addressed the challenge of authenticating identical twin users in e-Learning platforms. It proposes a twin-aware multimodal and continuous authentication architecture that combines facial, vocal, and behavioural biometrics, extending previous work on multimodal security models for e-Learning. The present work provides an integrated authentication methodology combining multimodal biometrics and continuous authentication for identical twins in e-Learning, showing its benefits but also some weak points for potential improvements. The *specific contributions* are: a twin-aware multimodal biometric system architecture, with specific design for identical twins in online learning

environments; a basic mathematical foundation of the feature space- a feature space design, together with an adaptive fusion scheme and similarity between twin and non-twin users; an experimental protocol using synthetic data (simulation), with performance metrics estimation and illustrative results.

The steps toward full implementation include real-world testing (deploying the system in universities to validate its performance and collect empirical data), optimization of the multimodal algorithms (using Artificial Intelligence for continuous adaptation to individual behaviour and to reduce false positives), user education (to increase the trustness and acceptability), extending the application areas.

The more concrete future works include collecting a dedicated multimodal twin-e-Learning dataset (face, voice, keystroke), exploring more advanced fusion methods- such as neural networks with attention mechanisms or meta-learning, to learn fusion strategies directly from data, implementing formal privacy-preserving mechanisms, evaluating user perception and acceptance of continuous biometric authentication in educational environments.

Acknowledgments

The work presented in this paper is supported by the Core Program within the National Research Development and Innovation Plan 2022-2027, carried out with the support of MCID, project no. 23380601, "Advanced research in the Metaverse and emerging technologies for the digital transformation of society".

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The Virtual Presence Pedagogy (VPP): A sistematic review of foundational elementes in immersive digital ecosystems (2023- 2025)

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Abstract: *The emerging digital ecosystem, centered on the Metaverse, promises profound transformations in education, moving from transmissive learning to deeply immersive, collaborative, and personalized experiences. This transition requires a new pedagogical framework that manages socio-technological and ethical challenges. Although traditional theories define presence as physical, recent research extends it to virtual environments through multisensory interactions. Thus, an integrative discipline that defines and optimizes authentic human presence in these augmented spaces is lacking.*

Using the PRISMA 2020 protocol, this study conducted a systematic review based on OpenAlex data (period 2023-2025), identifying 132 relevant records. Bibliometric analysis using VOSviewer confirmed that emerging pedagogical transformation is strongly related to cutting-edge fields, especially Computer Science, Virtual Reality and Psychology.

Based on this synthesis, the research proposes "Virtual Presence Pedagogy" (VPP) as a fundamental discipline, which redefines the notion of human presence in education by expanding it into three complementary dimensions: cognitive presence, social presence and identity presence.

We conclude that VPP will represent an appropriate methodology for creating an integrated educational ecosystem, transforming the Metaverse from a digital space into a pedagogy of augmented proximity, essential for the 21st century skills formation.

Keywords: Advanced technology, Metavers, Educational trends, Pedagogy, Virtual presence.

1. Introduction

The global context is defined by accelerated technological change, automation and digitalization, with over 60% of current professions expected to undergo major transformations (Di Battista et al., 2025). These developments require the educational system to transition from a teacher-centered model to a student-centered one (Gabor, Iftimoaei & Vevera, 2024), oriented towards the development of 21st century skills, such as critical thinking, complex problem solving, cognitive flexibility and resilience.

The metaverse, as a persistent and immersive digital ecosystem, represents a continuation of the efforts to digitize education post-COVID-19. It promises to be not just a tool, but an environment capable of ensuring deeply immersive,

<https://doi.org/10.58503/icvl-v21y202639>

collaborative and personalized learning, facilitating the formation of those skills necessary to adapt to the major challenges of the 21st century.

However, integrating the Metaverse into education requires a solid theoretical framework. Although the literature addresses the technological aspects (learning through 3D virtual environments, artificial intelligence, augmented reality and virtual reality) and the benefits of immersive learning, there is a gap in defining and authentically managing the human experience in this space. Thus, it is necessary to create a new discipline that combines traditional learning theories with new technologies.

The paper presents a vision through which traditional education can be transformed into an authentic virtual presence, into an augmented educational ecosystem. By systematically analyzing and reviewing emerging academic trends for the period 2023-2025, which define the intersection between pedagogy and immersive digital ecosystems, we consider it necessary to propose and substantiate a new methodological framework, which we call "Virtual Presence Pedagogy" (VPP).

2. Background - the main challenges of the transformation from traditional pedagogy to that of virtual presence

In classical educational theories, presence is associated with the physical participation of teachers/instructors and students in the educational process. Recent research in this field (Ahmed, 2024) emphasizes that presence can be recreated in virtual environments, through multisensory and collaborative interactions, thus generating an authentic perception of human presence, beyond the simple substitution of real space.

The literature defines three complementary dimensions of virtual presence (Kaczko & Ostendorf, 2023), which can be expanded through PPV:

1. Cognitive presence: Active student involvement in constructing educational meaning, stimulated through interaction and immersive practical experiences;
2. Social presence: The authentic and empathetic communication capacity of participants, facilitating effective collaboration of participants in virtual spaces;
3. Identity presence: The form of expression and self-reflection on the purpose of learning through the educational avatar.

All these dimensions define the epistemological framework of PPV, providing the structure for transforming the pedagogy of physical presence into a virtual one.

3. Method (systematic review- PRISMA 2020)

Using the PRISMA 2020 methodology (Page et al., 2021), we conducted a systematic review of studies identified in academic, open source databases, namely the OpenAlex database (Web of Science, Scopus, etc.). Focusing on recent academic trends (2023-2025), we targeted those works associated with the main

criterion "pedagogy of virtual presence". The key terms used in the searches included variations such as: Metaverse, pedagogy, virtual presence, immersive learning and education.

Using the bibliometric mapping tool VOSviewer, the searches yielded 132 records. The application was used to visualize term correlations, identify thematic clusters, and establish interrelationships between domains.

The bibliometric analysis of the 132 records generated 70 topics, of which the most relevant, ordered by the number of citations, are: Virtual Reality Applications and Impacts (21), Online and Blended Learning (14), Educational Innovations and Challenges (5) and Innovative Educational Technologies (4).

Mapping the co-occurrence relationship of terms (Figure 1) revealed eight main thematic groups at the intersection of education and the Metaverse. The most prominent are: Computer Science, Psychology, Mathematics, Pedagogy, Sociology, Human-Computer Interaction, Virtual Reality and Multimedia.

Subsequently, we applied three search filters for the criterion Human Interaction in Metaverse, in the domains of Life Sciences, Physical Sciences and Social Sciences, obtaining a series of inter-relationships between the searched terms (Figure 2), with Pedagogy, the main subject of the analysis. Thus, we obtained a thematic model from which we can deduce the emerging trends of transformation of the educational process through Metaverse.

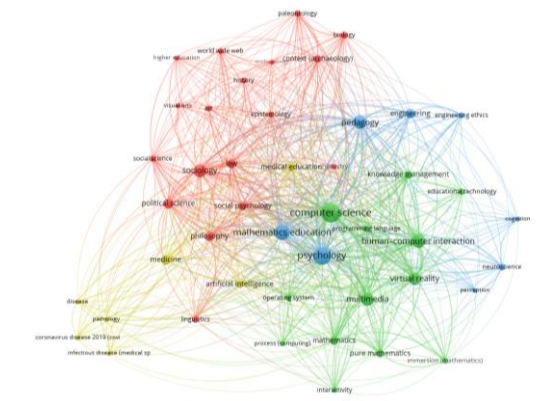


Figure 1. Interrelationships and main thematic groups of related fields

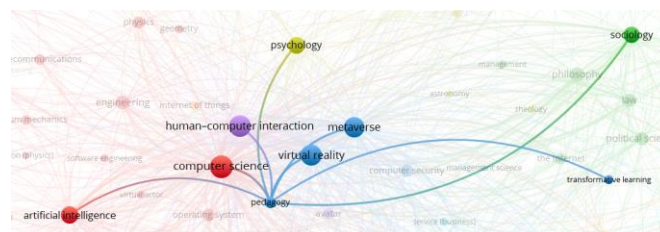


Figure 2. Interrelationships of pedagogy with socio-technological fields

The strongest interrelationships of the Metaverse and the Pedagogy domain are established with the Computer Science, Psychology and Virtual Reality

4. Results – emerging qualitative aspects

- Through Virtual Reality, it is emphasized that the metaverse has the potential to become a tool with an important role in the teaching-learning process, being able to create immersive and interactive environments (Crivellaro & Mandaio, 2023);
- Through Computer Science, some technologies related to Metavers are already educational tools. We have identified projects implemented in the educational process for the inclusion of students with special needs, for the disciplines of history, philosophy, operating systems theory and architecture (Maneita et al., 2024). Due to the increasing digitalization of society, computational thinking has become an increasingly important component in education, especially in primary education (Coelho et al.,

2025). Moreover, in Brazil, a perspective of teaching philosophy has been realized, through OCHE pedagogical practices, centered on Eurocentric models, in order to obtain a global, theoretical and practical, critical and transformative knowledge, adapting the educational process to forms that transcend the simple transfer of content to one adapted for reflection and transformation (Freire & Rodrigues, 2025).

Positive use case of Metavers in pedagogy: Through the perspective of transforming pedagogical methods to the new digitalized context, we support the following advantages that emerge towards the most promising scenarios:

1. Immersive, interactive and experiential learning is more effective and engaging in practical contexts, with mixed virtual environments allowing the recreation of scenarios that cannot be easily replicated in reality (da Silva et al., 2025);
2. Personalization and adaptability create a flexible educational environment, centered on individual needs. Metaverse can support various pedagogical methods, from autonomous to collaborative learning, based on problem solving, through tools adapted to the diversity of students (Tlili et al., 2022; Soviany, Gheorghe & Gheorghe-Moisii, 2024);
3. Extended learning communities, through Metavers, will integrate multimedia resources, complex simulations and transdisciplinary collaborations that are difficult to achieve traditionally (Almeman et al., 2025);
4. Developing creativity, critical thinking, communication skills and collaboration through real-life or near-real-life services can become an ideal space for activated pedagogies, projects and problem-based learning (Tlili et al., 2022);
5. Democratizing access to education and developing the model of lifelong continuous education (continuous training, professional retraining, on-formal courses, etc.) can be achieved through Metavers (De Felice et al., 2023).

5. Discussions: Implications of virtual presence pedagogy

The analysis demonstrates that a new pedagogy must adapt to the changes in the digital society, including the need to develop resilience, emotional intelligence and self-management, aspects increasingly sought after in the labor market. To combat the superficiality of vocational training, it is essential that the academic environment provides tools that stimulate curiosity and life-long learning.

This new discipline, which we call Virtual Presence Pedagogy (VPP), will constitute a pedagogical method that responds to this requirement because:

1. Ensures authentic co-presence: The virtual presence of the teacher/instructor becomes an authentic perception of human

co-presence, generating augmented cognitive and emotional experiences, not simple substitutions;

2. Promotes higher engagement: Although digital education is accessible, PPV can bring higher cognitive and emotional engagement, fostering collaboration, empathy, and self-reflection;
3. Reconfigures the role of the teacher: The teacher/instructor becomes a guide in navigating information resources and validating sources of knowledge, capable of creating learning communities and coordinating cognitive reflection.

In this new educational ecosystem, being present does not just mean participating but experiencing knowledge that combines multimedia resources, complex simulations and transdisciplinary collaborations.

6. Conclusions

Virtual Presence Pedagogy (VPP) fundamentally redefines human presence in education, expanding it in cognitive, social and identity terms. By integrating Metaverse technologies, VPP transforms the traditional model into a pedagogy of augmented proximity, eliminating not physical presence, but the distance between knowledge and experience.

PPV transforms the metaverse into an instrument of relationship and reflection, shaping a future of the ecology of presence that coherently integrates the real, the digital and the immersive into a whole oriented towards the development of the Society 5.0 model, where technologies support the well-being and continuous development of citizens.

Acknowledgments

This paper is supported by the Core Program within the National Research Development and Innovation Plan 2022-2027, carried out with the support of MCID, project no. 23380601, „Advanced research in the Metaverse and emerging technologies for the digital transformation of society”.

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Designing and integrating mobile Damath: A digital game-based instructional innovation to enhance students' mathematical performance and engagement in integer operations

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Abstract: *This study examined the effectiveness of a mobile Damath game as a digital instructional design tool to enhance Grade 8 students' performance and engagement in integer operations. Conducted at Badas National High School, City of Mati, Davao Oriental, Philippines, the research utilized a quasi-experimental design involving 60 students equally assigned to experimental and control groups. The experimental group learned through the mobile Damath game, while the control group received traditional instruction. Data gathered using a validated mathematics achievement test and an AI-assisted engagement survey were analyzed using mean, standard deviation, t-test, and Pearson correlation. Results showed that both groups started at the Beginning proficiency level; however, the experimental group achieved a statistically significant improvement ($p = 0.004$) and advanced to the Developing level. Although engagement levels were high, no significant correlation was found between engagement and performance. The findings highlight the potential of digital game-based learning as an innovative instructional design approach that supports active, contextualized, and technology-driven learning. A strategic action plan was formulated to institutionalize mobile Damath integration in mathematics instruction, aligned with the BEDP 2030 and MATATAG Agenda for inclusive and future-ready education.*

Keywords: Game-based learning, Integer operations, Mobile Damath, Strategic plan, Student engagement.

1. Introduction

The persistent low performance of Filipino students in Mathematics, particularly in integer operations, remains a pressing educational concern (Mbarute & Ntivuguruzwa, 2022). Mastery of integers is not only a basic competency but also a prerequisite for later topics such as inequalities, algebraic equations, and problem-solving (Chong et al., 2022). Yet many learners struggle because they carry misconceptions about positive and negative numbers, which can weaken both conceptual understanding and accuracy in computation (Tanghal, 2020). This

<https://doi.org/10.58503/icvl-v21y202640>

foundational difficulty is reflected in large-scale assessment results: the 2022 Programme for International Student Assessment (PISA) reported that only 16% of Filipino learners achieved Level 2 proficiency in Mathematics compared to the OECD average of 69%, and TIMSS 2019 reported an average score of 297, far below the international mean of 500 (Mullis et al., 2020; OECD, 2023). These outcomes point to the need for instruction that is not only evidenced-based but also responsive to how today's learners engage with content in digital learning environments.

In the context of Instructional Design in the Digital Era, mathematics teaching increasingly emphasizes active learning, meaningful interaction, and tools that help students construct understanding rather than memorize procedures. Game-based learning, particularly in digital formats, has gained attention because it can combine practice with motivation, feedback and sustained engagement. These conditions are often difficult to maintain in purely lecture-based instruction (Godoy, 2020; Cano et al., 2024). Studies in this area commonly report improved participation, interest, and enjoyment when learning activities resemble the interactive and learner-centered experiences students are familiar with (Shah, 2023; Sangode et al., 2024). In mathematics, these benefits are especially relevant because engagement can influence time-on-task, persistence, and willingness to work through challenging concepts.

One technology-enhanced approach that responds to these needs is the mobile Damath game, a digital adaptation of the traditional Filipino board game created by Jesus Huenda. By blending mathematical computation with strategic gameplay, mobile Damath aims to make integer operation more concrete and meaningful while increasing learners' motivation (Ramos et al., 2013; Baog, et al., 2024). Recent work describes mobile Damath and similar tools as contextually relevant interventions that can support active participation and create a more engaging learning climate (Ramirez & Mercado, 2023; Berdiyorovna & Uktamovna, 2025). However, the literature also suggests that the effect of game-based tools is not always uniform across outcomes: some studies highlight strong gains in engagement without significant improvements in performance, while others report advantages in cognitive and metacognitive processes that can translate to achievement over time (Baog et al., 2024; Shah, 2023; Sangode et al., 2024). This mixed evidence suggests that the value of mobile game-based interventions may depend on how engagement relates to measurable learning gains and how the intervention compares with traditional instruction in a specific context.

This concern is evident in Badas National High School, where Grade 8 learners have shown consistently low-test scores in integer operations and limited participation during Mathematics classes. Traditional approaches may not sufficiently address diverse learning needs or sustain interest, which can lead to weak retention and limited mastery of foundational skills (Chong et al., 2022; Tanghal, 2020). Given these realities, mobile Damath offers a student-centered and culturally grounded alternative that may help learners experience integer operations through meaningful interaction and healthy competition, potentially improving

both motivation and achievement (Ramirez & Mercado, 2023; Berdiyrovna & Uktamovna, 2025).

In response, this study investigates the effectiveness of the interactive mobile Damath game in improving Grade 8 students' performance in integer operations at Badas National High School. Specifically, it examined: 1) the relationship between students' engagement, measured through attitude and motivation, and their academic performance, and 2) the difference in outcomes between students exposed to mobile Damath and those taught through traditional instruction. Using quasi-experimental design with control and experimental groups, the study employed pre- and post-tests, and validated engagement surveys. Findings are expected to inform teachers' instructional decisions, support administrators and curriculum developers in adopting technology-based interventions, and guide parents and policymakers in strengthening digital approaches to mathematics learning. Ultimately, the study aligns with the Department of Education's K–12 reform goals of improving mathematics instruction and supporting learners' digital readiness.

This study adopted a unified conceptual framework explaining how mobile Damath may influence Grade 8 learners' integer-operation achievement by integrating technology acceptance, constructivist learning, and game-based learning (GBL). Drawn from Technology Acceptance Model (TAM), students are expected to engage more meaningfully when they perceive mobile Damath as useful and easy to use, fostering positive attitudes and willingness to participate (Davis, 1989; Venkatesh & Davis, 2000). Grounded by constructivist theory, learning is strengthened through active practice, timely feedback and reflection, which are embedded in the gameplay and reflection sessions (Vygotsky, 1978; Hattie & Timperley, 2007). Consistent with game-based learning research, the games' goals, rules, challenge, and feedback loops are expected to sustain motivation and time-on task, supporting skill development (Garris et al., 2017; Plass et al., 2015). Evidence from meta-analyses also indicates that game-based learning can enhance learning and motivation, including mathematics (Wouter et al., 2013; Tokac et al., 2019). Accordingly, the framework posits that mobile Damath influences post-test/gain scores partly through engagement (attitude and motivation), consistent with evidence linking engagement and achievement (Lei et al., 2018) and models of engagement in technology-mediated learning (Hu & Hui, 2012).

2. Methods

This study used a quasi-experimental design with pre- and post-tests involving experimental and control groups to examine the effect of Mobile Damath on students' performance in integer operations and their engagement. The experimental group played Mobile Damath as an instructional tool, while the control group received traditional teaching. Pre-tests established baseline performance, and post-tests measured learning gains.

Purposive sampling was employed in this study using intact Grade 8 classes from Badas National High School, Mati City, Davao Oriental, Philippines. All 106 Grade 8 learners took a pre-test on integer operations, and the 60 lowest-performing students were selected to examine the effect of mobile Damath among learners most in need of remediation. Eligible participants were enrolled in Grade 8 Mathematics, regularly attending, and had parental consent and willingness to participate; students with irregular attendance, no consent, or requiring specialized instruction were excluded. Because random assignment was impractical, intact classes were maintained to avoid disrupting school schedules (Creswell & Creswell, 2017), and the sample was divided into experimental ($n = 30$) and control ($n = 30$) groups with baseline comparability supported by pre-test results and pre-post measures.

Data were collected using a demographic questionnaire, a teacher-made 40-item pre- and post-test, and an AI-assisted engagement survey assessing motivation and attitude toward Mobile Damath. The pre- and post-test showed good reliability (Cronbach's $\alpha = 0.735$), while the engagement survey achieved strong reliability (Cronbach's $\alpha = 0.828$). Student performance was categorized according to DepEd standards, and engagement was rated on a five-point scale.

The intervention lasted three weeks with daily 60-minute sessions. Experimental group sessions included a 10-minute review, 40 minutes of gameplay, and a 10-minute reflection, while the control group received traditional instruction using lectures and exercises. Laptops and internet access were provided to ensure equitable use of Mobile Damath, and monitoring prevented misuse or cross-group contamination.

Data analysis involved descriptive statistics (mean, SD, frequency, percentage) and inferential tests (independent t-test for performance differences and Pearson correlation for engagement–performance relationships). Normality and homogeneity assumptions were verified to justify parametric testing.

Ethical considerations included approval from the university ethics board, informed consent from participants and parents, voluntary participation, data confidentiality, and mitigation of risks such as screen fatigue. The control group received access to Mobile Damath after the study to ensure fairness.

3. Results

3.1 Demographic profile of respondents

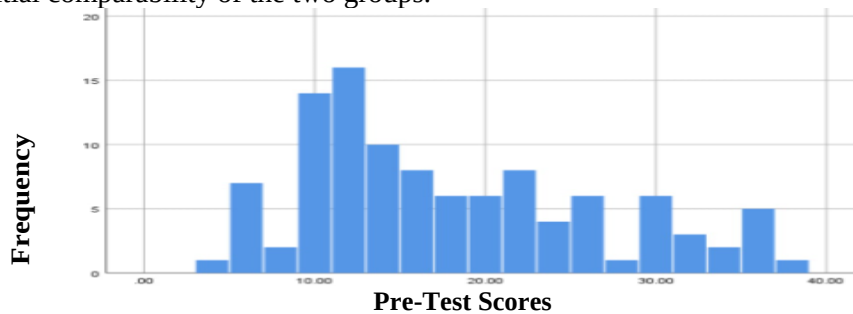
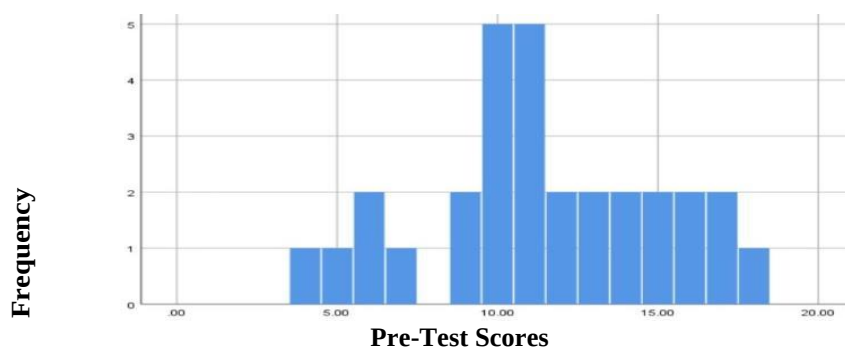
The demographic characteristics of the respondents provide context for interpreting results (Table 1). Most respondents (48.33%) were 14 years old, corresponding to the typical age range for Grade 8 students. In terms of gender, 60% were male and 40% were female, indicating a slightly male-dominated sample.

Table 1. Demographic profiles of the participants

Groups	Frequency (n=60)	Percentage (100%)
Age		
13 years old	10 (Exp), 10 (Ctrl)	20
14 years old	13, 16	29
15 years old	4, 3	7
16 years old	3, 1	4
Gender		
Male	16, 20	36
Female	14, 10	24

3.2 Pre-test performance of students

Prior to intervention, a pre-test on integer operations established the baseline proficiency of both groups. Results revealed that the majority scored between 10 and 15 out of 40 items, suggesting limited mastery (see Figure 1). The experimental group (see Figure 2) had a mean score of 11.43 (SD = 4.58), while the control group scored 11.23 (SD = 4.07) (see Figure 3), both falling under the Beginning proficiency level ($\leq 74\%$). The nearly identical averages confirm the initial comparability of the two groups.

**Figure 1.** Pre-test score distribution: grade 8 integer operations**Figure 2.** Pre-test performance of grade 8 students in the experimental group

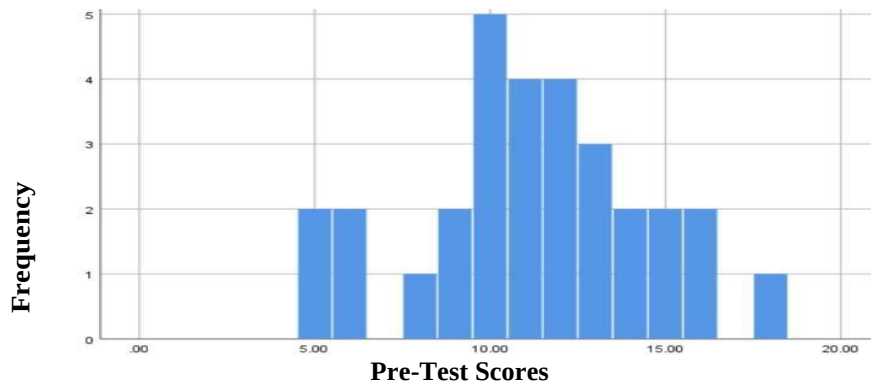


Figure 3. Visual representation of the pre-test results of the control group

3.3 Students' engagement with the Mobile Damath game

Students' engagement with the Damath game was evaluated in terms of attitude and motivation. Results indicated very high engagement levels across both dimensions (see Table 2). In terms of attitude, mean scores ranged from 4.37 to 4.60, with an overall mean of 4.48 (SD = 0.28). For motivation, scores ranged from 4.03 to 4.77, with an overall mean of 4.47 (SD = 0.28). Students reported strong enjoyment, attentiveness, and perseverance during gameplay.

Table 2. Student Engagement Mobile Damath: attitude and motivation

	Mean	SD	Descriptive Interpretation
Attitude			
I regularly engage in the mobile Damath game as part of my daily routine	4.47	0.57	Very High
I actively participate in the gameplay with others on a regular basis.	4.37	0.61	Very High
I prefer to play the game alone with an AI opponent	4.53	0.63	Very High
I am highly focused and attentive while playing the mobile Damath game	4.43	0.50	Very High
I enjoy competing and strategizing while playing the mobile Damath game.	4.47	0.51	Very High
I keep track of my previous scores/record to monitor my progress	4.60	0.50	Very High
Overall	4.48	0.28	Very High
Motivation			
I play the mobile Damath game regularly to challenge myself and test my abilities.	4.03	0.49	High

I am motivated to play the mobile Damath game because it is enjoyable and fun.	4.43	0.50	Very High
I enjoy playing the mobile Damath game because it allows me to compete with others.	4.23	0.57	Very High
I am motivated to learn new strategies to improve my performance in the mobile Damath game.	4.30	0.65	Very High
I enjoy the challenge of solving difficult problems in the mobile Damath game.	4.37	0.67	Very High
I feel overwhelmed every time I get high score over my opponent	4.53	0.51	Very High
My progress in the mobile Damath game motivate me to play more	4.40	0.50	Very High
I feel a sense of accomplishment when I complete a level in the game	4.47	0.51	Very High
I am driven to understand the rules of the mobile Damath game deeply to improve my skills	4.77	0.43	Very High
Overall	4.47	0.28	Very High

3.4 Post-test performance and comparative analysis

After three weeks of implementation, both groups took a post-test to assess improvement. The experimental group achieved a mean score of 77.35% (SD = 4.23), corresponding to the Developing level, while the control group scored 73.61% (SD = 5.44), remaining within the Beginning level (see Table 3).

Table 3. Post-test mathematics performance: experimental vs control

	Groups	Average	Proficiency Level	SD	df	t-stat	P-value	Decision on H_0
Post - Test	Experimental (n=30)	77.35 %	Developing Level	4.23	58	2.97	0.004	Reject
	Control (n=30)	73.61 %	Beginning Level	5.44				

An independent samples t-test revealed a statistically significant difference between the groups, $t(58) = 2.972$, $p = 0.004$, with an effect size (Cohen's $d = 0.77$) indicating a moderate to large impact. The experimental group's improvement from 64.29% to 77.35% demonstrates that the Damath intervention effectively enhanced comprehension and performance in integer operations.

3.5 Relationship between engagement and academic performance

Correlation analysis examined the link between engagement (attitude and motivation) and academic performance. The results showed a significant positive correlation between attitude and motivation ($r = 0.371$, $p = 0.044$), confirming that positive attitudes foster motivation (see Table 4). However, the correlations between engagement and math performance were negative and statistically insignificant (attitude, $r = -0.101$, $p = 0.594$; motivation, $r = -0.045$, $p = 0.814$).

Table 4. Performance-engagement correlation in damath (attitude and motivation)

Attitude		Motivation	Overall Student	Math
			Engagement	Performance
	r-value	1	.371	.822
				-.101
Attitude	p-value		.044	0.001
	r-value	1	.833	-.045
Motivation	p-value		.000	.814
Overall Student	r-value		1	-.088
Engagement	p-value			.645
Math Performance	r-value			1
	p-value			

4. Discussion

The study demonstrates that Mobile Damath significantly enhanced students' mathematical performance compared with traditional instruction. The experimental group achieved a post-test mean of 77.35% (Developing level), while the control group remained at the Beginning level. The moderate-to-large effect size (Cohen's $d=0.77$) suggests that a well-designed digital game can meaningfully improve conceptual understanding in integer operations.

The results can be explained theoretically through a combined constructivist and game-based learning lens: mobile Damath situates integer practice in an interactive setting where learners actively test strategies, receive immediate feedback, and refine misconceptions, conditions central to knowledge construction (Plass et al., 2015). Consistent with TAM, the high motivation ($M = 4.77$) and attitude ($M = 4.60$) scores indicate that perceived usefulness and enjoyment can support students' willingness to engage with the tool (Davis, 1989; Sun et al., 2021). However, the lack of a direct engagement-performance correlation implies that motivation alone does not guarantee learning engagement: achievement gains are more likely when gameplay is paired with teacher-guided scaffolding and

reflection that helps students consolidate concepts and transfer learning to assessments (Hillmayr et al., 2020)

These findings align with previous studies showing that digital and game-based interventions improve learning outcomes by fostering active participation, immediate feedback, and contextualized experiences (Magsombol, 2021; Cano et al., 2024; Plass et al., 2015; Sharma & Shukla, 2023). High engagement and positive attitudes, reflected in motivation ($M = 4.77$) and attitude ($M = 4.60$) scores, support the Technology Acceptance Model (TAM), suggesting that perceived usefulness and enjoyment drive the adoption of educational technology (Davis, 1989; Sun et al., 2021). Students reported enjoyment, competitiveness, and focus, demonstrating that Mobile Damath can make mathematics interactive, appealing, and relevant for digital-native learners.

The absence of a direct correlation between engagement and performance highlights that motivation alone is insufficient to guarantee achievement, reinforcing the need for structured guidance, reflection, and scaffolding (Okigbo & Onoshakpokaiye, 2023; Sangode et al., 2024). Pedagogically, teacher-mediated debriefing ensures that students actively construct knowledge and consolidate conceptual understanding (Hillmayr et al., 2020).

Hence, these findings show that strategically designed digital games, integrated with scaffolding and feedback, exemplify learner-centered instructional design in the digital era, offering a sustainable, effective approach to enhance both engagement and learning outcomes in mathematics education.

5. Conclusion

The study demonstrates that Mobile Damath effectively enhances students' performance in integer operations, highlighting the value of interactive, game-based learning in the digital era. Significant gains in the experimental group indicate that well-designed digital interventions can meaningfully supplement traditional instruction. High engagement and positive attitudes reflect the motivational potential of mobile-based learning, while the need for structured guidance and reflective activities underscores the importance of instructional design in converting engagement into conceptual mastery. Aligning with constructivist principles and the Technology Acceptance Model, these findings suggest that Mobile Damath provides a scalable, technology-driven, learner-centered approach for enhancing engagement, achievement, and meaningful learning in 21st-century mathematics education.

The findings suggest that mobile Damath can effectively support learning in integer operations, but its benefits are greatest when gameplay is teacher-guided rather than treated as stand-alone activity. Teachers should set clear learning targets, use short timed practice cycles, and include "stop-and-check" prompts that require students to justify their move, supported by simple tools such as a misconception checklist and brief reflection log. To address differences in game literacy, a short orientation and low-stake practice round should be provided, with

strategic pairing of roles (player, checker, explainer) to ensure equitable participation. Finally, teachers should manage cognitive load by chunking gameplay by concept, providing visual aids, and conducting a consistent debriefing after each session to connect game actions to formal integer rules and strengthen transfer to assessments.

Acknowledgment

The researcher sincerely expresses gratitude to Badas National High School, the Faculty of Advanced and International Studies of Davao Oriental State University, and all participating students and teachers whose support and cooperation made this study possible.

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Computational thinking and critical thinking in the context of extended reality-based learning environments

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Abstract: *The article examines how computational thinking and critical thinking address the cognitive demands of extended reality (XR)-based learning environments. Drawing on educational policies and computer science curricula, the study highlights the limitations of traditional approaches centered on abstract algorithmic reasoning when applied to immersive, interactive, and dynamic contexts. Based on a systematic literature review, the paper discusses cognitive processes such as spatial reasoning, embodied interaction, and real-time decision-making that characterize XR learning experiences. The article proposes an integrative perspective in which computational thinking is complemented by the evaluative and reflective mechanisms of critical thinking. The conclusions emphasize the educational significance of this approach for curriculum design, pedagogy, and teacher training, and outline directions for future research on how cognitive processes are reorganized within immersive educational environments.*

Keywords: Computational thinking, Critical thinking, Extended reality, Cognitive processes, Immersive learning.

1. Introduction

The rapid digitalization of educational systems over the past two decades has highlighted the importance of cognitive competencies that enable learners to understand, interact with, and modify the digital world. European educational policy documents and studies coordinated by the Joint Research Centre (JRC), such as the reports *Developing Computational Thinking in Compulsory Education* (Bocconi et al., 2016) and *Reviewing Computational Thinking in Compulsory Education* (Bocconi et al., 2022), define *computational thinking* as a transversal cognitive competence essential for problem formulation, the design of algorithmic solutions, and forms of reasoning that can be implemented in computational systems. These systems are understood as integrated hardware–software assemblages capable of executing algorithms, processing data, and automating problem-solving processes (Bocconi et al., 2016; Bocconi et al., 2022).

At the same time, recent European studies indicate that informatics and computer science have gradually become well-defined subjects within primary and secondary education. The Eurydice report on computer science education in European schools shows that curricula place strong emphasis on core areas such as algorithms, programming, and data processing, confirming the importance of

computational thinking for the development of digital competence. However, the same report highlights curricular imbalances, as areas such as modelling and simulation, design and development, and human–system interaction remain underrepresented, despite their growing relevance in contemporary digital environments (Eurydice, 2022).

In parallel, learning environments are undergoing a profound transformation. Beyond the increasingly widespread use of conventional digital technologies in education, extended reality (XR) technologies encompassing virtual, augmented, and mixed reality are being integrated with increasing frequency. These technologies go beyond the mere digitalization of educational content and fundamentally transform how learners interact with knowledge by creating learning experiences based on the overlap and integration of physical and virtual realities.

Although computational thinking provides a relevant framework for understanding algorithmic problem solving and the functioning of digital systems, it does not fully encompass the cognitive processes involved in the effective use of immersive and interactive XR environments. Traditionally, computational thinking emphasizes abstraction, decomposition, and automation, operating predominantly through symbolic manipulation and mediated interaction with technology. In contrast, learning in XR environments involves spatial reasoning, multisensory integration, and the continuous adaptation of actions within a dynamic context in which physical and virtual elements interact permanently in real time.

This divergence between the cognitive characteristics of computational thinking (CT) and the specific nature of XR experiences points to the need for a more detailed analysis of how CT and critical thinking manifest and complement each other in immersive contexts. Rather than introducing a new construct, the article adopts an integrative perspective, examining the limitations of current operationalizations of CT in relation to XR requirements and the role of critical thinking in the evaluation, validation, and justification of decisions in complex digital environments.

Within this framework, the article pursues three main objectives:

- (1) a critical evaluation of the role and limitations of *computational thinking* in European education, as defined and implemented in current policies and curricula;
- (2) an analysis of the cognitive demands specific to learning in XR environments and the identification of areas in which these demands are insufficiently addressed by current curricular practices (e.g., modelling and simulation, design and development, human–system interaction);
- (3) an examination of how *critical thinking* can function as a cognitive regulatory mechanism (evidence evaluation, error detection, decision justification, reflection on consequences) to support the application of computational thinking in XR contexts.

Accordingly, the article seeks to clarify how the evolution of cognitive competencies in digital education can be understood through the interaction between computational thinking and critical thinking in XR contexts, outlining the

implications of this interaction for curriculum structuring, learning task design, and methods for assessing cognitive performance.

Critical thinking is viewed as an active process of analysis and reflection through which individuals evaluate information, arguments, and evidence in order to make well-founded decisions (Facione, 2023). It involves examining reasoning processes, identifying errors or informational limitations, comparing available options, and anticipating the consequences of decisions, particularly in complex and uncertain situations. By contrast, computational thinking refers to a structured approach to problem solving based on abstraction, task decomposition, the design of algorithmic solutions, and their verification through testing and debugging, with the potential for implementation in computational systems (Bocconi et al., 2016; Bocconi et al., 2022).

In extended reality environments, these two cognitive frameworks are not mutually exclusive but complementary. Computational thinking supports the organization and modelling of digital interactions, providing the structural foundations for XR systems to function. At the same time, critical thinking plays an essential role in regulation and validation, helping learners to assess the relevance of information, evaluate the quality of system-generated feedback, and justify decisions made in contexts characterized by dynamism, time pressure, and real-time feedback. From this perspective, the use of XR environments underscores the need for the explicit integration of critical thinking into computational thinking-based activities, particularly in tasks involving interpretation, uncertainty management, and the assumption of responsibility for the consequences of actions within an immersive environment.

2. Computational thinking in European educational policies

Over the past decade, computational thinking has assumed a central role in European educational policies, being recognized as a key element for understanding and leveraging information and communication technologies in contemporary educational and social contexts. The increasing emphasis on computational thinking (CT) also reflects a paradigmatic shift in the conceptualization of digital competences: from narrowly defined technical skills associated with operating ICT tools toward cognitive processes focused on problem solving, reasoning, and innovation across all fields of study. Within the context of educational policies, computational thinking is not limited to programming; rather, it represents a mode of thinking that develops problem-solving strategies through the execution, with the support of computers, of solutions constructed through systematic reasoning (Bocconi et al., 2016).

At the European level, debates and policy orientations concerning computational thinking have been significantly shaped by the work of the Joint Research Centre (JRC) of the European Commission. According to the report *Developing Computational Thinking in Compulsory Education* (Bocconi et al., 2016), computational thinking is defined as “a problem-solving methodology that extends the scope of computer science across disciplines, offering a distinctive way

of analyzing and developing solutions to problems that can be solved computationally. Through its emphasis on abstraction, automation, and analysis, computational thinking constitutes a core element of the broader field of computer science.” The same document states that “computational thinking can be regarded as one of the transversal cognitive competences,” alongside literacy and numeracy, which are “fundamental for active participation in contemporary information societies.”

Within this conceptual framework, computational thinking is commonly associated with a set of foundational cognitive practices, including abstraction, decomposition, algorithmic thinking, automation, debugging, and generalization. European educational policy documents emphasize that these practices enable learners to analyze complex problems, decompose them into manageable components, and construct structured solutions that can be implemented by humans, computational systems, or a combination of both. From this perspective, programming is highlighted as a means for developing computational thinking rather than an end in itself.

From a curricular standpoint, European countries have adopted diverse approaches to integrating computational thinking into compulsory education. In some education systems, computational thinking is embedded within computer science or informatics subjects across all levels of schooling (primary, lower secondary, and upper secondary), whereas in others it is treated as a transversal competence, less dependent on a specific discipline, and incorporated into mathematics, science, or digital competence frameworks. This diversity of integration approaches is illustrated in Figure 1, which presents the positioning of computational thinking (CT) within curricula based on the results of a survey conducted among ministries of education in various European countries (Bocconi et al., 2016, p. 16).

Table 5. Curriculum location based on the survey of MOEs

Country	Within a subject	Across all subjects	Depends on regional or school curricula
Austria	Informatics (upper secondary level)		
Denmark	Information/technology (in grades 10-12)	(in grades 0-9)	X
Finland	Mathematics (grades 1-9) Crafts (grades 7-9)	Transversal competences (e.g. ICT competences)	X
France	Mathematics (Cycle 2-3, primary level) Math and Technology (Cycle 4- lower secondary)		
Hungary	Information technology (grades 1-4; and grades 9-12)		X
Italy	Informatics/ technology IT Curriculum - Applied Science	X	X
Israel	Computer Science		X
Lithuania	Informatics and Information Technology (IT) (grades 5 -12)		
Malta	ICT subject	Part of Digital Literacy (primary level)	X
Poland	Informatics (grades 0-12)	X	
Portugal	- ICT subject (grades 7-8) - Informatics (grades 10-12)		
Switzerland	X	X (primary and lower secondary level German speaking schools)	
Turkey	ICT and Informatics (grade 5-6)		

Figure 1. Positioning of computational thinking in the compulsory education curriculum (adapted from Bocconi et al., 2016, p. 16).

The observed differences are attributable not only to national educational traditions but also to how the role of computational thinking is conceptualized within the curriculum—sometimes as a distinct subject, and in other cases as a transversal dimension integrated across various areas of study. Beyond these divergent approaches, the report identifies a shared objective at the European level: ensuring that all learners complete compulsory education having developed basic computational thinking competencies.

Although computational thinking has been widely adopted in European educational policies, the report's authors highlight several significant challenges related to its implementation. These include the lack of a universally accepted definition, uncertainties regarding the curricular positioning of computational thinking, challenges associated with teacher education and professional development, as well as difficulties related to assessment practices. On the one hand, educational policies emphasize the role of computational thinking in fostering analytical and problem-solving abilities. On the other hand, conceptual tensions persist in how it is approached, oscillating between an understanding of computational thinking as a cognitive process and its treatment as curricular content predominantly focused on programming activities.

Moreover, European research in the field of computer science education indicates that the policy-driven emphasis on computational thinking has led to a strong concentration on algorithmic and programming skills, at times to the detriment of other relevant areas of computer science. The Eurydice report on computer science education in Europe highlights that algorithms and programming are addressed at all educational levels, whereas domains such as human-system interaction, design, and development receive considerably less attention (Eurydice, 2022).

From a cognitive perspective, this policy orientation reflects a predominantly symbolic and abstract understanding of digital competence, centered on logical structures, representations, and formal processes. While such an approach is appropriate for traditional digital environments, it proves limited in relation to emerging immersive, interactive, and multisensory learning contexts that characterize innovative educational environments, particularly those integrating emerging technologies such as extended reality, which are increasingly being adopted within European education systems.

In this context, computational thinking can be regarded as an important but insufficient cognitive framework for addressing the demands of contemporary digital education. Although it has been successfully implemented in European policies as a core competence for interacting with the digital world, the transformation of learning environments into experience-centered contexts calls for the development of more comprehensive cognitive frameworks capable of capturing the specific demands of extended reality environments—demands that are not fully addressed by the current, predominantly abstract definition of computational thinking.

3. Computer science education in Europe

The increasing emphasis placed on computational thinking in European educational policies has been accompanied by a significant expansion of computer science education from the early years of schooling. As highlighted in the Eurydice report *Informatics Education at School in Europe*, there is a growing recognition of informatics as an autonomous scientific domain with its own body of knowledge, methods, and ways of thinking, rather than merely a set of operational digital skills.

In this context, the majority of European education systems have integrated informatics either as a distinct subject within the curriculum or as a component of other subjects, most notably mathematics, science, and technology.

To facilitate cross-national comparisons, Eurydice has identified ten core domains of informatics that are commonly reflected in national competence frameworks and curricula: data and information; *algorithms*; *programming*; *computing systems*; *networks*; *human-system interaction*; *design and development*; *modelling and simulation*; *awareness and empowerment*; *safety and security*.

This framework provides a coherent and systematic basis for the classification and analysis of learning outcomes associated with informatics competences across European education systems.

An analysis of this framework reveals that, at all levels of compulsory education, algorithms and programming constitute the most strongly emphasized areas of computer science education, being the most extensively covered domains in the majority of European countries. In many education systems, algorithmic thinking skills and basic programming concepts are introduced as early as primary education and are progressively developed throughout lower and upper secondary schooling.

By contrast, Eurydice data indicate a far more uneven curricular coverage of other informatics domains. For example, *modelling and simulation* are explicitly addressed in only a very limited number of primary-level curricula and remain marginal even at the upper secondary level (Table 1).

