Immersive technologies, AI integration, and STEAM pedagogical innovations at AREdu 2025

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Abstract

This review synthesizes research studies from AREdu 2025 examining the intersection of digital technologies and education, with particular emphasis on immersive learning environments, artificial intelligence applications, and STEAM education methodologies. Through systematic analysis of twenty empirical investigations, theoretical frameworks, and implementation case studies conducted between 2024 and 2025, the synthesis reveals three dominant paradigms shaping contemporary educational technology: the integration of augmented and virtual reality tools for enhanced experiential learning, the deployment of adaptive AI systems for personalized education, and the development of interdisciplinary frameworks combining technical and pedagogical innovations. The reviewed literature encompasses diverse geographical contexts, educational levels, and disciplinary domains, collectively involving over 3,500 participants across experimental, quasi-experimental, survey, and mixed-methods designs. The analysis identifies critical success factors including teacher preparedness (affecting 48-68% of implementation challenges), technological infrastructure requirements, and the necessity for systematic evaluation frameworks. The studies demonstrate measurable improvements in student engagement (35-64% increase across different interventions), learning retention (10-42% improvement), and the development of twenty-first century competencies. However, significant barriers persist, including resource limitations in 48% of institutions, insufficient teacher digital literacy, and the absence of standardized assessment metrics for emerging technologies. Critical patterns emerge across three analytical dimensions: the tension between technological capability and pedagogical integration, the role of crisis as catalyst for innovation, and the emergence of pedagogical hybridity blending traditional and digital methodologies. The review concludes with recommendations for policy development, institutional support structures, and future research directions that address the evolving landscape of digital education while maintaining focus on pedagogical efficacy, educational equity, and human agency. These findings provide essential guidance for educators, administrators, and policymakers navigating the complex terrain of educational technology integration in an era of rapid technological change and global disruption.

Keywords

augmented reality in education, virtual reality learning environments, artificial intelligence in education, adaptive learning systems, STEAM education, immersive technologies, educational technology integration, mobile learning applications, gamification, digital transformation, teacher readiness, TPACK framework, crisis-driven innovation, pedagogical hybridity, educational resilience

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1. Introduction

Figure 1: AREdu 2025 logo.

Augmented **R**eality in **Edu**cation (AREdu) is a peer-reviewed international Computer Science workshop focusing on research advances and applications of virtual, augmented and mixed reality in education.

The 2025 edition of the workshop highlighting the continueius convergence of augmented reality with artificial intelligence technologies. This intersection presents new opportunities for creating more adaptive, intelligent, and personalized learning experiences. The workshop's focus on immersive technologies, AI integration, and STEAM pedagogical innovations reflects the growing recognition that these technologies, when combined, can provide powerful tools for addressing contemporary educational challenges and supporting innovative pedagogical approaches like STEAM.

The 8th International Workshop on Augmented Reality in Education (AREdu 2025), held on May 13, 2025, in Kryvyi Rih, Ukraine, provided a dynamic platform for researchers, educators, and technology developers to share their latest findings and experiences in the rapidly evolving field of AR and AI in education. Building on the success of previous editions [1, 2, 3, 4, 5, 6, 7], AREdu 2025 attracted a diverse array of contributions exploring the design, implementation, and evaluation of AR/AI-based learning environments across various educational levels and subject areas.

This volume represents the proceedings of the AREdu 2025. It comprises 20 contributed papers that were carefully peer-reviewed and selected from 29 submissions. At least three program committee members reviewed each submission.

The workshop's proceedings showcase the breadth and depth of current research on educational AR. From theoretical frameworks to empirical studies and practical applications, the papers collectively demonstrate AR's immense potential to enhance learning experiences, foster engagement and motivation, and develop critical 21st-century skills.

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2.1. Research questions

The landscape of education has undergone profound transformation through the integration of digital technologies, fundamentally altering pedagogical approaches, learning methodologies, and educational outcomes. Contemporary educational technology research has shifted beyond simple efficacy questions to more nuanced explorations of how specific interventions interact with pedagogical practices, institutional contexts, and sociocultural factors. This review examines twenty contemporary research studies conducted between 2024 and 2025, representing diverse geographical contexts and educational levels, to synthesize current understanding of technology-enhanced learning environments.

The acceleration of digital transformation, catalyzed by global disruptions such as the COVID-19 pandemic [54], geopolitical conflicts [55], and rapid technological advancements [56], has necessitated a comprehensive examination of emerging educational technologies and their implementation strategies. The studies under review collectively address three critical questions:

RQ1: How do immersive technologies reshape learning experiences?

RQ2: What role does artificial intelligence play in personalizing and enhancing education?

RQ3: How can interdisciplinary approaches, particularly STEAM education, leverage technology for improved learning outcomes?

These investigations capture education systems in a state of flux, documenting both incremental changes and revolutionary adaptations. Contemporary challenges demand innovative solutions that transcend traditional boundaries, with AR [57], VR [48], AI [58], and gamification [59] representing a reconceptualization of educational processes. This review employs thematic analysis to identify patterns, convergences, and divergences, providing a comprehensive understanding of current research trajectories and practical applications.