Table 1. Representation of the modelling and simulation domain in European computer science curricula

Country	Educational level	Formulation of learning outcomes
Bulgaria	Primary	Explicit learning outcomes related to computational modelling and simulation are specified
Czech Republic	Primary	Introduction of modelling and simulation concepts
	Lower secondary	Consolidation of competences related to the use of models and simulations
	Upper secondary	Application of modelling and simulation to investigate phenomena
Greece	Primary	Use of simulation tools to understand real-world systems and formulate predictions
	Lower secondary /	Progressive development of modelling and

	Upper secondary	simulation competences
France	Primary	Modelling reality using physical, geometric, and digital models
	Lower secondary	Digital simulation of the struct
	Upper secondary	Programming and development of models for physical, economic, and social phenomena
Slovenia	Primary	Explicit learning outcomes related to modelling and simulation
Ireland	Upper secondary	Development of computational models to test scenarios; problem solving through simulation
Netherlands	Upper secondary	Computational modelling of phenomena from other scientific disciplines; use of simulations

The *modelling and simulation* domain remain modestly represented in European curricula, being explicitly included at the primary education level in only five countries (Bulgaria, the Czech Republic, Greece, France, and Slovenia). Among these, only three countries (the Czech Republic, Greece, and France) ensure a coherent and progressive development of this domain across all three educational levels. At the upper secondary level, although modelling and simulation are present in approximately one third of European education systems, they are addressed primarily within interdisciplinary and STEM-oriented contexts. This orientation suggests a fragmented and application-driven integration of the domain rather than a systematic and progressive construction of competences throughout compulsory schooling.

Similarly, design and development, as well as human–system interaction, are among the least frequently addressed themes in European computer science education, despite their high relevance for contemporary digital systems, which increasingly depend on user experience, interaction design, and system modelling. When included, these domains typically appear in optional or specialized computer science courses at the upper secondary level (Table 2).

Table 2. Presence of the design and development and human–system interface domains in European computer science curricula

Domain	Educational level	Countries
Design and Development	All three educational levels	Greece, Poland, Turkey
	Lower and upper secondary	Ireland, France, Latvia
	Upper secondary (predominantly)	More than one third of European education systems
Human–system interface	Primary	Greece, Croatia, Hungary
	Lower secondary	Latvia
	Upper secondary	Denmark, Estonia, Sweden

The uneven distribution of learning outcomes suggests that computer science curricula predominantly emphasize abstract, symbolic, and procedural dimensions, while experiential, interactive, and system-centered components remain less

developed. From a pedagogical perspective, computer science is thus approached primarily as an algorithmic discipline, in line with the classical view of computational thinking promoted at the European level. Although this approach is appropriate for traditional digital platforms, it is less suited to understanding emerging educational environments based on interaction and immersion.

At the same time, the Eurydice report highlights that curricular progression is not uniform across all domains of computer science. While the number of learning outcomes increases from primary to lower and upper secondary education, this progression is particularly evident in areas such as algorithms, programming, and safety and security. By contrast, domains related to human–computer interaction and design and development do not exhibit a clear developmental trajectory, suggesting a lack of continuity in the formation of these competences throughout schooling. In this context, recent empirical evidence from lower secondary education indicates that the use of visual programming environments enhances students’ computational thinking, motivation, and transdisciplinary competences, supporting the role of project-based approaches in addressing curricular gaps (Veverița, 2025). Comparative studies of primary digital education curricula across Europe show clear differences in how programming, algorithms, and digital skills are taught, pointing to ongoing challenges in ensuring coherent and continuous learning across educational levels (Veverița & Braicov, 2025).

From a cognitive perspective, these curricular gaps point to a deeper issue that extends beyond curriculum design alone. The limited emphasis on modelling, simulation, and human–system interaction suggests a potential misalignment between the current framework of computer science education and the cognitive demands associated with functioning in complex digital environments. As educational technologies increasingly evolve toward the use of extended reality, the development of competences such as spatial reasoning, embodied interaction, and real-time problem solving becomes essential—competences that are insufficiently addressed in current computer science curricula.

Taken together, Eurydice findings indicate that, despite the progress made in integrating computer science and computational thinking into compulsory education across Europe, certain educational and cognitive gaps persist. These gaps are particularly evident in domains directly relevant to extended reality environments. Identifying and addressing them therefore requires a reconsideration of the cognitive frameworks underpinning computer science education. It is within this context that *the analysis of the cognitive demands of extended reality-based learning environments and the need to articulate an expanded perspective on thinking—one that goes beyond the conceptual limits of computational thinking—become especially pertinent.*

4. Cognitive demands of extended reality environments

The curricular gaps identified in computer science education in Europe become far more apparent when examined in relation to the cognitive demands specific to extended reality (XR)-based learning environments. XR technologies—

including virtual, augmented, and mixed reality—not only extend but fundamentally transform traditional digital technologies used in interactive learning contexts, generating new forms of interaction, meaning-making, and experiential engagement with knowledge. Current research shows that XR can create immersive three-dimensional environments that facilitate complex visualization and interaction, thereby supporting knowledge acquisition in ways that are largely inaccessible to traditional digital environments (Burke et al., 2025).

One of the defining characteristics of XR environments is *presence*, often described in the literature as the feeling of “being there”, which engages learners as active participants in an adaptive environment rather than as passive observers (Al-Samarraie et al., 2025). Presence involves a continuous perception–action–decision cycle, influencing learning processes by intensifying cognitive engagement and intrinsic motivation, as highlighted in analyses of cognitive factors within immersive learning models (Zhi et al., 2023).

A second essential feature of XR environments is *embodied interaction*, in which bodily movement, gestures, and spatial orientation constitute central modes of interaction. Recent studies indicate that XR applications employ a wide range of natural interaction techniques—such as gesture, motion, and voice-based interaction—which increase users’ cognitive engagement and shape the ways in which they adapt their behavior during learning activities (Logothetis, 2025).

In this context, XR environments require learners to coordinate information originating from both the physical and digital worlds, particularly in augmented and mixed reality, where these layers coexist and dynamically influence one another. This coordination involves *spatial reasoning* processes manifested in the continuous construction and updating of complex mental models of space and interaction. Consequently, recent research highlights the potential of XR to support the investigation of cognitive processes in learning contexts that closely approximate real-world situations (González-Erena, Fernández-Guinea & Kourtesis, 2025).

The *temporal dimension* further contributes to increased cognitive complexity in XR environments, where users’ actions are followed by immediate system responses. This rapid coupling between action and feedback requires learners to observe the consequences of their decisions, evaluate them, and continuously adjust their interactions. As a result, XR environments demand more frequent decision making and more careful management of cognitive load than traditional problem-solving contexts, a finding confirmed by recent systematic reviews on the use of XR in education (Burke et al., 2025).

Taken as a whole, the dimensions of presence, embodiment, spatial reasoning, and real-time interaction reveal a set of cognitive demands that are only partially addressed by existing conceptualizations of computational thinking. While computational thinking provides a robust framework for problem analysis and abstract reasoning about systems, it does not conceptualize cognition as lived, spatial, and embodied experience. This limitation becomes increasingly evident as XR environments assume a more prominent role in education, including in the

design of immersive learning systems.

XR environments introduce a higher volume of information and more complex learning situations by combining visual, spatial, and action-oriented elements within continuous interaction. This complexity requires learners to interpret information rapidly, evaluate the consequences of their actions, and avoid premature conclusions. In this context, alongside computational thinking, critical evaluation becomes essential, supporting informed decision making and cognitive self-regulation in immersive learning experiences.

Consequently, the cognitive characteristics of extended reality environments point to the need for a more comprehensive conceptual framework—one that connects algorithmic reasoning with the spatial, embodied, and experiential dimensions of thinking. At the same time, this perspective highlights the limitations of current computer science curricula and educational policies in preparing learners for immersive learning situations. In this regard, the findings reviewed here suggest research directions focused on understanding how cognitive processes adapt and reorganize when learning occurs in extended educational environments, beyond the traditional frameworks of digital thinking.

5. Systematic analysis of thinking models in the context of extended reality

The literature analysis aims to provide a critical evaluation of the main conceptual frameworks used to describe different models of thinking by examining how these models are defined and operationalized in scholarly research. The analysis focuses on three distinct yet interrelated domains: critical thinking, computational thinking, and the cognitive processes involved in extended reality (XR) contexts. The purpose of this analysis is to examine the extent to which existing models of thinking address the cognitive demands specific to immersive learning environments, thereby clarifying the adequacy of computational thinking and critical thinking in explaining and supporting cognitive performance in XR contexts.

Although critical thinking and computational thinking are well-established theoretical frameworks in both educational research and public policy documents, recent literature on learning mediated by extended reality technologies highlights the emergence of specific cognitive demands, such as spatial reasoning, embodied interaction, and the management of presence. In this context, the literature review examines theoretical arguments and empirical findings indicating changes in the conditions under which computational thinking is applied (Shute et al., 2017), as well as shifts in the function of critical thinking in XR environments, without assuming the existence of a distinct cognitive construct. From this perspective, processes such as spatial reasoning, multisensory integration, and real-time decision making are treated as contextual demands of XR environments that can be supported through adaptations of computational thinking tasks and through self-regulatory and evaluative mechanisms specific to critical thinking.

The literature review was guided by the following research questions:

- 1) What definitions and conceptualizations of critical thinking and computational thinking are present in educational and digital research?
- 2) Which cognitive processes are central to empirical research on learning and interaction in XR environments?
- 3) To what extent can critical thinking and computational thinking account for the cognitive demands identified in XR contexts?
- 4) What theoretical and empirical gaps suggest the need to adjust the operationalization and assessment strategies of computational thinking and critical thinking in XR contexts?

The systematic literature review was conducted in accordance with best-practice recommendations for systematic reviews in education and the social sciences, as outlined in the PRISMA 2020 guidelines and in foundational methodological literature (Page et al., 2021; Siddaway et al., 2019).

To ensure comprehensive coverage of research in education, human-computer interaction, and immersive technologies, the ERIC (Education Resources Information Center) database was consulted. Only peer-reviewed journal articles and full papers published in peer-reviewed conference proceedings were included. The selected publications appeared between 2017 and 2025 and focused primarily on lower secondary, upper secondary, and higher education contexts.

Structured Boolean search strategies were applied by combining keywords related to:

- (a) critical thinking;
- (b) computational thinking;
- (c) cognition in extended reality contexts (VR, AR, MR, XR).

This strategy enabled the identification of both conceptual frameworks and empirical studies conducted in educational and training settings.

The inclusion criteria required that studies:

- (a) explicitly address thinking or cognitive processes;
- (b) involve digital or XR environments;
- (c) report conceptual models or empirical findings relevant to learning or cognitive performance.

The exclusion criteria eliminated editorial materials, purely technical studies lacking cognitive or educational relevance, clinically oriented research without transfer potential to educational contexts, and publications that did not meet standards of methodological rigor.

For the purpose of rigorous comparative analysis, studies were coded along three analytical dimensions:

- *Critical thinking* (CrT): evaluation, inference, argumentation, use of evidence (Shute et al., 2017);
- *Computational thinking* (CT): abstraction, decomposition, algorithmic thinking, automation, debugging (Angeli & Giannakos, 2020);

- *XR-specific cognition*: spatial reasoning, embodiment, multimodal processing, presence, real-time adaptation, and cognitive load management (Hsu et al., 2018; Johnson–Glenberg, 2018).

The application of this coding scheme facilitated the identification of both overlaps and gaps between existing *theoretical models of thinking* and the cognitive demands specific to extended reality environments.

In the context of immersive technologies used to support cognitive processes, the literature defines *cognitive augmentation* as the extension of human cognitive functions—such as attention, memory, and decision making—through active interaction with immersive digital environments (Johnson–Glenberg, 2018).

Recent research indicates correlations between the use of XR environments and improvements in spatial abilities, mental representation of three-dimensional objects, and long-term memory performance, compared to traditional learning environments (Alazmi, 202). These outcomes are largely attributed to the high level of immersion afforded by XR, which enables learners to engage in complex tasks closely aligned with real-world application contexts (Radianti et al., 2020). The literature suggests that embodied interactions, supported by sensorimotor coupling, play a central role in shaping cognitive processes, extending beyond models based exclusively on symbolic processing (Johnson–Glenberg, 2018).

In educational contexts, studies indicate that XR environments can support deep learning through active engagement, reflection on action, and the strengthening of learners' confidence in their own decisions, thereby facilitating the transfer of competences across learning and application contexts (Jensen & Konradsen, 2018; Makransky et al., 2021).

At the same time, recent studies highlight the risk of cognitive overload associated with poorly designed XR environments. In this regard, the application of cognitive load theory principles becomes increasingly important to balance the benefits of immersion with learners' processing capacities (Makransky & Petersen, 2019; Sweller, 2020).

Analysis of literature published after 2017 reveals a marked increase in interest in cognition in XR environments, particularly from 2020 onward. Most studies adopt empirical approaches, focusing on specific cognitive dimensions such as spatial reasoning, attention, and memory retrieval (Radianti et al., 2020). The field is predominantly interdisciplinary, with educational research increasingly informed by cognitive psychology and immersive technologies.

Thematic synthesis of the recent literature identified four central directions:

- (1) the role of spatial and embodied cognition in XR environments;
- (2) multimodal interaction as a driver of cognitive stimulation;
- (3) presence and immersion as mediators of learning effectiveness;
- (4) the need for adaptive cognitive support to manage task complexity.

These dimensions are weakly represented in classical computational thinking frameworks.

Overall, the synthesis highlights a conceptual gap between traditional models of thinking and the cognitive demands of XR environments. While the

computational thinking paradigm offers a comprehensive model for algorithmic problem solving (Angeli & Giannakos, 2020), it provides only partial explanatory power in immersive contexts.

Overall, the literature analysis clarified the principal definitions of critical thinking and computational thinking used in educational research and identified the cognitive processes examined in studies of learning and interaction in XR environments. The findings indicate that, although computational thinking and critical thinking can partially account for the cognitive demands of these environments, they exhibit limitations when applied in their traditional forms to contexts characterized by spatiality, embodiment, and real-time interaction. The literature therefore points to theoretical and empirical gaps that suggest the need to adjust the operationalization and assessment of these frameworks, particularly through interaction-based tasks, modelling and simulation activities, and decision making under conditions requiring real-time adaptation.

In this context, the results underscore the explanatory limits of the computational thinking paradigm when applied in its traditional form to immersive learning contexts. While computational thinking provides a robust framework for algorithmic problem solving and digital system modelling, the reviewed literature indicates the need to adapt its operationalization and assessment in XR tasks, as well as to strengthen the role of critical thinking as a mechanism for evaluation, justification, and reflection on decisions and evidence in immersive interaction contexts.

The main findings of the systematic review, categorized by the analytical dimensions and their implications for the proposed framework, are synthesized in Table 3.

Table 3. Synthesis of the literature across reviewed dimensions and the proposed conceptual framework

Dimensions	Relevant sources	Key findings from the literature	Integration into the proposed conceptual framework
Computational Thinking (CT) and curricular gaps	Bocconi et al. (2016, 2022); Eurydice (2022); Angeli & Giannakos (2020); Digital Education Action Plan 2021–2027 (European Commission, 2021).	CT is predominantly centred on algorithms and programming, while modelling and human–system interaction are marginalised.	Defines the need to extend CT through XR environments in order to address modelling and simulation domains.
Embodied and spatial cognition	Johnson–Glenberg (2018); Hsu et al. (2018); Logothetis et al. (2025); Rianti et al. (2020)	Gestures, movement, and spatial orientation are essential for learning in XR environments.	Proposes a shift in CT from symbolic manipulation (code) toward problem solving through physical–virtual interaction.

Presence, immersion, and cognitive load	Makransky et al. (2019, 2021); Sweller (2020); Jensen & Konradsen (2018); Johnson–Glenberg (2018);	Immersion increases presence but may lead to cognitive overload, reducing resources available for learning.	Positions CrT as a self-regulatory mechanism for managing attention and cognitive resources in complex environments.
Multimodal assessment and training	Shavelson et al. (2019); González–Erena et al. (2025); Alazmi & Alemtairy (2024)	XR enables real-time assessment of users’ behaviours and affective responses in simulated real-world situations.	This supports moving assessment from code to decision-making in XR
Critical Thinking (CrT) as a regulatory mechanism	Facione (2023); Halpern & Dunn (2022); Shute et al. (2017)	CrT involves analysing available information, identifying errors, and justifying decisions under conditions of uncertainty.	Positions CrT as a validation mechanism for solutions generated through CT, supporting reflection on consequences.
Analysis of trends and affective responses in XR	Al–Samarraie et al. (2025); Burke et al. (2025); Radianti et al. (2020); Zhi & Wu (2023)	A correlation is identified between the level of immersion and learners’ affective responses, highlighting the role of perceived presence in learning task success.	Justifies the integration of CrT mechanisms to balance affective and intuitive reactions, ensuring reflective application of CT processes in dynamic learning environments.

6. Reconfiguring computational thinking and critical thinking in extended reality contexts

There is a growing need to reconsider the role of computational thinking in the contemporary digital classroom in light of the transformations introduced by extended reality (XR) environments in the way’s learners interact with information, solve problems, and make decisions (Shute, Sun & Asbell–Clarke, 2017; Burke, D. et al., 2025). Within this context, it becomes particularly relevant to examine how computational thinking and critical thinking can be integrated into a coherent approach capable of addressing the cognitive demands of digital literacy in a dynamic, immersive, and interactive environment (Facione, 2023; Makransky & Petersen, 2019).

In XR environments, learners receive immediate feedback in response to their actions, which directly influences how situations are interpreted and decisions are made (Radianti et al., 2020; Makransky et al., 2021). Under these conditions,

learners may make rapid decisions based on elements that attract immediate attention within the immersive space, potentially leading to misinterpretations or unwarranted generalizations (Dede, 2009). In this context, critical thinking functions as a self-regulatory mechanism that tempers intuitive reactions and supports deliberate evaluation of information and outcomes, thereby complementing the procedural function of computational thinking (Facione, 2023; Halpern & Dunn, 2022).

From an operational perspective, critical thinking in XR environments can be observed and assessed through indicators such as:

- (a) explicit formulation of hypotheses and verification criteria;
- (b) justification of the chosen course of action in relation to task objectives;
- (c) comparison of alternative options and justification of the selected approach;
- (d) identification of errors—whether user or system-related and revision of decisions;
- (e) reflection on the consequences of actions, including considerations of safety, equity, and user impact.

Integrating these indicators into the design of XR tasks strengthens the role of critical thinking as a mechanism for validating and regulating the application of computational thinking in immersive contexts (Facione, 2023; Shavelson et al., 2019).

Computational thinking emerged in response to the increasing pervasiveness of computational systems in the world. Its abstract, algorithmic, and structured nature can be understood as a cognitive approach tailored to environments in which interaction with reality is mediated primarily through symbolic representations and formal procedures. This approach enables highly effective understanding and design of computational systems and continues to play a central role in computer science education (Shute et al., 2017; Angeli & Giannakos, 2020). In XR educational contexts, however, these characteristics must be aligned with processes of critical analysis, information evaluation, and reflection on the consequences of decisions—processes that are intrinsic to critical thinking.

Extended reality environments fundamentally alter this relationship. In XR contexts, learners no longer conceptualize or manipulate computational processes from an external standpoint; instead, they enter and inhabit environments in which physical and virtual components coexist and interact. Cognition unfolds through perception, movement, and real-time interaction, requiring learners to continuously coordinate multiple streams of information. This shift reconfigures problem-solving activity, moving it away from abstract and sequential modes of reasoning toward context-dependent and dynamic forms of cognition (Johnson-Glenberg, 2018; Makransky et al., 2021).

From this perspective, extended reality environments require a contextualized application of computational thinking competences, complemented by the regulatory mechanisms of critical thinking. Abstraction remains a central process, but it is enacted in relation to spatial and experiential structures rather than exclusively symbolic ones (Burke et al., 2025; Radianti et al., 2020).

Decomposition involves breaking down complex environments and interactions into manageable components, while algorithmic thinking manifests through the anticipation of interaction patterns and the consequences of actions. Within this framework, critical thinking supports decision evaluation, information validation, and reflection on the learning experience.

This complementary relationship between computational thinking and critical thinking in extended reality contexts is synthesized in Table 4, which highlights the distinct yet interrelated roles of the two cognitive frameworks in XR-based learning activities.

Table 4. Manifestations of computational thinking and critical thinking in extended reality contexts

Dimension	Computational Thinking (CT) in XR	Critical Thinking (CrT) in XR
What learners do	Construct models and define rules governing system behaviour and interaction	Analyse choices made and evaluate the outcomes obtained
Relation to the environment	Engage in controlled interaction with digital elements	Develop a holistic understanding of the situation and judge actions in relation to context
Decision-making	Follow clearly defined, step-by-step procedures	Continuously adjust decisions based on ongoing observation and feedback
Role in thinking	Supports the organisation and procedural resolution of problems	Supports verification, correction, and reflective evaluation of solutions
Validation of results	Test whether the solution functions correctly and debug errors	Justify conclusions and solutions through argumentation
Responsibility and consequences	Focus on achieving a functional solution	Evaluate risks and the impact of decisions on users and the learning context

Table 4 highlights that XR environments do not imply a replacement of computational thinking, but rather an expansion of the contexts in which it is applied. Within such environments, computational thinking retains its central role in modelling, structuring, and anticipating the behaviour of digital systems, while critical thinking becomes essential for evaluating decisions, interpreting information, and reflecting on the consequences of actions within an immersive and dynamic context.

More fundamentally, this shift forms part of a broader paradigmatic transformation in how knowledge is produced and used in computationally mediated spaces. While computational thinking remains well aligned with epistemological frameworks that prioritise representation, formalisation, and control, XR environments amplify the importance of experience and direct interaction, thereby necessitating the systematic integration of critical thinking processes into learning activities.

From this perspective, the use of XR environments underscores the need for an integrative educational approach in which computational thinking is supported by critical thinking, enabling learners to analyse complex situations, justify decisions, and reflect on immersive learning experiences. Preparing learners for contemporary digital ecosystems must therefore be grounded in a solid foundation in computational thinking, alongside the development of competences related to critical evaluation and cognitive self-regulation.

Overall, the literature analysis has clarified how computational thinking and critical thinking are defined within educational research and has identified the core cognitive processes examined in XR environments. The findings indicate that, although these frameworks partially account for the cognitive demands of immersive learning, they become limited when applied in their traditional forms. In this context, the literature points to the need to adapt both the evaluation and application of these frameworks through tasks that involve interaction, modelling, and decision making under dynamic conditions.

7. Educational implications for European curricula

Extended reality (XR)-based learning environments introduce significant changes for curricular developments in European computer science education. Although current curricula have effectively supported computational thinking as a foundational skill, the emphasis has been placed primarily on abstract algorithmic reasoning (Bocconi et al., 2016; Bocconi et al., 2022; Angeli & Giannakos, 2020). The integration of XR technologies into education highlights the need to reconsider curricular priorities so that educational objectives respond more adequately to emerging cognitive and pedagogical demands, through a balanced and coherent articulation of computational thinking and critical thinking (European Commission, 2021).

7.1. Implications for curriculum design

At the curricular level, the integration of XR environments underscores the need to move beyond the predominant focus on algorithms and programming toward a more balanced representation of the various domains of computer science. Analyses conducted by Eurydice indicate that areas such as modelling and simulation, design and development, and human-system interaction remain insufficiently represented in many European curricula, despite their increasing relevance for interactive and immersive digital contexts (Bocconi et al., 2022; Eurydice, 2022).

From an applied perspective, this shift entails embedding computational thinking competences within educational activities carried out in XR environments, alongside the systematic development of critical thinking, which supports decision evaluation, information interpretation, and reflection on learning experiences. In particular, at the upper secondary level, students can be engaged in modelling, simulation, and design tasks that require both algorithmic reasoning and critical analysis in dynamic and situated contexts (Facione, 2023; Halpern & Dunn, 2022).

7.2. Pedagogical implications

From a pedagogical standpoint, XR environments support the development of educational approaches centred on learning through interaction and experience. In these contexts, simulation and exploratory activities align with constructivist and experiential learning models, in which understanding is constructed through action, reflection, and real-time feedback.

Integrating XR technologies into teaching practice does not imply abandoning algorithmic thinking or formal problem-solving approaches. On the contrary, effective instruction requires the continuous articulation of computational thinking with critical thinking. For example, learners may use computational thinking to analyse a problem and construct a model, while employing critical thinking to evaluate the model's behaviour within an XR simulation, reflecting on the consequences of decisions made and on the validity of the results obtained (Makransky et al., 2020; Shavelson et al., 2019).

7.3. Implications for initial teacher education and professional development

The use of XR environments is particularly relevant in the context of initial teacher education and continuous professional development. European reports consistently emphasise the central role of teachers in implementing computer science curricula and highlight the challenges associated with preparing educators to teach emerging digital competences (European Commission, 2021; Bocconi et al., 2022).

Within this framework, teacher education programmes should aim to develop competences in designing educational activities that coherently integrate computational thinking and critical thinking in XR contexts. This includes providing teachers with direct hands-on experiences with immersive technologies, as well as opportunities for pedagogical reflection on their effective use in teaching and learning processes (Jensen & Konradsen, 2018).

7.4. Alignment with European educational policy frameworks

The integration of XR environments into computer science education is fully aligned with European policies on digital competence, innovation, and future-oriented education. European strategies seek not only to develop technical skills but also to strengthen cognitive capacities related to problem solving, critical analysis, and adaptation to rapidly evolving technological contexts (European Commission, 2021).

From this perspective, leveraging XR environments as educational spaces supports the application of computational thinking and critical thinking in authentic learning situations, contributing to the development of advanced digital competence. Such an approach promotes a forward-looking vision of computer science education and provides a coherent framework for adapting European curricula to the demands of contemporary digital ecosystems.

8. Conclusions and future research directions

The findings of this study indicate that *traditional cognitive models do not adequately capture the learning processes occurring in extended reality (XR) environments*, which are characterized by immersion, presence, and real-time interaction. In this context, *computational thinking, when applied in isolation, proves insufficient*, making it necessary to complement it with evaluative, reflective, and interpretative processes associated with critical thinking.

The analysis of computer science curricula across Europe reveals notable *gaps in domains that are essential for XR-based learning*, such as modelling and simulation, design and development, and human-system interaction. These findings support *the need for a closer articulation between computational thinking and critical thinking*, without introducing a new cognitive construct.

The main contribution of this paper lies in proposing an integrative perspective that explains how these two forms of thinking complement each other in supporting cognitive performance in XR environments. From an educational standpoint, the results point to significant implications for curriculum design, pedagogical strategies, and teacher education.

Further empirical studies are needed to examine the development of computational thinking and critical thinking in XR contexts, as well as to evaluate educational interventions based on modelling, simulation, and critical reflection. In addition, future research may explore the influence of different types of XR environments and investigate ways to systematically integrate these cognitive processes into existing digital competence frameworks.

Acknowledgments

This study was conducted within the framework of the research and innovation project “New extended reality technology for cognitive augmentation based on the superimposition of interactive experiences”, strategic direction: “Innovative Technologies, Sustainable Energy, Digitalization”, registered in the State Register of Projects in the field of Science and Innovation of the Republic of Moldova, project code 25.80013.5007.60ROMD.

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SECTION 4

NON-TECHNOLOGICAL DIMENSION OF ONLINE LEARNING

Geopolitics and manipulated realities: the diplomatic response to disinformation campaigns

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Abstract: *Disinformation has emerged as a central instrument of geopolitical strategy, with the Russia–Ukraine war amplifying its use in destabilizing democratic states. Romania, as a frontline EU and NATO member bordering Ukraine and Moldova, has become a key target for Russian-linked disinformation campaigns aimed at undermining public trust, electoral legitimacy, and regional alignment.*

Over the past four years, Romania has faced coordinated influence operations that promoted anti-Western narratives, manipulated political discourse, and amplified social divisions. These efforts intensified around national elections, the arrival of Ukrainian refugees, and debates over economic hardship, with actors exploiting Romania's low media literacy and deep institutional distrust.

This study investigates how Romania's diplomatic institutions have responded to these campaigns. It addresses the broader problem of how mid-sized democracies in strategic regions adapt to foreign disinformation as part of hybrid warfare. Here we examine Romania's case through a qualitative analysis of official statements, academic literature, and monitoring platforms.

We find that Romania has primarily responded by aligning with EU and NATO messaging frameworks while issuing reactive diplomatic rebuttals. However, proactive and strategic public diplomacy remains underdeveloped. These findings suggest that current responses are insufficient in the face of evolving digital threats.

Keywords: Disinformation, Strategic communication, Hybrid warfare, Romanian diplomacy, Narrative manipulation.

1. Introduction

In the past decade, disinformation has become a powerful tool of geopolitical influence, used to undermine public trust, disrupt democratic processes and destabilize institutions. The 2022 Russian invasion of Ukraine marked a shift in the use of disinformation as an integral component of hybrid warfare, operating alongside cyber operations, energy pressure and conventional threats (Hybrid CoE, 2023). This strategic use of manipulated narratives is central to Russia's broader goal of reshaping influence zones and weakening Western cohesion.

Romania has emerged as a key target in this context. As a frontline member of NATO and the EU with direct borders to Ukraine and Moldova, Romania faces

constant exposure to Russian-backed disinformation campaigns. These operations do not attempt to promote Russia's image directly, given historical tensions, but instead aim to erode trust in the West. According to the EU DisinfoLab, Russian-linked narratives circulating in Romania often focus on themes such as national sovereignty, energy insecurity and cultural decay, while co-opting local actors to enhance credibility (EU DisinfoLab, 2023).

Between 2020 and 2024, disinformation in Romania intensified around key moments such as the COVID-19 pandemic, refugee arrivals from Ukraine and electoral events. Narratives have included claims of electoral fraud, vaccine conspiracies and portrayals of Romania as a "colony" controlled by NATO and the EU. These narratives were amplified by nationalist-populist figures, religious institutions and media outlets with obscure funding (Pop, 2023).

Romania's vulnerability to disinformation is exacerbated by systemic weaknesses in media literacy and institutional trust. Balan (2025) notes that widespread conspiracy beliefs, nostalgia for authoritarianism and limited civic education create fertile ground for manipulation. A 2023 survey cited by the EU DisinfoLab found that 65% of Romanians believed COVID-19 was a tool of global control and more than 50% expressed favourable views of the communist past (EU DisinfoLab, 2023).

Despite growing exposure to foreign influence operations, Romania's institutional and diplomatic responses remain fragmented. The MFA, National Defence Council and intelligence agencies have acknowledged the threat, but comprehensive and sustained diplomatic strategies are still lacking (Pop, 2023; Balan, 2025).

In parallel with security and diplomatic dimensions, the paper also acknowledges that disinformation circulates through digitally mediated environments that increasingly include virtual education and hybrid learning settings. In this sense, digital literacy and media-and-information literacy developed through education represent not only social-policy priorities but also resilience levers relevant to reducing susceptibility to foreign influence campaigns.

This article investigates Romania's diplomatic response to disinformation campaigns in the context of Russian hybrid tactics. Using a qualitative case study approach, it draws on academic research, official reports and media monitoring data to examine the narratives deployed, the state's response mechanisms and the challenges involved. It seeks to answer the central research question: How has Romania adapted its diplomatic practices to respond to the challenges of foreign disinformation campaigns? The findings aim to highlight not only gaps in Romania's current approach but also concrete recommendations for improving digital resilience and diplomatic communication.

To complement the qualitative analysis, this paper introduces a short quantitative context snapshot that captures structural conditions linked to susceptibility to disinformation. We compute a Vulnerability Context Index (VCI) using three observable indicators: media literacy, basic digital skills coverage, and a trust-in-media benchmark. The VCI is used descriptively, as a baseline for

interpreting why certain narratives can diffuse and persist in the Romanian information environment.

2. Literature review

Disinformation has increasingly been studied as a core component of hybrid threats that combine military and non-military tools to influence populations and weaken democratic institutions. Scholars conceptualize hybrid warfare as a strategy in which information manipulation, cyber operations, economic pressure, and political influence are integrated into broader security competition. Patel et al. (2020) describe disinformation and misinformation as key elements of hybrid warfare, especially in the context of Russia's actions in Ukraine, where information operations function as extensions of military conflict by eroding public trust and shaping perception. Patel et al. (2020) further emphasize the need to distinguish disinformation (intentional deception) from misinformation (unintentional inaccuracy), underscoring its strategic use by state actors.

Russia's use of information warfare is well documented in analyses of hybrid strategies. Academic work on Russian hybrid warfare emphasizes the role of the information space in contemporary conflicts. For example, studies on Russia's hybrid toolkit show that disinformation is deeply integrated with influence operations, where narratives are crafted to exploit social divisions and question the legitimacy of Western institutions (Bachmann & Gunneriusson, 2015). These accounts align with research that positions disinformation as a deliberate element of strategic competition aimed at disrupting consensus among allies and weakening opponents without direct military confrontation (Hansen, 2017). The European Union and NATO have recognized this threat and developed institutional frameworks to enhance resilience, monitor disinformation, and coordinate responses. Ahmadly (2022) notes that NATO and the EU have adjusted their security paradigms to combat hybrid threats, including disinformation, through structured monitoring, strategic communication initiatives, and joint resilience efforts.

The relationship between disinformation and diplomacy is increasingly central to scholarly discussion. Studies of digital and hybrid diplomacy argue that the rise of online influence operations poses new challenges for public diplomacy and foreign policy. Research on digital diplomacy identifies misinformation and disinformation as significant barriers to effective diplomatic engagement, undermining state credibility and complicating international cooperation on issues ranging from health crises to conflict resolution (Munteanu, 2025). This literature suggests that diplomats must adapt their roles to incorporate strategic communication practices in contested information environments (Genini, 2025).

Within this broader context, the literature also highlights how disinformation affects democratic societies. Arribas et al. (2023) show that disinformation and historical revisionism have been used as instruments of foreign influence, particularly by Russia in the post-Soviet space. These narratives, often rooted in manipulated historical references, aim to legitimize aggressive policies and distort

public understanding of conflicts such as the war in Ukraine. Arribas et al. (2023) further demonstrate that such influence campaigns rely on recurring narrative patterns that can be mapped and anticipated. Similarly, research on state–society interactions emphasizes that open, democratic environments are more vulnerable to hybrid threats because free speech protections can be manipulated by malign actors to spread false narratives widely. Genini (2025) argues that this vulnerability calls for new diplomatic strategies that balance openness with resilience to information threats.

Critical research also examines how institutions respond to these challenges. Hybrid CoE (2025) maps how democratic states grapple with limited resources against well-financed information aggressors. The report argues that cooperation between governmental and non-governmental actors is necessary to detect, monitor, and react to disinformation, and that states should explore tools such as sanctions, labeling, and legal measures to impose costs on adversaries. Munteanu (2025) further shows that NATO has increasingly framed disinformation as a multidimensional threat, capable not only of eroding trust but of weakening collective defense frameworks, making strategic communications central to allied resilience.

The expansion of online and hybrid learning has also made virtual education environments relevant to disinformation dynamics, both as exposure channels and as resilience-building spaces. The European Commission's Digital Education Action Plan (2021–2027) frames digital education as a strategic priority for strengthening digital competences and ensuring quality and inclusive digital learning in response to the acceleration of online learning (European Commission, 2020). In parallel, EU guidance for teachers explicitly links education to societal resilience by emphasizing that digital literacy education should include the ability to identify and evaluate information, understand manipulation techniques, and respond responsibly in online environments where disinformation circulates at scale (European Commission, 2022). UNESCO similarly positions media and information literacy as a sustainable public-good approach for building resilience to disinformation and strengthening trust in the information ecosystem (UNESCO, 2021). In practical terms, research on “prebunking” (inoculation) suggests that scalable learning interventions can reduce susceptibility to misinformation by training users to recognize common manipulation strategies before encountering them in real contexts (Roozenbeek et al., 2020).

Despite these contributions, there is still a gap in the literature when it comes to examining how specific diplomatic institutions operationalize responses to foreign disinformation. Much of the existing work focuses on macro-level frameworks for resilience or comparative defense strategies, but fewer studies explore national diplomatic behavior and narrative management in response to coordinated influence campaigns. Romania, as an EU and NATO member on the eastern flank of the alliance system, exemplifies this research need given its exposure to disinformation operations linked to the Russia–Ukraine war. Filling this gap requires deeper engagement with literature on hybrid warfare, strategic

communication, and diplomacy that not only identifies threats but also analyzes institutional responses and strategic adaptations.

2.1 Problem statement / research question

The increasing use of disinformation as a tool of geopolitical influence poses a serious threat to democratic stability, institutional trust and international diplomacy. In the context of the Russia-Ukraine war, disinformation has become central to hybrid warfare, targeting not only military and political institutions, but also public perceptions of legitimacy, sovereignty and alliances. Situated at the eastern border of the EU and NATO, Romania has emerged a frontline state in this strategic information conflict. Russian disinformation campaigns in Romania aim less to generate support for Russia than to undermine confidence in Western institutions, discredit democratic processes and exacerbate internal divisions. These campaigns are amplified by local vulnerabilities, including low media literacy, polarized public discourse and limited institutional capacity for strategic communication.

While the literature offers extensive conceptual work on hybrid threats and disinformation, fewer studies explain how diplomatic institutions translate these frameworks into operational practice, particularly in frontline EU and NATO states. In Romania's case, sustained exposure to influence operations linked to the Russia-Ukraine war increases the need to understand not only institutional response capacity but also the societal resilience conditions that shape disinformation diffusion. These resilience conditions include digital and media literacy, which are increasingly formed in digitally mediated contexts such as online and hybrid learning environments. As diplomacy expands beyond traditional negotiations into the digital and information spaces, it is urgent to understand how diplomatic services confront narrative warfare. Without this understanding, Romania risks remaining reactive rather than resilient in the face of escalating information threats.

The unfolding of disinformation campaigns in Central and Eastern Europe has highlighted the urgent need for coordinated diplomatic responses tailored to the current information environment. In this context, this study aims to analyze how Romania, as an EU and NATO member state bordering Ukraine, has responded to the strategic influence exerted through false and manipulative narratives. The focus is on the period 2020–2024, a period marked by key events such as the pandemic, the Russian invasion of Ukraine, and national elections. The research aims to identify the main themes of disinformation directed at Romania, to assess the responses provided by diplomatic institutions, in particular the Ministry of Foreign Affairs, and to determine the extent to which these responses were proactive, coherent, and effective in combating narrative manipulation and strengthening public trust. At the same time, the study analyzes the structural and operational difficulties faced by Romanian diplomacy in developing a strategic response, as well as potential courses of action to strengthen resilience in the face of information warfare.

In this respect, we have developed the following research questions:

- RQ1. What are the main disinformation narratives targeting Romania in the context of the Russia–Ukraine war and regional destabilization efforts?
- RQ2. How have Romanian diplomatic institutions, particularly the Ministry of Foreign Affairs, responded to these disinformation campaigns between 2020 and 2024?
- RQ3. To what extent have Romania’s diplomatic responses been proactive, coordinated, and effective in addressing narrative manipulation and restoring public trust?
- RQ4. What challenges and limitations do Romanian diplomatic actors face in developing a strategic response to disinformation, and what opportunities exist for strengthening this response in the future?

Given the expansion of online and hybrid learning, the paper also recognizes that virtual education environments influence digital literacy and verification habits, which in turn shape vulnerability to disinformation and the conditions for restoring public trust. Therefore, in the discussion of future opportunities (RQ4), education-based digital literacy and media-and-information literacy measures delivered through virtual learning contexts are considered as complementary resilience options alongside diplomatic and institutional responses.

3. Methodology

This study employs a qualitative case study approach to analyze how Romania’s diplomatic institutions responded to disinformation campaigns related to the Russia–Ukraine conflict from 2020 to 2024. Romania was chosen as the case study due to its strategic location in the region and its vulnerability to targeted influence operations. This study relies on academic literature, official communications, policy documents, media analysis, and data from monitoring platforms such as EUvsDisinfo and EU DisinfoLab. These sources were triangulated to ensure credibility. The analysis follows three steps: mapping disinformation narratives, evaluating institutional responses, and identifying gaps in strategy and coordination. Although the study is limited to open-source materials and does not include classified data or interviews, it provides insight into how Romania’s diplomacy operates under pressure from foreign disinformation.

To complement the qualitative mapping of dominant disinformation narratives in Romania, this paper adds a concise quantitative snapshot of societal vulnerability indicators that shape receptivity to misleading content. We operationalise “vulnerability” using (i) Media Literacy Index (MLI) scores and ranks—an index designed to approximate societies’ resilience to disinformation using cross-national indicators (e.g., media freedom, education, and trust-related measures)—and (ii) basic digital skills coverage, which is relevant to individuals’ ability to navigate and evaluate online information environments. As an additional

contextual benchmark, we include Romania’s relative standing on trust in media as reported in a dedicated disinformation landscape factsheet. These indicators do not measure disinformation exposure directly; rather, they provide empirically grounded context for interpreting why certain anti-EU/anti-Western narratives can diffuse rapidly and persist in the public sphere.

Table 1. Quantitative indicators supporting RQ1 (societal vulnerability context)

Indicator	Year	Romania value	Unit/scale	What it captures (how you can interpret it in RQ1)	Source
Media Literacy Index (MLI) Rank	2022	31	Rank (out of 41)	Relative position in resilience to disinformation; lower rank implies higher vulnerability	OSI–Sofia, Media Literacy Index 2023 (table comparing 2023 vs 2022)
Media Literacy Index (MLI) Score	2022	36	Score (0–100 scale)	Level of resilience; decline suggests worsening structural conditions for narrative resistance	OSI–Sofia, Media Literacy Index 2023
Media Literacy Index (MLI) Rank	2023	34	Rank (out of 41)	Deterioration in rank indicates Romania moving toward the more vulnerable cluster of societies	OSI–Sofia, Media Literacy Index 2023
Media Literacy Index (MLI) Score	2023	32	Score (0–100 scale)	A measurable drop consistent with reduced resilience to misleading narratives	OSI–Sofia, Media Literacy Index 2023
Population with basic digital skills	2023	27.8	% of population	Capacity to operate in digital environments (a necessary—but not sufficient—condition for effective information evaluation)	EU Digital Skills & Jobs Platform, “Romania: a snapshot of digital skills”
Population with basic digital skills	2024	27.7	% of population	Near-stagnation suggests limited improvement in digital capability	EU Digital Skills & Jobs Platform, “Romania: a

Trust in media – relative standing	in	that could support information discernment snapshot of digital skills”				
		(repo- rted)	29th / 38	Rank (out of 38)	Low trust can create fertile ground for alternative “counter-elite” narrative ecosystems (often used by sovereigntist/pro-Kremlin framings)	EU DisinfoLab factsheet, Disinformation Landscape in Romania

Source: Author's own computation

To summarise the quantitative context indicators in Table 1 into a single interpretable measure, we compute a Vulnerability Context Index (VCI). The VCI is designed as a normalised composite (0 to 1) that increases when (i) media literacy is lower, (ii) basic digital skills are lower, and (iii) trust in media is relatively weaker. This compact index supports Research Question 1 by providing an empirical baseline for Romania's structural susceptibility to disinformation narratives, without implying direct causality.

$$\begin{aligned}
 VCI &= \frac{1}{3} \left[\left(1 - \frac{MLI}{100} \right) + \left(1 - \frac{BDS}{100} \right) + \left(\frac{r-1}{N-1} \right) \right] \\
 1 - \frac{MLI}{100} &= 1 - \frac{32}{100} = 0.68 \\
 1 - \frac{BDS}{100} &= 1 - \frac{27.7}{100} = 0.723 \\
 \frac{r-1}{N-1} &= \frac{29-1}{38-1} = \frac{28}{37} = 0.7568 \\
 VCI &= \frac{0.68 + 0.723 + 0.7568}{3} = 0.7199 \approx 0.720
 \end{aligned}$$

MLI is the Media Literacy Index score (0–100), BDS is the share of population with basic digital skills (%), and $(r-1)/(N-1)$ is the normalized trust-in-media rank, with r the rank and N the total number of countries.

To synthesise the quantitative context indicators in Table X into a single descriptive measure, we compute a Vulnerability Context Index (VCI). The VCI aggregates three observable dimensions relevant to susceptibility to disinformation: (i) the Media Literacy Index (MLI) score, (ii) the share of the population with basic digital skills, and (iii) a trust-in-media benchmark expressed as a country rank. The index is not intended to establish causality; rather, it provides a compact empirical baseline for interpreting how a country's structural conditions may enable the diffusion and persistence of disinformation narratives.