3. Methodological considerations

The methodological landscape across the AREdu 2025 studies reflects the multidisciplinary nature of educational technology research (table 1). Experimental and quasi-experimental designs predominate in quantitative investigations, enabling causal inferences about intervention effectiveness. Sample sizes vary from small-scale case studies (e.g., 8 students in [60]) to large implementations (e.g., 343 students in papers [61] and [62]). This diversity strengthens collective findings through triangulation but highlights the need for standardized evaluation frameworks.

Survey methodologies feature in several studies, with samples ranging from 16 experts [72] to 206 teachers [74]. Mixed-methods approaches often compensate for limited scale by combining quantitative metrics with qualitative insights. Temporal scopes mostly cover single semesters, though some extend to multiple years (e.g., 5 years in [62]), providing insights into sustainability.

Content analysis and computational methods appear in studies like [67] and [76], developing novel metrics tailored to educational challenges. The heterogeneity in approaches raises questions about comparability, yet detailed protocols in papers like [69] facilitate replication.

Table 1
Methodological approaches across reviewed studies.

Paper	Method	Sample	Duration
Pacala and Pacala [60]	Case study	8 students	3 months
Semerikov et al. [63]	Conceptual model	N/A	N/A
Verbovetskyi and Oleksiuk [64]	Design research	Multiple iterations	1 year
Potapchuk et al. [65]	Experimental	58 participants	6 months
Kolhatin [66]	Systematic review	200+ sources	N/A
Sharyhin et al. [67]	Experimental	50 texts, 712 versions	3 months
Chornyi et al. [68]	Development	N/A	6 months
Prus and Nechypurenko [69]	Quasi-experimental	2 grade levels	1 semester
Ilkova et al. [70]	Simulation	15 scenarios	4 months
Soroko and Ovcharuk [71]	SWOT analysis	16 experts	6 months
Bohachkov et al. [72]	Survey	16 experts	3 months
Shapovalov et al. [73]	Graph analysis	System-wide	Ongoing
Morze et al. [61]	Mixed methods	343 students	2 years
Klochko et al. [74]	Survey	206 teachers	1 year
Tokarieva et al. [75]	Experimental	18 participants	1 semester
Shapovalov and Shapovalov [76]	Mathematical modeling	Biogas studies	2 years
Kovtoniuk et al. [77]	Factor analysis	82 participants	N/A
Bilyk et al. [78]	Comparative	6 applications	6 months
Kuzminska et al. [79]	Survey	58 staff	1 year
Pikalova [62]	Experimental	343 students	5 years

4. Thematic analysis

4.1. Immersive technologies and experiential learning

Nine studies (Pacala and Pacala [60], Semerikov et al. [63], Verbovetskyi and Oleksiuk [64], Potapchuk et al. [65], Chornyi et al. [68], Bohachkov et al. [72], Tokarieva et al. [75], Kovtoniuk et al. [77], Kuzminska et al. [79]) examine immersive technology applications, revealing consistent implementation patterns and pedagogical transformations. The integration of AR/VR technologies demonstrates measurable improvements in spatial reasoning capabilities, with studies reporting 35-45% better performance in three-dimensional conceptualization tasks [65, 68].

The evolution from isolated tools to comprehensive ecosystems marks a significant shift in immersive learning. Bohachkov et al. [72] addresses the fragmentation challenge through systematic catalogization of VR/AR resources, employing expert consensus to establish filtering criteria. Their framework identifies critical adoption factors, with behavioral intention to use immersive VR significantly influenced by performance expectancy, effort expectancy, and personal innovativeness, accounting for 50% of variance in adoption decisions.

Mobile-first approaches emerge as democratizing forces in experimental learning. Pacala and Pacala [60] demonstrates how smartphone-based physics experiments transform traditional laboratory paradigms, achieving comparable learning outcomes while requiring minimal infrastructure. Students report that smartphones make "science more accessible and part of everyday life, not just something you do for school," with enhanced conceptual understanding resulting from the immediacy and personal ownership of devices. The Phyphox application enables measurement of acceleration due to gravity and magnetic flux density using internal sensors, bridging abstract concepts with tangible experiences.

Cloud architectures fundamentally reshape accessibility parameters. Semerikov et al. [63] presents an integrated conceptual model revealing how cloud-based infrastructures enable "anytime, anywhere" learning while reducing institutional investment requirements by 60-75%. The emergence of cross-platform standards like WebXR and OpenXR promises to reduce fragmentation, enabling content functionality across devices from high-end VR headsets to basic smartphones.

Gamification mechanisms show nuanced effectiveness patterns. Tokarieva et al. [75] reveals differen-

tial impacts between intrinsic and extrinsic motivators, with intrinsic game elements yielding 42-64% sustained behavior changes compared to 12-28% for external reward systems. The study identifies critical design principles: challenge-skill balance maintenance, immediate feedback provision, and narrative coherence integration. Students exposed to well-designed gamified environments demonstrate increased time-on-task (average 34.8 minutes versus 22.4 minutes traditional), improved self-efficacy scores (3.8/5.0 versus 2.9/5.0), and enhanced problem-solving persistence.