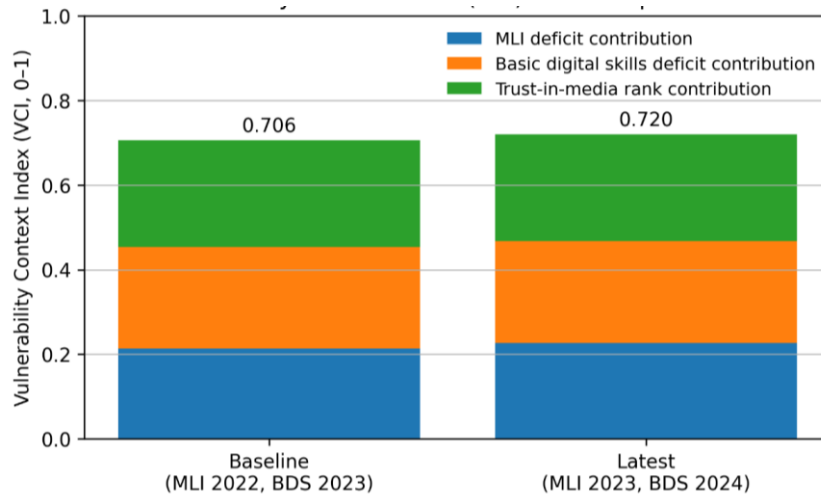


Figure 1. Romania's Vulnerability Context Index (VCI) and component contributions (baseline vs latest)

(Source: Author's own computation)

The figure reports the VCI as a normalised composite (0–1) and decomposes it into three additive contributions: (1) the MLI deficit component, (2) the basic digital skills deficit component, and (3) the trust-in-media rank component. Baseline uses MLI 2022 and basic digital skills 2023; latest uses MLI 2023 and basic digital skills 2024. The trust benchmark is taken as 29th out of 38 countries examined.

Interpretations and result

The VCI increases from 0.706 (baseline) to 0.720 (latest), indicating a slightly more vulnerable structural context for disinformation diffusion over the period covered by the underlying indicators. The change is driven primarily by the decline in MLI (36 → 32), while basic digital skills remain nearly unchanged (27.8% → 27.7%), suggesting stagnation in the population's baseline capacity to navigate digital information environments. The trust-in-media term contributes a substantial and constant share of the index, consistent with the characterization of low trust as a persistent enabling condition for alternative narrative ecosystems. Overall, the index should be read as a descriptive composite (sensitive to the chosen components and equal weighting), useful for contextualising narrative vulnerability rather than making statistical claims about significance or causal effects.

4. Results and discussions

From 2020 to 2024, Romania was the target of repeated disinformation campaigns that claimed election interference, weakened sovereignty due to

EU/NATO ties, and government bias in favour of Ukrainian refugees. These narratives were amplified through local influencers, fringe media, and anonymous channels and were confirmed by monitoring platforms such as EUvsDisinfo and DisinfoLab.

In response, Romanian diplomacy, mainly through the Ministry of Foreign Affairs, aligned with EU and NATO efforts, issued clarifications, and supported media literacy initiatives. However, these actions were limited and reactive, lacking national coordination. Reliance on supranational frameworks exposed Romania's inability to respond quickly and independently to fast-moving disinformation.

Current strategies fall short of the demands of digital diplomacy today: real-time engagement, narrative building, and building domestic trust. Romania lacks a dedicated communication unit, consistent interagency collaboration, and specialized training for diplomats. These gaps have allowed false narratives to spread unchallenged, eroding public confidence.

To move forward, Romania must invest in a strategic communications centre, incorporate digital resilience into its diplomatic education, and collaborate with civil society to improve outreach. As disinformation becomes more sophisticated, Romanian diplomacy must become more agile and proactive in shaping narratives that protect national security and democratic stability.

5. Conclusions

This study explored how Romania, as a frontline EU and NATO member, has responded diplomatically to disinformation campaigns, particularly those linked to Russian strategic influence between 2020 and 2024. It focused on the narrative patterns used to undermine institutional trust, examined Romania's diplomatic responses and evaluated their effectiveness in addressing both the symptoms and sources of disinformation. The findings provide insight into the intersection of digital influence, national vulnerability and strategic communication in the context of contemporary diplomacy.

Alongside diplomatic and institutional measures, strengthening digital literacy through virtual education and hybrid learning initiatives can support long-term resilience by improving citizens' ability to identify manipulation techniques and evaluate information credibility, thereby reinforcing the trust-restoration dimension addressed in RQ3 and the future opportunities emphasized in RQ4.

Response to research questions

The study first identified key disinformation narratives targeting Romania. These included claims of election fraud, depictions of NATO and the EU as colonial actors, anti-refugee sentiment and economic insecurity linked to external pressure. These narratives aligned with broader Russian strategic goals aimed at destabilizing Romania's alignment with Western institutions and eroding public

trust. Platforms like EUvsDisinfo and DisinfoLab provided detailed tracking of these campaigns, confirming their recurring and coordinated nature.

Second, the research analysed Romania's institutional responses, especially those led by the MFA. While Romania has aligned closely with the EU and NATO counter-disinformation frameworks, national-level diplomatic responses have been limited in both scope and speed. Statements and clarifications have often followed media pressure or public outcry rather than proceeding them. There is evidence of participation in multilateral communication initiatives, but less emphasis on developing Romania's own narrative strategy or diplomatic agility in the digital space.

Third, the findings suggest that Romania's responses have been mostly reactive, fragmented across institutions and insufficiently visible to the public. Despite increasing awareness of disinformation threats, the country lacks a coordinated strategic communication infrastructure to address the information challenge proactively. Efforts in training, digital engagement and public diplomacy remain underdeveloped compared to the scale and sophistication of the threat.

Finally, the study highlighted structural and operational challenges. These include low media literacy among the population, limited digital diplomacy training for Romanian diplomats and over-reliance on external messaging provided by EU and NATO institutions. The lack of localized engagement strategies weakens the state's ability to build domestic resilience against narrative manipulation.

Theoretical and practical implications

Theoretically, this study contributes to the evolving understanding of diplomacy as not only institutional negotiation, but also narrative defence. Romania's case illustrates how small and mid-sized states are caught between global influence campaigns and limits national capacity to respond.

Practically, the findings suggest that Romania must prioritize public diplomacy as a strategic function of foreign policy, strengthening internal coordination, investing in digital communication training and creating a centralized counter-disinformation hub are all necessary steps to shift from defensive postures to resilient engagement,

The quantitative context results reinforce this interpretation by indicating an elevated vulnerability environment for narrative diffusion. As shown in Table 1, Romania combines low and largely stagnant baseline skills indicators with a relatively weak trust-in-media position; Figure 1 synthesises these dimensions into the VCI. This index should be read as a descriptive composite rather than a test of statistical significance, but it provides an empirical anchor for the paper's broader argument about why disinformation narratives can remain resilient over time. In practical terms, these conditions strengthen the case for proactive and coordinated diplomatic communication measures alongside reactive rebuttals.

Limitations and future research directions

The study relies exclusively on open-source data, public reports and secondary literature. As such, it cannot access classified communications or internal decision-making processes within Romania's diplomatic institutions. Furthermore, the analysis does not include interviews with practitioners or policymakers, which could provide valuable insight into institutional dynamics and internal constraints.

Another limitation is that the study focuses primarily on Romania's response and does systematically compare it with other frontline states in the region. While this allows for depth, it limits the generalizability of the findings.

Future studies should explore the operational side of diplomatic communication, how strategies are designed, coordinated and implemented within ministries and embassies. Comparative research with countries such as Lithuania, Estonia and Poland may reveal models of successful adaptation to information threats. In addition, integrating perspectives from civil society, media and international partners could provide a more holistic view of the diplomatic ecosystem needed to resist disinformation in the long term.

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Enhancing competence-oriented learning in grade 5 through online educational resources

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Abstract: *This study investigates the integration of digital educational resources into fifth-grade mathematics instruction, aligned with the Moldovan National Curriculum for lower secondary education. It highlights how these resources apply constructivist and formative principles to create an interactive, personalized learning experience. Through an analysis of exercise typologies and specialized digital tools, the study shows that digitalization fosters essential mathematical competencies and critical thinking. The findings indicate significant potential for improving learning quality through adaptive platforms, interactive simulations, and digital formative assessment, highlighting that the strategic integration of technology fosters 21st-century skills and supports educational equity.*

Keywords: Digital mathematics education, Interactive educational resources, Constructivism in mathematics teaching, Digital formative assessment, Mathematical competencies.

1. Introduction

In the context of the educational transformations driven by digitalization, mathematics textbooks can no longer be viewed exclusively as printed supports, but rather as integral parts of a complex digital ecosystem. This ecosystem includes a wide range of online educational tools, such as interactive applications, educational games, and collaborative learning platforms. These resources can significantly expand the possibilities for learning mathematics, offering students opportunities for visual exploration, simulation, and self-assessment. Through their interactive functionalities, multimedia elements, and dynamic activities, digital resources become essential tools for stimulating students' critical thinking and developing their digital skills. This aligns with the requirements of contemporary education and the objectives of the National Curriculum, whose mission is to ensure quality, inclusive, and equitable education (Andrițchi et al., 2025).

Thus, the Mathematics Curriculum for lower secondary education and its associated educational process are based on the constructivist principle (of structural learning) – which requires a spiral approach for the systematic review and in-depth study of essential concepts, aimed at developing mathematical thinking – and on the formative principle, oriented towards the direct development of the student's personality (National Curriculum, Mathematics, Grades V-IX, 2020).

Complementarily, online educational resources – such as web applications, digital textbooks, specialized mathematics teaching-learning websites, and mathematical games – enhance the learning experience through interdisciplinary and interactive approaches, playing a fundamental role in transforming the educational process. The convergence of digital textbooks and other digital learning environments is redefining mathematics instruction, creating a dynamic, participatory, and competency-oriented framework (Balmuş & Chiriac, 2021).

In this regard, the interaction between digital education and mathematical thinking becomes essential, not only for modernizing the learning process but also for developing a flexible mathematical mindset. By using digital resources, students not only learn mathematical concepts but also develop critical problem-solving and self-assessment skills, thereby becoming more capable of applying their knowledge in complex and diverse situations. Furthermore, digital education contributes to the development of a deeper and more adaptable mathematical thinking, preparing students to face the educational and professional challenges of the future.

Mathematics textbooks intended for the 5th grade integrate a wide variety of exercises and problems designed to support the gradual development of mathematical competencies specific to this age level. In the Republic of Moldova, the 5th-grade Mathematics textbook is based on a curricular structure organized around fundamental chapters such as: Natural Numbers, Sets, Divisibility, Fractions, Decimal Numbers, Elements of Geometry, and Units of Measurement (Mathematics, textbook for the 5th grade, 2020). The content is supported by a progressive system of exercises, designed with increasing levels of complexity, from introductory and consolidation activities to tasks involving reasoning, exploration, and practical application, all meant to stimulate students' logical thinking and cognitive autonomy.

Given these considerations, this article aims to analyze how digital educational resources can leverage the principles of the curriculum to enhance the teaching-learning process for the 5th grade. By referencing the constructivist and formative principles of the National Curriculum (National Curriculum, Mathematics, Grades V-IX, 2020), the research seeks to highlight the educational value, interactive functionalities, and formative potential of these tools, as well as their impact on active learning and the development of students' digital competencies.

This article is structured around a literature review on integrating digital tools into fifth-grade mathematics. It examines the theoretical foundations of constructivism and formative assessment, detailing their implementation via digital resources. The analysis also covers textbook exercise typologies to determine their role in promoting active learning and critical thinking. Ultimately, this work elucidates how online educational resources modernize mathematics teaching and explores the interplay between digital education and mathematical thinking in lower secondary students.

The research presented in this article was supported by the project “Innovation in the Design and Implementation of Interactive Digital Math

Textbooks for Lower Secondary Education” (Strategic Direction: “Innovative Educational Technologies and Products”), project code 25.80012.0807.42SE.

2. Competence-oriented learning in mathematics education

The concept of “competence-based learning” refers to an educational paradigm that shifts the emphasis away from the passive knowledge acquisition but toward the development of skills and attitudes required for effectively solving complex problem situations by integrating theoretical and practical knowledge in an applicable manner. Competencies, according to this viewpoint, involve not only knowledge acquisition but also the ability to apply knowledge in practice; they also include students' capacity to apply what they know in real-world situations.

According to the European Key Competences Framework (European Commission, 2019), key competences are defined as an integrated set of knowledge, skills, and attitudes essential for personal development, social inclusion, employability, and active participation in society. This definition emphasizes the role of competences as tools for individual autonomy and adaptation to the demands of a complex and dynamic society.

At the conceptual level, competence can be understood as an integrated system (Andrițchi et al., 2025) that combines knowledge (factual, conceptual, and procedural information), skills (the ability to apply knowledge to achieve results), and attitudes or values (dispositions and principles that guide actions and reactions). Consequently, competence-based learning focuses on applicability, transferability, and cognitive autonomy, offering students the opportunity to use what they learn in creative and responsible ways.

In the context of teaching mathematics in grade 5, concrete mathematical skills, as formulated in the National Curriculum (2020), include: identifying, reading, writing, representing, comparing, ordering and rounding natural numbers, fractions and finite decimal numbers; manipulating sets and determining whether an object or number belongs to a given set; performing arithmetic operations and applying their properties; solving problems; selecting, organizing and interpreting data from texts, tables, schemes or diagrams; representing and making plane geometric figures; measuring and comparing values, expressing them in appropriate units; describing geometric figures and bodies, recognizing their elements, calculating perimeters, areas and volumes; and justifying the steps and results through one's own arguments.

Integrating these skills into practice aligns with “competence-based learning,” providing students with opportunities to apply knowledge in varied contexts, developing reasoning and critical thinking, as well as stimulating autonomy and creativity (Burlacu, 2019). Educational resources and digital textbooks enable the consolidation of these skills through practical activities, simulations, contextualized problems, and visual explorations (Balmuş & Doroftei, 2021), making mathematical knowledge more transferable and applicable in real-world situations.

The report “Mathematics for Europe” (2016) highlights the essential role of mathematics as a fundamental tool in technological progress and in solving complex societal problems. In this context, the development of mathematical competence at the individual level becomes a priority, being defined in the European Union’s “Key Competences for Lifelong Learning” (2019) document as the ability to develop and apply mathematical thinking and intuition in order to solve problems in everyday life.

Specialized research deepens mathematical competence from complex perspectives, highlighting multiple interconnected dimensions. As Lee’s (2016) analysis highlights, mathematical competence is multidimensional, and its assessment can be approached through two distinct paradigms: one based on norms and the other on criteria. Also, the perspective on its structure oscillates between a hierarchical and a continuous view, and its development is influenced by both biological and educational factors. Essentially, this diversity of perspectives highlights the fact that mathematical competence is not a universal and static concept, but a dynamic one, the understanding of which is shaped by methodological choices, educational values and the complex interaction between individual predispositions and the learning environment.

The competence-oriented approach, as described, is implemented and developed organically through the application of constructivist and formative principles in the mathematics curriculum. These principles provide the theoretical and methodological framework necessary for transforming the competencies established at the curricular level into tangible educational realities, ensuring deep and sustainable learning. Therefore, the analysis of constructivist and formative principles becomes essential to understand how the curriculum supports the gradual and integrated acquisition of mathematical competencies.

3. Constructivist and formative principles in the mathematics education

In the context of modern education, constructivism asserts itself as a fundamental theory of learning, placing the student at the center of the educational process as an active constructor of knowledge, and the teacher in the role of facilitator. Murugesan et al. (2016) state that constructivism radically shifts the mathematics education paradigm towards active learning and critical thinking. In this model, the student constructs knowledge while the teacher facilitates, guiding exploration and providing tailored support. Assessment becomes formative, focusing on the learning process rather than final outcomes. While this approach helps students apply knowledge in real-world contexts, its implementation faces challenges in teacher training, classroom management, and alignment with standardized tests.

Díaz (2017) elaborates that mathematics learning is an internal, constructive process dependent on a student's cognitive development. Authentic learning occurs when students actively build new understanding by integrating practical experiences into existing mental schemas, a process driven by the resolution of cognitive conflicts during social interaction.

An effective practical transposition of constructivism is the 5E instructional model, considered a representative pedagogical tool, as highlighted by Shittu and Alex (2025). This model provides a coherent structure for lesson design, through the stages of engagement, exploration, explanation, elaboration and evaluation. This progressive approach guides students from activating curiosity and prior knowledge, through investigation and conceptualization, to applying and transferring knowledge in new contexts.

Çibukçiu (2025) provides empirical support, demonstrating that constructivist methods significantly enhance mathematical problem-solving skills compared to traditional approaches. In a study with third-graders, average scores rose from 39.77 to 59.46 following a constructivist-based intervention ($p < 0.001$). The author concludes that by centering on the student through discussions, group work, and real-world problems, constructivism facilitates active and sustainable knowledge building.

While constructivism provides the theoretical framework for how students learn, formative principles provide the practical tools necessary to guide and evaluate this process. Formative assessment thus joins constructivist pedagogy as an essential component, focused on obtaining continuous feedback that supports the simultaneous improvement of learning and teaching. Maskos et al. (2025) establish that the efficacy of formative assessment in mathematics is contingent upon the sustained use (a minimum of three months) of interactive digital tools that are clearly aligned with learning objectives. This approach is particularly effective for low-achieving and disadvantaged students, thereby promoting educational equity through enabling real-time pedagogical adjustments.

3.1 Interactive exercises for developing digital competencies in constructivist learning

The constructivist and formative principles promoted by the National Mathematics Curriculum (2020) for Grade 5 are directly reflected in the structure of the exercises included in the school textbook (Mathematics for Grade 5, 2019). More precisely, these principles illustrate the concrete application of curricular guidelines in teaching practice, integrating them into learning activities through methods that support the development of both students' mathematical and digital competencies.

Within the theoretical framework of constructivist learning, the diversity and interactivity of the exercises allow students to progress from the mechanical practice of mathematical procedures to their conceptual understanding. These exercises not only support the fixation of mathematical procedures, but also develop a deep understanding of mathematical concepts in a framework in which technology plays an essential role.

An essential category within the textbook are *algorithmic exercises* (e.g.: adding and subtracting multi-digit numbers; fraction operations; calculating perimeters and areas using standard formulas). These are designed to ensure the

consolidation and automation of computational skills. The digital environment supports this type of exercises through drill & practice applications or exercise generators with immediate feedback, facilitating adaptive learning and self-regulation.

A second important category is *conceptual recognition and understanding exercises* (e.g.: completing a table with the divisors and multiples of given numbers; ordering large numbers; representing fractions on the number line). These exercises help students identify properties, classify mathematical objects, and establish relationships between concepts. In digital format, these can include interactive drag-and-drop activities, matching, or dynamic visualizations, which increase conceptual accessibility.

Also, *applied problems* require the transfer of mathematical knowledge in various contexts, often taken from everyday situations such as: calculating costs, determining distances or converting units of measurement. Significantly, the digital environment extends these activities through the use of spreadsheets, educational modeling applications or graphical representation tools, stimulating algorithmic thinking.

Another important category is represented by *reasoning and demonstration exercises* (for example: "prove that the sum of two even numbers is always an even number"; "justify geometric properties of triangles"), which aim to develop logical thinking and mathematical argumentation capacity. To this end, the digital environment offers interactive applications such as GeoGebra, where students can visualize the demonstrated steps, verify hypotheses and represent concepts through visual simulations.

Formative assessment and self-assessment exercises (such as: decimal number review tests; unit conversion problems) reinforce the formative process by providing personalized feedback and encouraging reflection on one's own progress. As a result, automated electronic tests contribute to the development of self-regulation skills and the assumption of responsibility for one's own learning path.

Overall, these typologies allow the achievement of the general competencies provided by the school curriculum, balancing procedural and conceptual learning and integrating digital skills. The structure of the exercises thus reflects the convergence between constructivist principles and formative assessment, transforming the mathematics textbook into an active, adaptive and digital learning tool.

4. Integration of digital tools in 5th grade mathematics education

4.1. The role and impact of digital tools on learning

The integration of digital educational resources into 5th grade mathematics teaching is a key element in the modernization of education, supported by the requirements of the National Curriculum for Mathematics, Grades V-IX (2020) and other official documents. This involves not only transferring content to an

electronic format, but also restructuring the interaction between the student and the learning task, allowing for the personalization of the educational process according to the pace, style, and competence level of each student.

Digital transformation becomes concrete by correlating content units with activities and learning products recommended in the curriculum – concept maps and chapter-level schemes, idea plans, solved exercises or complex STEM projects. In this framework, the integration of modern educational applications supports the achievement of mathematical competencies provided by the curriculum and pedagogically reconceptualizes traditional tasks, capitalizing on the innovative potential of digitizing exercises.

Taukebayeva & Bakirova (2024) emphasize that digital technologies support personalized learning through adaptive platforms, offering exercises and support adapted to students' strengths and weaknesses. Also, interactive applications, educational games and simulations can increase their motivation and academic engagement.

Complementing this view, Gavrilă (2024) argues that ICT makes mathematics a dynamic, interactive process rather than an abstract domain. This shift is facilitated by platforms that allow for the visualization of concepts and provide personalized feedback. The integration of STEAM further develops practical problem-solving skills and innovative thinking.

Each type of exercise integrates effectively into specialized digital tools, contributing to the development of specific mathematical skills. Examples include:

- *Recognition and association*: LearningApps, Kahoot! – dynamic activities and immediate feedback;
- *Algorithmic exercises*: Desmos, GeoGebra, ThatQuiz – adaptive practice;
- *Applicative problems*: PhET, Math Apps, interactive spreadsheets – simulations and practical scenarios;
- *Investigation and exploration*: Scratch, Blockly – visual programming and mathematical projects;
- *Reasoning and demonstration*: GeoGebra Geometry, Desmos Geometry – interactive modeling and hypothesis testing;
- *Formative assessment and self-assessment*: Quizizz, Edpuzzle, LearningLemur – immediate feedback, progress analysis and personalized recommendations;
- *Collaboration*: Padlet, Miro – discussions and collective constructions of mathematical reasoning.

Thus, digital integration in teaching mathematics in the 5th grade ensures a holistic approach, which combines fundamental mathematical competencies with the digital skills needed in the 21st century. The strategic correlation between the targeted competencies, the types of exercises and the digital tools facilitate a coherent didactic planning adapted to the individual needs of the students.

4.2 A Comparative analysis of digital platforms for 5th grade mathematics

The digital transformation of education has led to the emergence of numerous learning platforms aimed at improving mathematical understanding through interactive, adaptive and collaborative methods. Below is a comparative analysis of the most relevant platforms used for learning mathematics in 5th grade. However, this abundance of digital resources generates a real challenge for teachers: identifying and integrating the most appropriate digital tools, which are consistent with curricular objectives and adequately respond to the diversity of learning styles of 5th grade students.

Although the theoretical advantages of using digital technologies in the teaching-learning process are well presented in the specialized literature, in practice there remains a significant gap between the pedagogical potential of these resources and their effective integration into educational activities. In particular, the educational context of the Republic of Moldova reveals an increased need for correlation between existing digital resources and the requirements of the National Curriculum for Mathematics, grades V–VIII.

In this context, a comparative analysis of the main international and national digital platforms used in teaching mathematics in grade V is proposed. The analysis is guided by the following research question: *To what extent do existing digital platforms, both national and international, support the specific learning objectives and the competence-centered approach of the mathematics curriculum for grade V in the Republic of Moldova?*

To answer this question, the evaluation of the platforms will be carried out based on pedagogical criteria, aligned with curricular requirements and contemporary teaching practices, namely:

- *curriculum alignment* – the extent to which the content, typology of exercises and learning scenarios reflect the chapters, competencies and formative values stipulated in the National Curriculum (for example: natural numbers, fractions, geometry, logical reasoning);
- *pedagogical basis* – the coherence between the platform structure and the assumed educational paradigm (algorithmic practice, digital constructivism, collaborative or project-based learning);

In this context, 10 digital platforms were selected – 8 from the Moldovan and Romanian space and 2 international – which meet the following basic criteria:

- contain relevant content for 5th grade mathematics;
- are accessible in Romanian or have an intuitive interface;
- offer significant free options.

The results of the analysis presented in Table 1 contribute to strengthening a critical perspective on how digital resources can be synchronized with the objectives of contemporary mathematics education, supporting teachers in the process of strategic planning of digital learning, oriented towards the development of mathematical and digital skills necessary in the knowledge society.

Table 1. Analysis of digital mathematics platforms for grade 5:
alignment with curriculum and pedagogical principles

Online platform	Alignment with the National Curriculum (Mathematics, 5th Grade)	Pedagogical Principles
Educație Interactivă https://educatieinteractiva.md	Aligned with the National Curriculum of the Republic of Moldova, it is a digital application/library with over 8,000 lessons for grades 1–12, in Romanian and Russian; includes resources for core topics in 5th grade mathematics.	Based on visual and active learning; emphasizes the connection between theory and applications.
MozaWeb https://www.mozaweb.com	A global platform offering digital textbooks, interactive content, and exercises; implemented in 195 institutions in the Republic of Moldova under the "Digital Innovations in the Educational System" project (mecc.gov.md).	Interactive digital pedagogy; exploration through 3D scenes, digital textbooks, interactive exercises, online tests, automated feed-back, and visual activities.
VirtualSchool https://virtualschool.ro/	Content partially aligned with the 5th grade curriculum; covers general topics (numbers, fractions, geometry), but not all exercises are competency-based.	Promotes guided learning; focuses on individual practice and consolidation.
Digitaliada https://www.digitaliada.ro	Fully aligned with the Romanian curriculum and compatible with the Moldovan curriculum. Offers over 4,000 digital educational resources (lessons, tests, exercises) accessible for school use.	Based on digital constructivism; students discover through exploration, applications, and gamified activities.
Clasa Digitală https://www.clasadigitala.ro	Provides digital textbooks and exercises aligned with Romanian	Focused on blended learning and student autonomy.

	national school programs; good support for core topics (numbers, fractions, geometry).	
Genizz https://genizz.ro/	Includes common mathematical topics (arithmetic, algebra, geometry).	Focused on motivation and educational games; learning through challenges and rewards.
Eduboom https://eduboom.ro/	Content aligned with the Romanian curriculum; contains video lessons and exercises, automatic grading tests.	Explanatory and constructivist pedagogy; focuses on clarity and recap through visual examples.
Pauza de Mate https://pauzademate.ro/gimnaziu-lectii/	Support for teaching mathematics in middle school, especially for 5th grade, with well-organized, accessible lessons and useful video resources	Predominantly lesson viewing, not necessarily student activity; set of video lessons.
Usable Math https://usablemath.org/	An open educational resource designed for elementary school students, includes activities for 5th grade, aimed at developing problem-solving skills in mathematics. In the context of digitalizing textbooks and ICT resources, it offers a great opportunity to integrate external material without access barriers.	Integrates student-centered digital pedagogy; based on constructivist and socio-constructivist principles; promotes active, reflective, and collaborative learning.
Zearn https://www.zearn.org/	Designed for American standards; can be adapted to the national curriculum with linguistic and curricular adjustments; covers most core areas for 5th grade.	Supports active learning through direct student involvement in problem-solving and selecting appropriate strategies for each situation.

The comparative analysis of digital platforms for learning mathematics in the 5th grade highlights the significant potential of digital educational resources in supporting competence-centered learning and in line with the National Curriculum. The results indicate that most of the selected platforms offer relevant content for the fundamental chapters of mathematics – natural numbers, fractions, geometry,

logical reasoning – and allow the integration of constructivist and formative principles in the teaching-learning process. The *Digitaliada*, *MozaWeb* and *Usable Math* platforms are distinguished by their interactive, student-centered pedagogical approach. Other platforms, *Pauza de Mate* or *Eduboom*, offer more traditional or lesson-based educational support, which can limit the active involvement of students if they are not complemented by interactive practical exercises. International platforms, such as *Zearn*, can be successfully adapted to the local context, offering personalized learning opportunities and automated feedback, but require linguistic and curricular adjustments.

5. Conclusion

This paper has revealed that the integration of digital educational resources in teaching mathematics in grade 5 represents a fundamental necessity in the current educational context, being essential for achieving the objectives set by the National Curriculum. Following the analysis, it was found that digital platforms, both national and international, play a significant role in applying constructivist and formative principles, transforming the learning process from a mechanical activity into an interactive, personalized educational experience focused on developing skills. The comparative analysis revealed a diversity of digital resources that can be effectively adapted to the educational context of the Republic of Moldova. The *Educația Interactivă* and *Digitaliada* platforms offer a higher degree of alignment with the National Curriculum, offering well-structured educational content and relevant interactive activities. On the other hand, international solutions, such as *MozaWeb* and *Zearn*, bring additional value by implementing innovative pedagogical approaches and advanced interactive functionalities, which can support personalized and adaptive learning of students.

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Transformational leadership as the engine of technology-enabled educational projects in the era of AI

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Abstract: *In an era of rapid technological disruption, particularly through AI, educational systems are under pressure to evolve. Technology disruption in education reshapes organizational routines, teacher roles, and student learning, yet implementation outcomes vary widely across schools. The successful implementation of technology-enabled educational projects is not guaranteed by the technology itself; it heavily relies on effective school leadership. This paper examines how transformational leadership catalyzes successful technology-enabled educational projects. Using a mixed-methods design, we analyze mechanisms linking leadership behavior such as vision-setting, individualized support, intellectual stimulation, and modeling change, to project acceptance, teacher professional growth, and early learning effects. Results indicate that clear, co-constructed visions accelerate teacher professional development with psychological safety improves classroom experimentation and practices. These findings demonstrate that the principal's use of transformational practices, inspirational motivation, intellectual stimulation correlated with increased teachers professional and transversal skills, enhanced digital competence and the successful integration of both hard and soft skills lead to bringing transformational leadership skills into the school. This study provides a practical model demonstrating that leadership is the critical success factor for translating technological potential into pedagogical reality by showing how human-centered leadership turns technological disruption into equitable, measurable improvement in teaching and learning.*

Keywords: Transformational leadership, Technology, Education projects.

1. Introduction

The 21st century is defined by relentless technological change, with Artificial Intelligence (AI) because AI now emerging as a powerful, disruptive force (Railean, Pavalachi & Ceobanu, 2023; Railean, 2024; Railean, 2025). For the education sector, this is not a distant-future scenario but a present-day reality, placing the theme of *Changing Education because of Technological Disruption* at the forefront of academic and policy discussions. Schools around the world are initiating technology-enabled projects to adapt, but a significant gap persists between investment and impact (Railean, 2014; Railean, Valeyeva & Kupriyanov, 2020). More often than not, it's not technology that fails us, but the human mind's inability to implement strategy effectively within a sound leadership model.

<https://doi.org/10.58503/icvl-v21y202644>

This paper points out that the critical variable for success is not the *technology* itself, but the *leadership* style of manager that guides its adoption, using both teachers' hard and soft skills. The central thesis is that transformational leadership acts as the essential engine for driving and sustaining technology-enabled educational projects. (Yusof et al., 2021) To move this argument from theory to practice, this paper presents a detailed case study of the „Ioan Bădescu” Secondary School in Romania. It analyzes how this specific leadership model was used to overcome teacher resistance, foster a culture of innovation, and ultimately link technological tools to concrete pedagogical goals.

First, the paper examines the disruptive force of AI and the resulting changes in pedagogy, management and leadership. Secondly, it analyzes the dynamics of leadership models, positioning the transformational model as the ideal „engine” for this change. (Railean, 2024) Thirdly, it connects this leadership model to the critical need for updating teacher skills, using the Ioan Bădescu projects as an example. Finally, it provides a deep dive into the development of both professional digital competences (as defined by EU frameworks like DigCompEdu) and the transversal skills teachers need to cultivate 21st-century skills in their students. Ultimately, this paper provides a practical model, shown in the Romanian context, for how school leaders can effectively harness the power of technological disruption to create meaningful, lasting educational change (Railean, Pavalachi & Ceobanu, 2023).

So technological disruption is creating anxiety and resistance in teachers. The resistance is a *human* problem, not a technical one. The leadership at Ioan Bădescu recognized this and implemented the *Școala Încrederii* project *first* to address the school's culture. (David Publishing Company, 2024) This paper will demonstrate how the *Școala Încrederii* project, driven by transformational leadership, created the cultural foundation of trust necessary for the successful adoption of technology-enabled educational projects (European Commission, 2022).

2. AI Technology as a disruptive force in teaching and learning

The development of Artificial Intelligence, particularly the recent emergence of Generative AI models, is not merely an incremental update to educational technology. It represents a fundamental disruptive force that is actively reshaping the very nature of teaching and learning (Holmes & Tuomi, 2022; Railean, 2018). This disruption, which is the central theme of this conference section, is not just about new tools; it is about the *consequences* of those tools, which necessitate a profound change in the teacher's role and pedagogical approach. This transformation is not theoretical and it is being actively addressed at the highest levels of international policy. UNESCO's (2023) *Guidance for generative AI in education and research* explicitly calls for a human-centred vision. It recognizes GenAI's capacity to automate tasks but urgently calls for regulation and the development of new competencies to manage its ethical and pedagogical implications. Secondly the European Commission's (2022) *Ethical guidelines on*

the use of AI and data in teaching and learning, part of the broader Digital Education Action Plan (2021-2027), provides a practical framework for primary and secondary educators. It moves the conversation from *if* AI should be used to *how* it can be used responsibly, firmly placing the *teacher's and learner's* pedagogical judgment at the center of the learning process. These documents establish that the changing of teaching is not an optional side-effect but a required, policy-driven outcome of AI development. (UNESCO, 2022)

For decades, the pedagogical model of the sage on the stage (King, 1993) has been challenged (Railean, 2008; Railean, 2020; Railean, 2025). AI is now the force that makes its obsolescence undeniable. Studies and surveys clearly show that AI is automating the traditional, classical didactic components of teaching. Teachers are already embracing this for efficiency. A 2024 survey from Cambium Learning found that K-12 educators are using AI for lesson planning (44%), proofreading (47%), and creating personalized learning experiences (56%). A 2025 report from *Education Week* noted that 69% of teachers felt AI improved everybody's teaching methods, and 55% said it gave all of them more time to interact directly with students. This automation *frees* the teacher from being the primary source of information and assessment, forcing a role change. The teacher's new, essential function is to become a guide on the side, or as DiploFoundation (2025) suggests, a mentor, guide and ethical interlocutor. In this new model, the teacher's value is no longer in *what* they know, but in their ability to facilitate the critical thinking skills such as helping students question, validate, and critique the plausible-sounding outputs from GenAI, some social-emotional learning by providing the empathy, support, and human connection that AI cannot replicate (Holmes & Tuomi, 2022) and finally the ethical guidance by leading discussions on data privacy, algorithmic bias, and academic integrity. (Holmes & Tuomi, 2022)

This new role is enabled by new AI-driven pedagogies. This is AI's most significant promise for transformational leadership. Systematic reviews (e.g., Hwang et al., 2020; RSIS International, 2024) confirm that AI-driven adaptive platforms can create truly varied, personalized, and relevant learning paths, helping to differentiate instruction in a way a single teacher cannot. More than this, AI shifts assessment from a summative (end-of-unit) event to a continuous, formative process. AI tools can provide real-time, iterative feedback, allowing the teacher to focus on higher-order conceptual misunderstandings rather than basic skill-and-drill. However, these opportunities create new, complex problems. A 2025 *Education Week* survey found that while teachers see benefits, 70% worry AI weakens critical thinking and research skills, and 50% of students feel "less connected" to their teachers. Studies warn of the augmentation paradox: AI may boost short-term performance while slowing the development of long-term independent learning (David Publishing, 2024). In summary, AI technology is the catalyst. It is fundamentally altering the pedagogical landscape by automating old tasks and demanding a new, profoundly human-centric set of skills from the teacher. This creates an urgent and massive need for professional development. As the 2024 Cambium survey identified, the number one barrier to AI adoption is not

sufficient training for teachers. This new, complex, and high-stakes pedagogical environment cannot be navigated by teachers alone. It demands a supportive, visionary, and human-centered leadership model to guide the entire school community through this disruption. (DiploFoundation, 2025)

3. The dynamicity of leadership models

The technological disruption outlined in the previous section acts as a powerful *catalyst*, but it does not guarantee a positive *change*. The *engine* that determines whether a school successfully adapts or simply fails to implement its new projects is its leadership. (Couros, 2015) This section will argue that traditional leadership models are insufficient for this task and that a transformational model, as evidenced at „Ioan Bădescu” Secondary School, is the critical success factor. In stable educational environments, leadership models like *Instructional Leadership* or *Transactional Leadership* can be effective. *Transactional Leadership* operates on a system of contingent rewards and punishments (Bass & Avolio, 1994). It is a management model designed to maintain the status quo and ensure compliance with existing rules. This model is fundamentally unsuited for technological disruption, as it offers no mechanism to inspire innovation, only compliance with a mandate—which often leads to superficial adoption or outright resistance (Gumusluoglu & Ilsev, 2009). Meanwhile, *Instructional Leadership*, more focused on pedagogy, is primarily concerned with *coordinating* and *improving* the *existing* curriculum and teaching practices (Hallinger, 2005). It is designed for first-order, incremental change. However, the integration of AI is not an incremental change; it is a second-order disruption that challenges the very foundations of pedagogy (Leithwood & Jantzi, 2000). A leader focused only on *current* instruction may see technology as a distraction rather than a necessary evolution. A 2024 report in the *Journal of Educational Administration* notes that during periods of rapid digital change, leadership that is purely managerial or instructional often fails. This is because it is too narrow to build the organizational capacity for change required to navigate the fear and uncertainty that teachers associate with new technologies (Ng, 2024). *Transformational Leadership* is not about managing the *status quo*; it is about *transforming* it. This model is uniquely suited to the challenge of technological disruption because it focuses on building trust, articulating a compelling vision, fostering innovation, and supporting individuals through the change process. A 2025 meta-analysis published in *Computers & Education* confirmed that the success of school-wide technology projects is significantly and positively correlated with principals who exhibit transformational behaviors. This leadership acts as the engine by operationalizing its four key components: the Four I's (Bass & Avolio, 1994), to drive the educational projects. Here is how each component translates from theory to the practical reality of a technology project, as seen in our case study:

a) The Leader as Role Model is seen as an idealized influence. The leader acts as a role model whose character, values, and actions earn trust and respect. They walk the walk. For a technology project, this is the most direct way to build credibility. If the principal mandates a new platform but is never seen using it, teachers will perceive it as a compliance task. Studies on technology adoption (Yusof et al., 2021) show that a principal's willingness to be a lead learner, to publicly experiment with the new tools, admit their own challenges, and champion the project's values, is a critical factor. At „Ioan Bădescu” Secondary School, the *idealized influence* was demonstrated when the principal because she was the first to complete the introductory AI training, she used the new smartboard in all staff meetings and she publicly celebrated teachers who shared their 'intelligent failures' with a new tool, according to the survey. The leader didn't just mandate the Școala Încrâderii project; they lived it. They were the chief advocate for its values (empathy, trust, respect), modeling the vulnerability and openness they expected from teachers. This built the trust needed to ask them to try new, scary technologies later.

b) The inspirational motivation seemed to be very important, because the leader articulates a clear, appealing, and inspiring vision of the future. This is the why that motivates people to move beyond their own self-interest for the good of the group. This is the antidote to tech for tech's sake. A leader using this component frames the project not as, *We must use AI*, but as, *We will use these tools to empower every student, close achievement gaps, and prepare our students for a future we cannot yet imagine*. This reframes the project as a moral and pedagogical imperative. As educator George Couros (2015) states, technology will never replace great teachers, but technology in the hands of great teachers is transformational. It needs both hard and soft skills as well. Our school's leadership provided inspirational motivation by consistently communicating a vision where the new projects were linked to the school's core mission, and also framed as a way to give Romanian students a competitive edge, not as a top-down mandate. The vision was not to use AI. The vision provided by Școala Încrâderii was to become the kind of school built on trust and well-being. This human-centric vision is far more inspiring. The leadership then connected this to technology by saying the fact that we trust each other, so we explore these new tools together to help our students.

c) The Intellectual Stimulation is kind of safe to fail environment, in which the leader challenges old assumptions and encourages creativity, innovation, and risk-taking. They foster an environment where followers feel safe to question and experiment. This seems to be the most critical component for technology. Teachers *must* be allowed to experiment, and in doing so, they will sometimes fail. A 2024 study in *Teaching and Teacher Education* found that psychological safety is the number one predictor of whether teachers will move beyond basic substitution and use technology for innovative pedagogy. Intellectual stimulation creates this safety. In our school case the intellectual stimulation was operationalized through *workshops* where teachers could play with new software without fear of evaluation,

by creating innovation teams, or by replacing critical feedback with „What did we learn from this?“ during the project rollout, using both hard and soft skills as well. You cannot have a safe-to-fail environment for technology if you do not first have a culture of trust. Școala Încrăderii is the project that builds this psychological safety. Because the Școala Încrăderii project had already established norms of non-judgmental feedback and mutual respect, teachers felt safe to experiment with new digital tools. They were not afraid of being shamed if a new tech-based lesson failed. This project was the mechanism that made risk-taking possible.

d) Another important issue is the differentiated support because the leader acts as a coach or mentor, recognizing that each follower has different needs, skills, and motivations. Thus, they provide personalized support. A one-size-fits-all professional development day for a new technology project is doomed to fail. It bored the digital natives and terrify the tech-hesitant veterans. The surveys applied on teachers consistently show that their top barrier to tech use is a lack of relevant, ongoing, and differentiated training (Marr, 2023). So, individualized consideration means the leader recognizes this and provides multiple pathways for support. The leadership in our school demonstrated individualized consideration by scrapping whole-school training in favor of a menu of options, creating a peer-mentoring program and providing one-on-one coaching for teachers who were struggling with the project's tools. By applying this four-part model, the leadership at „Ioan Bădescu” Secondary School did not just *manage* a project; it *led* a cultural transformation. This engine is what created the conditions for the next, most crucial step: updating the skills of the teachers themselves. The Școala Încrăderii project is, at its core, about socio-emotional learning (SEL) and well-being. This shows the leadership cared for teachers as people, not just as employees. Using both soft and hard skills is very important because the leadership team from Ioan Bădescu Secondary School used the principles of Școala Încrăderii to support teachers through the tech projects. They didn't just offer technical support, they offered emotional support, acknowledging the stress of change and providing coaching based on individual teachers' anxieties and needs.

4. The need for novel teaching skills in response to AI disruption

The preceding sections have established the *disruption* (AI) and the *engine* (transformational leadership). This section demonstrates the *mechanism*: the tangible, necessary, and intentional updating of teacher skills. The technology-enabled projects at „Ioan Bădescu” Secondary School were not the *goal* in themselves; they were the strategic vehicle for this critical professional development. This transformation of skills must occur in two parallel, interconnected domains: the professional/digital and the transversal.

4.1 The professional teaching skills

From the perspective of EU model of competences any technology project to be sustainable and pedagogically sound, it must be grounded in a common framework of professional competence. In the European context, the benchmark is the European Framework for the Digital Competence of Educators (DigCompEdu) (Redecker, 2017). This framework is essential because it moves the focus from basic ICT literacy on how to use the tool, to digital pedagogy, why and how to use the tool for learning. It outlines six key areas of competence for educators: the professional engagement, by using digital tools for collaboration, reflection, and professional development; the digital resources, sourcing, creating, and sharing digital content; the teaching and learning, thus managing and orchestrating digital tools in the learning process; the assessment issues, by using digital tools for formative and summative assessment, empowering learners by using digital tools for differentiation, active engagement, and personalization and facilitating learners' digital competence by helping students become digitally competent themselves. The transformational leadership at „Ioan Bădescu” Secondary School *intentionally* used its projects to move teachers along the DigCompEdu progression model, from A1 Newcomer to B1 Integrator and B2 Expert. The *Școala Încrederii* project is the foundation for Area 1: Professional Engagement. This area is about collaboration, communication, and reflective practice with colleagues. This project gave teachers the trust and skills to truly collaborate for the first time, which they then applied to co-designing the new technology projects.

4.2 The need of developing teachers' transversal competences

Secondly, it is the development of transversal competences. These are the 21st-century skills for teachers. the very skills they are now expected to foster in their students. These are also known as soft skills or durable skills (America Succeeds, 2021) and include: critical and innovative thinking, collaboration and teamwork, interpersonal skills such as communication and empathy, intrapersonal skills demonstrated in adaptability, resilience and self-direction, media and information literacy. A core argument is that teachers cannot effectively teach 21st-century skills if they are not actively practicing them. The *process* of implementing the technology projects at „Ioan Bădescu” Secondary School, guided by a transformational leader, was the professional development. The projects, by design, forced teachers out of their traditional, isolated silos and into collaborative teams. When the Classroom platform failed by being proved ineffective, the safe-to-fail culture, fostered by intellectual stimulation required teachers to engage in real-time, high-stakes problem-solving and collaboration. They needed to be resilient and flexible. The teachers became lead learners and co-collaborators with their pupils as a result of the initiatives' direct development of their own transversal skills. Afterwards, implementing Școala Încrederii in our school was the ideal decision to foster transversal qualities in the entire school community, including

empathy, communication, teamwork, and flexibility. Therefore, there was no separate training to teach the transversal skills teachers needed to carry out the technology projects. Through their involvement in the *Școala Începătorii* program, they also naturally developed. Teachers learnt how to cooperate and communicate more effectively initially, which made co-designing digital lessons possible.