Technical implementation reveals "computational craftsmanship" emergence. The Merge Cube platform [65] exemplifies how physical-digital integration enhances spatial thinking through tangible AR interactions. Similarly, Chornyi et al. [68] details comprehensive 3D modeling workflows using Blender, covering concept development through optimization phases. The technical pipeline – modeling, texturing, rigging, animation, optimization – requires 6-month development cycles but yields reusable educational assets with demonstrated engagement improvements.

4.2. Artificial intelligence and adaptive systems

Kolhatin [66], Sharyhin et al. [67], Ilkova et al. [70], Morze et al. [61], and parts of [77] explore AI integration, highlighting transformative potential and complexities. Kolhatin [66] provides a comprehensive framework for generative AI integration, emphasizing human-centered approaches that balance automation with agency preservation. The study identifies three dominant architectural patterns: retrieval-augmented generation (RAG) for factual accuracy, specialized pedagogical models for domain expertise, and teacher-assist frameworks maintaining educator control. Hybrid architectures combining these elements demonstrate particular effectiveness, reducing hallucination rates by 65% while maintaining generation flexibility.

Adaptive learning systems show remarkable efficacy when properly calibrated. Morze et al. [61] documents 40-50% learning outcome improvements through Moodle LMS adaptive implementations, though success requires addressing multiple challenges. Technical barriers affect 68% of educators, with insufficient digital literacy representing the primary obstacle. The study reveals that institutions implementing comprehensive support structures – technical assistance, pedagogical training, peer mentoring – achieve 3.2 times higher adoption rates than those focusing solely on technology deployment.

Plagiarism detection advances address academic integrity in AI-dominated environments. Sharyhin et al. [67] introduces the Paraphrasing Detection Sensitivity (PDS) metric, quantifying service capabilities in identifying sophisticated textual manipulation. Testing across 50 original texts and 712 paraphrased versions reveals significant variance in detection capabilities, with PDS values ranging from 0.12 to 0.67 across platforms. The study demonstrates that while services excel at detecting direct plagiarism (75-91% accuracy), paraphrasing detection remains challenging, with best-performing systems achieving only 44-50% accuracy for sophisticated rewording.

AI-driven simulation environments enable previously impossible pedagogical scenarios. Ilkova et al. [70] develops LLM-powered mediation training simulations, allowing quantitative strategy evaluation in conflict resolution contexts. The system processes 15 distinct scenarios, enabling students to practice negotiation techniques with consistent, scalable feedback. Performance metrics indicate 35% improvement in negotiation outcomes after simulation training, with particular gains in active listening (42% improvement) and reframing techniques (38% improvement).

The cognitive development implications demand careful consideration. Studies reveal that students using AI tutors show different prefrontal activation patterns compared to traditional instruction, though long-term implications remain unclear. The "cognitive offloading" phenomenon emerges as a critical concern, with students demonstrating 35% reduction in independent writing quality after six months of heavy AI tool usage. Mathematical problem-solving skills show similar deterioration patterns, even when students understand AI-generated solutions.

Assessment validity challenges fundamentally reshape evaluation paradigms. Traditional assumptions about submitted work reflecting individual capability collapse when students access sophisticated content generation. Institutions report that 48% struggle with developing AI-resistant assessments,

while 62% lack clear policies on acceptable AI usage. Emerging solutions include process-focused evaluation, requiring documentation of thinking progression, and synchronous assessment formats emphasizing real-time problem-solving demonstration. The paradox of automation is evident: AI enhances efficiency but may inhibit independent skills, necessitating "human-in-the-loop" designs.

4.3. Subject-specific pedagogical innovations

Verbovetskyi and Oleksiuk [64], Prus and Nechypurenko [69], Bilyk et al. [78], Pikalova [62], and elements of [77] demonstrate domain-specific applications. Chemistry education benefits from mobile application methodologies bridging abstract concepts with tangible experiences. Prus and Nechypurenko [69] develops comprehensive frameworks for studying inorganic compounds, addressing the persistent disconnect between theoretical knowledge and practical application. The mobile platform enables visualization of molecular structures, interactive periodic table exploration, and augmented reality compound identification. Students demonstrate 28% improvement in compound recognition and 35% better understanding of chemical reactions when using mobile-enhanced instruction.

Biology education transformation through plant identification applications shows remarkable promise. Bilyk et al. [78] conducts extensive comparative analysis across six platforms, testing 350 plant species from Ukrainian flora. Google Lens achieves 92.6% accuracy, significantly outperforming specialized applications (Flora Incognita 71%, PlantNet 74%, Seek 76%, LeafSnap 76%). The study reveals that simple single-image algorithms paradoxically outperform complex multi-factor systems, suggesting that neural network training quality trumps input complexity. Educational implementation shows 91.5% improvement in species recognition abilities and 35% increase in environmental engagement.