4.3 The need for a digitally competent teacher

The only person who can successfully assist students in developing 21st century abilities is a teacher who is technologically possesses strong transversal skills (Van Laar et al., 2017). So transformational leadership created a supportive environment for educational projects which served as the vehicle to develop teachers' digital (DigCompEdu) and transversal skills and this allowed those teachers to fundamentally shift their pedagogy from simple information delivery to the active facilitation of students' 21st-Century skills where the 4Cs: Critical Thinking, Communication, Collaboration, and Creativity are considered. The proof of the project's effectiveness was not only that instructors used the new tools, but how their usage affected student learning.

A history lesson prior to the assignment might include both a lecture and an exam. Following the project, the teacher, now proficient in DigCompEdu Area 3 called Teaching & Learning and skilled in collaboration, creates a task in which students work in groups, use digital archives to analyze multiple sources such as critical thinking and media literacy, and create a short documentary to present their findings using their creativity and communication. By emphasizing teacher skills as the mechanism for change, this model demonstrates that leadership is the spark that transforms technology's potential into the reality of 21st-century learning.

Teachers who implement the *Școala Începătorii* Project and master new digital tools can create a safe classroom environment for students to collaborate, think critically, and take creative risks.

5. Conclusions

The main focus of this piece is the enormous external demands on our institutions. However, as this study has demonstrated, technology is not the driver of change, but rather the fuel. The primary motor is and has always been leadership. This research used the case study of „Ioan Bădescu” Secondary School to provide a clear, repeatable model. It shown that transformational leadership, through its four fundamental techniques of idealized influence, inspiring motivation, intellectual stimulation, and customized concern, serves as the crucial catalyst. This human-centered regarded as soft skills and AI-centered approach illustrated as hard skills were important prerequisites for innovation. It fostered a resilient, flexible community that saw technology as an opportunity rather than a danger.

This study, grounded in the Romanian environment, provides a practical, evidence-based model: to successfully adopt technology, leaders must first construct a *Școala Încrăderii* kind of school environment. The disruption is here. The question is not whether we will change, but how we will lead the change. This article finds that a transformative, human-centered approach is the most effective and compassionate method to guarantee that technology meets our educational objectives.

In conclusion, transformational leadership fosters the required culture of trust, inventiveness, and psychological safety, allowing technology-enabled educational initiatives to progress from requirements to real, teacher-led change. The disruption is here. This study contends that transformational leadership is the most effective and compassionate strategy to guarantee that technology supports, rather than dictates, our educational aims. The project at „Ioan Bădescu” Secondary School demonstrated that technological disruption is a human challenge, not a technical one. Thus transformational leadership, through the strategic implementation of the *Școala Încrăderii* created the essential foundation for psychological safety and collaborative trust.

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Students' insights on the impact of digital remote learning

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Abstract: *The main goal of this study was to analyse the various factors that influenced students' experiences during the period of digital remote learning (DRL). This involved exploring the challenges they faced, such as technical difficulties, limited personal interaction with instructors and peers, and issues with internet connectivity. Additionally, the study aimed to identify the aspects of DRL that students found convenient and beneficial. A 17-question survey was conducted with 147 students from seven academic specialties, yielding diverse insights into their experiences. The findings from this study strongly suggest that remote learning can serve as a viable alternative to traditional face-to-face instruction when implemented effectively. Nevertheless, the results also indicate that students exhibit ambivalence towards this teaching approach, likely stemming from the negative experiences they encountered during the transition. Many reported feeling a lack of direct engagement with educators and fellow students, as well as challenges associated with relying on technology for their learning. The results revealed that a blended method, which combines face-to-face teaching with online resources, was favoured by 72% of students. This hybrid model not only addresses the shortcomings of purely DRL but also enhances the educational experience by providing opportunities for in-person interaction and collaboration, thus fostering a more supportive learning environment. Institutions will benefit from implementing alternative DRL mode programs. Such initiatives will provide students with enhanced options and increased flexibility in achieving their academic objectives. By adopting these programs, institutions can better accommodate diverse learning preferences and extend support to a wider range of students.*

Keywords: Digital remote learning (DRL), Academic experiences, Students' insights.

1. Introduction

The Faculty of Technics and Technology (FTT) at Trakia University - Stara Zagora implemented digital remote learning (DRL) during the pandemic. In the aftermath of this transition, the project titled "*Post-Pandemic Learning Trends: Digital Online Teaching*" was launched to evaluate the effectiveness of the DRL approach. Throughout the COVID-19 pandemic, online learning has become a new experience for many students, teachers, and academics (Suwanto et al., 2021; Aristovnik et al., 2023; Baber 2023; Yang, 2023; Broadbent et al., 2023; Webster, 2024; Simamora & Nababan, 2025). The sudden shift to online education has presented various challenges. Educators had to adapt quickly and develop strategies to promote student participation and engagement in virtual classes. However, there are concerns about the effectiveness of online education as a long-

<https://doi.org/10.58503/icvl-v21y202645>

term solution (Karim et al., 2025). Students have struggled with the transition to online learning, facing obstacles such as the need for independent study and limited access to reliable internet connectivity. Despite these challenges, many students have found online learning to be both cost-effective and time-efficient, allowing for easy access to study materials. However, the lack of interaction with peers and teachers, along with excessive screen time, has led to dissatisfaction among some students. Hence, while online learning has become necessary during the pandemic, it is essential to address the challenges and improve the online learning experience for both students and educators.

The goal of manuscript is to investigate the essential factors that significantly influence student motivation and engagement in educational settings, particularly within the context of DRL. The study seeks to identify students' preferences for custom-made learning methods. By illuminating these preferences, the research intends to equip educators and policymakers with actionable insights to project more innovative and responsive teaching strategies. Ultimately, the goal is to enhance student outcomes and cultivate an engaging and supportive educational environment that meets the diverse needs of all learners.

2. Method

2.1 Participants

Students from all academic programs at FTT-Yambol, encompassing both full-time and part-time formats, participated in a comprehensive survey concerning their experiences with distance learning during the pandemic. A total of 147 students across seven distinct specialties engaged in the research, comprising 62 full-time students who typically attend classes on a regular schedule, and 85 part-time students who often balance their studies with other commitments.

The demographic breakdown of the participants revealed a diverse group, with 38 women and 109 men contributing to the findings. The average age of respondents was 32.67 years, reflecting a mature cohort of learners. The ages varied significantly, ranging from 20 to 58 years, indicating that students from various life stages and backgrounds were involved in the survey. This diversity in age and experience provides valuable insights into the effectiveness and challenges of distance learning during an unprecedented time in education.

2.2 Method of preparation and analysis

A survey with the main research topics has been created and conducted during October 2023, winter semester. The inquiry was anonymous, consisting of 17 questions that cover the research topics of study: *“What/if bothered students during DRL”*; *“Classify, what/if was comfortable and convenient from DRL”*; *“What/if helps them to be motivated during DRL”*; and *“What/if discourages or disappoints them from DRL”*.

Table 1 lists several questions, and the article reports their results.

Table 1. Questions from the conducted survey

No	Question	Possible answers
1	Point out the positive aspects of online learning	- more free time – no need to travel; - saving money on travel and accommodation; - opportunity to review the lecture; - opportunity to be at work and listen to the lecture; - this way I am more focused and motivated; - availability of more online resources for self-study; - I can more easily combine: studying and resting, studying and working, studying and family commitments;
2	What is not accepted in online courses?	- isolation from the group I study with; - lack of direct contact with the teacher; - dependence on good quality internet and computer device; - difficulty motivating and organizing myself;
3	What was difficult for you during online learning?	- lack of good technology; - lack of good computer training; - I had no difficulties; - family commitments; - lack of change of environment, monotony, uniformity; - social isolation;
4	Are you a supporter of traditional face-to-face learning?	- Absolutely YES; - YES; - Rather YES than NO; - NO; - Absolutely NO;

Likert-type questions were employed in the survey to gauge participants' levels of agreement, disagreement, or feelings about specific statements. These questions are effective because they transform subjective opinions into structured, measurable data that researchers can analyze easily. The survey results were primarily examined using Excel. For group comparisons, the t-test and ANOVA (Analysis of Variance) were utilized as inferential statistical methods, focusing specifically on whether the observed differences between sample groups likely indicate real differences within the overall population. The trends identified in the data were illustrated with various charts and diagrams, which are presented and discussed in the article.

The research is a part of the scientific project titled "*Post-Pandemic Learning Trends: Digital Online Teaching*" conducted under contract No. 3 FTT/2023.

3. Results

3.1 Benefits of DRL According to Student Opinions

The survey results show that a significant percentage of students identified several advantages of DRL (Figure 1). One notable benefit mentioned by 21% of the students is that DRL provides them with more free time that allows them to engage in other activities or manage additional responsibilities since they do not need to spend time commuting to and from educational institutions.

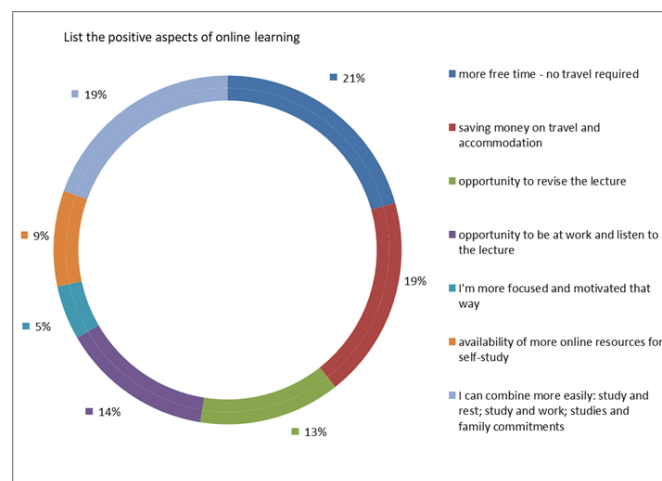


Figure 1. Positive aspects of DRL according to students' opinion

One advantage noted by 19% of the students is that remote learning is less expensive. This means they do not have to incur costs related to commuting, such as transportation fares or accommodations near the educational institution. As a result, remote learning can be a more cost-effective option for these students. Additionally, 19% of the students mentioned that remote learning allows them to easily balance their studies with other commitments, such as rest, work, or family responsibilities. This flexibility enables them to manage their time effectively and engage in their studies while also fulfilling other important obligations in their lives (Figure 1). Many other authors have reported similar findings. A survey of various academics found that remote learning has several positive aspects. Specifically, 21% of students indicated that it gives them extra free time and eliminates the need for travel (Dokuchyna, 2023). Moreover, 19% of students noted that remote learning is more cost-effective (Hadijaya & Wahyuni, 2023). Furthermore, another 19% stated that remote learning allows them to conveniently balance their studies with relaxation, work, or family responsibilities (Riega-Virú et al., 2023).

3.2 Negative perceptions of DRL according to Students' Opinion

According to the data presented in Figure 2, a significant majority of students—approximately 51% reported that they experienced no difficulties while undergoing DRL. However, around 17% of students stated facing challenges related to social isolation. Also, 11% encountered issues due to a lack of effective techniques, while another 11% felt hindered by an unchanging environment, which led to a sense of monotony. These findings emphasize the need for strategies to address the challenges students face in DRL, particularly those associated with social isolation and the development of effective learning techniques. It is essential to implement methods that can enhance students' success in DRL environments.

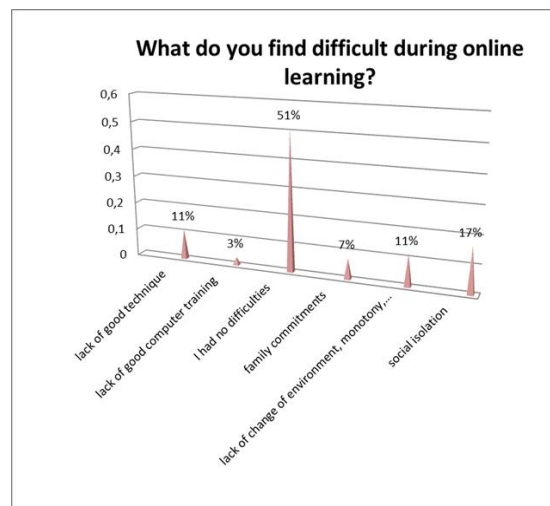


Figure 2. Negative aspects of DRL according to students' opinion

Other researchers have reported similar findings. For instance, about 51% of students indicated that they experienced no difficulties while undergoing DRL (Ding et al., 2022), as it was received in the current survey (Figure 2). However, around 17% of students reported facing social isolation as a challenge (Garingo & Cajucum, 2022), it also corresponded exactly to the same value of our investigation (Figure 2). The students encountered difficulties due to a lack of effective techniques, according Akyüz & Ergöl, (2022), is 11%, while another 11% felt hindered by a lack of changes in their environment, which led to feelings of monotony and uniformity (Yan et al., 2021). Those results overlap the obtained meaning of students' insights about DRL from our examination (Figure 2).

One major concern expressed by students regarding remote digital learning is the lack of direct contact with their teachers, with 45% of respondents indicating this issue in a recent survey. This absence of face-to-face interaction can make it challenging for students to understand the material, ask questions, and receive prompt feedback from their instructors. The 45% figure suggests that a substantial number of students feel this way, as illustrated in Figure 3.

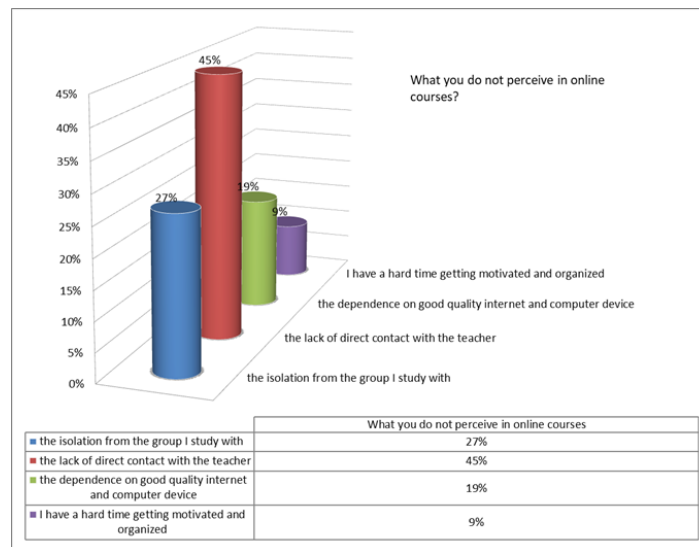


Figure 3. Students' opinions on negative perceptions of DRL

A significant negative aspect of Distance Remote Learning (DRL) is the feeling of isolation from peers, which was mentioned by 27% of students. This indicates that many students experience a sense of loneliness or disconnection during the learning process.

A significant number of students (19%) have expressed concerns about their reliance on good-quality internet and computer devices during remote digital learning. Many students feel frustrated by the fact that their learning experiences depend heavily on a reliable internet connection and suitable computer equipment. The lack of these resources can hinder their ability to fully participate in online classes, access learning materials, and complete assignments. Additionally, less than 9% of students reported difficulties with motivation and organization during remote digital learning (Figure 3). These challenges can negatively impact their engagement with the learning materials and their ability to meet course requirements.

Many studies have investigated the challenges students face with DRL. One of the primary concerns expressed by students is the lack of direct contact with their teachers. Approximately 45% of students have identified this absence of face-to-face interaction as a significant drawback (Lloyd, 2023). Without the benefit of in-person communication, students often experience difficulties in understanding instructions, encounter communication barriers, and feel disconnected from the learning process. Furthermore, 27% of students reported feeling disconnected from their peers, making it the second most common issue (Anggreyani & Dewi, 2023). This disconnection can result in feelings of isolation and loneliness, as students struggle to interact with their classmates and share their thoughts and experiences. The lack of peer interaction can also lead to decreased motivation and hinder the learning process. Around 19% of students identified the dependence on high-

quality internet and computer devices as a significant problem (Sujariati & Wanci, 2023). When these resources are unavailable, it becomes challenging for students to keep pace with the curriculum. Less than 9% of students cited difficulties in staying motivated and organized during remote learning (Kostina et al., 2023). The absence of a structured learning environment, combined with home distractions, can contribute to low motivation and poor organization.

These findings align with our own and highlight the importance of addressing the challenges associated with remote digital learning. To ensure the success of remote education, it is essential to enhance the interaction between teachers and students, reduce feelings of isolation, improve access to technology, and provide support for student motivation and organization.

3.3 Preferences for effective learning methods

Based on the responses gathered from student questionnaires, over 50% of students believe that combining face-to-face teaching with online resources is an effective learning method. This approach, known as blended learning, has been utilized for many years, even before the pandemic lockdown (see Figure 4).

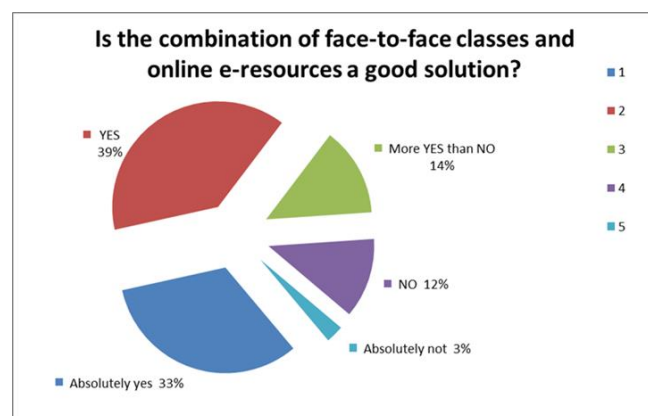


Figure 4. Students' opinion about methods of teaching and learning

According to recent research, remote learning has proven to be a highly effective alternative to traditional face-to-face learning. Studies have shown that about 72% of students prefer a combination of in-person teaching and online e-resources, also known as blended learning. This method of education has gained popularity among students seeking for a more comprehensive and engaging learning experience (Wahid, 2023; Zhang, 2023; Wahyuni et al., 2023). Blended learning has been in use for many years, before the pandemic lockdown (Indriani & Sulaiman, 2023). DRL empowers students to better manage their time, save money, and balance their academic studies with other obligations. By offering flexibility and convenience, DRL has emerged as a compelling option for students who seek to pursue their academic aims accommodating other responsibilities.

4. Discussions

DRL offers advantages, such as increased free time, cost-effectiveness, and the ability to balance studies with other commitments (Mawene et al., 2020; Mlodawski et al., 2022a). These findings highlight the potential benefits of DRL for students, including improved time management, financial savings, and greater flexibility (Ober & Kochmańska, 2024; Mlodawski et al., 2022b). Researchers believe that remote online learning could be a valuable part of high-quality education in the future, rather than just a temporary solution (Sanita et al. 2021).

Remote online learning has proven to be an effective way to maintain education during crises and wars, such as the ongoing war in Ukraine (Kuzheliev et al., 2023). Many students have expressed their satisfaction with the DRL during the COVID-19 pandemic (Kalniņa et al., 2023). However, there are some challenges associated with DRL, such as developing digital competencies, ensuring access to technology, and designing effective online learning materials (Wang, 2023).

Studies reveal that first-year students struggle more than fourth-year students to adapt and communicate in a new social environment during DRL (Rahim et al., 2024). Furthermore, sentiment analysis and topic modeling techniques have shown that e-learning during the pandemic has had some negative effects on individuals' emotions (Linnes et al., 2024). Nevertheless, the pandemic has prompted educators to teach remotely, leading to the largest distance-learning experiment in history and highlighting the potential for remote online learning to be a valuable component for delivering high-quality education in the future.

The experiences gained during the outbreak prompted a reevaluation of educational practices post-pandemic, emphasizing the necessity to adapt to the new normal and explore opportunities for improvement (Tonna et al., 2023; Svihus, 2024). The alteration to distance learning during the pandemic brought significant implications, leading to a need for changes in education worldwide (Popławska et al., 2023). Educators had to evolve their practices significantly to fit the new online instructional mode, highlighting the transformative nature of teaching and learning, which necessitates further investment in teacher education to facilitate remote teaching effectively. Karim et al. (2025) identify three primary challenges within online education system: digital accessibility issues, pedagogical difficulties, and concerns about assessment integrity. They propose practical solutions to address these problems, as improving infrastructure, developing faculty training programs, and implementing AI-enhanced assessment methods.

Considering the pandemic, educators from various institutions have acknowledged the vital role that online teaching has played in maintaining continuity in student learning. The transition to virtual classrooms has enabled the delivery of education despite restrictions on physical gatherings, allowing students to continue their studies safely from home. However, educators have also recognized its long-term limitations (Zhang & Gillespie, 2023; Tondeur et al., 2024). They have noted that DRL cannot fully replace the benefits of face-to-face interactions between students and teachers, which are essential for fostering meaningful connections,

providing personalized support, and building a sense of community. Despite these drawbacks, educators agree that online teaching has become an integral part of the educational landscape and will continue to be an important resource.

4. Conclusion

The research findings strongly suggest that remote learning can be an effective alternative to traditional face-to-face education. Combining in-person teaching with online resources proves effective for about 72% of students. However, many students neither fully embrace nor completely reject this blended approach, possibly due to negative experiences they encountered during remote learning -such as the lack of direct interaction with teachers and peers, dependence on a stable internet connection, and technical issues.

Despite its challenges, remote learning provides several benefits, such as improved time management, cost savings, and the ability to balance studies with other commitments. The flexibility and convenience of distance remote learning (DRL) make it an appealing choice for students aiming to achieve their academic goals while managing other responsibilities. These findings offer valuable insights into how DRL can enhance student outcomes and improve the overall educational experience.

Institutions are encouraged to explore and implement alternative DRL mode programs in order to provide students with enhanced options and flexibility for achieving their academic objectives.

Acknowledgements

This research is part of a scientific project titled "Post-Pandemic Learning Trends: Digital Online Teaching," conducted under contract No. 3 FTT/2023.

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Designing an ecosystem for fake news detection and enhancing resilience to disinformation in the romanian–russian bilingual space

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Abstract. *The RealInfo project introduces an integrated information system designed to detect fake news and enhance media literacy skills within the bilingual Romanian–Russian context of the Republic of Moldova. The system combines a modular microservices architecture with an AI/ML engine trained on local media data through fine-tuning of multilingual BERT models. The analysis pipeline ensures comprehensive text preprocessing, classification, and explainability, while a continuous feedback mechanism enables the ongoing improvement of model performance. Interactive educational components complement the technological infrastructure, providing users with resources, exercises, and micro-courses aimed at fostering critical thinking and informational responsibility. Thus, RealInfo demonstrates how artificial intelligence and media education can be integrated into a unified system that strengthens the information resilience of society.*

Keywords: Artificial Intelligence, Disinformation, Fake news, Media literacy, Information resilience.

1. Introduction

In a global context marked by the acceleration of information flows and the proliferation of manipulative content, combating disinformation has become a major challenge for society, education, and governance. The impact of fake news goes beyond the media sphere and affects social cohesion, public trust, and democratic processes (Cenușa, 2024). In particular, the Republic of Moldova, due to its bilingual Romanian–Russian cultural and linguistic specificity, faces increased vulnerability to disinformation, which requires the development of intelligent tools adapted to the local context. In the case of fake news, the manipulation of emotions becomes a central strategy of influence, while social networks play a major role in amplifying this process by providing a favorable environment for the rapid circulation of content that provokes intense emotional reactions and reduces users’ critical thinking (Cover, Haw & Thompson, 2022).

Media consumers tend to react more strongly to information with emotional content, especially to negative information, which more easily attracts attention and is perceived as more relevant or credible (Soroka, Fournier & Nir, 2019).

In this context, the MIDECOD project responds to these needs by proposing a pedagogical model that combines artificial intelligence technologies with interactive educational methodologies. The model offers users not only the possibility to verify the authenticity of information, but also the opportunity to learn how to evaluate it critically and rationally, thus contributing to the consolidation of a cognitive and educational infrastructure designed to support the informational resilience of society.

2. Technological architecture of the RealInfo system

The central digital component of the pedagogical model is the RealInfo information system, an authentic AI-based platform currently under development, which will be launched as a pilot project in March 2026. The system is capable of automatically detecting false content and providing educational feedback to learners. The authors conducted a relevant comparative analysis of existing information systems specialized in fake news detection, fact-checking, and deepfake identification, highlighting the lack of content specific to the national context, which limits the effectiveness of these systems when addressing new or locally relevant topics. Consequently, the need was identified for the development of a hybrid AI-based disinformation detection system that integrates fake news detection (using BERT (RO, RU) models adapted for the Romanian and Russian languages and trained on Moldovan specific narratives), deepfake detection (with images processed through neural networks combined with forensic techniques), and fact-checking (Globa et al., 2025).

The technological dimension includes the improvement of automatic detection algorithms and the integration of functionalities for identifying manipulative content, including deepfakes, while the educational dimension focuses on the development of competences in critical analysis and applied research. Figure 1 presents the five functional layers that constitute the overall architecture of the RealInfo system:

- The *Frontend Layer* brings together the user-facing interfaces, including the web application developed in React, optimized for desktop access, and the browser extension for real-time analysis. The mobile component was intentionally excluded in order to ensure more efficient resource management and increased system performance.
- The *API Gateway* serves as the central access point of the system and is implemented in FastAPI (Jurafsky & Martin, 2025) to ensure high execution speed, scalability, and automatic documentation.
- The *Backend Microservices* are organized according to the single-responsibility principle, with each microservice performing a clearly defined function: the authentication service manages the OAuth2 protocol; the analysis service processes media content; the reporting service collects and structures user feedback; the educational service manages interactive modules and courses.

- The *AI/ML Engine* is responsible for performing automatic content analysis (Devlin et al., 2019). It integrates a bilingual NLP processor capable of recognizing the language of the text and activating the appropriate deep learning model—BERT-RO for Romanian and BERT-RU for Russian.
- The *Data Storage Layer* is based on a hybrid architecture that combines relational and non-relational databases. Within this structure, PostgreSQL manages structured data, MongoDB is used for storing media metadata, and a vector database such as Pinecone or Weaviate supports semantic search and the identification of similar content.

Given that the project targets interaction with different age groups—from school pupils and university students to older adults, the system is designed to be intuitive and accessible for all users. It is designed with a clear interface, easily interpretable visual elements, a logically structured sequence of steps, and language tailored to the digital competence level of each user group.

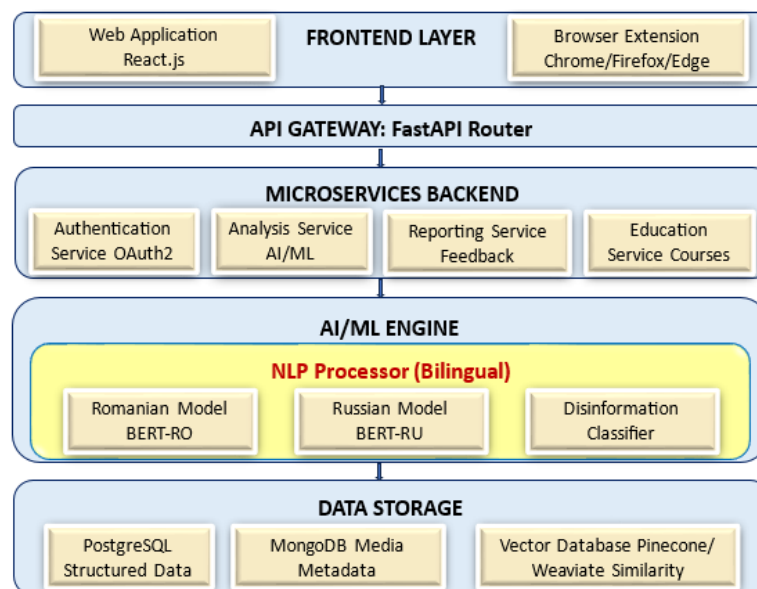


Figure 1. General architecture of the RealInfo system

3. Data processing flow

The analysis begins with identifying the language of the text and routing it to an NLP model specific to that language. The NLP processing stage includes tokenization, lemmatization, part-of-speech (POS) tagging, and dependency parsing, all performed in a language-sensitive manner. Subsequently, named entities (persons, organizations, locations, and relevant concepts) are extracted to support contextual understanding. Semantic vectorization converts the text into a dense numerical representation, enabling content evaluation through a hybrid

algorithm that combines AI-generated classification scores with similarity analysis against previously verified content.

The AI analysis pipeline of the RealInfo system represents the logical sequence of stages through which textual data are processed, analyzed, and evaluated in terms of content veracity (Figure 2). This flow integrates procedures for linguistic preprocessing, semantic analysis, automatic classification, and contextual validation, all coordinated by a microservice-based orchestration mechanism (Zhou & Zafarani, 2020).

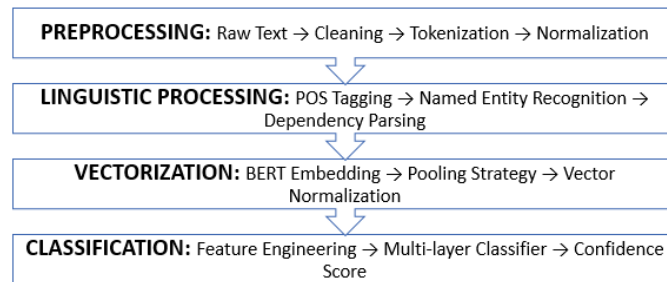


Figure 2. AI analysis pipeline

Preprocessing serves to standardize the text by removing special characters and applying cleaning rules adapted to Romanian and Russian.

Linguistic processing applies part-of-speech (POS) tagging to identify grammatical elements; *Named Entity Recognition (NER)* is used to identify and extract significant entities from the text, such as relevant persons, organizations, and locations, and *Dependency Parsing* analyses syntactic dependencies, highlighting grammatical relations and the hierarchy among the words in the sentence.

Vectorization transforms the text into dense numerical representations, using fine-tuned BERT models optimized for the Romanian and Russian languages.

Classification applies feature engineering techniques, combining semantic embeddings with additional linguistic features and employing multi-layer classifiers to generate the final decision regarding the veracity of the content.

Through this analysis pipeline, RealInfo ensures a comprehensive, automated, and transparent process for detecting fake news, combining artificial intelligence with human expertise.

The database architecture of the RealInfo system was designed to meet the complex requirements of an automatic disinformation analysis system that processes large volumes of heterogeneous data, including texts, media metadata, analytical results, and semantic vectors.

USERS table. A distinctive element of this structure is the use of the preferences field, stored in JSONB format, which allows the dynamic recording of individual preferences such as interface language, level of detail of reports, or type of notifications.

The *ANALYSES table* represents the core of the operational process and contains data related to individual analysis requests submitted by users. Each

record includes the original text, the source, the detected language, and associated metadata such as the request date, processing time, and analysis status.

The *ANALYSIS_RESULTS* table stores the results generated by the AI/ML engine for each analysis performed. It includes credibility scores, the classification label (e.g., true, disinformation, neutral), and the associated explanations derived from the internal interpretation of the model, thereby ensuring a clear and transparent presentation of the results for the user and facilitating subsequent verification of algorithmic decisions.

The *VECTOR_EMBEDDINGS* table is intended for storing dense numerical representations (embeddings) resulting from the semantic processing of texts by the BERT-RO and BERT-RU models. This table enables the system to automatically compare the analyzed texts with a verified knowledge base and to identify similar or potentially derived content, and the integration of this component contributes directly to the performance of the analysis pipeline and the accuracy of the final results.

By combining these tables, the RealInfo system establishes a direct link between the user, the analysis request, the processing result, and the semantic representation of the content.

The Browser Extension of the RealInfo system is designed with a modular architecture structured around four main components: Content Script, Background Worker, Popup Interface, and Overlay UI. Its purpose is to provide direct access to the system's functionalities without requiring navigation to the main web platform, while offering an integrated real-time information verification experience:

- *The Content Script* component runs directly in the context of the web page visited by the user and is responsible for analysing its structure through continuous monitoring of the Document Object Model (DOM). The script automatically identifies content fragments that may represent news articles, posts, or headlines with manipulative potential, using a set of predefined rules and simple semantic filters.
- *The Background Worker* represents the logical core of the extension and is responsible for managing communication between the interface component and the server infrastructure. It maintains a secure connection with the RealInfo API, forwarding analysis requests from the Content Script and receiving the results provided by the processing pipeline.
- *The Popup Interface* constitutes the visible element of the extension and provides users with an intuitive control point over the verification process.
- *The Overlay UI* allows the analysis results to be displayed directly on the page in the form of warning banners, coloured highlights, or floating windows. This component provides immediate feedback that is visible in the reading context without interrupting the user experience.

Through the proper interaction of its components, the browser extension combines advanced technology with accessibility and educational impact, while its modular structure allows the addition of new features, such as clickbait

detection or integration with educational platforms, maintaining a safe and smooth user experience.

4. Machine learning pipeline

The AI models within the RealInfo system are developed through a rigorous iterative pipeline (including data collection, cleaning, labeling, training, and validation), with the aim of detecting disinformation adapted to the linguistic and media context of the Republic of Moldova (Figure 3).

The training *data* come from a mixed corpus of media sources from the Republic of Moldova, reflecting the thematic, stylistic, and ideological diversity of the local information space and enabling the models to learn the specific features of Romanian and Russian, including forms of code-mixing (Nițu & Dascălu, 2024).

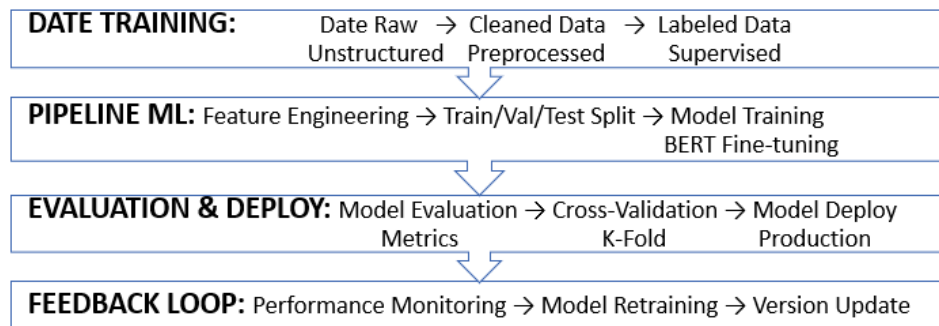


Figure 3. Machine Learning Pipeline

The *machine learning pipeline* (ML pipeline) is modular in structure and integrates components for feature engineering, fine-tuning, and adaptive evaluation.

Model evaluation is carried out on a separate dataset that is not used during training, by applying metrics specific to disinformation detection. These include: Precision – the proportion of correct labels out of all positive predictions; Recall – the ability of the model to detect all existing disinformation cases; and F1-Score – the balance between precision and recall.

The operational *feedback loop* continuously monitors model performance in the production environment. The results obtained from real-world use – including corrections provided by experts or trained users are collected and integrated into the periodic retraining process, thereby continuously improving the accuracy and adaptability of the models.

Through this training and evaluation architecture, the RealInfo system goes beyond the role of a simple automatic detector, becoming an adaptive learning ecosystem grounded in the collaboration between artificial intelligence and human expertise. The proposed model ensures not only algorithmic performance but also scientific and ethical sustainability in the process of countering disinformation.

The educational component of the RealInfo system extends the technological functionality of the system through a pedagogical dimension intended to support education for informational resilience, addressing diverse age groups and different levels of digital competence.

5. Conclusions

The RealInfo system demonstrates the potential of integrating artificial intelligence with media education into a unified approach capable of addressing the complex challenges of disinformation within the socio-linguistic context specific to the Republic of Moldova. The system creates favorable premises for the further development of research focused on multilingual and multimodal disinformation detection models, as well as for the integration of the RealInfo platform into educational programs and public media literacy initiatives. Thus, RealInfo is not only a technological innovation but also a concrete step towards a more informed, critical, and resilient society in the face of informational manipulation.

Acknowledgements

This article is produced as part of the scientific research project „The methodology of development of an Integrated Model for the Detection and Counteraction of Disinformation in the Republic of Moldova: A Technological and Socio-Educational Approach” (MIDECOD), with the code 25.80012.0807.65SE.

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Enhancing students' environmental competence through green language instruction in higher education

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Abstract: *This study examines the impact of green language education as an interdisciplinary pedagogical approach on enhancing environmental competence and foreign language skills among university students. In the context of escalating global environmental challenges, higher education institutions are increasingly expected to develop not only professional competences but also ecological literacy and sustainable attitudes. The paper explores how the integration of sustainability-related content into English language instruction contributes simultaneously to environmental awareness, critical thinking, and linguistic development. A mixed-methods research design was employed, combining quantitative surveys and qualitative classroom observations involving 33 undergraduate students and 15 language instructors. Quantitative data were analysed using descriptive statistics and correlational analysis, while qualitative data were thematically coded. Findings indicate that project-based learning, collaborative discussions, and eco-focused assignments contribute to the development of students' environmental competence while also enhancing reading comprehension, vocabulary acquisition, writing skills, and oral fluency. Despite positive outcomes, challenges related to teacher readiness, curriculum constraints, and limited instructional resources persist. The study concludes with recommendations for curriculum redesign, professional development, and future longitudinal research.*

Keywords: Green language education, Environmental competence, Higher education, Sustainability, Interdisciplinary pedagogy, Eco-literacy.

1. Introduction

People cannot inherently be separated from their surroundings. Occasionally, variations in climate and environmental conditions arise from both natural and human influences. Clearly, the environmental elements are nearly out of human regulation. However, the human factors are largely within human control. Therefore, this study attempted to identify human elements that lead to climate and environmental changes that have detrimental impacts on human existence on the planet. These human factors consist of air, water, and land contamination, release of greenhouse gases, tree removal, land degradation, discharge of carbon dioxide, carbon monoxide, and additional harmful gases.

Natural factors encompass volcanic eruptions, ocean fluctuations, solar changes, tectonics, thermohaline circulations, etc. (Laşcu, 2023). Surprisingly, the

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study found that there is an absolute disregard for climate and environmental education within the education systems of numerous nations, including Moldova.

This has been demonstrated due to the lack of provisions for climate and environmental education in the National policy of education until the more recent period of 2023. This forms the basis for the paper's argument supporting the incorporation of climate and environmental education within Moldova's educational framework.

Proposed policy statements were put forward that will improve climate and environmental education, which will inform individuals about the risks of causing damage to the environment. Once this is accomplished, there will be a significant decrease in the adverse impacts of climate and modifications to the environment, it is anticipated. Currently, we face a significant lack of integration of this important issue into the curriculum at the university level.

Consequently, this area constitutes our primary current interest and the main goal of the project we have been working on since September 2025. The research project Integrating and Promoting Green Education in the Initial Training of English Language Teachers (strategic priorities: societal challenges; strategic direction: Innovative Educational Technologies and Products; project code: 25.80012.0807.56SE), which looks at integrated approaches to green education within English language learning contexts, includes this conceptual study. The project investigates cutting-edge teaching strategies that simultaneously help students become more digitally literate, environmentally conscious, and proficient in English.

Conventional university education employs distinctly different teaching methods than those utilised in modern environmental education; thus, integrating environmental education into the university curriculum offers both cognitive and operational challenges for educators. This research investigates the efforts of three university associate professors from Chisinau, Moldova, as they participate in a research initiative aimed at integrating environmental education into university curriculum classes. Throughout three months, we have been evaluating and conversing about our perspectives and career growth associated with the project. The consequences are especially significant for universities from Moldova, where the integration of environmental education into science curricula has been required.

The ability to comprehend, evaluate, and respond to ecological concerns is known as environmental competence, and it has emerged as a key objective of higher education (UNESCO, 2019). Because language education integrates communication abilities with understanding of cultures, critical thinking, and global perspectives, it offers a special platform for integrating sustainability themes.

In order to foster students' ecological literacy while upholding high standards of linguistic proficiency, green language education incorporates environmental issues into language instruction. This integration is especially important in multicultural classrooms because students from different backgrounds can share different perspectives on sustainability, which promotes intercultural communication and cooperative problem-solving (Ellis, 2020).

The following research questions are addressed in the current study: In what ways does teaching green languages help students become more environmentally competent? Which instructional techniques work best for incorporating sustainability into language learning? What obstacles must educators overcome to adopt green education in higher education?

2. Literature review

The examination of current higher education curriculum resources emphasizes how environmental themes are included to help students become more environmentally competent. The materials, which include workbooks, theme modules, and skills-based courses, are intended to foster both ecological consciousness and academic English ability. Students are encouraged to critically engage with environmental concerns while enhancing the fundamental academic abilities required for success in English-medium higher education by integrating sustainability-related information into language activities.

Green education, also known as education for sustainable development (ESD), focuses on the knowledge, attitudes, and skills required to promote sustainability (Tilbury, 2018). In language teaching, green education encourages students to engage critically with environmental issues through reading, writing, discussion, and project-based activities.

A recent study emphasises interdisciplinary approaches, which combine ecological problems with cultural studies, languages, and digital media (Sterling, 2019). Such integration not only improves language skills but also raises environmental consciousness, ethical reasoning, and political engagement. However, problems include insufficient teacher preparation, a lack of curricular flexibility, and restricted access to educational materials (Wals, 2020).

3. Methodology and research design

A mixed-methods approach combining quantitative surveys and qualitative classroom observations was used to investigate the impact of green language education on students' environmental competence.

3.1 Participants

The study involved 33 undergraduate students enrolled in language programs at the Faculty of Foreign Languages and Literatures, State Pedagogical University "Ion Creangă" in Chişinău. Initially, the research aimed to interview university students; however, the first step involved administering a survey to English language instructors. Fifteen teachers participated in the survey, which consisted of ten questions concerning the integration of green education activities in their courses. Among these participants, ten were university-level instructors, four taught at the high school level, and one at a college in Moldova. Given that the majority of respondents were university-level teachers, it was subsequently decided

to incorporate a second step in the research, targeting university students. Consequently, a questionnaire was administered to the 33 undergraduate students, who were asked to respond to statements organised across six thematic rubrics.

3.2 Ethical considerations

Participation was voluntary, with informed consent obtained. All data were anonymised to ensure confidentiality.

3.3 Instruments and data analysis

Data were collected through two online questionnaires and classroom observations. The teacher survey, entitled Green Education in Language Teaching, consisted of ten items examining awareness, attitudes, instructional practices, and perceived challenges related to education for sustainable development.

Fifteen English-language teachers were interviewed, ten of whom taught at the university level. Consequently, the study focused on university-level teaching. Taking into account the perspectives of university instructors, the research was based on a quantitative methodology using the survey “Green Education in Language Teaching” (<https://forms.gle/fCvgGfL3ZS1Z9oMRA>). The survey aimed to investigate language teachers’ awareness, attitudes, and instructional practices concerning green education (education for sustainable development). All responses were treated confidentially and intended to inform strategies for better supporting environmentally friendly and sustainability-focused teaching approaches. The survey included the following questions:

1. What subject(s) and level(s) do you currently teach?
2. How many years of teaching experience do you have?
3. How familiar are you with the concept of green education or education for sustainable development (ESD)?
4. How important do you think it is to integrate environmental topics into language education?
5. In your opinion, what role can language teachers play in promoting environmental awareness among students?
6. Have you ever included environmental or sustainability-related topics in your language lessons?
7. If yes, please give an example of an activity, text, or discussion topic you have used.
8. What challenges do you face in integrating green education themes into your language teaching?
9. What types of materials or support would help you integrate green education more effectively?
10. Would you be interested in professional training or workshops on integrating sustainability and environmental awareness into language teaching?

Data collected from the instructor survey were analysed using descriptive statistics. Frequency distributions and percentages were calculated to identify trends in teacher preparedness, resource availability, and attitudes toward Green Education. Open-ended responses regarding challenges and support needs were subjected to thematic content analysis to categorise the primary pedagogical barriers and determine the specific types of professional support required.

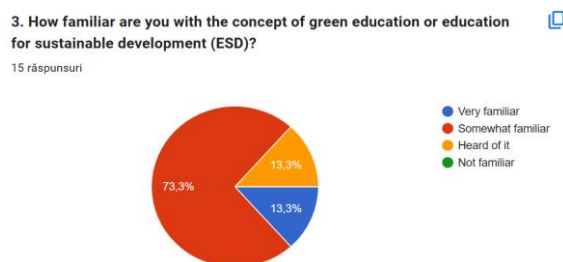


Figure 1. Teacher survey, question 3, results

Survey results indicate that the majority are university teachers, with a few coming from secondary schools and adult education. Teaching experience ranges from 0 to 21+ years, providing a mix of novice and experienced perspectives. The majority of respondents are "somewhat familiar" with Green Education / ESD, with a few being very familiar or having heard of it. This indicates that there is an opportunity to raise awareness and develop professional skills in ESD concepts. Almost all participants believe that integrating environmental topics into language education is very important or important. Only one respondent marked it as neutral, indicating widespread agreement on its worth.

Furthermore, based on the survey rubrics, we discovered that the key themes from open-ended responses are: Language teachers play an important role in raising environmental awareness. Teachers see their role as educators and advocates for sustainability, emphasizing the importance of raising awareness and motivating students to take action. Some emphasized the transdisciplinary nature of language education, linking it to worldview formation, empathy, and global citizenship. Integration of Environmental Topics: Debates, reading articles, descriptive essays, online discussions, lesson packs, practical eco-actions (such as recycling and planting green gardens), AI-related activities, and project-based learning are all examples. Activities frequently include interactive and discussion-based learning.

Both curriculum integration and extracurricular activities are mentioned, implying a comprehensive approach. Common challenges faced by teachers include a lack of training and a desire for more guidance on sustainability.

Integrating green topics may add to the workload due to time constraints. Some teachers may struggle to modify content due to curriculum constraints. There is often a lack of teaching materials and ready-made activities. Student engagement is sometimes cited as a limiting factor.

Teachers need support and resources such as guides, lesson plans, activities, and worksheets, professional development workshops and CPD opportunities, use practical materials such as videos, PPTs, flashcards, and activity spaces. Respondents also asked to provide examples of successful initiatives or model projects to replicate.

Most respondents are eager to improve their green education integration skills through training or workshops, indicating a strong interest in professional development.

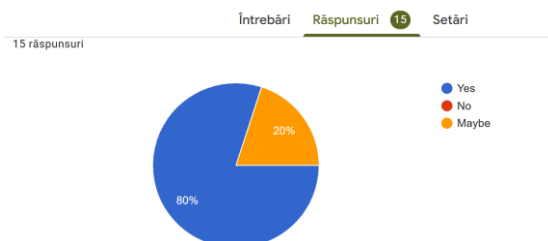


Figure 2. Teacher survey, question 10, results

The survey clearly revealed existing gaps in education concerning green awareness, highlighting a noticeable lack of appropriate instructional materials to support teachers in their daily pedagogical practices. It also shed light on the challenges faced by language educators, as well as their expressed interest in and need for specialised training and professional support in this area.

It helped us trace our plan and methodology within our project and its study. It also contributed to outlining the plan and refining the methodology of our project and its associated study.

The table below shows a summary of the responses provided by the questioned teachers.

Table 1. Teacher survey responses (condensed)

Question	Summary of Responses
1. How many years of teaching experience?	21+ years: 7 teachers; 11–20 years: 5; 6–10 years: 1; 0–5 years: 2
2. Familiarity with green education/ESD	Somewhat familiar: 11; Very familiar: 2; Heard of it: 2
3. Importance of integrating environmental topics	Very important: 12; Important: 2; Neutral: 1
4. Examples of activities used in lessons	Eco-tourism, Green-cities, recycling discussion, SDGs projects, descriptive essays (eco-friendly house, country), climate change text analysis, sustainability in students' final projects, online materials discussion, debate on green education trend, AI prompt writing with eco-focus
5. Challenges faced	Limited resources, insufficient teacher preparation, curriculum constraints
6. Support needed	PPTs, worksheets, training, ready-made lesson packs, videos, flashcards, articles, games, short presentations, workshops on green education

The survey successfully blends qualitative (open-ended) and quantitative (such as teaching experience, familiarity, and importance) questions to provide both quantifiable data and in-depth teacher insights. It helped us identify the next steps in our study and formulate several recommendations to guide our future actions, such as:

- *Create professional training courses on ESD and green education that focus on awareness and useful teaching techniques.*
- *Produce pre-made materials specifically designed for teaching languages, such as lesson plans, PowerPoints, worksheets, discussion starters, role-playing, and project-based exercises.*
- *Promote the exchange of best practices among educators, such as through workshops, online forums, or group projects.*
- *When feasible, incorporate sustainability into curricula by matching activities to learning goals rather than treating them as "extra" material.*

Observation: Attended classes and observed university lecturers teaching. Focused on the methods, student interactions, and the use of eco-focused materials - qualitative method.

The observation aimed to gain a direct understanding of how university lecturers incorporate environmental awareness and sustainability principles into their language teaching practices.

Classroom observation served as a qualitative method to supplement the survey's quantitative findings, providing a more in-depth and nuanced view of teacher-student interaction and instructional behaviour. To assess the use of eco-focused or sustainability-themed materials in the classroom, as well as their relevance and pedagogical effectiveness. The observation sought to document effective teaching practices as well as the challenges faced by lecturers in incorporating green education themes into language instruction. The insights gained from observing were intended to guide the design of professional development initiatives and teaching materials that address the identified gaps and assist educators in promoting environmental competence.

Additionally, we attended classes in order to observe students' proficiency levels and linguistic skills, as well as to examine how teachers integrate the process of teaching new vocabulary into their lessons. The purpose of these observations was to diagnose the existing situation and to obtain a clear picture of what could be improved and, more importantly, how this should be done. Based on the insights gained from classroom observations, we incorporated these findings into the methodological guide by developing modules focused on teaching environmental awareness while enhancing students' linguistic competence in this area. Thus, the primary aim of observing lessons was to identify concrete ways in which we could support teachers and determine what content and strategies should be included in the guide.

Survey: Given that the study focused on the university level, a survey was administered to undergraduate students to examine their environmental awareness, attitudes, and anticipated learning outcomes. This stage of the research employed a quantitative methodology using the survey "Green Language Education and Environmental Competence" (<https://forms.gle/Yn5WqVom48zdjzyx8>). The survey was designed to explore students' experiences and perceptions regarding the integration of environmental topics into their language courses.

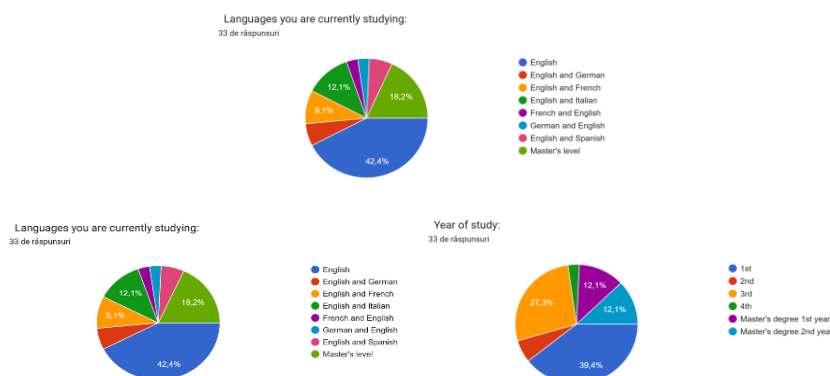


Figure 3. Student survey: year of study and foreign language(s) studied

Here is a detailed analysis of the student survey data and some of our observations and conclusions. The majority of students rated themselves 4-5, indicating moderate to strong awareness of issues such as climate change, pollution, and sustainability. Some first-year students, particularly those aged 17-19, rated themselves lower (1-3), highlighting the need for introductory awareness-raising. Overall awareness is high, particularly among Master's students, indicating increased knowledge with age and study experience. Introductory sessions on global environmental issues could bridge gaps for first-year or less experienced students.

Most students have strong agreement (4-5) and are confident in their understanding of the concepts of sustainability and ecological responsibility. Lower ratings (1-3) may indicate a lack of understanding of sustainability or ecological responsibility among younger students or those in their early studies. The majority of students rated themselves 3-5, indicating moderate confidence in their ability to practice eco-friendly actions. Some respondents cited challenges understanding or applying sustainability practices. The majority of students agreed with the statements below, with responses ranging from 60% to 77% selecting “Strongly Agree” or “Agree.”

Table 2. Student survey responses (condensed)

Statement	% Strongly Agree/Agree
Discussing sustainability in a multicultural classroom helps me understand different cultural perspectives	60–77%
Projects and assignments on environmental topics improve critical thinking skills	60–77%
Green language activities improve reading comprehension on environmental topics	60–77%
Green language activities enhance writing skills on ecological subjects	60–77%
Green language activities increase vocabulary related	60–77%

Statement	% Strongly Agree/Agree
to sustainability	
Green language activities improve ability to discuss environmental issues orally	60–77%
I enjoy project-based learning activities focused on environmental topics	60–77%
Use of digital tools (videos, simulations, online collaboration) is helpful	60–77%
I feel that my instructors are adequately prepared to teach green language education	33%

While the majority of students agreed with most statements (60–77% selecting “Strongly Agree” or “Agree”), only 33% felt that their instructors were adequately prepared.

- *I feel that my instructors are adequately prepared to teach green language education.*

Responses are mixed; some students believe teachers are ready, while others point out the need for additional instruction and helpful advice.

Short workshops or modules could be used in the curriculum to explain sustainability and ecological responsibility in easy-to-understand terms. Real-life examples, such as local environmental initiatives, can improve understanding.

Practical exercises can help students reduce their environmental impact in everyday life. Recycling projects, energy-saving initiatives, or eco-friendly campus campaigns can help reinforce this skill.

Most students (ratings 4–5) found that incorporating environmental topics enhances their learning experience. Some students remain neutral, indicating that integration should be relevant and engaging to increase interest.

Many students rated environmental issues in class as 4–5, indicating high motivation; hands-on, collaborative, and real-world focused activities reinforce motivation. Most students (mostly 4–5) concur that multicultural conversations enhance their comprehension of various viewpoints.

Some first-year students received lower ratings, perhaps as a result of their lack of discussion experience. Overall, there is a high degree of agreement; students agree that environmental assignments encourage critical thinking (ratings 4–5).

Table 3. Language skills improvement via green activities

Skill	Observations	Comments
Reading comprehension	Many students reported improvement (4–5)	Short articles, reports, and texts on environmental issues enhance vocabulary and reading skills.
Writing skills	Improvement noted, though some report challenges with scientific terms	Writing essays, reflections, or project reports can be integrated with vocabulary scaffolding.
Vocabulary	Strong agreement; new	Glossaries and pre-teaching

Skill	Observations	Comments
	environmental terms learned	ecological terms help reduce comprehension gaps.
Speaking/oral skills	Ratings 4–5; lower for beginners	Discussions, debates, and role-plays improve fluency and confidence in eco-topics.

Beyond general improvement, the study highlights a direct correlation between sustainability topics and the development of advanced linguistic competence (CLIL). Engaging with authentic environmental texts requires students to master English for Specific Purposes (ESP) vocabulary (e.g., biodiversity, carbon footprint), pushing them from B1 to B2 proficiency. Furthermore, debating complex issues like climate justice necessitates the use of high-level cognitive and linguistic functions, such as hypothesising (conditionals), persuading (modals of obligation), and structuring complex arguments, which are essential for academic fluency.

Ultimately, we can state that multiple language skills are positively impacted by green language activities. To help with comprehension issues, support resources like glossaries, templates, and video prompts are advised.

Students also mentioned that videos, simulations, and online collaboration are examples of digital tools that are beneficial, especially for interactive learning and reading comprehension.

Students understand the importance of green language instruction, which promotes language learning, ecological consciousness, critical thinking, and cultural comprehension. Collaborative and project-based learning is very successful, especially for older and more advanced students. There are still issues with vocabulary, understanding technical concepts, and resource accessibility. The success of green language education is largely dependent on teacher readiness and instructional design. Multimedia, digital tools, and practical projects greatly improve learning and engagement. Practice suggestions include the use of interactive, project-based, multimedia-supported assignments with scaffolding for ecological terms and teacher professional development.

It is obvious from students' answers that practice, vocabulary building, and guided discussion activities lead to increased confidence. Using structured discussion tasks, role-plays, and debates can enhance language and ecological competence. Activities should be interactive and practical, such as debates, multimedia content, and real-world projects. Project-based learning appears to be highly motivating (Golubovschi & Mascaliuc, 2023).

Teachers should relate environmental topics to practical, everyday actions, encouraging personal initiatives, such as "no plastic day" and campus recycling, can boost intrinsic motivation.

While honing language skills, group projects, multicultural case studies, and cooperative discussions can improve cultural awareness. Comparing global perspectives on environmental issues improves intercultural and linguistic competency. Project-based and problem-solving exercises work well for

integrating cognitive abilities, ecological awareness, and language acquisition. Using real-world environmental issues, teachers can concentrate on tasks involving analysis, evaluation, and synthesis.

They can make use of multimedia to dynamically and visually represent environmental concepts. Online simulations, collaborative platforms, and video documentaries can enhance understanding and participation.

Based on the analysis of the two surveys and observations made during the lessons, we arrived at the following major conclusions:

- Workshops for professional development on incorporating sustainability into language instruction could be beneficial for teachers.
- Offering pre-made lesson plans, organized project guides, and eco-language exercises could improve the caliber of instruction.
- Teachers can use multimedia, create interesting, interactive tasks, simplify materials, and offer bilingual glossaries.

4. Curriculum design

To strengthen the integration of green education within university curricula, a redesigned curriculum framework is proposed, incorporating linguistically scaled sustainability modules across different proficiency levels:

• B1 level: Topics such as eco-friendly daily habits, focusing on modal verbs, basic argumentative structures, and functional vocabulary; • B2 level: Climate change debates and sustainable development goals, emphasising persuasive speaking, extended reading, and structured writing tasks; • C1 level: Academic discussions on green innovation and environmental policy, developing critical analysis, academic writing, and formal oral presentations.

Such modular integration ensures that sustainability content is aligned with students' linguistic competence and learning outcomes.

The primary rationale for initiating a revision of the university curriculum is the integration of topics on green education, sustainability, and ecological awareness. The "University Curriculum, GREEN EDUCATION for Future English Language Teachers Field 011: Educational Sciences", targets the following courses:

Cycle I (Bachelor's Program)

- English Language and Communication I: English Lexis
- English Language and Communication II
- Information and Communication Technologies
- English: Lexis and Communication III
- English: Lexis and Communication II: English Lexis
- Integration of Information Technologies into Teaching Practice
- Situational Study of English I
- Situational Study of English II
- Simulation of Problem-Based Situations in English I

- Simulation of Problem-Based Situations in English II

Cycle II (Master's Program)

- Study Program: English Language and Multicultural Education
- Contemporary English in Multicultural Contexts
- Interdisciplinary Approaches in English Language Studies
- Functional Grammar and Teaching Planning
- Methodology of Scientific Research
- Geoculture in the Anglophone World

To operationalise these findings, the research team has successfully designed and published the comprehensive university curriculum Green Education: For Pre-Service English Language Teachers (Laşcu et al., 2025a). This is accompanied by a practical resource, the Methodological Guide: Green Education (Laşcu et al., 2025b).

As we plan to pilot the integration of these modules across each course unit in March 2026, conclusions regarding results, outcomes, challenges, or successes will be formulated only after this implementation stage. The experimental phase will involve collaboration with five English language teachers, who will integrate the environmental modules into their teaching practices. They will use the guide and the tasks it contains with their students.

To ensure the curriculum is developmentally appropriate, as requested by the Scientific Committee, sustainability topics in these new resources are scaled according to the Common European Framework of Reference for Languages (CEFR). The following table illustrates how these modules are structured:

Table 4. Proposed linguistically scaled green modules (Pilot 2026)

Competence Level	Sustainability Topic	Linguistic Focus	Sample Activity (from Methodological Guide)
A2-B1 (Basic User)	Daily Habits & Recycling	Imperatives, Modal verbs (must/should)	Designing a "Green Rules" poster for the dormitory.
B2 (Independent User)	Eco-Tourism & Smart Cities	Future forms (prediction), Conditionals	Writing a review of an eco-friendly hotel.
C1 (Proficient User)	Global Policy & Ethics	Passive voice, Academic argumentation	Debating the economic impact of carbon taxes.

5. Elaboration of the „METHODODOLOGICAL GUIDE: Green Education”

In line with the objectives of the project, a key outcome was the development of a guide, entitled “METHODODOLOGICAL GUIDE: Green Education” (Laşcu et al., 2025b), which provides practical materials and tasks aimed at teaching sustainability to university-level students. The guide is designed

to be integrated across a range of syllabus courses, focusing specifically on the subjects and study units outlined in the discipline curriculum. This resource not only supports instructors in incorporating green education into their teaching practices but also promotes students' environmental awareness and competence in alignment with contemporary educational priorities.

Another outcome of the study was that, during the observation phase, the following teaching strategies emerged as particularly effective:

- Project-based learning on environmental issues.
- Collaborative debates in diverse groups to address sustainability issues.
- Use of online tools to simulate scenarios related to the environment and promote global collaboration.

The final stage of the project involves organising workshops and training sessions aimed at empowering language instructors with the knowledge and tools necessary to teach their students more effectively and successfully, thereby promoting environmentally conscious and sustainability-focused practices within higher education (planned for spring 2026).

Quantitative data were analysed using descriptive statistics and correlational evaluation, while qualitative data were thematically coded to identify successful instructional methods and implementation challenges.

Challenges with educator readiness and curriculum constraints highlight the importance of institutional assistance and programs for professional development. Including digital resources, such as online group discussions and interactive simulations, improves engagement among learners and interdisciplinary learning (Coyle et al., 2010).

The findings demonstrate that green language education is a successful strategy for increasing students' environmental competence while improving their language skills. Multidisciplinary methods and project-based tasks were especially effective at engaging students and encouraging critical thinking. Multicultural standpoints enriched classroom discussions, allowing students to examine ecological issues from various perspectives.

6. Limitations of the study

The study is exploratory in nature and subject to several limitations. The relatively small sample size restricts the generalisability of findings beyond the institutional context. Data were collected over a limited time span and relied partly on self-reported perceptions. Future studies involving larger samples and extended observation periods would strengthen empirical validity. Future research should adopt a longitudinal perspective to examine the long-term impact of green language education on students' professional practices and environmentally responsible behaviour beyond the academic context.

7. Conclusion

Green language education greatly enhances students' environmental competence and general holistic development. Important suggestions for higher education institutions involve integrating sustainability topics into language curricula. Instructors will receive professional development in green pedagogies, encouraging interdisciplinary collaboration among faculty, and using digital tools to increase engagement and global awareness. To validate the efficacy of the newly designed curriculum (Lașcu et al., 2025a), a longitudinal study is proposed for the 2026–2027 period. This follow-up research will track graduates into their first years of teaching to analyse their actual professional behaviour - specifically, the extent to which they independently integrate the green methodologies piloted in 2026 into their own classrooms.

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WarLang: AI-assisted linguistic tool for discourse analysis of war-related language

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Abstract: *This paper presents a study on the potential of large language models for the critical analysis of war-related discourse in media texts. It introduces the concept and design of the WarLang chatbot – an intelligent analytical tool based on generative artificial intelligence that functions as a linguistic discourse analyst. Through a case study involving a speech by Winston Churchill, the paper demonstrates WarLang’s ability to uncover ideological, metaphorical, and rhetorical strategies embedded in war discourse. An expert evaluation of the generated results is conducted, confirming the analytical precision of the chatbot. Finally, the educational potential of WarLang is outlined as a tool for teaching discourse analysis, critical reading, and media literacy in the humanities and social sciences.*

Keywords: War language, Discourse analysis, War-related discourse, Large language models, LLM, Generative artificial intelligence, GenAI.

1. Introduction

In recent years, military vocabulary has been used with increasing frequency and intensity in the public sphere. The language of war permeates the media in various contexts, including the description of social, political, and even economic processes. Subtly yet persistently, militaristic discourse influences public opinion and collective attitudes, establishing a conflict-oriented approach within the sphere of communication. Here, the concept of “discourse” is used in the sense established by Michel Foucault, namely discourse as a source of the social effects of power and, correspondingly, of symbolic violence (Foucault, 1972). It shapes a specific mode of thinking by constructing antagonistic representations of “us” and “them,” “we” and “the others,” thereby normalizing violence as an acceptable practice and affecting societal attitudes. The adoption of a systematic and analytical approach to the language of war – one that reveals its structures, meanings, and functions beyond the immediate content of texts – contributes to a deeper understanding and critical reflection on this phenomenon. Such an approach makes visible the mechanisms through which language constructs realities, legitimizes violence, and shapes collective representations and identities.

Discourse analysis provides precisely such a methodological framework. It views language not merely as a means of describing reality, but as an instrument that actively constructs and sustains it. In the context of war-related texts, discourse analysis enables the examination of lexical units, metaphorical models, semantic fields, and rhetorical strategies through which war is legitimized, heroized, or presented as inevitable. By analyzing context, ideological markers, and the functional load of linguistic units, it becomes possible to trace how images of the enemy are constructed, how collective identities are formed, and how specific actions are justified. In this way, discourse analysis emerges as a key tool for the critical understanding of contemporary conflicts at both linguistic and cognitive levels.

The role of this type of analysis is particularly important in the education of students in the humanities and social sciences. Engaging with war-related discourses supports the development of higher-order thinking skills. Rather than approaching texts passively, students are encouraged to identify implicit assumptions, manipulative strategies, and to evaluate the mechanisms through which influence over the reader is achieved. In this way, discourse analysis of the language of war not only contributes to the scholarly study of conflicts but also fulfills an important educational function by preparing students for critical and responsible participation in contemporary public discourse.

The emergence of large language models (LLMs) and generative artificial intelligence (GenAI) provides a new toolkit for linguistic analysis. LLMs enable the partial automation of discourse analysis of the language of war and allow it to be presented in a structured and practically applicable form. This paper presents the modeling of the WarLang chatbot for conducting discourse analysis, as well as an analysis of the results obtained from its operation.

2. State of the art

In recent months, an increasing number of studies have focused on the analysis of the language of war using artificial intelligence-based tools. Research in this area is relatively recent but is developing at a rapid pace, driven by advances in LLMs and GenAI. GenAI models are trained on vast text corpora, within which they learn statistical and probabilistic relationships among linguistic units. As a result, they are capable of identifying complex linguistic patterns, extracting semantic and pragmatic relations, and interpreting discursive structures across different contexts.

In (Jester, 2024), a virtual AI-driven chatbot named Charlie is presented, which simulates military veterans. The chatbot is equipped with a military ontology that contextually defines objects and actors falling within the scope of the concept of “war.” Through this ontology, the boundaries of war are delineated by reproducing various military narratives. Such chatbots may legitimize state-sanctioned interpretations of war and encourage indirect forms of militarism. In this way, representations of nationhood, gender, national and racial identity, among others, can be reproduced and reinforced.

Makhortykh and colleagues conduct an empirical study examining how LLM-powered chatbots developed by Google, Microsoft, and Perplexity address disinformation related to the Russia–Ukraine war (Makhortykh et al., 2024). The authors analyze the chatbots’ ability to provide accurate information on the topic across different languages and temporal contexts.

Paziuk and colleagues develop an LLM-based tool called Attack-Index to investigate the creation and dissemination of manipulative narratives in the context of cognitive warfare during the Russia–Ukraine conflict (Paziuk et al., 2025). They employ a mixed-methods approach that combines AI-generated semantic analysis with expert validation. The authors propose an integrated analytical framework that merges semantic clustering with AI-based discourse detection, enabling the identification and monitoring of information threats in real time.

Another study focusing on the ability of artificial intelligence to perform discourse analysis is presented in (Rubab, Ali & Khan, 2025). The authors examine media texts covering the Palestine–Israel and Russia–Ukraine military conflicts. They conduct a critical discourse analysis (CDA), including dimensions such as power and ideology, lexical choice and agency, silences and emphases, and recontextualization. The study finds that AI is capable of critically uncovering ideological patterns in media discourse, while at the same time reflecting biases embedded in dominant Western ideological frameworks.

Verbytska examines the representation of the Russia–Ukraine war in media discourses (Verbytska, 2024). She employs various natural language processing techniques, topic modeling using Latent Dirichlet Allocation (LDA), and the BERT language model to reveal how media organizations shape narratives through strategic framing. The identified frames are further analyzed through named entity recognition using roBERTa, sentiment analysis with distilBERT, and corpus-linguistic methods implemented with LancsBox X, followed by an interpretation of different nuances in narratives, public perceptions, and political decision-making against the backdrop of the ongoing war.

In (Lu, Chen & Wang, 2025), a study is presented on the attitudes and roles of international scientific organizations in the Russia–Ukraine conflict. A total of 923 official statements are analyzed using a combination of discourse analysis and natural language processing (NLP) techniques, including sentiment analysis and topic modeling. The findings indicate that these organizations play a strategic role in shaping discourse and international relations and exert significant influence during geopolitical crises.

Another study aimed at evaluating sentiment in United Nations speeches on the Russia–Ukraine conflict is presented in (Kertcher & Zwilling, 2025). The authors employ the VADER and BERT models and compare their effectiveness. They conduct sentiment analysis to uncover emotional aspects and narrative analysis to examine context and implications. The study identifies sentiments favoring global cooperation and Ukraine, challenging claims of a divide between the Global North and the Global South. The authors emphasize that political discourse shapes public opinion and international relations, and that its analysis provides valuable insights into global politics.

Other scholars conduct research using data from social and clickstream media. Mir & Sofi set out to examine and analyze sentiments and discussion topics related to the Russia–Ukraine war (Mir & Sofi, 2024). They employ Tweet Archiver and extract a total of 49,994 tweets for analysis, covering the period from August 30 to September 30, 2022. Data processing is carried out using Python and its libraries; BERTopic is used for topic analysis, while the VADER library is applied for sentiment analysis. The study identifies ten dominant topics around which discussions revolve. The most prevalent topic, with the highest number of tweets, is “NATO’s involvement in the Russia–Ukraine conflict,” followed by “Geopolitical tensions and energy policy in China, India, Russia, and Ukraine.” Sentiment analysis shows that most tweets are negative, with positive sentiments being least common, while many remain neutral toward the war.

Tretiakov et al. analyze over 23 million messages from 1,491 Telegram channels, focusing on key themes related to the Russia–Ukraine conflict and political tensions in Europe and the United States between 2016 and 2023 (Tretiakov et al., 2025). Their objective is to detect and measure toxicity in political content disseminated through Telegram channels. The study is conducted using a fine-tuned RoBERTa model. By combining data analysis, time-series analysis, and BERTopic modeling, the authors demonstrate how toxicity varies by topic, country, and time period.

Islam et al. analyze comments posted under YouTube videos published by major news outlets such as CNN, BBC, and others, with the aim of understanding public opinions about the war (Islam, Ferdusi & Aurpa, 2025). They use VADER to perform sentiment analysis and the BERT model to identify ten key war-related topics. Subsequently, the authors develop a model that combines BERT’s ability to capture contextual information with the strengths of convolutional neural networks (CNNs) for feature extraction. This hybrid model classifies sentiments with an accuracy of 92.26%, confirming the applicability of contemporary artificial intelligence technologies in both practical and scientific research.

The conducted review reveals a wide diversity of artificial intelligence algorithms, technologies, and tools that are employed in different ways to automate the processes of data extraction, processing, analysis, and investigation of various aspects of war-related discourse.

3. Chatbot WarLang – concept, design, and core functionalities

The understanding that language does not merely describe war, but also creates, justifies, and sustains it motivates the development of the WarLang chatbot. Its purpose is to support the critical interpretation of war-related discourse. The chatbot is designed as an intelligent tool that reveals how realities, ideologies, and emotional attitudes are constructed through language. It serves as a means through which users can understand how media, political actors, and cultural narratives shape our perception of war.

At its core, WarLang supports the interpretation of texts by combining contextual understanding of language through its social and cultural meanings with

the examination of different levels of language itself—primarily the semantic and pragmatic levels. WarLang aims to uncover hidden meanings, functions, and implicit messages within the context of militaristic rhetoric and to illuminate the mechanisms through which language becomes a weapon. Its **conceptual framework** is grounded in the methods of critical discourse analysis, cognitive linguistics, and military rhetoric.

The **design** of the chatbot is guided by the requirement to combine academic precision with functional clarity. Its visual and communicative logic follows the principles of a scientific instrument rather than those of a conventional conversational agent: it does not merely respond, but analyzes, classifies, and provides argumentation. Its linguistic style is academic, neutral, and analytical, which ensures objectivity when working with ideologically charged texts. The chatbot adopts a modular approach, whereby each step of the analysis constitutes a self-contained component that can be adapted to different types of data, such as media publications, speeches, and literary texts.

The visual and functional design adheres to the principles of transparency and traceability: users can clearly observe how the analysis is performed, which categories are applied, and on what basis conclusions are drawn. In this way, the chatbot conveys a sense of scientific reliability and analytical depth by combining linguistic expertise with technological precision.

The core **functionalities** of the chatbot are designed to provide a comprehensive and structured analysis of the language of war. It functions as a linguist and discourse analyst specialized in war-related language. The chatbot is configured to operate in an academic style – analytical, precise, and free from emotional evaluation. Its main functions include a step-by-step discourse analysis across eight dimensions:

1. **Context and Tone** – Identification of the overall context and the communicative purpose of the text (e.g., propaganda, testimony, patriotic narrative). Description of the tone and the ideological position of the speaking subject.
2. **Extraction of Lexical Units** – Identification of key lexical units related to war. This includes military terminology (weapons, combat actions, ranks, and structures), neologisms, slang, metaphors, and offensive or ideologically charged expressions.
3. **Semantic Classification** – Classification of lexical items into semantic groups, such as: Weapons and Technology; Combat Actions and Strategies; Emotions and Psychological States; Heroization and Victimhood; Images of the Enemy; Cities and Symbolic Places; Ideological Markers; and Others. A brief commentary is added to indicate which groups dominate and what this suggests about the discourse.
4. **Functional Analysis** – Analysis of the functions of these lexical units in a tabular format, focusing on: Evaluative Load (positive/negative connotations), Metaphoricity (literal or figurative usage), and Ideological Charge (nationalism, propaganda, legitimization).

5. **Thematic Lexicon** – Construction of a thematic lexicon organized by groups. For each word or expression, a brief explanation or contextual description of its use is provided.
6. **Metaphor Analysis** – For each metaphor, a determination is made as to whether it is conceptual (linked to deep cognitive models and frames) or thematic (situational and context-dependent). Metaphors are classified according to conceptual frameworks, such as “War as a Game,” “The Enemy as Disease/Monster,” “Home as a Fortress,” “Weapons as Saviors,” among others. An explanation is provided of how these metaphors shape the understanding of war.
7. **Discursive Strategies** – Description of the strategies employed for: legitimizing violence, constructing enemy images, and creating ideological narratives (e.g., demonization of the enemy, heroization of “one’s own” victimization of the people, moral justification of actions). The linguistic means through which these strategies are realized are identified.
8. **Genre Identification** – Identification of the genre of the text (e.g., dramatic, epic, lyrical, journalistic) and justification for its classification based on lexical choice, style, and rhetorical devices. Possible genre hybridity is also identified.

The model of the WarLang chatbot is presented schematically in Figure 1.

In order to select the language model to power the chatbot, multiple experiments were conducted with various models, including GPT-5, Claude-Haiku-4.5, Gemini-2.5-Pro, Grok-4, DeepSeek-v3.1, Perplexity-Sonar-Pro, among others. To perform a comparative analysis of these models’ ability to generate discourse analysis of the language of war, different LLMs were tested using the same prompt on identical texts. The results exhibited varying levels of analytical depth and precision. Some of these outputs are available for review, including GPT-5 (GPT-5, 2025), Claude-Haiku-4.5 (Claude-Haiku-4.5, 2025), Gemini-2.5-Pro (Gemini-2.5-Pro, 2025), Grok-4 (Grok-4, 2025), DeepSeek-v3.1 (DeepSeek-v3.1, 2025), and Perplexity-Sonar-Pro (Perplexity-Sonar-Pro, 2025). Based on the results obtained at the time of the experiment, GPT-5 was selected as the most suitable model.

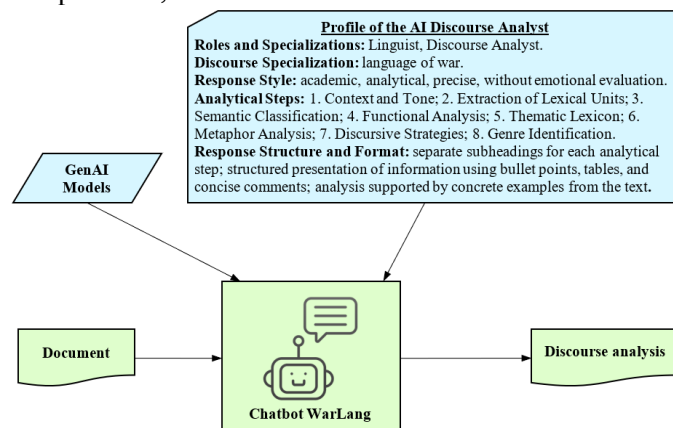


Figure 1. WarLang chatbot model.

The developed chatbot is available at: <https://poe.com/WarLang-EN> (WarLang-EN, 2025).

4. Use case

To illustrate the operation of the chatbot, we present a concrete example. A short text – “War Speech, 1939” (Churchill, 1939) – was selected. This is a speech by Winston Churchill delivered at the beginning of World War II. It is striking and rhetorically powerful, drawing on heroic models from the past – war in the name of peace, rights, freedom, and the dignity of ancestors. The speech aims at national mobilization and the rhetorical legitimization of war, making it a compelling object for examining language as an instrument of power and persuasion in a moment of global conflict. In addition, the text is lexically rich and highly metaphorical. The discourse analysis generated by the WarLang-EN chatbot is available at: <https://poe.com/s/YgujcavLexyrxb0SKXk7>. An excerpt is presented in Figure 2.

- Metaphors/symbolic frames:
 - Natural disaster/weather (“storms,” “gales,” “lashed,” “fury”); disease (“pestilence”); architecture/rock (“foundation,” “impregnable rocks”); light/progress (“sunlight”); body stature (“stature of man”); time/ancestry (“days of yore”).
 - Comment on dominance:
 - Ideological markers and metaphoric framing dominate over concrete military terminology, suggesting a discourse centered on moral legitimization, collective identity, and endurance rather than operational detail.

4. Functional Analysis (selected units)

Unit/expression	Example (citation)	Evaluative polarity	Metaphoricity	Ideological load
repeated efforts for peace	“our repeated efforts for peace”	Positive (self-valorizing)	Literal	Legitimization (just cause)
trial and tribulation	“trial and tribulation of modern war”	Negative adversity	Figurative (religious/legal)	Sacral-moral framing of endurance
storms of war	“Outside, the storms of war may blow”	Negative	Figurative (natural disaster)	Inevitability; collective endurance
pestilence of Nazi tyranny	“the pestilence of Nazi tyranny”	Strongly negative	Figurative (disease)	Demonization; just-war framing
comradeship and brotherhood	“whose comradeship and brotherhood are	Positive	Mixed literal/figurative	Social cohesion; national solidarity

Go to @WarLang-EN on Poe

→ Continue chat

New chat

Figure 2. Partial output of the discourse analysis generated by the WarLang chatbot

The discourse analysis produced by WarLang was subjected to a critical review by a domain expert (a philologist). Each step of the analysis was evaluated. The main findings are as follows:

1. **Context and Tone.** The chatbot is fully accurate in identifying the context (military-political) and the tone of the communicative situation (solemn). It also highlights traces of sermonic register due to the sublime resonance of the expressions “At this solemn hour” and “Our conscience is clear,” which can indeed be symbolically associated with the Eucharistic rite held on a Sunday and requiring complete spiritual purity from those who partake in communion. It correctly determines that the rhetoric operates in two registers – deliberative and epideictic (laudatory). The ideological position is presented as liberal-democratic, deriving its legitimacy through the suggestion of a civilizational mission. The evidence provided is fully relevant to the ideological stance of the speaker as identified by the chatbot.
2. **Extraction of Lexical Units.** The extraction and classification of lexical units is correct and appropriate, demonstrating that the chatbot identifies all relevant lexical items associated with war and militaristic rhetoric. The structure of the text is analyzed comprehensively and in depth. The chatbot captures all ideologically marked lexemes, as well as metaphorical and symbolic meanings consistent with the epideictic tone. No false units are found in the lexical extraction, which indicates precision in the chatbot’s handling of lexical items.
3. **Semantic Classification.** Semantic classification is performed consistently and multidimensionally, demonstrating contextual precision in interpreting polysemous words, as well as appropriately identifying ideologically charged images related to victimization and heroization. A key and important observation is the chatbot’s recognition of the metaphorical frameworks of discursive persuasion through moral legitimization and collective identity, rather than through literal designations of combat actions and weaponry. This indicates that lexical items are not extracted mechanically, but with sensitivity to their conceptual dimension.
4. **Functional Analysis.** The functional analysis, based on criteria such as emotional evaluation, metaphoricity, and ideological charge, adequately represents the expressions and lexical items employed in the rhetoric of democratic deliberation and praise. The extracted lexical units are more complex in nature, being presented as multi-word expressions and phrases, which is also indicative of the conceptual relevance of the analysis.
5. **Thematic Lexicon.** The thematic lexicon generated by the chatbot demonstrates interpretative and analytical precision. The selected lexical items are diverse while simultaneously reflecting the ideas and themes that are central to the discourse analysis of militaristic discourse. The

terms are supported by relevant textual citations and are conceptualized in light of the targeted ideological markers. The discursive sample is representative of the topic and, in this sense, functions as a viable model for the thematic grouping of lexical units.

6. **Metaphor Analysis.** In the metaphor analysis, the chatbot demonstrates a high level of critical and differentiated approach. It is exhaustive in identifying key conceptual and thematic metaphors. A particularly valuable extension in this regard is the presentation of the metarhetorical effect produced by each metaphor. Here, the chatbot offers key observations that may assist in uncovering hidden propaganda.
7. **Discursive Strategies.** All examples related to specific discursive strategies are appropriately selected and correspond well to the overall semantic and rhetorical effect of the speech. The analysis progresses from broader discursive units – such as enemy images, political justification, and ideological narratives – toward specific linguistic features associated with the use of tropes and figures that enhance the elocutionary function of the speech.
8. **Genre Identification.** With regard to genre identification, the chatbot performs flawlessly. It is important to note the usefulness of the proposed differentiation between a primary genre and hybrid subgenres associated with certain striking phrases in the speech that convey a sense of ritual solemnity and grand historical significance of the forthcoming event. The examination of genre heterogeneity within the text represents an important aspect of discourse analysis.

Overall, the discourse analysis is accurate and comprehensive, and it is logically well structured. It is presented in a clear and consistent academic style, with appropriate terminology. The analysis is distinguished by a high degree of precision in identifying and interpreting discursive strategies and ideological load.

5. Conclusion

The results of the study indicate that the developed chatbot can be successfully used to support and enhance the efficiency of linguistic analysis. The proposed model is flexible and can be easily configured and applied to other thematic areas of discourse analysis.

The study has several limitations inherent to the use of large language models. The interpretative framework is dependent on the data on which the employed GenAI model has been trained. For this reason, the chatbot cannot fully replace the contextual and cultural sensitivity of human analysis. An additional limitation stems from the demonstrative nature of the empirical material, which does not encompass the full genre and media diversity of war-related discourse, as well as from the limited scope of expert validation.

Nevertheless, WarLang offers significant benefits in an educational context. It can be used by instructors as a didactic tool for the illustrative demonstration of the stages of discourse analysis and in the preparation of teaching materials. For

students, the chatbot creates an environment for active learning in which they can experiment with different texts and develop their linguistic competencies.

Future research will involve the implementation of a targeted empirical experiment aimed at the systematic evaluation of the ability of generative artificial intelligence to perform discourse analysis. For this purpose, a corpus of texts representing different genres and types of war-related and militarized discourse will be compiled, on the basis of which discourse analyses will be generated using various generative models. The resulting analyses will then be subjected to expert evaluation through standardized survey instruments completed by specialists in linguistics and discourse studies. This approach will enable both quantitative and qualitative assessment of the analytical adequacy, interpretative depth, and methodological reliability of GenAI, as well as the identification of its strengths and limitations as a tool for scholarly and educational discourse analysis.

Acknowledgment

This research was funded by Burgas State University “Prof. Dr. Assen Zlatarov”, Project № NIH–524/2025 “The Language of War – Functional and Conceptual Approaches” and by the Research Fund of the University of Plovdiv “Paisii Hilendarski” Project № MUPD25-FMI-015 “School for ICT Innovations: AI Technologies for Educational Transformation”.

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Healthy habits, healthy minds? AI-based evidence on lifestyle effects on student success and stress

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Abstract: *Understanding how students' daily habits shape their academic outcomes and well-being has become increasingly important in digitally enhanced and virtual learning environments, where autonomy, self-regulation, and balanced routines are critical for success. In this study, machine learning and SHAP-based explainability were applied to explore how study time, sleep, extracurricular activities, social interaction, and physical exercise influence GPA and stress levels among university students. Results showed that while increased study hours improved performance, excessive workloads elevated stress, highlighting the importance of maintaining a balanced daily routine. These findings provide practical guidance for improving student support and designing healthier learning ecosystems in virtual and hybrid educational contexts. This work directly contributes to UN SDG 4 (Quality Education) by providing evidence-based insights to promote equitable and sustainable academic success in modern digital learning settings.*

Keywords: Higher education policy, Virtual learning, Student success, Stress prediction, Explainable AI, Student well-being, Quality education.

1. Introduction

Virtual and technology-driven learning environments have transformed higher education, offering flexibility and access while placing greater responsibility on students to manage their time, motivation, and well-being. As digital platforms become central to academic life, gaining insight into how daily behaviors influence academic success and stress has become crucial for both educators and policymakers. Understanding the connection between lifestyle patterns and performance can inform more supportive instructional designs, foster healthier academic cultures, and lead to targeted interventions that promote student well-being.

In this study, machine learning techniques were employed to predict Grade Point Average (GPA) and stress levels based on students' daily routines, and explainable AI, SHapley Additive exPlanations (SHAP), was applied to uncover how each habit shaped the outcomes. By identifying optimal ranges for study time, sleep, physical activity, social engagement, and extracurricular participation, the research highlights how balanced lifestyles can enhance academic success while preventing stress escalation. These insights are particularly relevant for virtual and hybrid learning environments, where student autonomy is high and structured

<https://doi.org/10.58503/icvl-v21y202649>

support can be limited. Moreover, the study contributes to UN SDG 4 (Quality Education) by providing data-informed recommendations to foster equitable, supportive, and holistic learning environments in digitally mediated education settings.

2. Literature review

The link between students' habits, lifestyles, and academic outcomes has been widely explored, revealing that daily behaviors significantly influence both performance and stress. Research on study habits shows that the quality of learning strategies is more influential than the total amount of study time. Active methods such as self-testing and elaboration predict higher exam scores, whereas distraction hinders results (Walck-Shannon et al., 2021). Similarly, motivation, a preference for visual learning, and memory recall are correlated with better academic achievement among medical students (Aljaffer et al., 2024).

Studies on lifestyle behaviors support this view, emphasizing the importance of sleep, diet, and regular physical activity. Regular routines and hygiene are associated with stronger performance, while overly strict eating patterns show no clear advantage (Zhang et al., 2025). Balanced sleep and diet also enhance academic performance, as indicated by GPA (Shafie et al., 2022; Mahfouz et al., 2024).

Evidence linking lifestyle and stress highlights that academic strain undermines well-being and learning (Pascoe et al., 2019). Poor diet, insufficient sleep, and inactivity increase anxiety and depression risks (Rahimi et al., 2024; AlHamlan et al., 2025). Physical activity consistently reduces stress levels, though standardized protocols remain lacking (Guerriero et al., 2025).

The COVID-19 pandemic intensified these effects. Online learning has been linked to the development of unhealthy routines and increased stress (Salazar-Granizo et al., 2024a, 2024b), with students reporting greater well-being in face-to-face learning environments. Overload and time imbalance were key stressors, mitigated through planning and emotional support (Pérez-Jorge et al., 2025). International students also showed convergent behavioral adaptations (Kulykovets et al., 2025).

Recent data-driven research identifies psychological and physiological predictors, particularly anxiety and sleep quality, as the most critical stress factors (de Filippis & Foysal, 2024). Collectively, these findings suggest that regular habits and active study methods enhance performance, while maintaining healthy sleep, nutrition, and exercise helps protect against stress. However, few studies model these effects jointly. The present work addresses this gap through an Explainable AI-based analysis of the dual impact of daily habits on student success and stress.

3. Methodology

3.1 Dataset and preprocessing

This study used a dataset consisting of 2,000 university students, each providing daily lifestyle information covering five key habits: hours spent studying, participating in extracurricular activities, sleeping, socializing, and engaging in physical exercise (Rogg, 2024). GPA served as an indicator of academic success, while stress was categorized into three levels (low, moderate, high) based on daily routines and behaviors.

The dataset was already complete and clean, with no missing or inconsistent values. Therefore, only minimal preparation was necessary before analysis. The main preprocessing step involved converting the stress categories into numerical labels (Low = 0, Moderate = 1, High = 2) so that machine learning models could process them effectively.