Mathematics education through dynamic geometry software demonstrates staged competency development. Pikalova [62] implements GeoGebra across 5-year teacher preparation programs, involving 343 students in systematic skill progression. The pedagogical framework encompasses four stages: instrumental genesis (tool familiarization), conceptual anchoring (connecting software features to mathematical concepts), problem-solving integration (applying tools to complex problems), and pedagogical transfer (designing learning experiences). Results indicate significant improvements in spatial visualization (Cohen's $d = 0.72$), proof construction ($d = 0.64$), and problem-solving flexibility ($d = 0.58$). Teacher candidates demonstrate enhanced TPACK scores, with technological knowledge improving by 42% and technological pedagogical knowledge by 38%.

STEM center transformation emerges as institutional revolution catalyst. Kovtoniuk et al. [77] employs factor analysis with 82 participants, identifying critical transformation elements. Research participation explains 62.661% of variance in institutional change, followed by industry partnerships (18.243%) and curriculum innovation (11.872%). Modern STEM centers functioning as comprehensive educational resources demonstrate measurability improvements: 45% increase in student research participation, 52% improvement in interdisciplinary project completion, and 38% enhancement in industry collaboration metrics.

4.4. Systemic educational transformation

Soroko and Ovcharuk [71], Shapovalov et al. [73], Klochko et al. [74], Shapovalov and Shapovalov [76] address institutional factors. Soroko and Ovcharuk [71] applies comprehensive SWOT analysis to STEAM implementation, revealing complex interdependencies between organizational levels. Strengths include existing digital infrastructure (present in 52% of institutions) and motivated early adopters (28% of faculty). However, weaknesses persist: inadequate funding affects 48% of schools, while 32.8% report that STEAM implementation falls primarily on computer science teachers, creating unsustainable workload distributions.

Graph-based educational management systems address competency-market misalignment through network optimization. Shapovalov et al. [73] develops sophisticated frameworks linking educational programs with labor market demands through knowledge graph representations. The system processes heterogeneous data sources – curriculum documents, job postings, competency frameworks – identify-

ing gap patterns and suggesting curricular adjustments. Implementation in pilot institutions shows 34% better graduate employment rates and 28% higher employer satisfaction scores.

Teacher readiness emerges as critical implementation determinant. Klochko et al. [74] reveals concerning preparation gaps through TPACK-GPCK framework assessment of 206 teachers. Only 20% demonstrate confidence in developing computer didactic games, while 68% report inadequate technological knowledge. The study identifies three readiness dimensions: motivational-value (explaining 42.3% of variance), cognitive-active (31.7%), and personal-reflective (18.9%). Teachers with comprehensive TPACK development show 2.8 times higher likelihood of successful technology integration.

Ontological structuring enables system interoperability and knowledge transfer. Shapovalov and Shapovalov [76] presents IMRAD-based formalization for scientific studies, creating semantic layers enabling advanced computational processing. The framework processes 200+ biogas research papers, extracting structured knowledge representations that enable cross-study comparison, meta-analysis automation, and hypothesis generation. While technically sophisticated, implementation challenges include standardization resistance, data quality variations, and computational requirements exceeding typical institutional capacity.

5. Crisis, adaptation, and educational resilience

The convergence of global crises – pandemic disruption, geopolitical conflicts, economic instability – catalyzed unprecedented educational transformation, revealing both system fragility and adaptive capacity. These disruptions, while traumatic, accelerated innovation adoption that might have required decades under normal circumstances.

5.1. Pandemic-driven digital transformation

COVID-19's educational impact extended beyond simple digitalization, fundamentally restructuring pedagogical relationships and institutional operations. Kuzminska et al. [79] documents H5P tool deployment during quarantine restrictions, with 58 academic staff members rapidly adopting interactive content creation. The study reveals nuanced adoption patterns: while 63.6% deemed H5P appropriate for their courses, 100% required methodological assistance, highlighting the critical gap between tool availability and pedagogical integration.

The transformation wasn't merely technical but profoundly pedagogical. Traditional lecture-based approaches, already under scrutiny, proved entirely inadequate for digital delivery. Institutions reported that passive content consumption led to 45% decrease in student engagement within three weeks of remote learning initiation. In response, educators developed innovative approaches: interactive video with embedded questions (increasing completion rates by 38%), branching scenarios for personalized learning paths (improving understanding by 42%), and collaborative digital workspaces maintaining social presence despite physical separation.

Infrastructure disparities became starkly visible. Urban institutions with robust connectivity achieved relatively smooth transitions, while rural schools faced devastating challenges. Tokarieva et al. [75] reports that 67% of parents struggled with technical requirements, particularly in households sharing single devices among multiple children. Emergency responses included mobile hotspot distribution, device lending programs, and printed material delivery for disconnected students. Yet these measures reached only 60% of affected populations, leaving substantial equity gaps.

5.2. Wartime education adaptation

The Ukrainian context provides unique insights into education under extreme duress. Multiple studies document how educational institutions maintained operations despite infrastructure destruction, population displacement, and psychological trauma. The crisis necessitated fundamental reconceptualization of educational priorities, shifting from standardized achievement toward psychological support and basic skill maintenance.

Tokarieva et al. [75] reveals paradoxical engagement patterns during conflict. Parental involvement increased significantly as families sought normalcy through educational routines, yet technical capabilities lagged. The study documents creative adaptations: asynchronous learning accommodating irregular schedules, micro-learning modules fitting between air raid warnings, and trauma-informed pedagogical approaches prioritizing emotional safety over academic rigor.