3.2 Machine learning models

To investigate the relationship between lifestyle habits and academic success and stress, three established machine learning methods were applied: Random Forest, Support Vector Machine (SVM), and Naive Bayes. These models were selected because they are commonly used for analyzing structured data and are known to work well in predicting academic outcomes. The models were trained separately for two tasks: predicting GPA and predicting stress levels as continuous measures. In the case of stress prediction, the stress level was modeled as a continuous value ranging between 0 and 2, allowing for continuous SHAP explainability analysis similar to that applied for GPA prediction. Standard training and evaluation procedures were followed to ensure fair and reliable comparison among the models.

3.3 SHAP-based explainability

After training the models, explainable AI techniques were applied to gain a better understanding of how each lifestyle factor influenced the predictions. SHAP was used to interpret the most successful model. This method provided clear and intuitive visual insights, illustrating how habits such as study time, sleep duration, or physical activity shaped the predicted GPA and stress levels. By offering transparent explanations, SHAP helped translate machine learning outcomes into practical, human-understandable guidance for educators, students, and well-being support teams.

4. Results

4.1 Machine Learning Results

Three machine learning models, Random Forest, Support Vector Machine (SVM), and Naive Bayes, were trained to predict both GPA and stress levels based

on students' lifestyle habits. The performance of each model was measured using Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE), as shown in Table 1.

Table 1. Comparison of performance metrics of different machine learning models for GPA and Stress-level prediction

		MAE	MAPE
GPA Prediction	Random Forest	0.1762	5.70%
	SVM (RBF)	0.1767	5.74%
	Naïve Bayes	0.1804	5.85%
Stress Level Prediction	Random Forest	0.0158	7.12%
	SVM (RBF)	0.1141	37.53%
	Naïve Bayes	0.1945	62.68%

The Random Forest model achieved the best results, with MAPE of 5.7% for GPA prediction and 7.12% for Stress level prediction. Because Random Forest showed the highest prediction accuracy, it was selected for further analysis using explainable AI techniques.

4.2 SHAP explainability results

To interpret how lifestyle habits affected academic performance, SHAP explainability was applied to the best-performing model. The goal was not only to predict GPA but also to show how each daily habit contributed to the prediction.

Figure 1, a SHAP beeswarm plot, displays how all student records influenced GPA predictions. Each dot represents a student. Dots on the right indicate habits associated with a higher predicted GPA, while dots on the left indicate lower predicted GPA. The vertical axis lists features in order of importance, with the most influential at the top. Dot colors show whether a student had a high (pink/red) or low (blue) value for that habit. For instance, pink dots far to the right for study hours indicate that higher study time increases predictions, whereas blue dots on the left show that low study time decreases GPA predictions.

Overall, study hours exerted the strongest and most consistent positive effect on GPA. Physical activity also contributed positively, though to a smaller extent. Sleep, social time, and extracurricular hours showed subtler influences, with most points clustered near the center, indicating modest but still meaningful effects.

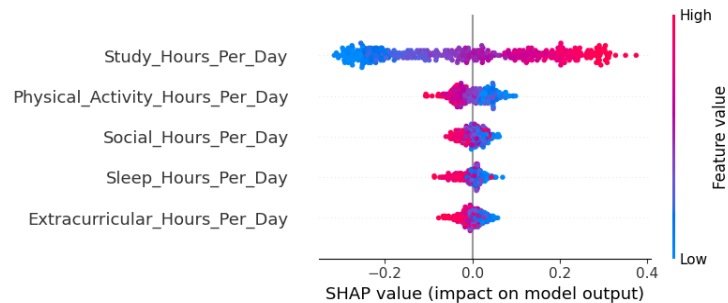


Figure 1. The SHAP Beeswarm plot explaining the factors contributing to student success (GPA)

For the stress prediction task, the SHAP results (Figure 2) show how daily habits influenced students' stress levels. As in the GPA model, each point in the beeswarm plot represents a student, illustrating whether their habits pushed stress predictions higher or lower. Higher SHAP values indicate factors contributing to increased stress, while lower values reflect stress-reducing effects.

Study hours were the most influential feature; however, unlike the GPA results, increased study time shifted SHAP values positively, indicating higher predicted stress. Students studying fewer hours showed lower stress predictions. Sleep was also a key determinant: longer sleep durations were associated with lower stress, whereas insufficient sleep clustered on the positive axis, indicating a heightened risk of stress, consistent with evidence linking sleep to emotional regulation.

Physical activity, social time, and extracurricular activities had smaller but noticeable effects. Engaging in more physical activity and spending more time socialising generally reduces stress. Extracurricular involvement displayed the weakest influence, indicating its impact is minor relative to study load and sleep.

Overall, the results show that intensive study and inadequate sleep most strongly increased predicted stress, while sufficient rest and regular physical activity support lower stress levels. These findings highlight a common trade-off: academic effort is vital, yet maintaining balanced routines and sleep is essential for managing stress effectively.

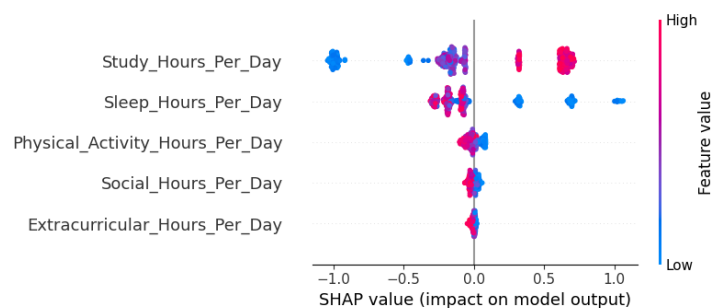


Figure 2. The SHAP Beeswarm plot explaining the factors contributing to stress levels

Before examining the SHAP dependence plots, it is important to recognize that even very small SHAP values matter. GPA and stress are not driven by a single habit; they result from the combined influence of many daily behaviors. Small positive or negative effects from each feature accumulate, ultimately shaping academic performance and well-being. The following plots highlight how each habit contributes when considered within the student's broader lifestyle.

Figure 3 illustrates the relationship between study hours per day and predictions for GPA (left) and stress (right). Each dot represents a student. The horizontal axis shows study hours, and the vertical axis shows the SHAP value (how much study time pushes the prediction up or down relative to the average). Higher dots indicate increased predictions (higher GPA on the left, higher stress on the right), while lower dots indicate decreased predictions. Vertical spread at the same study duration reflects differences in students' other habits, such as sleep or exercise.

For GPA, SHAP values increase steadily as study hours rise, indicating that more study time improves the predicted GPA. For stress, a threshold pattern emerges: up to about 6 hours/day, stress remains low or neutral, but beyond ~6 hours, values begin to increase, and beyond ~8 hours/day, they rise sharply, signaling high stress. In summary, more studying supports a higher GPA, but workloads exceeding 6–8 hours/day start to increase stress. Recognizing these patterns reflects the combined effect of all daily habits.

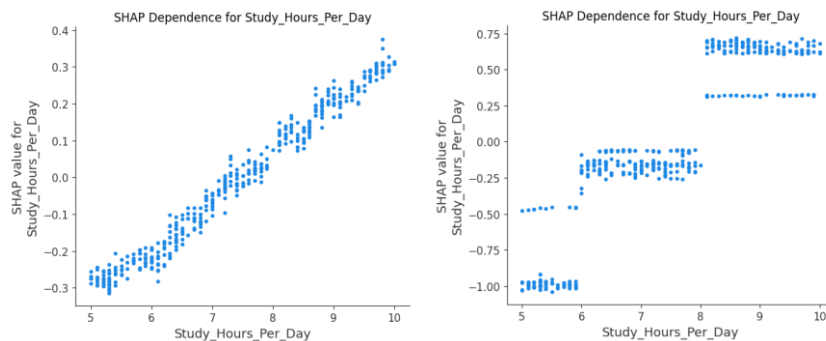


Figure 3. SHAP dependence plot explaining the effect of ‘study hours per day’ on GPA (left) and stress level (right)

Figure 4 illustrates how Extracurricular Hours per Day affect GPA (left) and stress (right). For GPA, the pattern is curved: increasing extracurricular time up to roughly 1.5 hours/day is associated with positive SHAP values, suggesting improved academic outcomes, likely due to structure, engagement, or skill-building. Beyond ~1.5 hours/day, SHAP values trend downward, indicating that heavier extracurricular loads may begin to reduce GPA, likely due to time trade-offs affecting study or rest.

For stress, the pattern shifts. Light involvement shows mixed effects, but after approximately 2 hours/day, SHAP values generally decrease, suggesting a stress-reducing effect (possibly due to physical activity, social interaction, or meaningful engagement) even though such levels may not support GPA.

In summary, moderate extracurricular participation (~1–1.5 hours/day) is associated with a higher predicted GPA, while broader involvement exceeding ~2 hours/day tends to reduce predicted stress.

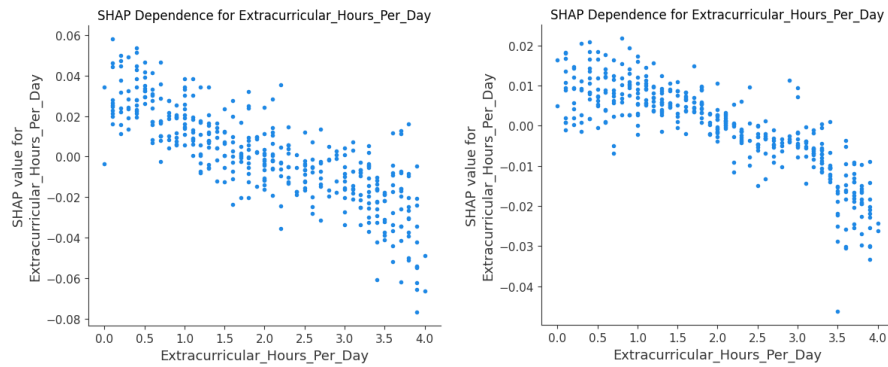


Figure 4. SHAP dependence plot explaining the effect of ‘extracurricular hours per day’ on GPA (left) and stress level (right)

Figure 5 shows how Sleep Hours per Day affect GPA (left) and stress (right). For GPA, a tipping pattern appears. As sleep increases from low levels to adequate rest, SHAP values rise, indicating a positive effect on GPA. Beyond approximately 8 hours/day, SHAP values decline, indicating that very long sleep predicts lower GPA, likely due to reduced study time or daytime engagement.

For stress, a clear lower-bound threshold exists. Sleeping for less than 6 hours/day produces high positive SHAP values, indicating sharply elevated stress. As sleep duration reaches 6–7 hours and beyond, SHAP values drop toward zero or become negative, indicating that adequate sleep reduces predicted stress.

In summary, adequate sleep supports learning and lowers stress, while very short sleep (<6 hours) strongly increases stress, and very long sleep (>8 hours) is associated with lower predicted GPA, recognizing that outcomes also depend on other daily habits.

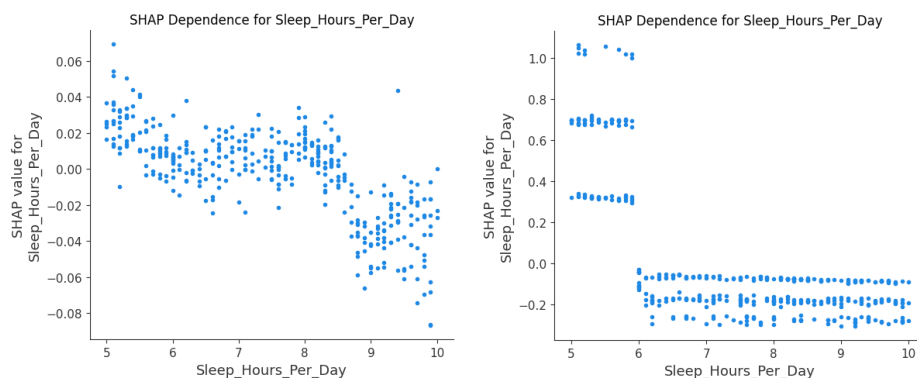


Figure 5. SHAP dependence plot explaining the effect of ‘sleep hours per day’ on GPA (left) and stress level (right)

Figure 6 illustrates how Social Hours per Day affect GPA (left) and stress (right). For GPA, a balanced pattern appears. Socializing up to about 1.5 hours/day generally corresponds to rising SHAP values, indicating a positive influence, likely due to emotional support, mental breaks, or improved time management. Beyond roughly 3.5 hours/day, SHAP values trend negatively, suggesting that excessive social time may reduce study or rest, thereby lowering the predicted GPA.

For stress, the pattern reflects the benefits of healthy social connections. Below ~2.5 hours/day, SHAP values trend upward, indicating higher predicted stress, which may be linked to isolation or academic pressure. Above ~2.5 hours/day, values decrease, indicating stress reduction through social support and relaxation.

Overall, moderate social engagement supports academic performance and well-being, while too much socializing may hinder GPA, and too little may increase stress.

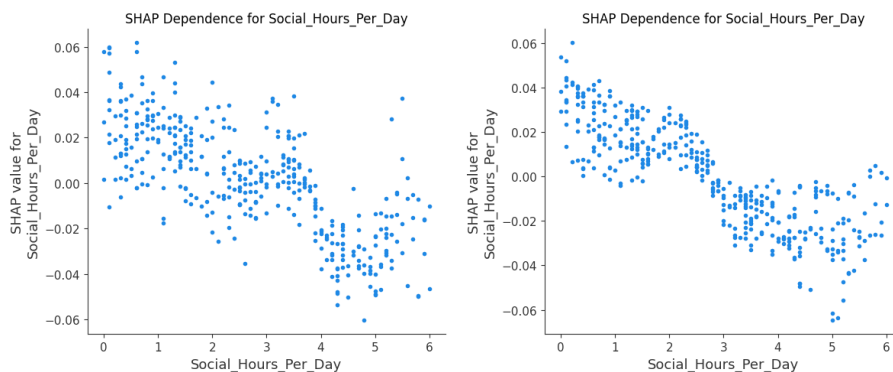


Figure 6. SHAP dependence plot explaining the effect of ‘social hours per day’ on GPA (left) and stress level (right)

Figure 7 shows how Physical Activity Hours per Day affect GPA (left) and stress (right). For GPA, physical activity appears beneficial up to about 2.5 hours/day. As exercise increases to this level, SHAP values rise, suggesting better predicted academic performance, likely due to improved focus, energy, and stress regulation. Beyond ~2.5 hours/day, SHAP values decline, indicating that excessive exercise may begin to compete with study time or recovery, reducing predicted GPA.

For stress, the effect is more pronounced. Students exercising more than roughly 2.5 hours/day generally show negative SHAP values, meaning lower predicted stress, consistent with established findings that sustained physical activity reduces stress through mood regulation, endorphin release, and improved sleep.

In summary, moderate daily exercise supports GPA and strongly reduces stress, while very high exercise levels may detract from academic performance.

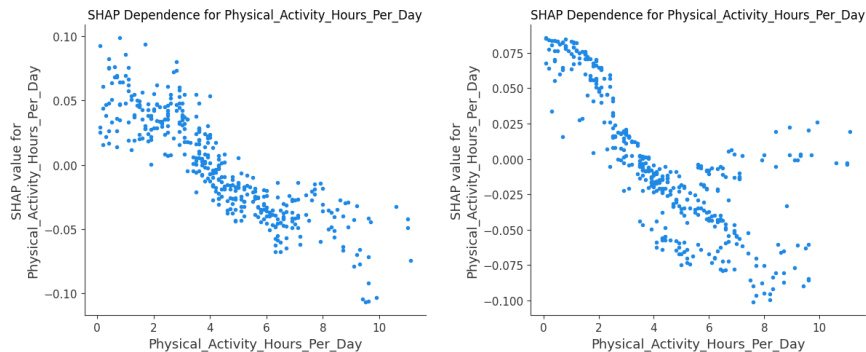


Figure 7. SHAP dependence plot explaining the effect of ‘physical activity hours per day’ on GPA (left) and stress level (right)

Altogether, the pattern suggests that moderate physical activity enhances academic performance, while higher amounts serve as a strong buffer against stress, though possibly at the expense of GPA if taken to an extreme. Maintaining a healthy balance of activities appears to support both academic and emotional well-being.

5. Discussion and implications

The results indicate that student success and stress are closely linked to everyday behavioral patterns. Study hours showed the strongest positive association with GPA, yet excessive study time beyond clear thresholds (particularly beyond six to eight hours) was tied to increased stress. Balanced levels of sleep, physical activity, social engagement, and extracurricular participation supported both performance and well-being, whereas extremes in any of these areas reduced the benefits. In particular, sleeping less than six hours was significantly associated with elevated stress, while prolonged sleep and very high exercise levels were associated with lower predicted academic outcomes. Overall, academic success appeared most sustainable when effort was complemented by rest, movement, and social connection, rather than being driven solely by intensity.

These insights are especially relevant in virtual learning environments, where independent study and self-regulated learning are prominent. Institutions can help students maintain healthy routines by designing balanced academic workloads, distributing assessments throughout the semester, and incorporating time-management and digital well-being guidance into online platforms. Virtual learning systems can integrate gentle nudges (such as reminders to take short breaks, maintain sleep routines, or log physical activity). At the same time, instructors can model balanced expectations by pacing content, offering structured social interaction opportunities, and encouraging brief movement breaks during long online sessions. Promoting virtual peer-learning groups and time-bounded online study circles may further support both success and mental health.

Taken together, the findings emphasize that maximizing academic effort alone does not guarantee optimal outcomes; instead, students thrive when learning

demands are balanced with restorative habits. Virtual and hybrid learning ecosystems that normalize healthy routines, provide structured engagement, and promote self-regulation are likely to enhance both academic performance and student well-being.

6. Conclusion

This study examined how everyday lifestyle habits influence students' academic performance and stress, emphasizing that achievement in higher education is shaped not by a single behavior but by the balanced interaction of study effort, rest, physical activity, and social connection. While increased study hours supported higher GPA outcomes, excessive workloads were associated with elevated stress, particularly when restorative behaviors such as adequate sleep or physical activity were limited. Moderate levels of sleep, movement, social engagement, and extracurricular participation contributed to better academic and emotional well-being, underscoring that sustainable success emerges from consistent balance rather than intensity alone.

These insights hold particular importance in virtual and digitally driven learning environments, where self-regulated learning, independent time management, and personal well-being practices play a central role. As students navigate remote coursework, online assessments, and flexible learning schedules, institutions should encourage healthy routines, integrate well-being guidance into digital platforms, and design virtual learning structures that promote both academic productivity and psychological resilience. For higher education policy-makers, this calls for embedding wellness and stress management modules into curricula, adopting workload policies that balance rigor with mental health, and supporting data-driven systems to monitor and assist students at risk. Collaboration between academic and student support units should be strengthened to ensure sustained academic success and well-being across digital and traditional settings.

By demonstrating the connection between lifestyle patterns and learning outcomes, this study offers actionable evidence for nurturing student-centred and supportive virtual learning ecosystems. Importantly, the work contributes to United Nations Sustainable Development Goal 4 (Quality Education) by advancing data-informed strategies that enhance learning experiences, promote equitable student success, and strengthen well-being, ensuring that digital and hybrid education environments support not only academic excellence but also healthy, resilient learners equipped for future challenges.

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Developing environmental awareness and digital competency through English language education

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Abstract: *Innovative educational paradigms that promote sustainability awareness and digital competency are required due to the rising urgency of environmental issues and the ubiquitous effect of digital technology. This paper investigates how environmental and digital aspects can be included in English language education to produce students who are proficient in the language, ecologically aware, and digitally competent. Moreover, it incorporates illustrative scenarios from the classroom, including interdisciplinary student projects, online debates, and digital sustainability initiatives. The paper offers educators a pedagogical framework for coordinating language education with global sustainability goals, establishing English language education as a tool for developing responsible, digitally empowered citizens prepared to tackle the ecological and technical challenges of the twenty-first century. The research used a mixed-method design that included observation notes and students' projects (digital posters, presentations, and reflective essays), a brief pre/post survey on students' self-perceived environmental awareness and digital competency. The study also covers potential difficulties such as curriculum design, teacher readiness, and ambiguous environmental content for learners with different skill levels. Findings demonstrate that the inclusion of environmental topics in English language education fosters learners' critical thinking, active learning and collaborative problem-solving. Consequently, the integration of interdisciplinary projects in the language education supports sustainable, digitally empowered citizenship by providing learners with skills to deal with the urgent environmental and technical issues of the twenty-first century.*

Keywords: Higher education, Digital pedagogy, Communicative language education, Content and Language Integrated Learning (CLIL), Education for sustainable development.

1. Introduction

The need for tackling environmental issues including pollution, biodiversity loss, and climate change has become more widely acknowledged in recent decades. The observable and palpable effects of these issues highlight the necessity for civilisation to produce environmentally educated individuals who can comprehend and resolve intricate ecological issues (UNESCO, 2020). This awareness is mostly fostered by education, which equips learners with the information, abilities, and mindsets needed to participate in sustainable activities and critically interact with environmental challenges (Tilbury, 2011).

<https://doi.org/10.58503/icvl-v21y202650>

Environmental education has always been regarded as a separate academic discipline. Nonetheless, recent studies emphasise the benefits of cross-curricular integration, which involves integrating environmental themes into language instruction as well as other disciplines (Ceprian & Junyent, 2015). There are two advantages of including environmental topics into English language instruction: it promotes critical engagement with global sustainability concerns while also aiding in the development of linguistic competence. Modern educational frameworks that emphasise transversal abilities like critical thinking, problem-solving, digital literacy, and global citizenship are in line with this integration (European Commission, 2024; Council of Europe, 2020).

There are still few thorough models that show how environmental education and digital learning can be integrated together into English language pedagogy, despite the fact that many studies have looked at these topics separately. The creation of cohesive solutions that link linguistic, digital, and ecological competencies is hampered by this lack.

This article uses a conceptual framework enhanced by real-world examples; it uses pedagogical illustration and theoretical synthesis to show the feasibility of an integrated approach. Based on the examination of educational models, EU policy documents, and actual classroom assignments, the methodology is qualitative and descriptive.

Thus, the study rethinks language education as a transformative process that fosters social engagement, digital empowerment, and environmental responsibility rather than just language instruction. The investigation is carried out within the research project *Integrating and promoting green education in the initial training of English language teachers*, strategic priorities: societal challenges, strategic direction: Innovative Educational Technologies and Products, with the code 25.80012.0807.56SE, which studies integrated approaches to green education in English language learning contexts.

In Higher Education settings in Eastern Europe like the Republic of Moldova, the incorporation of digital and environmental education into English language instruction is yet largely unexplored. Few empirical studies show how these principles may be operationalized in foreign language classrooms, despite European initiatives like the European Green Deal (2024) and the Digital Education Action Plan (2021-2027) calling for cross-curricular sustainability and digital skills. In order to close that gap, this study combines classroom experiment carried out in a Moldovan university context with theoretical viewpoints from communicative language teaching (CTL), content and language integrated learning (CLIL), and project- and problem-based learning (PBL). The research provides contextual evidence demonstrating that acquiring a language can enhance both digital skills and environmental awareness simultaneously.

According to recent studies, language learning is connected to both digital transformation in education (Godwin-Jones, 2022; Redecker, 2023) and sustainable (Goulah, 2021). Nevertheless, the majority of research looks at these areas independently. In Higher Education, particularly in English foreign language

programs in Central or Eastern Europe, few discuss their intersection. In order to achieve a digital-green integration paradigm in English language instruction, this study expands upon CLIL and sustainability-pedagogy frameworks. This paper aims to design a pedagogical sample that integrates environmental and digital competences into English language education in higher education settings.

2. Research methodology

The study investigates how students' environmental consciousness and digital competency in Higher Education might be improved by including sustainability-related content and digital tools into English language training. A small-scale exploratory research was conducted in the spring of 2025 at „Ion Creanga” State Pedagogical University of Chisinau, Republic of Moldova, to demonstrate the applicability of this integrated strategy. Fourteen second-year students from the English and French Language and Literature program participated in the study. The research used a mixed-methods design that included observation notes and students' projects (digital posters, presentations, and reflective essays), a brief pre/post survey on students' self-perceived environmental awareness and digital competency. Through project-based learning activities, the four-week intervention incorporated environmental themes – *sustainable cities*, *digital activism*, and *eco-lifestyles* into English classrooms. Every week, students used English to conduct research, have discussions, and create digital products on sustainability themes in accordance with CLIL principles. Qualitative data were categorized thematically to find recurrent patterns in students' reflections and observed behaviours.

The study was guided by the research questions:

- How much do students' environmental awareness levels increase when sustainability-related issues are incorporated into English language classes?
- In what ways does the use of digital tools in project-based English education help students become more digitally competent?
- How do students feel about learning English with technologically assisted, ecologically related assignments?
- The research questions developed the following hypotheses:
- Students' knowledge of the environment will rise dramatically when sustainability-related subjects are incorporated into English language instruction.
- Students' digital competency will be greatly improved by using digital technologies in English language projects.

The elaboration of educational activities, the choice of survey tools, and the ensuing examination of both quantitative (means and differences) and qualitative data (thematic analyses) were all influenced by these theories. All female students, aged 19-20, participated anonymously and the data were collected with the students' consent.

3. Theoretical background

3.1 Connection between digital and green skills in English language education

The rise of digital technology has created new opportunities for combining digital skills, ecological consciousness, and language learning. Interactive platforms, online collaborative projects, virtual classrooms, and gamified learning environments are examples of digital tools that can promote collaborative problem-solving, authentic communication, and access to global environmental content (European Commission, 2024). Teachers may train children to explore, evaluate, and convey complex information in a digital world by including digital competencies into language curriculum alongside environmental issues. This will promote sustainable digital citizenship.

Additionally, including environmental issues into English language teaching directly advances the strategic goals of the European Union, especially the European Green Deal, which aims to make Europe the first continent to achieve carbon neutrality by 2050 (European Commission, 2024). Students gain the critical thinking and communication abilities required to participate actively in sustainability issues through digitally enhanced language instruction. By encouraging green skills, environmental responsibility, and active engagement in social change, this approach enables language education to go beyond conventional learning results (UNESCO, 2020).

This makes English language instruction a strategic tool for developing students' language skills as well as their environmental awareness and digital literacy, which will help create a sustainable, climate-neutral future. One example of how multidisciplinary methods might meet the urgent educational and societal concerns of the twenty-first century is the integration of digital skills and environmental awareness into language instruction.

Several important theoretical underpinnings are used when integrating real-world concerns, such as environmental difficulties, into language education. In his research on second language acquisition, Krashen highlights that contextualised, meaningful language learning results in more significant language growth, which may be promoted by interacting with current world concerns like environmental sustainability.

Furthermore, Swain highlights the importance of the assignments that demonstrate genuine communication, which is a fundamental tenet of the EU's educational strategy (Swain, 2005).

Moreover, the development of environmental literacy is consistent with the EU's Education and Training 2030 framework, which emphasises lifelong learning and active citizenship. As a transversal ability, *environmental competence* is one of the key competences for lifelong learning, equipping students to critically engage with global issues like climate change in addition to being prepared to participate in the labour market (European Commission, 2024).

Through interactive learning environments, online collaboration platforms, and virtual classrooms, students may access real-world environmental knowledge, meaningfully express their ideas, and work together to solve problems across geographic borders. These resources aid in the growth of digital competency by enabling students to successfully engage in online communities, traverse situations that are rich in information, and critically assess sources (OECD, 2019; European Commission, 2024).

3.2. Pedagogical frameworks of CLIL, task-based, and project-based approaches

Problem-based learning enables students to actively address difficult environmental issues, utilising multidisciplinary knowledge and digital resources to create workable, sustainable solutions, while task- and content-based methodologies provide the foundation for meaningful language acquisition. An educational strategy known as *problem-based learning* puts students at the centre of their education by engaging them in the hands-on exploration and resolution of actual problems. Grounded in experiential learning and constructivist theory (Vygotsky, 1978), problem-based learning promotes the development of students' critical thinking and problem-solving skills.

Approaches like language teaching, task-based language teaching, and content and language integrated learning really encourage bringing environmental topics into English language classes.

Task-based language learning focuses on both language form and function by emphasising the use of real-world activities that mirror everyday circumstances.

Project-based learning, which adheres to the ideas of task-, content-, and problem-based methods, is a logical step towards education that is more independent and inquiry-driven. By involving students in lengthy, interdisciplinary projects with measurable results, it enhances the learning process.

Students that take part in initiatives like *actual environmental problems, such as waste reduction, the promotion of renewable energy, or biodiversity conservation*, develop a greater awareness of sustainability issues within the framework of green education. This experiential method turns the classroom into a creative and inquiry-based laboratory by encouraging students to create knowledge through action rather than passive absorption.

4. Pedagogical implications

It is equally important to promote green skills, such as environmental responsibility, sustainability literacy, and well-informed decision-making. Learners with green skills are better equipped to assess environmental issues, create long-term solutions, and behave responsibly in social, professional, and academic settings. When combined with language instruction, these abilities enable students to speak out about environmental concerns, support sustainable practices, and take

part in national and international campaigns, all of which encourage civic engagement and active citizenship.

The effect of digital and green abilities is increased when they work together. By making it easier to obtain current environmental data, enabling virtual cooperation, and assisting in the development of multimedia projects that convey sustainability themes, digital technologies help improve green abilities.

This combination promotes sustainable digital citizenship, where students are able to solve local and global issues with knowledge and are not just technologically proficient but also ecologically conscious.

As it gives students the opportunity to participate in problem-solving exercises based on actual problems, *task-based learning* works especially well for incorporating environmental themes. *Creating a sustainable city* is one example of such a challenge. Students collaborate in small groups to design a city plan that takes into account important environmental issues including *waste management, green areas, transportation, and energy systems*. Using online tools such as interactive simulations, articles, and digital maps, students first investigate sustainable urban design techniques. Then, using digital tools like Canva, Google Slides, or Mind Map, each group creates a picture of their city with a short description of it.

Content and language integrated learning, which builds on the ideas of task-based teaching, offers an additional way to incorporate environmental subjects while encouraging language learning and subject knowledge. Students may learn language through relevant subject matter, including conservation tactics, climate policy, or renewable energy, thanks to content-based training. For instance, reading English-language scientific publications, summarising the main conclusions, and producing a digital presentation might all be part of a *sustainable energy module*.

A *climate change campaign* effort serves as another example. Using information from a variety of academic fields, including science, economics, and social studies, students choose an environmental topic, such as pollution, climate change, or biodiversity loss, and undertake research in English. Students create an eco-friendly project, such as a recycling program, a campaign to raise awareness of renewable energy, or a local environmental project, using the data they have collected. They provide promotional materials, such as *brochures, posters, or postings on social media*, and they make a digital presentation that promotes their project.

By emphasising genuine conversation and meaningful engagement, incorporating environmental education also makes learning better.. *Role-plays, problem-solving conversations, and environmental debates* are all ways that communicative language teaching may be used.

Green and digital abilities work very well together. By facilitating virtual cooperation, giving access to up-to-date environmental data, and assisting in the production of digital material that successfully conveys sustainability messages, digital tools improve green abilities. In a risk-free, interactive setting, for instance, students may construct environmentally friendly metropolitan areas and apply sustainable practices by using virtual simulation platforms like SimCity or

Minecraft Education. In English, students record their creative process and results, share them with their peers, and consider how their choices may affect the environment.

Teachers may develop students' language skills, environmental awareness, and digital competency all at once by incorporating these ideas into their English lesson plans. Students gain the skills necessary to critically assess how human activity affects the environment, interact online, and communicate effectively about sustainability.

The sustainable agricultural initiative for local communities serves as a real-world illustration of problem-based learning in English classes. "*How can local communities adopt sustainable farming practices to improve food security and reduce environmental impact?*" is the real-world problem that students are given this assignment. Students start by choosing a particular area, such as *organic farming, water management, or soil conservation*, and talking about the significance of sustainable agriculture.

Students collaborate in groups to provide a workable solution for the topic area they have selected. For instance, they can suggest measures for encouraging *organic practices, soil restoration, or water conservation*. Using programmes like Google Slides, Canva, each group creates a digital presentation outlining the advantages, possible drawbacks, and interdisciplinary considerations of their approach. Students defend their ideas, answer questions from their peers, and participate in critical discourse throughout the presentation phase. They conclude by writing a reflective summary in English that examines their understanding of sustainable agriculture, the effects their solutions have on society and the environment, and the interdisciplinary knowledge they used.

As students read, write, and communicate in English throughout the project, this problem-based learning exercise enhances language competence while also fostering critical thinking, teamwork, and problem-solving abilities. While green skills are built as students apply sustainability concepts and assess environmental effects, digital skills are improved through internet research, digital content production, and multimedia presentations.

Other potential problem-based learning exercises include climate action campaigns, in which students create projects to lower carbon emissions or increase awareness of regional environmental issues, or sustainable city planning, in which students create environmentally friendly urban areas incorporating renewable energy, green transportation, and waste management techniques.

In order to investigate how technological innovation and digital culture support environmental sustainability, students work together to create and publish a digital class newspaper called *Eco-Digital Times: Technology for a Greener World*. The concept reflects the multidisciplinary aspect of contemporary education by combining language learning, environmental education, and digital competency.

For information gathering, students turn to reliable internet sources including TED Talks, websites with EU environmental policies, and blogs about recent sustainability. Among the various kinds of material they create are:

Example 1. News feature; Interview; Opinion article; Infographic; Student column.

Digital publishing platforms like Canva, Padlet, or Google Sites are used by each team to create, edit, and design their sites. While overseeing the process, the instructor places a strong emphasis on linguistic correctness as well as digital ethics including copyright, citation, and online communication. The project culminates with a classroom display or online publication where students showcase their digital newspapers and talk about the intersection of sustainability and technology in modern society.

Example 2. Green Documentary Project. For this project, students collaborate in small groups to create a brief documentary video about a regional environmental problem, such as waste management, energy efficiency, or waste pollution. The writing, interviews, and narration of their discoveries are all done in English. While practicing digital storytelling and video editing, students also improve their speaking, listening, and writing abilities. Peer learning and community involvement can be promoted by screening the finished documentaries at a school-sponsored “Eco Film Festival”.

Example 3. Designing a Green School Campaign. Students are expected to create a school-wide sustainability project, such as “green week”, an energy-saving campaign, or a recycling program. The instructor leads the class through the phases of stakeholder communication, project planning, and English persuasive messaging. They craft slogans, make banners, and publish information on social media to promote their campaign.

All things considered, project-based learning fosters interdisciplinary learning and ecological citizenship by placing English language instruction in a practical, socially relevant framework. Students are becoming active change agents who use language, technology, and teamwork to imagine and create sustainable futures rather than being passive consumers of knowledge.

5. Findings and discussions

The research included fourteen second-year undergraduate students in the English and French Language and Literature program. We examined qualitative information by coding the themes in the students' reflective essays, digital projects, and observational notes. We assessed the projects using rubrics that focused on language use, content accuracy, digital design, and ecological importance. We analyzed the survey findings by comparing pre- and post-means since the small sample size did not allow for inferential statistical analysis.

The results of the experiment demonstrate an increase in students' self-assessment of digital competency and environmental awareness. Three recurrent reflections emerged as a result of analysing data:

- When language activities dealt with actual ecological problems, students expressed greater interest;

- Students liked learning communicative sustainability themes using digital tools.

The results are illustrated in Table 1. The findings are consistent with the difficulties that students reported, such as a lack of technological resources and uneven confidence with online technologies.

Table 1. Modifications in Students' Digital Competency and Environmental Awareness (Pre- and Post-Intervention)

Competence	Pre-mean	Post-mean	Difference
Digital competency	3.1	4.0	+0.9
Environmental awareness	3.2	4.3	+1.1

(Scale 1-5; 1=low, 5=high)

Digital competency improved by +0.9, rising from a pre-intervention mean of 3.1 to 4.0. This implies that students' trust in using digital technology for educational reasons was much increased when digital tools were incorporated into language learning activities. Environmental awareness increased by +1.1, from 3.2 to 4.3, suggesting an even greater influence. The improvement shows how well environmental themes, such as eco-friendly communication and sustainable life-styles, may be used as linguistic content in English language learning assignments. The good growth in both categories shows that dual competence development can be promoted by incorporating digital literacy and sustainability topics into language education. The observed tendency supports the idea that contextualised, project-based learning promotes deeper engagement and skill acquisition. The results are positive, yet, the study is limited by the small number of participants and the short period of the experiment. Future research should take these facts into consideration.

A limitation of this research is that the questionnaire assessed students' self-reported environmental awareness and digital proficiency, rather than evaluating their knowledge or abilities through objective testing. While self-assessment tools are valuable for gauging shifts in motivation and attitudes, they do not fully represent actual knowledge or practical skills. Consequently, the findings should be understood as indications of heightened awareness and self-assurance, rather than as definitive proof of skill acquisition.

There are many potential and real-world difficulties in integrating digital competency and environmental consciousness into English language instruction. To effectively integrate digital and environmental issues into their courses, teachers might require specialized professional development. Developing digital pedagogical abilities, such as managing digital projects, utilizing online platforms for collaborative learning, and successfully integrating multimodal materials, is just as important as gaining environmental literacy. Differentiated teaching, careful curriculum scaffolding, and the selection of age-appropriate, contextually relevant resources are also necessary to adapt complex environmental ideas to learners'

varied language competence levels. Maintaining a pedagogical balance between communicative fluency, linguistic correctness, and environmental or digital learning outcomes – so that none of them overshadows the others – is another problem.

Notwithstanding these obstacles, incorporating digital and green competencies into English language instruction is a progressive strategy that is in line with current European educational frameworks and policies, including the Digital Education Action Plan (2021-2027), the European Green Deal (2024), and Education for Environmental Sustainability (UNESCO, 2023).

Teacher professional development is essential for the successful application of digital-green pedagogy. Teachers require training in environmental literacy and digital pedagogy. This includes the use of collaborative platforms, multimedia tools, and project-based assessment techniques. A modular professional development approach is suggested. This approach should incorporate (1) ecological content training, (2) digital tool proficiency, and (3) pedagogical integration workshops. These workshops would allow teachers to develop and test interdisciplinary tasks. This model promotes sustainable implementation and facilitates the scalability of the framework.

6. Conclusions

Teachers may create engaging learning experiences that link language practice to actual environmental and digital difficulties by utilizing the concepts of communicative language teaching, content and language integrated learning, and problem- and project-based approaches.

Besides, using digital tools can improve student engagement and promote multimodal literacy. Examples of these include data visualization software, digital storytelling programs, and online platforms for collaborative writing. Digital tools enable students to become content producers rather than just consumers by facilitating access to real environmental data and worldwide viewpoints. Students utilize English to debate, evaluate, and promote sustainable practices in digital arenas, transforming language courses into labs for active citizenship.

In the end, including digital and environmental topics into language instruction empowers students to be critical thinkers, effective communicators, and proactive changemakers both locally and internationally. By using such integrated techniques, education goes beyond its conventional bounds and equips students to interact with the complex ecological and technological realities of the twenty-first century in an ethical and knowledgeable manner in addition to learning a second language. This study has a great impact on some other researches from different fields proving how integrated language learning contributes to the increase of students' digital competence and environmental awareness.

It is suggested that self-perception evidence should be integrated with evidence of practice, specifically by use of standardized performance-based measures (atelier-specific, policy-oriented and appraisal-type) of digital competence, ecological literacy quizzes, and project work evaluated using rubrics.

The availability of such measures would permit stronger inferences about gains and facilitate between-context comparisons.

Although the results of this study explicitly show some increase in awareness and engagement, future research is warranted to determine whether awareness and engagement actually sustain behaviour change. An item here which could be added to a future research agenda is for longitudinal studies that monitor students' ecologies and digital practices beyond their participation on the course or project, including involvement with sustainability initiatives, digital activism and community 'action'. This type of research would offer further understanding on the lasting influence of language education as a catalyst for active citizenship.

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Models of knowledge representation applied in higher education

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Abstract: *A proper integration of knowledge in computer-based educational resources is essential for the efficiency of course teaching and student learning. In order to maintain the knowledge meaning in educational processes that are intermediated by computers it is necessary to choose a suitable way of representing knowledge. The paper presents an overview of knowledge representation models that are or can be applied in higher education. Also, it is presented a case study of representing knowledge for the course of Artificial Intelligence taught to Computer Science undergraduate students at Petroleum-Gas University of Ploiesti. The models that are discussed in the example are ontologies, knowledge graphs and procedural models. A synthesis of current trends in representing higher education knowledge is also included in the paper.*

Keywords: Knowledge representation model, Higher education, Ontologies, Knowledge graphs.

1. Introduction

Knowledge is the most important resource that is shared in educational processes. Each course that is taught to specific higher education specialization has its knowledge derived from books, textbooks, research articles, tutorials, other educational materials, and professor's experience. Also, each course has prerequisite knowledge that usually refer to courses that were studied by students in previous semesters or it refer to basic knowledge taught in school. Computer-based education requires efficient methods for representing knowledge so that it is kept the meaning and the teaching and learning processes are facilitated. There are several types of knowledge representation models starting from symbolic logic, procedural methods, structural methods and ending with large language models that started to be applied in education. An introduction on the subject of knowledge representation in artificial intelligence-based systems is presented in the textbook (Russell & Norvig, 2020). The models that are currently applied to knowledge representation are specific to artificial intelligence (AI) and linguistic.

The paper presents an overview on knowledge representation models focusing on those that were or can be applied in higher education. A case study of using knowledge representation models for the course of Artificial Intelligence

taught to Computer Science undergraduate students at Petroleum-Gas University of Ploiesti is discussed in detail. Finally, the current trends in representing higher education knowledge are highlighted.

2. Knowledge representation models

The main types of knowledge representation models (Russell & Norvig, 2020) are symbolic logic, procedural models, and structural models. Symbolic logic includes, usually, first order predicates logic and production rules. Procedural models refer to procedures and functions that represent knowledge. Structural models describe knowledge primarily as a structure with components and relations between them or as a detailed sequence of events that take place in a certain context. If uncertainty has to be included in knowledge representation there are several methods that can be used, as for example, fuzzy logic, uncertainty coefficients, probabilistic methods, and Bayesian Networks. These methods can be integrated in the knowledge representation models. An extensive analysis of various knowledge representation methods is given in the handbook (van Harmelen et al., 2008).

2.1 A taxonomy of knowledge representation models

The knowledge representation models can be classified in a hierarchy as shown in Figure 1. We have included some knowledge uncertainty representation models.

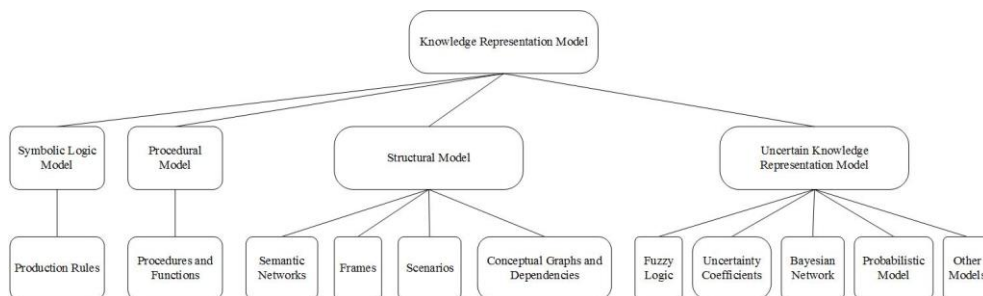


Figure 1. A classification of knowledge representation models

The symbolic logic model facilitates the representation of knowledge components and the relations between them usually, in terms of first order predicates or production rules, when it is a decision type knowledge that either derive new knowledge or executes a specific action.

A procedural model specifies step by step the instructions/actions that should be performed in sequence when knowledge is applied to solve a problem.

A structural model describes the structure of knowledge, its components and the relations between them either as a graph/network or as a prototyped form with slots and a specific program (a set of events). Examples of structural models, as they were reported in the literature, are: semantic networks (Quillian, 1967), frames

(Minsky, 1975), scenarios (Schank & Abelson, 1977), conceptual graphs (conceptual maps) and conceptual dependencies (Sowa, 2008). Most of the structural models are based on linguistic models. There are also models for representing uncertain knowledge such as fuzzy logic (Zadeh, 1965), uncertainty coefficients, Bayesian networks (Pearl, 1988), probabilistic models and other models (Russell & Norvig, 2020).

A semantic network is a graph with nodes representing concepts and arcs representing relations between concepts. The term of knowledge graphs was introduced in 2012 by Google and is similar to semantic networks. A frame is a model for representing a stereotype system with slots and facets. A scenario describes a sequence of events taking place in a specific context. Conceptual graphs and conceptual dependencies are linguistic models and they can be viewed as knowledge graphs (Serles & Fensel, 2024). Other models of knowledge representation include ontologies that conceptualize a specific domain of expertise (Staab & Studer, 2009) and large language models (Vaswani et al., 2017) specific to generative AI that use deep learning and the transformer architecture and are trained on massive text datasets generating answers to users in text format. A large language model (LLM) is a type of natural language processing model for writing and conversation.

In the next section it is presented a survey on knowledge representation models focusing on those that were applied in higher education or have the potential to be used in education. The articles were published in the period 2019-2026.

2.2 A survey of knowledge representation models for higher education

Several overviews on knowledge representation were presented in the literature in the last decade. A systematic review of the research work published in the period 1980-2017 with topics related to knowledge representation in educational environments is presented in (Buitrago & Chiappe, 2019). The authors selected 200 papers from three databases (Web of Science, Scopus and Scielo) and read in-depth 100 papers. One of the main conclusions was that the models that were most used for representing knowledge in educational environments are conceptual maps. Several types of educational activities were analysed as for example, learning assessment, problem solving, decision making, and learning styles analysis. Another literature review on the application of knowledge graphs in education is synthesized in (Rizun, 2019).

A case study of knowledge graphs use for databases course teaching activity is described in (Qin et al., 2020). Thus, a systematic teaching content was created with knowledge graphs, enabling an improvement of student learning quality.

The theory and practice of knowledge graphs focusing on recent trends is discussed in (Tiwari et al., 2021). Three types of knowledge graphs were analysed, general purpose KGs, expert KGs, and industrial KGs. In this research, a knowledge graph is a knowledge base represented in the graph. The main types of

KGs applications are: knowledge sharing, knowledge management, recommender system, knowledge management, dashboard, question-answering, dashboard and knowledge sharing.

An analysis of learners' knowledge representation modelled as cognitive networks is reported in (Siew, 2022). By using learning analytics on data related to educational practice of student's new knowledge is derived for adaptive learning.

An example of applying knowledge graphs in higher education of art and design is given in (Fan et al., 2024). The research work focused on applying knowledge graphs for curriculum design, student learning (providing personalized learning paths), teaching activity (providing innovative teaching methods), and assessment activity (including multi-dimensional assessment). The study revealed an improvement of students' abilities facilitated by knowledge graphs use.

A knowledge graph-based model for personalized educational and career recommendations simplifying the adaptation of university educational programs to the requirements of employers is introduced in (Ramazanov et al., 2024). The knowledge graphs are used to aggregate and analyse a variety of data related to university courses, skills, and job vacancies. Multilingual semantic similarity algorithms were applied for matching skills in educational programs and specific courses with skills necessary for job vacancies.

A methodology for educational knowledge graphs construction assisted by AI is presented in (Aytekin & Saygin, 2024). The ACE methodology combines machine learning (ML) techniques with expert knowledge and provides paths that students can follow in the learning activity.

An application of knowledge graphs and LLMs for the identification of core concepts included in educational resources is described in (Reales et al., 2024). The authors provided three solutions that build knowledge graphs from lecture transcripts by using LLMs and ontologies.

A new approach for representing curriculum in higher education is presented in (Piriyapongpipat et al., 2024). In order to provide a flexible and responsive curriculum, the authors proposed the extraction of basic knowledge (such as skills) from external source data into an ontology. Examples of using the proposed approach for courses in Computer Science domain are given.

A systematic review on LLMs use in smart education is reported in (Xu et al., 2024). The research work focuses on current technologies, challenges and future developments for personalized assessment in a smart educational environment.

A recent survey on using large language models in knowledge representation learning is presented in (Wang et al., 2025a) emphasizing the improvement of student learning ability.

A combination of three knowledge representation models, LLM, knowledge graphs and ontologies are discussed in (Kim et al., 2025). The authors introduced KONDA, a tool based on LLM for semantic annotation and creation of knowledge graphs with ontologies that was applied to research data.

Another research work that applied knowledge graphs to interdisciplinary higher education is presented (Wang et al., 2025b). Basically, interdisciplinary tools were developed for the construction of interdisciplinary knowledge graphs used for student learning in engineering management.

An example of using LLMs as teacher' assistants for teaching plans preparation is given in (Hu et al., 2025). A simulation of teacher-student interaction is presented, for the High School of Mathematics. LLMs were chosen for the enhancement of teaching plans quality.

A semantic model, an ontology, SmartLearningOnto, modelling various aspects of a smart learning environment in a smart campus is proposed in (Nagowah et al., 2025). The main goal of this ontology is to provide semantic interoperability facilitating data exchange between the systems included in an IoT-enabled smart campus as e.g. e-learning, smart library, smart classroom. Moreover, the ontology infers new knowledge that improve the student learning experience.

Another recent systematic review on LLMs use in educational environments (e.g. in Intelligent Tutoring Systems) is reported in (Shi et al., 2026). The period that was analysed is November 2022 - March 2025. The review revealed that most of the studies were performed in Asia, commonly for the domain of Computer and Technology.

The survey that was performed on articles published in the period 2019-2026 showed that knowledge graphs are most used knowledge representation model. Ontologies are also used in education and the current trends are related to the integration of LLMs and explainable AI. An example is given by a framework XAI-ED that includes explainable AI in education and is described in (Khosravi et al., 2022). A final remark is that conceptual graphs/maps, and semantic networks are basically knowledge graphs, being usually considered as synonym terms.

3. Case study

As a case study it is considered the discipline Artificial Intelligence that is taught at Petroleum-Gas University of Ploiesti to undergraduate students from the Computer Science specialization in the fourth year of study that has as educational activities, course teaching, laboratory and project. We have designed and implemented in Protégé (<https://protege.stanford.edu>) an OWL ontology named Onto-AI for Artificial Intelligence course teaching and student learning starting from the learning objectives that were established at the beginning of discipline planning.

The use of knowledge representation models for the following types of activities were analysed: discipline planning, course teaching and student learning.

3.1 Discipline planning

When planning the subjects covered by the Artificial Intelligence discipline several issues must be considering, as for example, the learning objectives, the

prerequisite knowledge, the order of course subjects and their synchronization with the laboratory activity and the project activity. Figure 2 shows a general knowledge graph related to AI discipline planning.

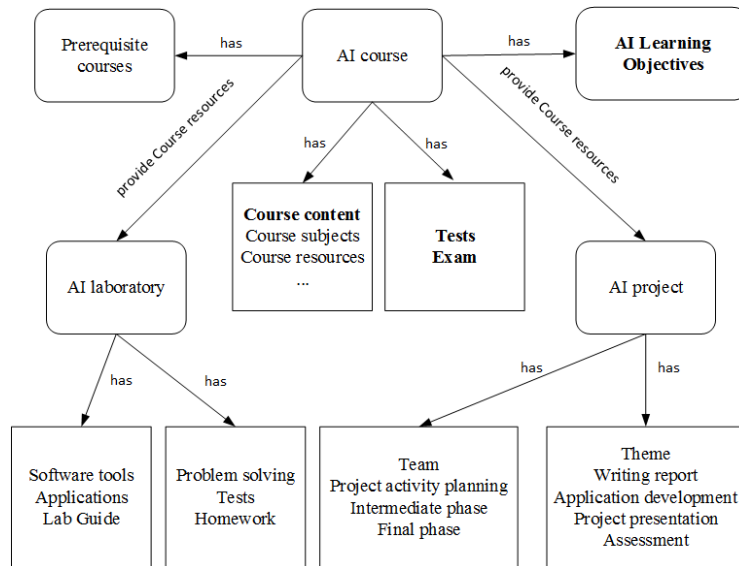


Figure 2. A general knowledge graph for AI discipline planning

Figure 3 presents the list of prerequisite courses as well as the main subjects covered by AI course and a list of general themes for AI project.

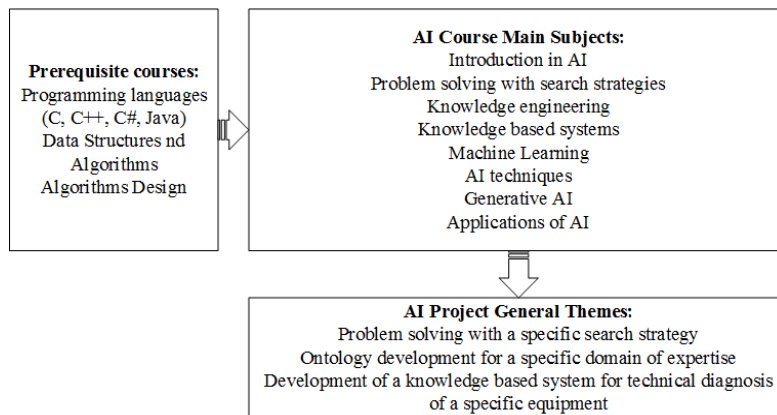


Figure 3. List of prerequisite courses, AI course subjects and the list of general themes for AI project

As the AI project has two phases, an intermediate one that refers to the design of the solution adopted for the project theme (i.e. solution design), and the final one that refers to the solution implementation and project report writing, the planning of the course main subjects that are necessary for the AI project was made so that the theory is taught before finalizing the intermediate phase.

3.2 Course teaching and student learning

A conceptualization of the AI course subjects was made under the form of an OWL ontology, *Onto-AI*, implemented in Protégé. The main concepts (implemented as classes in Protégé) were identified and defined for each course subject according to the AI course learning objectives. Next, the attributes and characteristics that are needed were defined as *DataProperties* and the relations between concepts were defined as *ObjectProperties*. Figure 4 shows a part of concepts hierarchy and Figure 5 shows a selection of *DataProperties* and *ObjectProperties*.

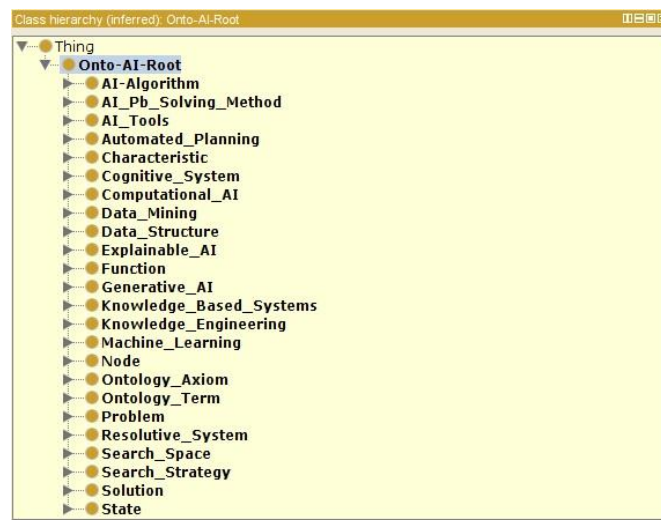


Figure 4. *Onto-AI* ontology concepts hierarchy in Protégé (selected classes)

We have included in the *Onto-AI* ontology some basic concepts that are needed by specific AI course subjects, as for example, the concepts of **State**, **Node**, **Solution**, **Search_Space** that are necessary for the subject of *Problem solving with search strategies*.

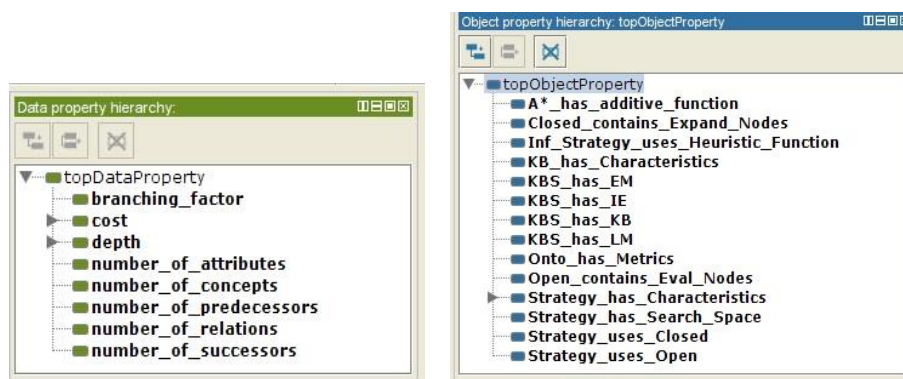


Figure 5. *Onto-AI* ontology selected *DataProperties* and *ObjectProperties* in Protégé

Examples of attributes that were needed for the definition of concepts from the *Problem solving with search strategies* subject are **branching_factor** for the **Search_Space**, **depth** and **cost** for the problem solution.

The knowledge provided by the Onto-AI ontology can be visualized as knowledge graphs with different visualization tools (e.g. OWL Viz for taxonomies, OntoGraph or GraphViz). These knowledge graphs are used for course teaching and for student learning with the goal of improving the educational processes related to the Artificial Intelligence discipline. Examples of taxonomies and knowledge graphs are given as follows.

Some basic knowledge resources that are used for teaching and learning the subject of *Problem solving with search strategies* are given in Figure 6. We have included a taxonomy for search strategies and a knowledge graph for the definition of Open and Closed lists that are used by the algorithm of the search strategy. A procedural model is used to represent the search strategy' algorithm (e.g. the A* algorithm).

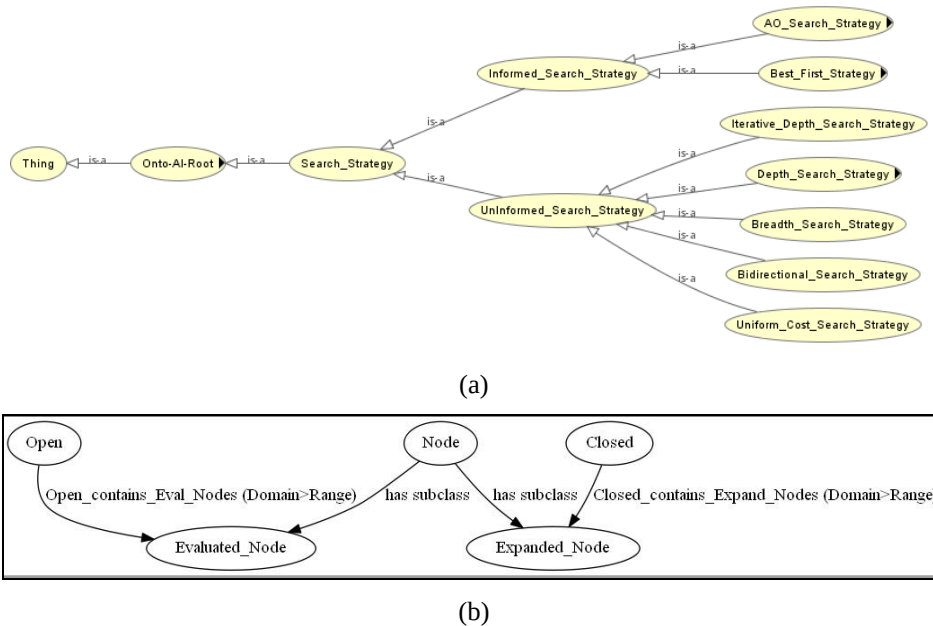
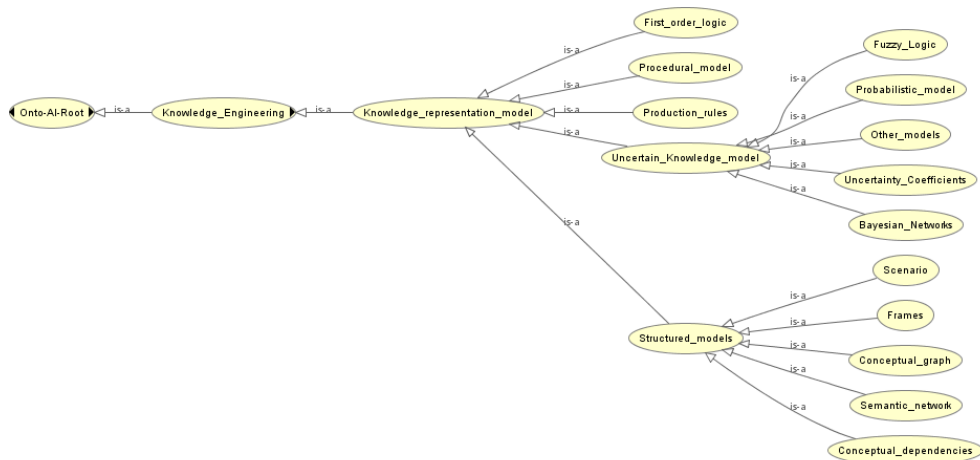


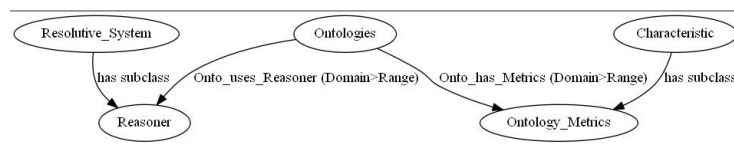
Figure 6. (a) A taxonomy for search strategies (in OWL Viz); (b) A knowledge graph for defining the lists Open and Closed used by search strategies (in GraphViz)

Three basic knowledge resources that are used for teaching and learning the subject of *Knowledge engineering* are shown in Figure 7. We have included a taxonomy for knowledge representation models used in AI and two knowledge graphs related to ontologies (specifying the resolutive system, the ontology evaluation metrics and the ontology terms).

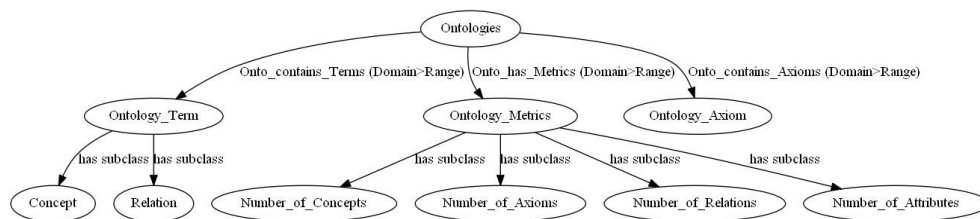
A knowledge graph that is used for teaching and learning the subject of *Knowledge based systems* is presented in Figure 8, including the components of a knowledge based system and the characteristics of a knowledge base.



(a)



(b)



(c)

Figure 7. (a) A taxonomy for knowledge representation models (in OWL Viz); (b) A knowledge graph related to ontologies, a resolvable system, and performance evaluation (in GraphViz); (c) A knowledge graph for defining ontologies and specifying some metrics (in GraphViz).

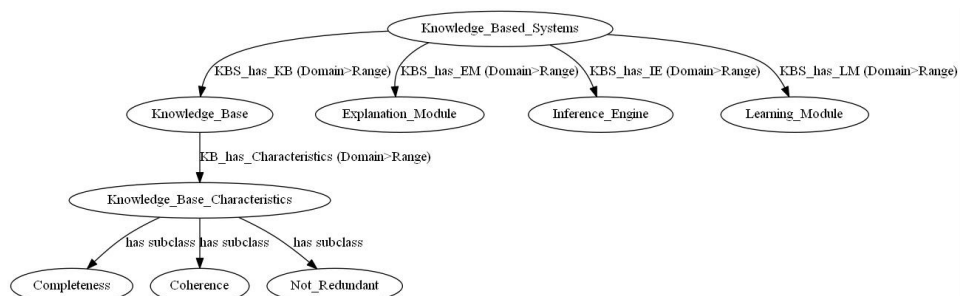


Figure 8. A knowledge graph related to knowledge based systems subject (in GraphViz)

The rule-based system reasoning algorithm is described as a procedural model.

A taxonomy that shows the software tools used to implement applications either at AI laboratory or AI project is presented in Figure 9.

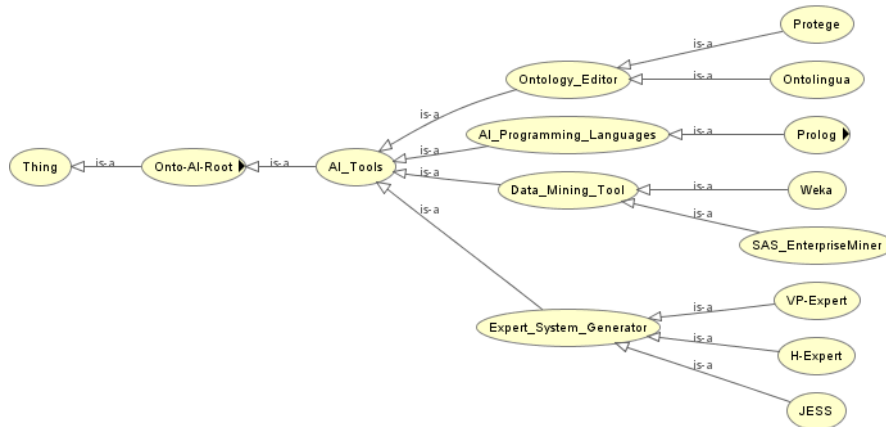


Figure 9. The taxonomy of AI tools included in the Onto-AI ontology (in OWL Viz)

In our case study, the inconsistencies of knowledge graphs were detected and solved by human experts (i.e. teachers) with the aid of Reasoner, the inference engine of Protégé.

So far, we have tested the Onto-AI ontology on a group of students during their fourth year of study at the AI project and AI laboratory work. The preliminary analysis revealed better marks at AI laboratory work assessment for those students that had chosen a topic on ontologies at the AI project, based on Onto-AI than those that had chosen a different topic (e.g. knowledge based systems) and did not use Onto-AI.

4. Conclusions and future work

Knowledge representation in computer-based educational systems is essential for increasing the efficiency of teaching and learning processes. The paper presented an overview on knowledge representation models that are or can be applied in higher education and described a case study of applying some models for the course of Artificial Intelligence taught to Computer Science undergraduate students at Petroleum-Gas University of Ploiesti. An OWL ontology, Onto-AI, was designed and implemented for this course, and examples of taxonomies and knowledge graphs were presented for specific AI course subjects. Procedural models were used for representing knowledge referring to algorithms such as BestFirst, A* or rule-based system reasoning.

The methodology followed in our research work can be applied to non-technical domains, as e.g. for a foreign language that students learn. The teacher can use knowledge graphs to explain the grammar of the language.

Despite of some problems that knowledge graphs can have (e.g. insufficient data, less explainability, incomplete, incorrect, or inconsistencies) they are an important educational visual resource that can improve the teaching and learning efficiency when more explanations are added and enough validated datasets are collected. Current trends include an extensive use of educational ontologies, knowledge graphs and large language models in higher education systems.

As a future work we shall extend the analysis of students' performance improvement when using the ontology and knowledge graphs for more groups of students that study the Artificial Intelligence discipline, from different specializations.

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Changing education amid technology disruption: Students' experiences, challenges, and coping strategies in mathematics learning

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Abstract: *This study explored the challenges, coping mechanisms, and learning experiences of secondary students during the abrupt shift to alternative learning modalities in Baganga, Davao Oriental, amid technology-driven disruptions. Using a qualitative phenomenological approach, five students were purposively selected for in-depth interviews, and data were systematically coded and analyzed according to the research questions. Findings revealed that students faced limited access to devices, unstable internet connectivity, absence of face-to-face teacher guidance, and difficulty following home learning plans. To cope, they employed strategies such as seeking assistance from peers and family, creating structured home learning setups, and borrowing learning resources. Students' experiences highlighted the importance of autonomy, time management, and self-directed learning, demonstrating their adaptability in navigating disruptions. Assessment practices such as feedback provision, supplemental video lessons, and performance-based tasks further supported their continued learning. These results underscore that student-centered learning can persist despite technology disruptions, emphasizing the need for instructional designs that balance digital tools with structured guidance. The study offers practical insights for fostering resilient, autonomous, and future-ready learners in the digital era.*

Keywords: Digital adaptation, Remote learning challenges, Self-directed learning, Student-centered learning, Technology disruption.

1. Introduction

The COVID-19 pandemic has significantly disrupted education worldwide, forcing schools to close and shifting learning from traditional classrooms to remote and modular modalities (UNESCO, 2020). In response, the Department of Education implemented the Basic Education Learning Continuity Plan (BE-LCP) for the 2020–2021 school year, which included alternative learning methods such as modular instruction, television- and radio-based lessons, blended learning, and online platforms (DepEd Order No. 12, 2020). The curriculum was decongested to focus on the Most Essential Learning Competencies (MELCs), promoting 21st-century skills such as collaboration, critical thinking, creativity, and

communication. This abrupt shift in instructional delivery transformed students' roles in the learning process, requiring them to become more autonomous and self-directed, while navigating new pedagogical approaches that are challenging to implement outside the traditional classroom setting (Lichoro, 2015).

Mathematics instruction, already considered a challenging subject, became even more demanding in remote or modular contexts. Students faced heightened math anxiety compounded by broader pandemic-related stress, limited access to digital devices, unreliable internet connectivity, and the absence of in-person teacher support (Sawchuk & Sparks, 2020). Parents, often unprepared to assist with mathematics learning, became essential facilitators in students' home learning environments. These challenges required students to develop coping mechanisms such as creating structured study routines, seeking help from peers or family, and leveraging available learning resources to sustain their academic performance.

This study explores the lived experiences of secondary mathematics students as they navigated these disruptions, focusing on the challenges they encountered, the strategies they employed to cope, and the insights they gained from their experiences. By examining students' adaptation to alternative learning modalities and assessment practices, the research aims to highlight effective self-directed learning strategies and provide evidence for designing resilient, student-centered instructional approaches. Understanding these experiences contributes to the broader discourse on changing education in the era of technology disruption, offering insights for future interventions that promote inclusive, flexible, and technology-driven learning.

2. Methods

This study used a descriptive phenomenological approach to explore the lived experiences of secondary mathematics students in Baganga, Davao Oriental during the abrupt shift to alternative learning modalities. Baganga is largely rural municipality of the Davao Oriental with limited internet infrastructure, so many students relied on paper modules, radio, or intermittent online classes. In keeping with phenomenological tradition, the study prioritized rich, in-depth narratives rather than a large sample size. Phenomenology is appropriate when the goal is to understand how individuals make sense of a shared experience, emphasizing depth and meaning rather than statistical generalization (Creswell, 2013; Giorgi, 2009).

2.1 Participants and sampling

Participants were selected through purposive sampling, consistent with phenomenological research that prioritizes depth of lived experiences over representativeness (Creswell, 2013; Polkinghorne, 1989). The inclusion criteria were as follows: 1) students were officially enrolled in secondary mathematics during implementation of alternative modes; 2) they resided in geographically dispersed barangays of Baganga, Davao Oriental, characterized by varying levels of internet connectivity and access to digital devices; 3) they actively participated

in modular, blended, or intermittent online learning modalities for at least one academic quarter; and 4) they were willing and able to articulate their learning experiences thru in-depth interviews.

To ensure variation in perspectives, participants were drawn from five (5) different public secondary schools, allowing study to capture diverse contextual realities within the same rural municipality. Students with limited exposure to alternative learning modalities or inconsistent participation during the study period were excluded. This selection process ensured that participants possessed sufficient experiential engagement with technology-mediated learning disruptions, thereby strengthening the credibility and richness of the data.

Although the sample size was small ($n = 5$), this is consistent with established phenomenological research standards. Scholars emphasize that phenomenological studies commonly involve small samples, often ranging from 3 to 25 participants, as the objective is to obtain rich, detailed accounts of lived experiences rather than broad generalizability (Creswell, 2013; Pokinghorne, 1989; Vagle, 2018). Data collection and analysis were conducted iteratively until thematic saturation was reached, indicating that no substantially new meanings or themes were emerging from the interviews (Guest, Bunce & Johnson, 2006).

2.2 Data collection

Data was collected through semi-structured, in-depth interviews conducted at a mutually agreed time and location. Participants were informed of the study's purpose, procedures, potential risks, and confidentiality measures prior to participation, and informed consent was obtained. Interviews were audio-recorded with permission, transcribed verbatim, and returned to participants for verification to ensure accuracy. Interview questions encouraged students to describe their challenges, coping strategies, learning insights, and experiences with assessment practices during the alternative learning setup.

2.3 Data analysis

The transcribed data were analyzed using Colaizzi's descriptive phenomenological method, which involves identifying significant statements, formulating meanings, clustering themes, and developing an exhaustive description of the phenomenon (Colaizzi, 1978). This systematic process allowed the researcher to capture both shared patterns and nuanced individual experiences. Reflexive journaling and peer debriefing were employed throughout the analysis to minimize researcher bias and enhance analytical rigor.

2.4 Trustworthiness and transferability

Trustworthiness was ensured through strategies addressing credibility, dependability, confirmability, and transferability (Lincoln & Guba, 1985). Credibility was established through member checking and peer review, while an audit trail supported dependability and confirmability. Although the findings are

context-specific, transferability was addressed through rich, thick descriptions of participants' contexts, learning conditions, and experiences. These detailed accounts enable readers to similar rural, low resource, or technology-constrained educational settings beyond Baganga, Davao Oriental (Lincoln & Guba, 1985; Creswell, 2013).

2.5 Ethical considerations

Ethical principles of voluntary participation, confidentiality, and data protection were strictly observed. Participants were assigned code names, and all recordings and transcripts were securely stored and accessed only by the research team. The methodology provided a rigorous and ethical framework for capturing authentic student experience and their adaptive responses to educational disruption.

3. Results

3.1 Challenging experiences of students in the abrupt transition of learning modality

Students encountered a range of difficulties as they adapted to modular and blended forms of distance learning. Figure 1 illustrates the interplay among three dominant challenges: the *absence of a physical teacher*, the *unfollowed weekly home-learning plan*, and the *lack of gadgets coupled with poor internet connectivity*.

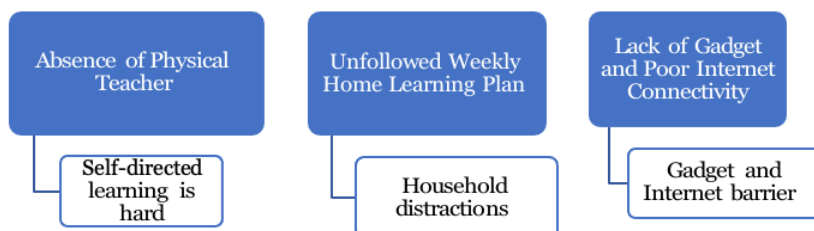


Figure 1. Key Themes in Students' Challenges During the Abrupt Shift in Learning Modalities

In the first theme, the *absence of a physical teacher* emerged as the most frequently cited source of difficulty. Students explained that mathematics requires direct explanation and step-by-step demonstration, elements that printed self-learning modules (SLMs) could not provide. Without immediate feedback, misconceptions persisted. One participant shared that "it is hard to understand the lessons when nobody explains the steps." The loss of real-time teacher–student interaction generated feelings of isolation and frustration, aligning with Moore's (2011) notion of *transactional distance*, where limited dialogue increases cognitive gaps between learner and content.

The second theme, unfollowed weekly home-learning plan, highlighted challenges in time management and home environment. Although the Department of Education prescribed a Weekly Home Learning Plan (WHLP), most students

admitted difficulty in following it due to household chores, family obligations, and distracting surroundings. They described studying late at night, multitasking with domestic responsibilities, or sharing learning spaces with siblings. These conditions disrupted the rhythm of learning and weakened focus, confirming earlier studies that home settings often lack the structure necessary for sustained academic engagement.

The third theme concerned *limited resources and unstable connectivity*. Many students reported the absence of personal gadgets, dependence on borrowed devices, and intermittent internet signals. Communication with teachers was delayed, and submission of outputs was often late. These conditions, shown in Table 1 (summary of students' resource constraints and effects on learning), constrained equitable access to learning and compounded students' stress and anxiety.

Table 1. Summary of students' reported challenges

Theme	Frequency (n = 5)	Illustrative Statement
Absence of physical teacher	5	"It's hard to learn math when no one explains."
Unfollowed WHLP / home distractions	4	"I can't follow the schedule because I help at home."
Lack of gadget / poor internet	4	"We share one phone and the signal is weak."

3.2 Coping mechanisms of students

Despite these challenges, students demonstrated notable adaptability. Three major coping strategies were identified: *seeking assistance from others*, *creating a home-based learning setup*, and *borrowing learning resources*. These strategies are conceptually summarized in Figure 2, which depicts students' movement from dependence to self-regulation.

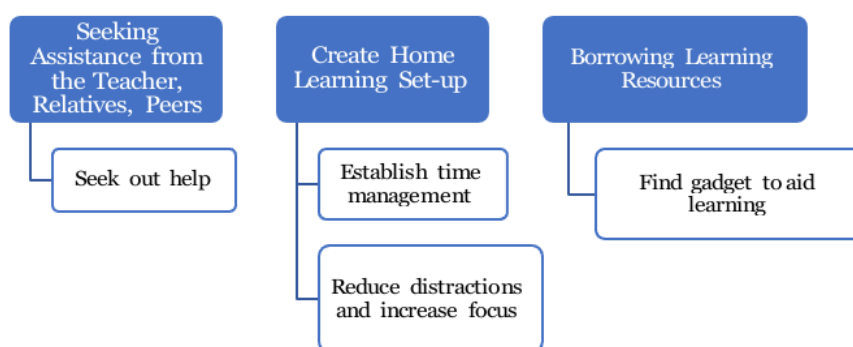


Figure 2. Key themes in coping mechanisms

Under the first strategy, *seeking assistance*, students actively reached out to teachers, relatives, and peers to clarify lessons. Family members, particularly siblings and parents, often served as immediate tutors. Peer-to-peer messaging

groups also became informal support systems where students exchanged solutions and moral encouragement. This social dimension of coping reinforced Vygotsky's principle that learning is socially mediated.

The second coping pattern involved *creating a home-learning setup*. Students converted corners of their homes into study areas, set personal schedules, and disciplined themselves to reduce distractions. This effort indicated a developing sense of self-regulated learning. Participants expressed pride in "learning to manage [their] own time," which transformed a previously passive learning habit into an active process of planning and goal setting.

The third coping mechanism, *borrowing learning resources*, showcased creativity in the face of scarcity. Learners borrowed mobile phones, laptops, or printed materials from relatives and neighbors, usually on a rotational basis. Some traveled to public areas with stronger signals just to send outputs or download modules. These accounts portray Filipino students' resilience and commitment to continuing education despite technological and financial limitations.

3.3 Insights of students on the alternative delivery mode

Students' reflections on their modular and blended experiences revealed three interconnected insights: student autonomy, the continuing need for a physical teacher, and the importance of time management. These are outlined conceptually in Figure 3 as overlapping spheres representing cognitive, affective, and behavioral growth.

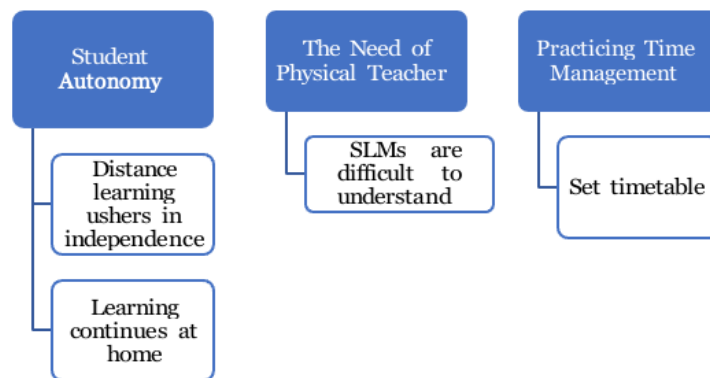


Figure 3. Key themes students' insights on alternative delivery modes

Student autonomy was widely acknowledged as both a challenge and a positive outcome. Learners realized that distance education required them to take responsibility for their own progress. They learned to read instructions carefully, search for additional references, and plan ahead. Although initially uncomfortable, this autonomy nurtured self-discipline and confidence.

At the same time, students emphasized *the irreplaceable value of teacher presence*. Many asserted that while modules guided them, they still needed teachers to explain complex mathematical concepts. The absence of real-time

interaction limited opportunities for questioning and clarification. This reinforces the argument that technology or printed materials cannot fully substitute for human facilitation in conceptual subjects such as mathematics.

Finally, *time management* emerged as a skill developed through necessity. Students described crafting daily routines, allocating specific hours for study, and balancing schoolwork with household tasks. Effective time management reduced stress and allowed them to meet submission deadlines, reflecting adaptive behavior under constrained conditions.

3.4 Assessment-related reflections

When asked about assessment practices, students appreciated performance-based and feedback-oriented evaluations. They preferred teachers who provided solution videos or annotated corrections rather than merely numerical scores. This formative approach helped them understand errors and guided their independent learning. Some students suggested incorporating short online consultations before module submission, reinforcing that assessment should serve not only as measurement but also as guidance.

4. Discussion

4.1 Challenges in learning modality transition

The absence of a physical teacher emerged as the most significant difficulty, aligning with Moore's (2011) concept of transactional distance, where reduced interaction increases cognitive gaps between learners and content. Globally, studies have documented similar experiences. In Italy, Garrote et al. (2020) reported that students in mathematics courses struggled with comprehension when teachers were not physically present, highlighting the critical role of direct explanations in conceptual subjects. Likewise, in India, it was noted that lack of teacher-student interaction contributed to misconceptions and decreased motivation among secondary students during remote learning (Do, 2024).

Unfollowed weekly home-learning plans due to household responsibilities and distractions also mirror patterns found internationally. Research in Turkey (Kalman et al., 2023) observed that students' home environments often lacked structured study spaces, leading to irregular study habits and reduced engagement. This highlighted that domestic obligations disproportionately affected students' ability to adhere to online learning schedules, underscoring socioeconomic influences on educational equity (Tate & Warschauer, 2022).

Limited access to gadgets and unstable internet connectivity is another challenge identified in this study. Globally, the digital divide has been a recurring issue during the pandemic. In Sub-Saharan Africa, Nyongesa & Van Der Westhuizen, J. (2025) reported that many students relied on shared devices and experienced poor connectivity, resulting in delayed submissions and reduced participation. The impact of digital teaching tools on student engagement and learning outcomes in higher education in Africa. In the United States, although

internet access is more widespread, low-income households faced similar barriers, affecting engagement in synchronous sessions (Reich et al., 2020). These findings demonstrate that technological constraints are a universal concern, though their severity varies by context.

4.2 Coping mechanisms

Students' coping strategies, seeking assistance, creating home-learning setups, and borrowing resources, reflect adaptive behaviors observed globally. Peer and family support, as noted in this study, aligns with Vygotsky's social constructivist theory and has been reported in other countries. For instance, in the Philippines and Kenya, peer-to-peer WhatsApp groups facilitated problem-solving and emotional support (Jacobs et al., 2023; Ndunge, 2020). Similarly, students' efforts to establish home-based learning routines reflect self-regulated learning strategies documented in Spain (Geduld, 2024), where learners who organized study schedules and minimized distractions demonstrated higher academic resilience. Borrowing resources or traveling to access connectivity mirrors findings from rural India (Singh et al., 2020), emphasizing students' creativity and commitment to learning despite resource constraints.

4.3 Insights on alternative delivery mode

Students' reflections highlighted the dual outcomes of autonomy and dependence. While autonomy fostered self-discipline and independent learning, the persistent need for teacher facilitation indicates that human interaction remains essential for understanding complex concepts. Internationally, similar observations have been made. In Hong Kong, Yeung and Yau (2022) found that students appreciated increased responsibility for their own learning but still required timely teacher guidance to prevent misconceptions. Time management as a learned skill has been documented in multiple contexts, including Canada and Italy, where students developed structured routines to cope with blended and distance learning (Spadafora & Marini, 2018; Garrote et al., 2020).

4.4 Assessment reflections

Students' preference for formative, feedback-oriented assessments aligns with global trends emphasizing assessment as a learning tool. In the United Kingdom, online formative feedback improved students' understanding and engagement during remote instruction (Moorhouse & Kohnke, 2023). Similarly, in China, annotated corrections and short online consultations were found to enhance students' conceptual grasp and self-efficacy (Chen et al., 2021). These parallels suggest that integrating guided feedback into ADMs can bridge gaps created by the absence of direct teacher presence.

5. Conclusions

This study revealed that secondary students demonstrated remarkable adaptability and resilience amid technology-driven disruptions in mathematics learning. Despite encountering significant challenges such as limited access to digital tools, unstable internet connectivity, absence of direct teacher interaction, and difficulty maintaining structured home-study routines, learners developed coping strategies that fostered autonomy and self-regulation. They sought academic and emotional support from peers and family members, created personalized study environments, and borrowed learning resources to sustain participation. These adaptive responses highlight that meaningful learning can persist even in constrained contexts when supported by responsive assessment and feedback practices. Ultimately, the findings affirm the need for instructional frameworks that integrate technological accessibility with strong teacher guidance, enabling students to become resilient, self-directed, and future-ready learners in an increasingly digital educational landscape.

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The digital divide in later life: ICT education and digital skills of the elderly in the EU

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Abstract: *The paper examines the digital divide at older ages in the European Union, with a focus on ICT education and the level of digital skills among older adults, in a context marked by the accelerated digitalisation of public services, education, and everyday life. The study conceptualises the age-related digital divide as a cumulative mechanism of social inequalities, with direct implications for social participation and digital citizenship. The methodology relies exclusively on secondary analysis of Eurostat data, using indicators related to ICT use, levels of digital skills, and participation in ICT education and training for the period 2013–2024. The analysis adopts a comparative perspective, focusing on the 65–74 age group in relation to the adult population, while taking into account differences across EU Member States and the influence of structural factors such as educational attainment, gender, and type of residence. The strategy combines descriptive analysis, the construction of composite indicators, and the identification of typologies of European Member States according to the degree of digital inclusion among older adults. This paper highlights the role of digital education as a key instrument for active ageing and social cohesion and formulates public policy recommendations regarding the integration of ICT education into lifelong learning and digital inclusion strategies targeted at seniors. The study aligns with the ICVL thematic framework through its critical and empirical approach to the use of digital technologies in education and training, offering a relevant comparative perspective for the design of public policies adapted to the digital society.*

Keywords: Digital divide, ICT education, Digital skills, Active ageing, Inclusion policy.

1. Introduction

The accelerated transformations generated by the digitisation of the economy, public services and everyday life have profoundly reconfigured the conditions of social participation, placing digital skills at the centre of contemporary citizenship. In this context, the digital divide can no longer be reduced to a simple problem of access to technology, but must be understood as a multidimensional phenomenon that reflects the unequal distribution of skills, uses and benefits associated with information and communication technologies (Eshet-

<https://doi.org/10.58503/icvl-v21y202653>

Alkalai, 2004; Ferrari, Punie & Redecker, 2012; Vuorikari et al., 2022; Kosse, et al., 2024). The literature emphasises that age is one of the most persistent lines of digital divide, with older people exposed to a cumulative risk of digital exclusion, fuelled by lower initial educational levels, limited opportunities for continuing education and reduced integration of technology into their professional careers (OECD, 2019; Schirmer et al., 2022; Iftimoaei & Vevera, 2024). At European level, recent strategies on the digital decade and digital education (European Commission, 2019; 2020; 2024) explicitly recognise the role of digital skills in promoting social inclusion and active ageing, but Eurostat and DESI data indicate that significant differences persist between Member States and between age cohorts. In this vein, the present study contributes to the debate on digital capital and lifelong learning, addressing the digital divide in older age as a structural mechanism of social inequalities, with direct implications for the autonomy, civic participation and quality of life of older people in the European Union.

2. Research methodology, indicators, data sources

The analysis carried out in this study is based on a set of harmonised European indicators provided by Eurostat, which allow for the assessment of internet use, digital skills and participation in education and training, with a focus on differences between age groups. The indicators are constructed on the basis of data collected through the EU survey on the use of Information and Communication Technologies (ICT) in households and by individuals and are comparable between European Union Member States. The age groups used in the analysis are defined in accordance with Eurostat's standard classifications, which differ depending on the policy area and target population of each dataset.

For all indicators, we will compare the working-age population aged 25 to 64 with the category of older people aged 65 to 74. This delimitation is justified both by data availability and conceptual considerations, as people under 25 are, for the most part, still engaged in formal education, while the 25-64 age group represents the core adult population targeted by lifelong learning and digital skills development policies. The 65–74 age group captures the transition to old age and is relevant for the analysis of digital inclusion, active ageing and the persistence of age-related digital divides.

Individuals who used the internet. The internet usage indicator measures the proportion of people who have used the internet at least once in the three months prior to the survey date. Internet use includes accessing the internet from any device (computer, mobile phone, tablet, etc.) and from any location (home, work, public spaces or mobile). The indicator is based on self-reported data collected through the Eurostat survey on the use of information and communication technologies.

Individuals – internet activities. The indicator reflects the percentage of individuals who have carried out various online activities in the three months prior to the survey. These activities include, for example, sending and receiving emails,

reading online news, participating in social networks, using online banking services, downloading or viewing multimedia content, searching for health information, online courses or learning materials, and other forms of digital interaction. The data allows for an analysis of how the population uses the internet for various purposes.

Individuals' level of digital skills. The indicator measures individuals' digital skills based on the activities they perform online in a variety of areas relevant to the use of digital technologies, including information and data management, communication and collaboration, digital content creation, online safety and problem solving. Based on these activities, individuals are classified into categories of digital skills (no skills, limited, low, basic and above basic), which allows for an assessment of the extent to which they possess essential or advanced digital skills.