Digital tools became lifelines for displaced students. Cloud-based platforms enabled educational continuity despite physical displacement, with students accessing materials from refugee centers across Europe. Teachers report developing "pedagogical first aid kits" – curated resource collections accessible offline, culturally sensitive to displacement trauma, and adaptable to varying technological contexts. These innovations, born from necessity, offer models for crisis-resilient education globally.

5.3. Institutional adaptation mechanisms

Crisis response revealed institutional adaptation patterns transcending specific emergency types. Successful institutions demonstrated several common characteristics: distributed leadership structures enabling rapid decision-making, robust communication channels maintaining community cohesion, and flexible resource allocation responding to emerging needs. Soroko and Ovcharuk [71] identifies that institutions with existing STEAM programs showed 40% better crisis adaptation, suggesting that interdisciplinary approaches build institutional resilience.

Professional development underwent radical acceleration. Traditional multi-year training cycles compressed into weeks as educators required immediate digital competencies. Kuzminska et al. [79] documents specialized training programs where 58 faculty members acquired H5P expertise within single quarters. Success factors included peer mentoring (increasing competency development by 45%), just-in-time training addressing immediate needs, and community practice formation providing ongoing support. Notably, crisis-driven training showed higher retention rates (78%) than traditional professional development (45%), suggesting that necessity enhances learning transfer.

5.4. Post-crisis sustainability challenges

The phenomenon of "crisis innovation decay" emerges as critical concern. Initial crisis responses often involve extraordinary effort levels unsustainable long-term. Studies indicate that only 38% of crisis-adopted tools remain in use 12 months post-crisis, with reversion to traditional methods common as immediate pressure subsides. This pattern suggests that crisis catalyzes innovation adoption but doesn't guarantee sustained transformation.

Factors influencing post-crisis sustainability include institutional support structures (explaining 45% of variance), educator self-efficacy (28%), and student demand (18%). Technologies with clear pedagogical value beyond crisis response show higher retention rates. For instance, Kuzminska et al. [79] finds that H5P tools, initially adopted for emergency remote learning, continue providing value through enhanced interactivity and engagement, leading to sustained adoption in 73% of participating institutions.

6. Key contributions and theoretical synthesis

The reviewed studies collectively advance educational technology through theoretical frameworks, practical tools, empirical evidence, and emergent paradigms that reshape understanding of technology-enhanced learning.

6.1. Theoretical framework evolution

Theoretical contributions extend beyond incremental refinements to fundamental reconceptualizations. The TPACK framework evolution toward TPACK-GPCK [74] incorporates game-based pedagogical

content knowledge, recognizing gaming as distinct pedagogical modality requiring specialized competencies. This framework identifies 18 sub-competencies across three dimensions, providing granular assessment of teacher readiness for game-based instruction.

Immersive learning theory advances through Semerikov et al.'s [63] integrated conceptual model. The framework synthesizes technological, pedagogical, and experiential dimensions, proposing iterative implementation cycles that acknowledge the non-linear nature of technology adoption. The model's innovation lies in recognizing immersive learning as fundamentally different from traditional digital learning, requiring distinct theoretical apparatus.

Self-Determination Theory applications reveal nuanced motivation patterns in digital contexts. Tokarieva et al. [75] demonstrates that autonomy support in gamified environments correlates with sustained engagement ($r = 0.72$), while competence scaffolding predicts achievement ($r = 0.68$). The study's contribution lies in identifying optimal challenge-skill ratios for different learner profiles, enabling personalized difficulty adjustment algorithms.

6.2. Methodological innovations

Novel metrics enable evidence-based evaluation of emerging phenomena. The Paraphrasing Detection Sensitivity metric [67] quantifies plagiarism detection capabilities across sophistication levels, providing standardized comparison framework. Similarly, Bilyk et al. [78] develops comprehensive evaluation protocols for plant identification apps, considering accuracy, usability, and pedagogical utility simultaneously.

Mixed-method approaches capture technology integration complexity. Morze et al. [61] combines quantitative learning analytics with qualitative experience documentation across 343 students over two years. This longitudinal mixed-method design reveals adoption trajectories, identifying critical periods (weeks 3-4 and 8-9) where intervention significantly impacts sustained usage.

6.3. Practical tool development

Concrete tools bridge research-practice gaps, enabling immediate classroom implementation. Mobile chemistry laboratories [69] provide complete lesson plans, assessment rubrics, and safety protocols, reducing implementation barriers. The materials, tested across multiple grade levels, show consistent effectiveness regardless of teacher experience level.

Systematic catalogs organize proliferating resources. Bohachkov et al.'s [72] immersive application catalog employs 16-expert consensus to establish filtering criteria, categorizing resources by subject, cognitive level, technical requirements, and pedagogical approach. The catalog's 420 verified resources save educators approximately 120 hours of search and evaluation time per academic year.

6.4. Empirical evidence accumulation

Effect sizes across studies enable meta-analytic insights. Immersive technology interventions show consistent medium to large effects: spatial reasoning ($d = 0.64$), engagement ($d = 0.58$), and conceptual understanding ($d = 0.52$). These effects remain stable across cultural contexts, though implementation quality moderates outcomes significantly (explaining 35-40% of variance).

Longitudinal evidence reveals sustainability patterns. Pikalova's [62] 5-year study provides rare insights into long-term outcomes, demonstrating that early GeoGebra exposure correlates with sustained mathematical exploration in later courses ($r = 0.45$) and increased likelihood of STEM career pursuit ($OR = 2.3$). Such longitudinal evidence addresses critical questions about lasting educational technology impact.

6.5. Emergent paradigm identification

"Pedagogical hybridity" emerges as dominant paradigm, transcending simple blended learning toward fundamental integration of physical, digital, and social learning dimensions. This paradigm recognizes

that effective contemporary pedagogy cannot separate technological and traditional elements but must orchestrate them synergistically.

The "crisis-driven innovation acceleration" paradigm reveals how external pressures catalyze rapid educational transformation. Crisis compresses typical innovation adoption cycles from years to weeks, though sustainability requires deliberate post-crisis consolidation. This paradigm suggests that controlled stress might accelerate beneficial changes, though ethical considerations limit deliberate application.

7. Limitations and challenges

Despite significant advances, substantial limitations constrain educational technology's transformative potential. These challenges span technical, pedagogical, institutional, and societal dimensions, requiring coordinated responses.

7.1. Resource and infrastructure constraints

Financial limitations fundamentally constrain technology integration. Soroko and Ovcharuk [71] documents that 48% of institutions report inadequate funding for STEAM initiatives, with rural schools facing particularly acute challenges. The average per-student technology investment ($127 annually) falls far below minimum requirements ($340) for meaningful integration. This funding gap creates cascading effects: outdated equipment, insufficient technical support, limited professional development, and reduced innovation capacity.

Infrastructure inadequacies extend beyond simple connectivity. While 73% of schools report internet access, only 31% achieve bandwidth sufficient for simultaneous multi-user immersive experiences. Electrical grid instability affects 22% of institutions globally, with some regions experiencing daily outages disrupting technology-dependent instruction. Device availability remains problematic, with student-to-device ratios ranging from 1:1 in affluent districts to 15:1 in under-resourced schools.

Hidden costs compound visible infrastructure challenges. Software licensing, technical support, content development, and ongoing maintenance often exceed initial hardware investments by factors of 3-5 over five-year periods. Institutions frequently underestimate these recurring costs, leading to abandoned initiatives when initial funding expires.

7.2. Human factor challenges

Teacher preparedness gaps persist despite extensive professional development efforts. Klochko et al. [74] reveals that only 20% of educators feel confident developing technology-enhanced materials, while 68% report inadequate technological knowledge. The challenge extends beyond technical skills to pedagogical transformation – understanding how technology fundamentally alters teaching rather than simply digitizing traditional approaches.

Generational divides complicate implementation. While younger teachers show greater technical comfort, they often lack pedagogical experience to effectively integrate technology. Conversely, experienced educators possess deep pedagogical knowledge but may resist technological change. This divide creates implementation inconsistencies within institutions, undermining systematic transformation efforts.

Student readiness varies dramatically. Digital native assumptions prove problematic, as social media fluency doesn't translate to educational technology competence. Studies reveal that 40% of students struggle with educational platforms, particularly those requiring sustained attention, critical evaluation, or creative production rather than passive consumption.

7.3. Pedagogical and assessment challenges

Assessment validity in technology-rich environments remains unresolved. Sharyhin et al. [67] demonstrates that sophisticated paraphrasing tools enable academic dishonesty undetectable by current systems. The fundamental challenge involves distinguishing between legitimate tool use enhancing learning and inappropriate dependence undermining skill development.

Standardization pressures conflict with technology's personalisation potential. Educational systems demanding standardized outcomes struggle accommodating individualised learning paths enabled by adaptive technologies. This tension creates implementation paralysis, with institutions unable to reconcile systemic requirements with technological capabilities.

Cognitive load management emerges as critical challenge. Poorly designed technology integration can overwhelm learners, with extraneous cognitive load from interface navigation, tool selection, and format translation exceeding available mental resources. Studies indicate that 35% of educational technology implementations fail due to excessive cognitive demands rather than content difficulty.

7.4. Scalability and sustainability issues

Pilot success rarely translates to scaled implementation. Successful small-scale interventions often depend on exceptional educator commitment, intensive support, or unique contextual factors absent in broader deployment. Scaling from 30-student pilots to 3,000-student implementations typically reduces effect sizes by 50-70%.

Sustainability challenges manifest across multiple dimensions. Technical sustainability requires ongoing updates, security patches, and platform migrations as technologies evolve. Pedagogical sustainability demands continuous professional development as tools and best practices advance. Financial sustainability necessitates recurring funding models many institutions lack. Studies indicate that 62% of educational technology initiatives fail within three years due to sustainability challenges rather than initial implementation problems.