Individuals' level of computer skills. The level of computer skills refers to the percentage of people who say they have basic computer skills, based on activities that are representative of general digital skills (e.g. using software, managing files, using the operating system, etc.).

Participation rate in education and training – last 12 months. The participation rate in education and training (in the last 12 months) represents the proportion of adults who have participated in formal or non-formal education and/or training activities in the last 12 months, relative to the total population in the same age group. The indicator is expressed as a percentage (%) and is used to assess the level of adult involvement in lifelong learning processes, based on data collected through the EU Labour Force Survey (EU-LFS). Formal education includes structured and institutionalised programmes, such as school, university or vocational training courses, while non-formal education refers to organised learning activities outside the formal education system, such as on-the-job training, seminars or specialist workshops.

3. Results and discussions

Eurostat data on internet use in the last three months show significant differences between the 25–64 and 65–74 age groups in the period 2013–2025. While the connection rate among adults (aged 25–64) was already high in 2013 ($\approx 76\%$ in the EU-27) and has grown steadily, older people (aged 65–74) started from much lower values ($\approx 34\%$) and have seen significant growth, but the gap with adults persists in most countries.

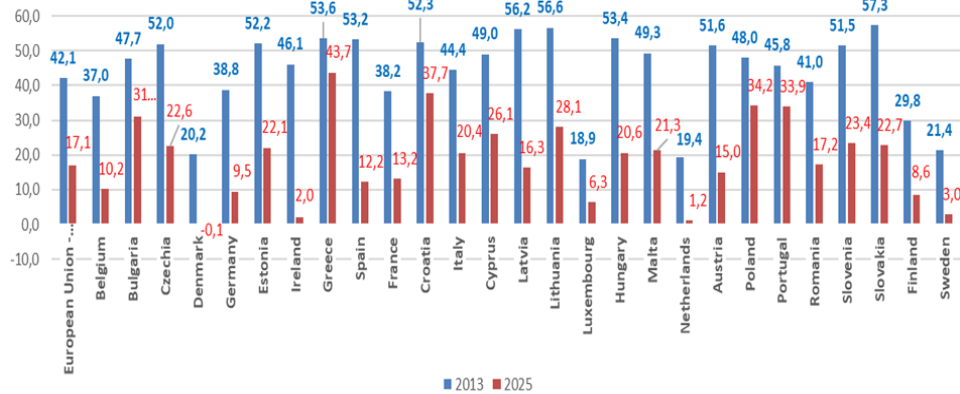


Figure 1. Evolution of the intergenerational gap in internet use in the EU: comparison between 2013 and 2025
(Source: own processing based on Eurostat data (2025))

Analysis of the intergenerational gap in internet use (see Figure 1), defined as the difference between the adult population (25–64 years) and the older population (65–74 years), reveals significant changes between 2013 and 2025, marked by a general trend towards convergence, but also by the persistence of structural disparities between European Union Member States. At EU-27 level, the average gap has narrowed substantially, from 42.1 percentage points in 2013 to 17.1 percentage points in 2025, indicating a considerable convergence between the two age groups. This development reflects the accelerated growth in internet use among older people, in the context of technological maturity and widespread expansion of digital access.

The smallest gaps in 2025 are found in the Nordic and Western European countries, which already had moderate differences in 2013. Denmark (20.2 → -0.1), the Netherlands (19.4 → 1.2), Ireland (46.1 → 2.0), Sweden (21.4 → 3.0), Luxembourg (18.9 → 6.3) and Finland (29.8 → 8.6) illustrate an almost total convergence between generations. In the case of Denmark, the negative gap suggests even higher internet use among people aged 65–74 compared to working-age adults, a rare but sociologically significant phenomenon. This development indicates that, in these countries, internet use has become a cross-cutting skill throughout the life course, supported by coherent public policies, high levels of digital education and high-performance technological infrastructures.

A second group of countries has seen a consistent reduction in the gap, without however eliminating it completely. Germany (38.8 → 9.5), Belgium (37.0 → 10.2), France (38.2 → 13.2), Spain (53.2 → 12.2), Austria (51.6 → 15.0) and Romania (41.0 → 17.2) fall into this category. Although generational differences persist, levels in 2025 are significantly lower than in 2013, indicating a gradual integration of older people into the digital environment. In these cases, convergence appears to be the combined result of younger cohorts entering the 65–

74 age group and increased access to essential digital services (e-government, banking, digital health), rather than policies dedicated exclusively to seniors. In contrast, several countries in Southern and Eastern Europe continue to show high intergenerational gaps in 2025, despite overall progress. Greece (53.6 → 43.7), Croatia (52.3 → 37.7), Poland (48.0 → 34.2), Portugal (45.8 → 33.9), Bulgaria (47.7 → 31.1) and Lithuania (56.6 → 28.1) are relevant examples in this regard. Although these countries have seen substantial increases in internet use among older people, the pace of adoption has been insufficient to significantly reduce the gap with the adult population. This suggests the existence of persistent structural barriers, such as lower levels of digital literacy, lower incomes, territorial disparities and limited access to training programmes tailored to the needs of older people.

An analysis of the activities carried out on the internet by people who have used this ICT resource in the last three months highlights significant differences both between Romania and the European Union average, and between the 25–64 and 65–74 age groups. Overall, the results indicate a lower level of diversity and intensity of internet use in Romania, especially among the elderly population, reflecting the persistence of a functional digital divide (Figure 2).

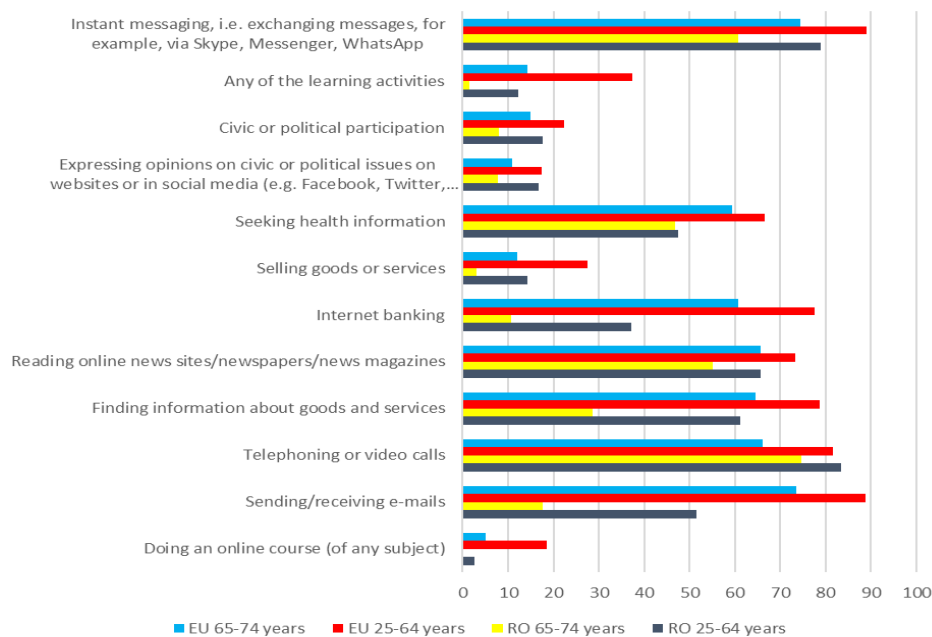


Figure 2. Online activities of internet users, by age group – Romania vs. EU in 2025
(Source: own processing based on Eurostat data)

Communication activities are the most common form of internet use in all categories analysed. Online phone or video calls are widespread, with very high values both in Romania (83.5% for the 25–64 age group and 74.6% for the 65–74 age group) and in the EU. The use of instant messaging applications is also

common, although levels in Romania remain below the European average, especially for the 65–74 age group. These results suggest that the internet is perceived primarily as a tool for interpersonal communication, including among older people.

In contrast, there are major differences between Romania and the EU in terms of economic and administrative activities. The use of internet banking services is significantly lower in Romania, both for adults aged 25–64 (37.1% compared to 77.7% in the EU) and especially for those aged 65–74 (10.6% compared to 60.7%). The same trend can be observed in the sale of goods or services online, where Romania's figures are well below the European average. These discrepancies indicate a low level of trust, skills or access to advanced digital services.

Searching for information is a relatively frequent use of the internet, but here too there is a consistent gap. Although over 60% of Romanians aged 25–64 search for information about goods and services online, the proportion drops sharply among those aged 65–74 (28.5%), well below the EU level. In contrast, searching for health information has comparable values between Romania and the EU for the 65–74 age group, suggesting that health-related needs can stimulate internet use even among people with limited digital skills.

Participation in online educational activities is extremely low in Romania, regardless of age. Only 2.5% of Romanian adults aged 25–64 and 0.2% of those aged 65–74 have taken an online course, compared to 18.5% and 5.1% respectively in the EU. Similarly, the aggregate indicator 'any of the learning activities' shows a marked gap, reflecting poor integration of the internet into lifelong learning processes. In terms of online civic and political participation, levels are low in both Romania and the EU, but Romanian values remain consistently below the European average, especially for the 65–74 age group. This suggests limited use of digital platforms as a space for civic engagement, especially among the elderly population.

Figure 3 highlights the differences in digital skills between Romania and the European Union, across two age groups (25–64 and 65–74), using the indicator Individuals with basic or above basic information and data literacy skills and its sub-components.

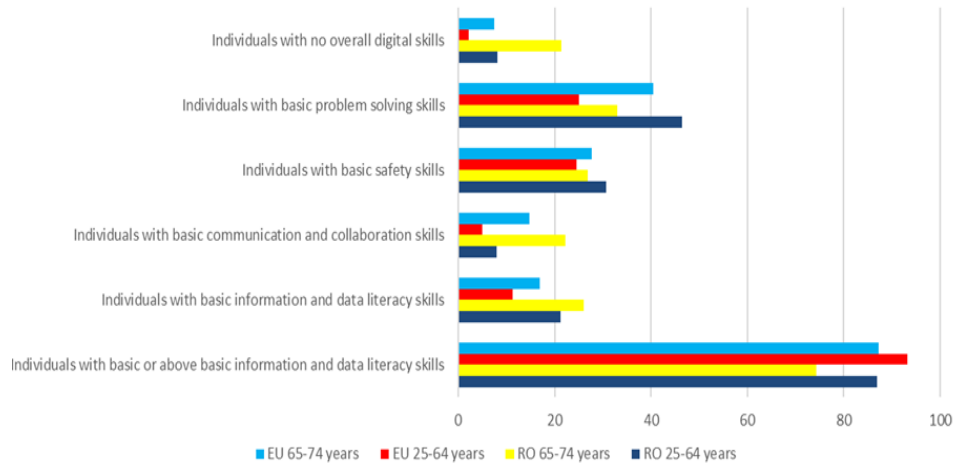


Figure 3. Age-related differences in digital skills in Romania and the European Union, 2025 (Source: own processing based on Eurostat data)

Both in Romania and at EU level, the proportion of individuals with basic or above basic digital skills is higher among the population aged 25–64 than among older people (aged 65–74). Romania has values of 86.9% for adults and 74.37% for older people, which is below the EU average (93.18% and 87.28% respectively), but still indicates partial convergence. This difference suggests that, although a large part of the population in Romania is exposed to basic digital skills, their intensity and diversity remain limited, especially among older people.

Information and communication skills. In Romania, the proportion of people with basic information skills is higher among older people (26.05%) than among adults (21.19%), which is the opposite of the EU average. This suggests that older people's use of technology is mainly focused on consuming information rather than on advanced uses. The differences are even more pronounced in the case of digital communication and collaboration skills. In Romania, only 7.88% of adults and 22.16% of older people have such skills, compared to 4.94% and 14.74% at EU level. This distribution indicates that digital use is concentrated on simple interactions, with a low level of integration into complex professional or collaborative contexts.

Safety and problem-solving skills. In terms of digital safety skills, the differences between Romania and the EU are smaller, and the values are relatively close between age groups. However, this result may reflect minimal awareness of digital risks rather than a high level of practical competence. The strongest contrast is in digital problem-solving skills. Romania has higher values for adults (46.44%) than the EU average (25%), but for older people the level drops significantly (32.96%), remaining below the European average (40.49%). This difference suggests that the transfer of complex digital skills between generations is incomplete, and that population ageing is associated with a reduction in the ability to adapt to new digital tasks.

A critical indicator is the proportion of individuals without general digital skills. In Romania, this reaches 21.4% among older people, compared to only 7.43% at EU level. Even for the adult population, Romania has a significantly higher value (8.18%) than the EU average (2.2%). These results confirm the existence of a hard core of digital exclusion, particularly among the elderly population, which is not described by internet usage indicators but becomes evident when actual skills are analysed. Overall, the data for 2025 show that Romania has made substantial progress in expanding basic digital skills, but their structure is unbalanced, being oriented more towards passive uses of technology. Compared to the EU average, the biggest differences are in complex skills and the proportion of people without digital skills, especially among older people. The results suggest that digitisation does not automatically guarantee functional digital literacy, and public policies should go beyond the goal of access and focus on developing advanced digital skills tailored to the life cycle.

The Individuals' level of computer skills indicator (see Figure 4) captures the practical dimension of digital skills, i.e. the ability of individuals to effectively use computers for functional and productive tasks. Unlike declarative digital literacy, this set of variables reflects the actual level of digital autonomy. A comparative analysis for Romania and the European Union, by age group (25–64 and 65–74), highlights systematic and persistent differences, both between generations and between geographical areas.

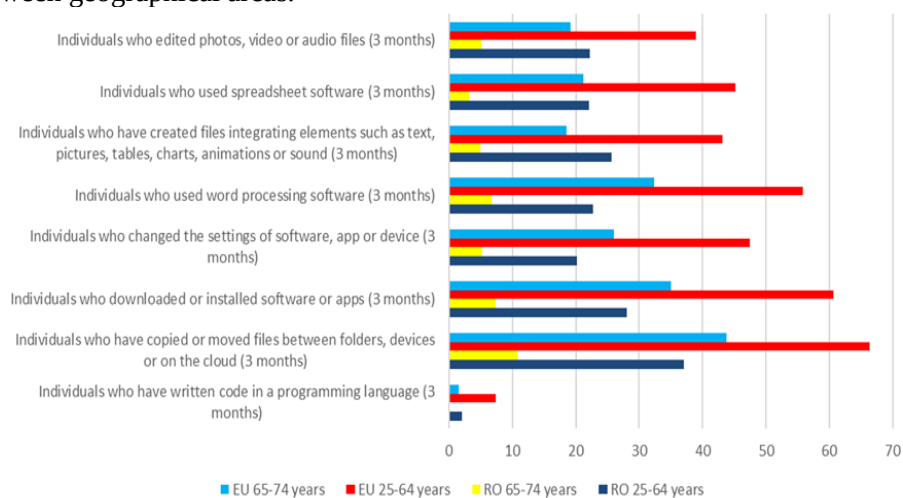


Figure 4. Individuals' level of computer skills by activity and age group in Romania and the EU, 2025 (Source: own processing based on Eurostat data)

Basic tasks: file handling and software installation. Among the population aged 25–64, Romania has moderate levels of basic operational skills. Only 37.05% of adults have copied or moved files between devices or to the cloud in the last three months, compared to 66.34% at EU level. The difference also holds true for downloading or installing software (28.09% in Romania compared to 60.64% in

the EU). For the population aged 65–74, the gap is much more pronounced. Only 10.79% of Romanian seniors have performed file management operations, compared to 43.74% in the EU. These results suggest a high dependence on third parties for the use of technology among seniors in Romania.

Use of productivity applications. The differences are even more evident in the case of productivity applications. The use of word processing programmes is reported by 22.71% of Romanian adults, compared to 55.78% in the EU, and the use of spreadsheets reaches only 22.05% in Romania, compared to 45.2% in the European average. For the 65–74 age group, the levels drop dramatically: 6.65% for word processing and 3.19% for spreadsheets, values that indicate extremely limited digital integration of this cohort in digital administrative or economic activities. Creating complex files (documents with text, images, tables or animations) and editing multimedia content are intermediate-level skills. In Romania, about a quarter of adults report such activities, compared to over 40% at EU level. Among Romanian seniors, these skills are almost absent (below 5–6%), suggesting that the use of digital technology is predominantly passive, focused on consumption rather than content production.

Programming remains a rare skill in all groups analysed, but the discrepancies are significant. In Romania, only 1.98% of adults and 0% of older people have written code recently, compared to 7.39% and 1.48% at EU level. This result reflects not only a generational gap, but also limited digital specialisation among the general population.

Participation in lifelong education and training is an essential indicator of social inclusion and workforce adaptability in a knowledge-based economy.

Table 1. Participation rate in education and training (in the last 12 months) at European Union level in 2025. (Data source: Eurostat)

Country	25-64 years	65-74 years	Country	25-64 years	65-74 years
European Union	28,5	7,0	Latvia	27,5	6,5
Belgium	35,5	7,3	Lithuania	24,7	6,9
Bulgaria	3,3	:	Luxembourg	37,5	6,0
Czechia	32,4	4,0	Hungary	49,3	5,0
Denmark	54,9	35,3	Malta	38,9	6,5
Germany	20,2	2,8	Netherlands	45,3	12,2
Estonia	53,7	16,2	Austria	37,5	7,2
Ireland	28,9	11,6	Poland	20,0	3,3
Greece	8,4	0,5	Portugal	34,5	6,5
Spain	29,7	6,5	Romania	14,4	0,4
France	37,9	13,3	Slovenia	40,3	14,2
Croatia	12,3	0,8	Slovakia	40,2	3,7
Italy	20,9	5,2	Finland	53,4	18,0
Cyprus	29,0	6,1	Sweden	61,2	29,5

A comparative analysis of participation rates (see **tabel 1**) for the 25–64 and 65–74 age groups in 2024 shows a pronounced intergenerational gap in most EU Member States, despite progress in lifelong learning. At EU-27 level, the

participation rate in education and training is 28.5% for the 25–64 age group, compared with only 7.0% for the 65–74 age group, resulting in an intergenerational gap of 21.5 percentage points. This significant difference indicates that participation in educational activities remains heavily concentrated in the active period of working life, and the integration of older people into continuing learning processes is still limited.

The Nordic countries and some Western European countries stand out with high levels of participation among both adults and older people. Sweden (61.2% vs. 29.5%), Denmark (54.9% vs. 35.3%), Finland (53.4% vs. 18.0%) and Estonia (53.7% vs. 16.2%) have the most advanced models of lifelong learning. In these countries, although the intergenerational gap persists, the participation of people aged 65–74 is substantially higher than the EU average. These performances reflect the existence of flexible education systems, active ageing policies and an institutionalised culture of continuous training that is not limited exclusively to the labour market.

A second group of countries, including France, Belgium, Austria, Slovenia, the Netherlands and Ireland, has relatively high rates for the 25–64 age group (between 28% and 45%), but much lower rates for older people (between 6% and 14%). For example, France reports 37.9% for adults and 13.3% for older people, and the Netherlands 45.3% compared to 12.2%. This pattern suggests that, although continuing education is well integrated during working life, the transition to learning in later life remains limited, possibly because training programmes are mainly geared towards the needs of the labour market.

The most pronounced gaps are observed in Southern and Eastern European countries. Romania (14.4% vs. 0.4%), Greece (8.4% vs. 0.5%), Croatia (12.3% vs. 0.8%), Poland (20.0% vs. 3.3%) and Bulgaria (3.3% for 25–64 year olds, data unavailable for 65–74 year olds) illustrate a pattern of extremely low participation, particularly among the older population. In these countries, participation in education and training after retirement age is almost non-existent, indicating significant structural barriers such as limited access to appropriate programmes, lower initial educational levels and a poorly developed culture of lifelong learning.

4. Conclusions

The statistical analysis highlights that the age-related digital divide remains a structural dimension of social and economic inequalities in the European Union, even in a context of accelerated digitisation of public services, education and everyday life. The results show a clear trend towards intergenerational convergence in internet use between 2013 and 2025, reflected in a significant reduction in the differences between the adult population (25–64 years) and the older population (65–74 years). However, this convergence is unevenly distributed across territories, being almost complete in the Nordic and Western European countries, but much slower and incomplete in Southern and Eastern Europe.

Analysis of online activities shows that there is a functional digital divide, not just a quantitative one. In Romania and other Eastern European countries in particular, internet use by older people remains focused on basic activities (interpersonal communication, information consumption), while activities with economic, educational, civic or administrative value are poorly represented. This pattern of use indicates limited integration of older people into the advanced digital ecosystem and confirms the hypothesis of predominantly passive digitisation.

The level of digital and computer skills reveals a disconnect between declared digital literacy and actual operational skills. Although a relatively high proportion of the older population reports basic digital skills, levels drop sharply when productive, problem-solving or content-creation skills are analysed. The high proportion of people without general digital skills, particularly in Romania, indicates the existence of a hard core of digital exclusion that is insufficiently captured by internet usage indicators.

The extremely low participation of people aged 65–74 in lifelong learning and training is one of the most robust conclusions of the study. Intergenerational differences in this area suggest that lifelong learning policies remain strongly anchored in the logic of the labour market, neglecting the dimension of digital education as a tool for active ageing, autonomy and social inclusion.

Overall, the general conclusion of the paper is that the digital divide in older age should be conceptualised as a cumulative mechanism of social inequality, in which age interacts with education level, income, place of residence and institutional infrastructure. Digitalisation is not, in itself, an equalising process. Without explicit public policies aimed at developing functional and advanced digital skills among older people, it risks reproducing and deepening existing forms of social exclusion.

The integration of ICT education for seniors into lifelong learning strategies, the adaptation of training programmes to the specific needs of older people, and the approach to digital inclusion as part of social cohesion and active ageing policies. In this sense, the paper makes a relevant contribution to both the literature and the debate on digital governance and educational policies in the European digital society.

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Artificial Intelligence for virtual learning: Bibliometric analysis

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Abstract: *The evolution of Artificial Intelligence has significantly influenced educational practices for students and teachers. For teachers, the importance lies in utilizing Artificial Intelligence to design assignments that help students enhance their knowledge. The students attempt to utilize Artificial Intelligence to complete assignments or to grasp certain concepts from the class. In this paper, we present a systematic analysis of scientific publications on the Web of Science that address the integration of AI in education. We are using bibliometric methods on a dataset of publications indexed in Web of Science to understand how this field evolved and the extent of interest in using Artificial Intelligence in education. The results show a significant increase in the number of publications in this field, as well as a rise in interest in how Artificial Intelligence can be applied in Education. Furthermore, the analysis identifies the leading countries and institutions driving research output and outlines the gaps that require further investigation. By providing a comprehensive quantitative overview of the scientific landscape, this study supports researchers and policymakers in understanding current directions and future opportunities in AI-enhanced education.*

Keywords: Artificial Intelligence, Education, Bibliometric analysis.

1. Introduction

In recent years, the accelerated development of artificial intelligence (AI) has produced significant changes in the educational system. Generative AI (GAI) systems, such as large language models, are increasingly being investigated for educational uses that include automated content generation, personalized feedback, support for adaptive learning, and assisting assessment processes. In this context, education system learning has consolidated itself as an essential framework for integrating these emerging technologies, using a rigorous analysis of existing research directions (Waltman et.al., 2010). Recent specialized studies indicate a sharp rise in scholarly interest in the use of AI in education, particularly within higher education and online learning settings. Current research highlights the significant potential of these technologies to personalize learning pathways and enhance students' experiences in digital environments. At the same time, the literature points to important challenges, including ethical concerns, issues of

academic integrity, and possible effects on students' cognitive development (Irwanto et al., 2025). This accelerated development of research in artificial intelligence field has led to an extensive but fragmented literature, which makes it difficult to identify main trends and underexplored areas.

In this context, bibliometric analysis is an appropriate methodology for the systematic mapping of an emerging scientific field. Through the quantitative analysis of publications, citations and collaborative networks, the bibliometric approach allows the identification of influential authors, relevant scientific sources and main research topics. Recent bibliometric studies have demonstrated the usefulness of this method in investigating research on GenAI in education, providing valuable insights into the intellectual structure of the field (Zhang et al., 2025). However, many of the existing analyses treat virtual learning as a secondary context, without approaching it as a distinct analytical dimension. Given the central role of virtual environments in the implementation of GenAI applications, it is necessary to perform a statistical analysis of scientific publication mainly focused on this educational framework. The use of those tools, such as VOSviewer and Bibliometrix, facilitates the visualization of keyword co-citation and co-occurrence networks, contributing to transparent and reproducible analyses (van Eck & Waltman, 2010; Aria & Cuccurullo, 2017). Therefore, this study aims to carry out a bibliometric analysis of research on generative artificial intelligence in virtual learning, with the following objectives:

- (1) analysis of the chronological evolution of scientific publications;
- (2) authors identification, and affiliations identification with major influence this field.

This article aims to provide, through the proposed bibliometric approach, not only a quantitative synthesis of the existing literature, but also a framework for critical reflection of the relationships between institutional actors and publication dynamics. Those allow a better understanding of the field and the level of theoretical convergence. In this way, the results can serve as a reference point for future research, facilitating the development of empirically grounded pedagogical models and supporting the responsible and efficient integration of GAI technologies into contemporary virtual education.

2. Literature review

As previously mentioned, the emergence of **Generative Artificial Intelligence** represents a **qualitative shift** in both the conceptual and practical architecture of *Artificial Intelligence in Education* (AIED). Recent studies highlight the need for systematic examinations of the **evolution, structure, and dominant trends** within the field.

Bibliometric analyses have become essential tools for mapping research trajectories, identifying influential contributions, and highlighting emerging themes that can guide future investigations (Prahani et al., 2022). Several large-scale bibliometric studies have analysed AIED literature using major databases such as Scopus and Web of Science (WoS). For instance, Prahani et al. (2022) examined

457 highly cited publications over the past decade, revealing exponential growth in AIED research, particularly over the last five years. Peer-reviewed journal articles were the dominant document type, with China emerging as the most productive country. Trend mapping identified six key thematic areas: (1) student-centered AI applications, (2) AI integration in engineering education, (3) AI-supported teaching methods, (4) e-learning and digital education, (5) educational systems, and (6) curriculum-level AI integration.

Complementary analyses confirm the central role of educational technology journals in shaping AIED research dissemination. A WoS-based study covering 2,686 publications between 2001 and 2021 highlighted *Computers & Education* and the *International Journal of Emerging Technologies in Learning* as the most prolific outlets (Talan, 2021). A broader investigation of approximately 8,660 Scopus-indexed articles published between 2000 and 2019 employed CiteSpace and alluvial flow analysis to examine publication outputs, international collaboration, cluster structures, and research evolution (Song & Wang, 2020). Five core intellectual clusters were identified: intelligent tutoring systems, learning systems, students, labelled training data, and pedagogy (Cîrnu, 2015). Longitudinal analysis conceptualized AIED research into four stages: (a) technological foundation, (b) technological breakthrough, (c) intelligent application, and (d) symbiotic integration of AI technologies with educational practices.

More recently, Derinalp (2024) adopted an extended temporal perspective, analyzing 905 WoS-indexed studies published between 1989 and 2023. Using Biblioshiny, the annual growth rate of publications was estimated at 18.7%, reflecting sustained and accelerating interest. China, the United States, the United Kingdom, Australia, and Spain emerged as leading contributors, while themes of articles demonstrated the diversification and maturation of research topics over time.

Recent bibliometric studies indicate that, from 2022 onwards, GAI has become a **central driver of growth** in AIED research. Ng and Ho (2025), analyzing 3,808 Scopus-indexed publications, documented an exponential increase in GAI-related educational research, with the majority of contributions coming from the United States, China, and Hong Kong. This geographic distribution reflects well-established research ecosystems, supported by institutional investment, digital infrastructure, and national AI policies. Keyword evolution further suggests a conceptual shift from technology-focused studies toward research emphasizing learner experience, cognitive engagement, and medium- to long-term pedagogical outcomes. Bahroun et al. (2023) highlight the dominant role of tools like ChatGPT and stress the importance of algorithmic transparency, bias mitigation, and responsible AI use.

With this evolving landscape of Generative AI in mind, it is crucial to explore its **practical and conceptual implications** across multiple dimensions, to understand how GAI is reshaping education and highlighting areas where further research and careful governance are needed.

Ethical, Normative, and Institutional Dimensions: A defining feature of recent GAI literature is the emphasis on ethical considerations and institutional

governance. Unlike earlier phases of AIED, where ethics were marginal, GAI poses direct risks to academic integrity, assessment authenticity, and authorship responsibility. These challenges are amplified by the **hybrid, multifunctional nature** of GAI systems. A systematic review by Arista et al. (2024) shows growing interest in ethical policies in higher education, peaking in 2024. Ganjavi et al. (2024) document normative fragmentation among publishers and journals, highlighting inconsistencies in transparency requirements and reporting, which may create uncertainty for authors and affect scientific integrity.

Educational Impact and Pedagogical Efficiency: Xiao-yu et al. (2024) report that around 70% of empirical studies find positive effects of GAI on learning outcomes, especially through personalized feedback and adaptive support. However, over-reliance on GAI can hinder creativity and critical thinking, highlighting the need for **clearly defined pedagogical frameworks**. Sharma and Panja (2025) further confirm the transdisciplinary nature of GAI research and its relevance for evidence-informed educational policies.

GAI, Sustainability, and Future Directions: Nikolopoulou (2025) emphasizes GAI's potential to support sustainability in higher education by optimizing educational resources, fostering inclusion, and promoting development-focused education. Nonetheless, most contributions remain theoretical, underscoring the need for **empirical and longitudinal studies** to assess GAI's real-world impact on institutional and educational sustainability.

Although the field of AI in education has grown rapidly and produced a wealth of studies, several gaps remain that point to promising directions for future research. Most notably, the bulk of recent work has focused on the period between 2022 and 2025 and largely on generative AI, leaving earlier phases of AIED and other types of AI—such as adaptive, predictive, or assessment-oriented systems—less explored. Furthermore, while these AI types often overlap in practical applications, research tends to examine them in isolation, limiting our understanding of how hybrid AI systems operate in diverse educational contexts.

3. Methodology

Before and after the widespread adoption of artificial intelligence, there has always been a significant interest in applying certain artificial intelligence techniques to assist either teachers or students in the educational field, especially for universities or schools with a large number of students. The accelerated growth in recent years of the use of artificial intelligence has also led to an increase in the number of articles addressing this issue. Therefore, we consider it necessary to perform bibliometric analyses that systematically present the evolution of the number of publications in the field of education for the use of artificial intelligence.

To carry out this analysis, metadata was collected regarding articles published and indexed in the Web of Science that contain the terms AI or Artificial Intelligence and the term education in the title. In this way, 21,665 articles that meet these conditions were identified. This metadata was sanitized and prepared for processing.

Python was used in this bibliometric analysis mainly to ensure reproducibility and to allow the study to be extended and explored in greater depth in the future. Working with scripts means that every step of the process data cleaning, filtering, calculating indicators, and creating visualizations is clearly documented, transparent, and easy to repeat or adjust. Unlike tools with fixed interfaces, this approach makes it possible to gradually build on the analysis by adding new datasets, time periods, variables, or methods without starting over, which increases both the flexibility of the methodology and the overall scientific reliability of the research.

The analysis aims to highlight the distribution of publications over time, identify the authors with the highest number of contributions, as well as institutions with intensive activity in the field.

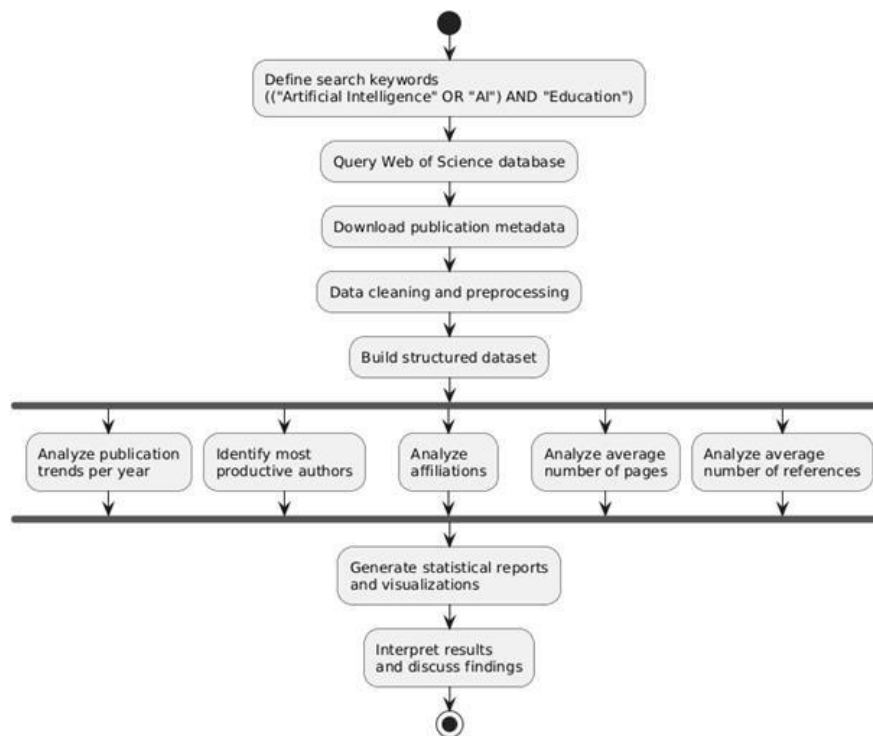


Figure 1. Methodology process

The general process of the methodology is schematically illustrated in Figure 1, which presents the stages of data collection, preprocessing, bibliometric analysis and reporting of results.

The analysis of institutional affiliations is relevant because it allows highlighting universities and research centers that invest in the development and application of Artificial Intelligence in education. In this way, active scientific communities and potential academic collaboration networks can be identified. In addition, the study includes the analysis of complementary indicators, such as the

average number of pages per article, the average number of references used and their evolution over time.

4. Results

The bibliometric analysis conducted for the works identified on the Web of Science that address the use of Artificial Intelligence in education highlighted an increase in the number of pages for the articles published recently. Although the dynamics of the average number of pages per article may suggest an increase in research complexity, this indicator is strongly influenced by editorial policies and publication formats. Still, it may show a deepening and growing interest of the scientific and academic community for the application of artificial intelligence in the educational environment, Figure 2.

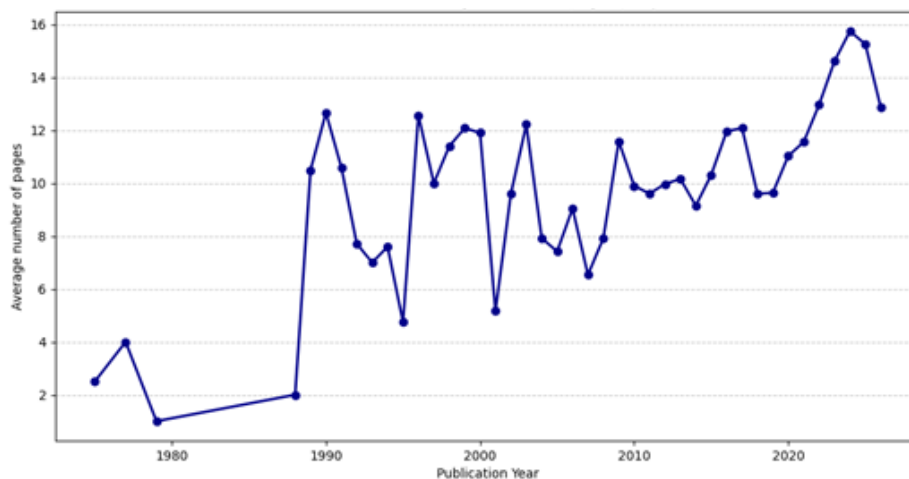


Figure 2. Evolution of the average number of pages per year

The average number of citations per article has increased significantly in recent years. This reflects the authors' concerns for a solid foundation of research in the field and for its integration into the existing literature. This increase over time also shows the consolidation of the field with a significant number of research and publications, Figure 3. This increase also highlights a gradual maturation of the field of Artificial Intelligence in Education.

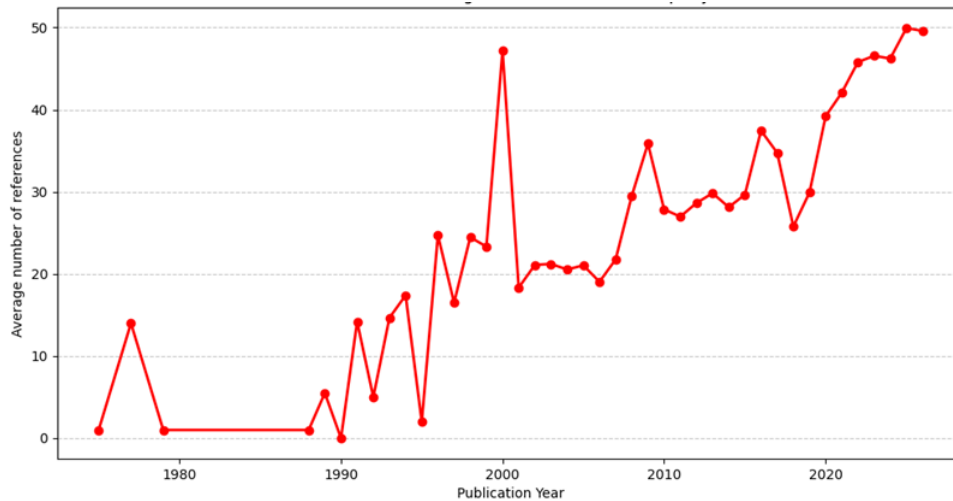


Figure 3. Evolution of the average number of references per year

The rise in citations around the year 2000 marked the moment AI in education truly found its place, moving from isolated lab experiments to validated pedagogical models. This phase of maturation laid the groundwork for the exponential explosion we witnessed after 2020, as Figure 4 shows. While the early 2000s were dedicated to refining the theory behind intelligent tutoring systems, the 2020 turning point - fueled by the convergence of Deep Learning, Big Data, and the global necessity for remote learning - transformed these concepts into scalable, everyday technologies. We can view the dynamics of 2000 as the field's 'conceptual birth,' whereas the post-2020 marks its global revolution—the point where AI stopped being just a research topic and became an essential infrastructure for modern education.

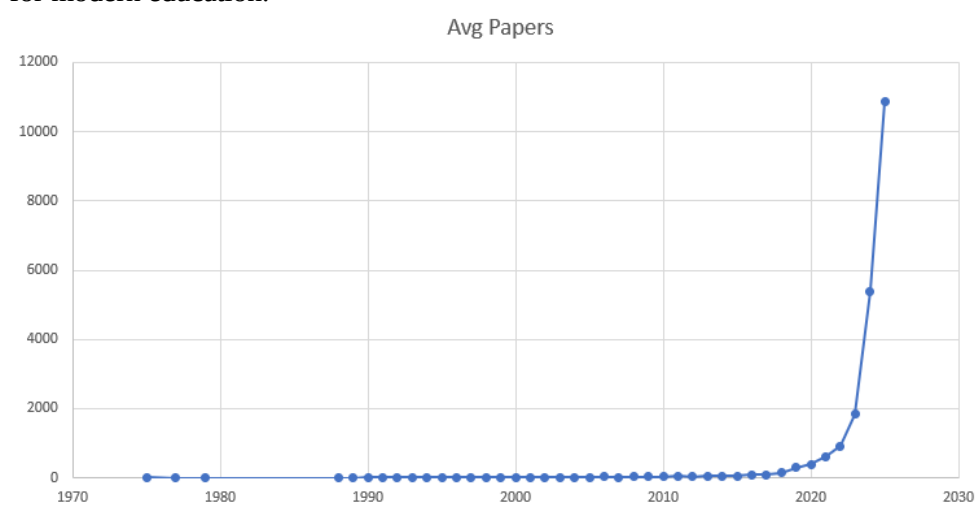


Figure 4. Evolution of the number of articles per year

This bibliometric analysis of publications dedicated to Artificial Intelligence in Education provides a clear overview of the evolution and structure of this emerging field. The results highlight a significant increase in the scientific community's interest in integrating AI-based technologies into educational processes, reflected in the upward dynamics of the number of published papers and the thematic diversity addressed.

Regarding the authors who have published in this field, the bibliometric analysis highlighted the top 20 authors with the highest number of published articles, indicating the existence of opinion leaders in this field of publication for the use of artificial intelligence in education, Figure 5.

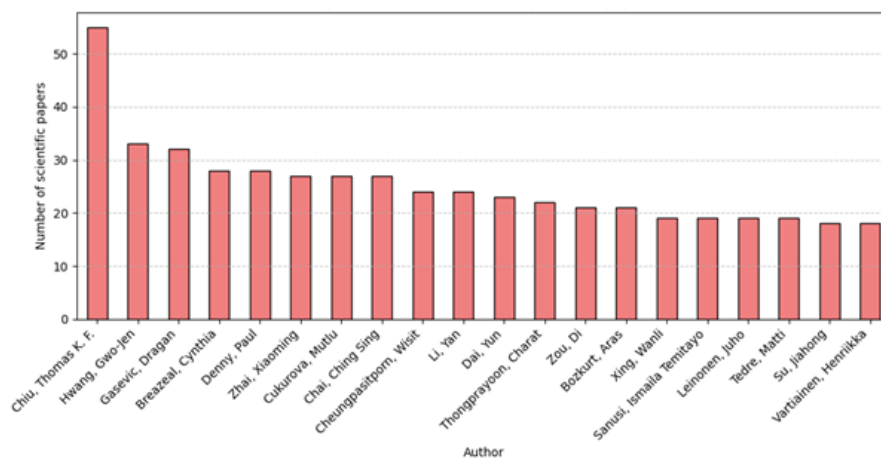


Figure 5. Top 20 authors with the most published papers

The institutional affiliations of the authors (Figure 6) of the analyzed publications show that universities mainly actively invest in the development, use and application of AI in education, contributing to the strengthening of scientific communities and research infrastructure in this field.

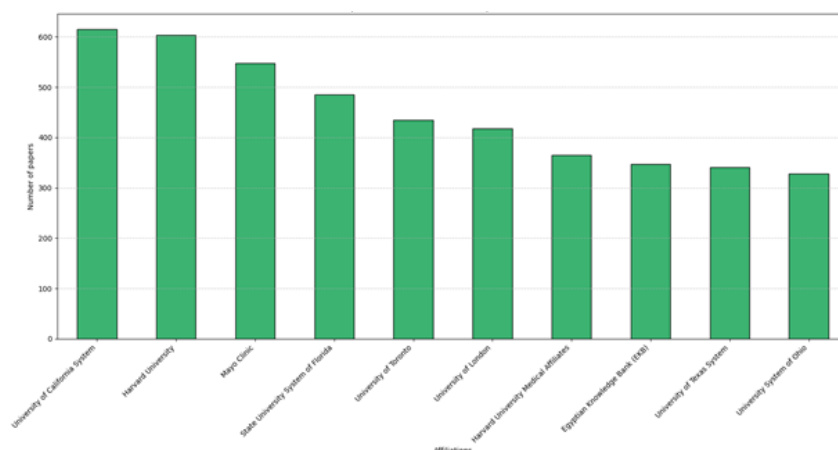


Figure 6. Top 10 affiliations with the most published articles

5. Conclusions

Overall, the bibliometric findings show that Artificial Intelligence in Education (AIED) has moved beyond being a narrow research niche and has developed into a well-established and fast-growing field. The steady rise in the number of publications, together with the increase in article length and the higher average number of citations, suggests not only more research activity but also greater depth and stronger connections with existing educational and technological studies. While factors such as journal requirements can influence structural aspects like article size, the combined trends in publication and citation patterns clearly reflect a growing and sustained interest from the scientific community, as well as the gradual strengthening of theoretical frameworks, research methods, and practical applications in education.

At the same time, the presence of highly productive authors and frequently cited works highlights the formation of a recognizable research community with key contributors and stable collaboration networks. This indicates that the field is maturing, as foundational theories, intelligent tutoring systems, learning analytics, and more recent data-driven and generative AI approaches are now part of a shared research landscape. The strong acceleration after 2020 further suggests a shift from mainly conceptual and experimental work toward broader, real-world implementation. In this context, AI is no longer seen only as an innovative topic of study, but increasingly as a core component of modern educational systems and future research directions.

Acknowledgment

This work is supported by the Core Program within the National Research Development and Innovation Plan 2022-2027, carried out with the support of MCID, project no. 23380601, „Advanced research in the Metaverse and emerging technologies for the digital transformation of society”.

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8-10, Maresal Averescu Avenue,
District 1, 011455, Bucharest, Romania
editura@ici.ro



ISSN 1844-8933
ISSN-L 1844-8933
ISBN 978-606-95858-6-3 (print)
ISBN 978-606-95858-7-0 (online)