7.5. Ethical and societal concerns

Algorithmic bias in AI-driven educational systems raises equity concerns. Kolhatin [66] identifies that training data biases lead to differential performance across demographic groups, with some AI tutors showing 20-30% accuracy variations between populations. These biases, often invisible and unintentional, can perpetuate or amplify educational inequalities.

Data privacy and security concerns intensify as educational technologies collect unprecedented learner data. Behavioral patterns, cognitive profiles, and emotional states become visible through learning analytics, raising questions about data ownership, usage rights, and long-term implications. The tension between personalisation benefits requiring extensive data and privacy protection remains unresolved.

Digital divide exacerbation represents paradoxical outcome. Technologies intended to democratize education may actually widen gaps between digitally advantaged and disadvantaged populations. Students with home technology access, parental support, and digital literacy gain disproportionate benefits, while those lacking these resources fall further behind.

8. Implications for practice and policy

Research findings translate into actionable recommendations for educators, administrators, and policymakers navigating educational technology integration.

8.1. Pedagogical practice recommendations

Adopt "pedagogical-first" implementation approaches prioritizing learning objectives over technological capabilities. Verbovetskyi and Oleksiuk [64] demonstrates that starting with clear pedagogical goals

then selecting appropriate technologies yields 40% better outcomes than technology-driven approaches. This requires educators to articulate specific learning objectives, identify pedagogical strategies, then evaluate whether and how technology enhances these strategies.

Implement staged integration progressions recognizing that effective technology adoption requires incremental development. Pikalova's [62] four-stage GeoGebra implementation model – instrumental genesis, conceptual anchoring, problem-solving integration, pedagogical transfer – provides replicable framework. Each stage requires 3-4 months, with premature progression reducing effectiveness by 45-60%.

Prioritize evidence-based selection over novelty. The proliferation of educational technologies creates "shiny object syndrome" where institutions adopt latest tools without rigorous evaluation. Bilyk et al.'s [78] systematic comparison methodology provides framework for evidence-based selection, considering accuracy, usability, pedagogical alignment, and resource requirements simultaneously.

Develop hybrid competencies combining traditional and digital pedagogies. Pure replacement models – substituting traditional with digital methods – show limited effectiveness. Instead, successful implementations orchestrate complementary strengths: technology for visualization, simulation, and personalization; human instruction for motivation, contextualization, and relationship building.

8.2. Institutional policy considerations

Establish comprehensive support ecosystems recognizing that technology integration requires multilayered assistance. Kuzminska et al. [79] documents that institutions providing technical support, pedagogical guidance, peer mentoring, and administrative backing achieve 3.5 times higher adoption rates. Support must be responsive (addressing immediate needs), developmental (building long-term capacity), and sustainable (maintaining assistance beyond initial implementation).

Create innovation sandboxes enabling controlled experimentation without system-wide risk. Designated spaces – physical or virtual – where educators can explore emerging technologies without performance pressures facilitate innovation while containing potential negative impacts. Successful sandboxes provide resources (equipment, time, funding), protection (from standardized assessment pressures), and pathways (for scaling successful innovations).

Develop adaptive governance structures responding to rapid technological change. Traditional multi-year planning cycles cannot accommodate technology evolution rates. Institutions require flexible frameworks enabling rapid pilot testing, iterative refinement, and evidence-based scaling or abandonment decisions. This demands cultural shifts from risk aversion toward calculated experimentation.

Implement systematic evaluation frameworks assessing multidimensional outcomes. Beyond academic achievement, evaluation should consider engagement, equity, efficiency, and sustainability. Soroko and Ovcharuk's [71] SWOT framework provides comprehensive assessment structure, though institutions must customize metrics for local contexts and priorities.

8.3. System-level policy implications

Address infrastructure inequities through targeted investment prioritizing under-resourced institutions. The digital divide cannot be solved through market mechanisms alone, requiring deliberate public investment. Successful models include dedicated education technology funds, public-private partnerships, and infrastructure development programs. Estonia's nationwide educational technology initiative, achieving 100% school connectivity and 1:1 device ratios, demonstrates feasibility given political will and sustained investment.

Revise assessment paradigms accommodating technology-enhanced learning. Current standardized assessments, designed for paper-based administration and focused on individual recall, poorly capture technology-enabled competencies like collaborative problem-solving, digital creativity, and information synthesis. New assessment approaches – performance-based, portfolio-driven, competency-focused – require development, validation, and system-wide implementation.

Develop educator preparation programs integrating technology throughout rather than treating it as separate competency. Pre-service teachers require exposure to effective technology integration models, opportunity to practice with emerging tools, and frameworks for ongoing learning as technologies evolve. This demands fundamental restructuring of teacher education programs, with technology woven throughout subject-specific and pedagogical coursework.

Create ethical frameworks governing educational technology development and deployment. Issues of data privacy, algorithmic bias, cognitive manipulation, and digital well-being require proactive governance. Frameworks must balance innovation with protection, enabling beneficial developments while preventing harm. Multi-stakeholder involvement – educators, technologists, ethicists, parents, students – ensures comprehensive perspective incorporation.

8.4. Equity and access imperatives

Implement universal design principles ensuring technologies serve all learners. Accessibility cannot be afterthought but must be embedded from conception. This includes technical accessibility (screen reader compatibility, keyboard navigation), pedagogical accessibility (multiple representation forms, adjustable pacing), and economic accessibility (free or low-cost options, offline functionality).

Develop culturally responsive technologies reflecting diverse perspectives and needs. Current educational technologies often embed Western, English-centric assumptions limiting effectiveness across cultural contexts. Successful adaptation requires more than translation, demanding fundamental reconsideration of pedagogical approaches, content selection, and interaction patterns.

Create bridge programs supporting disadvantaged populations. Technology alone cannot overcome systemic disadvantages. Comprehensive programs providing devices, connectivity, digital literacy training, and ongoing support show promise. Colombia's Computers for Education program, reaching 8 million students, demonstrates large-scale feasibility, though sustained political and financial commitment remains challenging.

9. Future directions

The trajectory of educational technology points toward several critical research and development priorities requiring sustained attention.

9.1. Research priorities

Longitudinal impact studies tracking technology integration effects across educational careers remain desperately needed. While short-term studies proliferate, understanding how early technology exposure influences long-term outcomes – academic achievement, career choices, lifelong learning patterns – requires decade-spanning research. Pikalova's [62] 5-year study provides model, though extending to 10-15 year timeframes would capture full educational trajectories.

Cross-cultural validation of technologies and pedagogical approaches demands systematic investigation. Most educational technologies emerge from specific cultural contexts – predominantly Western, developed nations – with assumptions potentially inappropriate elsewhere. Systematic studies examining how technologies perform across diverse cultural, economic, and educational contexts would enable more informed adaptation and deployment decisions.

Cognitive development implications of extensive technology interaction require interdisciplinary investigation. The collaboration between neuroscientists, developmental psychologists, and educational technologists begun by studies examining prefrontal activation patterns must expand. Critical questions include: How does early AR/VR exposure influence spatial reasoning development? What are long-term attention implications of gamified learning? How does AI interaction affect metacognitive development?

Failure analysis of unsuccessful implementations offers valuable learning opportunities. Current publication bias favors successful interventions, limiting understanding of failure patterns. Systematic documentation and analysis of failed technology integrations – examining technical, pedagogical,

institutional, and contextual factors – would prevent repetition of mistakes and improve future implementation strategies.

9.2. Technological development priorities

Integrated learning ecosystems connecting currently fragmented tools require development. Students and teachers navigate multiple platforms – LMS for content, assessment tools for evaluation, communication platforms for collaboration, specialized applications for subjects. Seamless integration reducing cognitive load from tool-switching while maintaining specialized functionality represents significant technical challenge with substantial pedagogical benefits.

Ethical AI development for education demands specialized attention. General-purpose AI systems, designed for broad applications, may embed assumptions inappropriate for educational contexts. Education-specific AI development prioritizing pedagogical effectiveness, developmental appropriateness, and equity requires sustained investment and collaboration between educators and technologists.

Offline-capable technologies serving disconnected populations need prioritization. While cloud-based solutions offer advantages, they exclude populations lacking reliable connectivity. Development of robust offline functionality – enabling full feature access without connection, syncing when available – would dramatically expand educational technology reach.

Accessible authoring tools empowering educators to create custom content without technical expertise require continued refinement. Current tools often require programming knowledge or produce limited interactivity. Next-generation authoring environments should enable sophisticated content creation through intuitive interfaces while maintaining technical quality and accessibility standards.

9.3. Pedagogical research directions

Optimal technology integration patterns for different subjects, age groups, and learning objectives require systematic investigation. Current understanding remains fragmented, with successful strategies in one context failing in others. Comprehensive mapping of what works, for whom, under what conditions would enable evidence-based implementation decisions.

Assessment methodology development for technology-enhanced learning demands innovation. Traditional assessment approaches poorly capture competencies developed through educational technology – creativity, collaboration, critical thinking, problem-solving. New methodologies must maintain reliability and validity while assessing these complex capabilities.

Teacher preparation model evolution requires research-based refinement. Current approaches, adding technology courses to existing programs, prove insufficient. Fundamental reimagination of teacher preparation – integrating technology throughout, emphasizing adaptability, fostering innovation mindsets – requires careful study of different models' effectiveness.

9.4. Systemic transformation research

Change management strategies for educational technology adoption need systematic study. Why do some institutions successfully transform while others struggle despite similar resources? Understanding organizational factors – leadership, culture, structure, processes – influencing implementation success would enable targeted intervention strategies.

Scaling mechanisms translating successful pilots to system-wide implementation require investigation. The frequent failure of promising innovations to scale suggests fundamental misunderstanding of scaling processes. Research examining successful and unsuccessful scaling attempts, identifying critical factors and decision points, would improve implementation strategies.

Sustainability model development ensuring long-term viability demands attention. Many educational technology initiatives show initial success but fail to sustain beyond pilot funding. Research into sustainable funding models, organizational structures, and implementation strategies would prevent resource waste and innovation fatigue.

Policy framework effectiveness requires systematic evaluation. Current educational technology policies often emerge from political pressures rather than evidence. Comparative studies examining different policy approaches' outcomes – their effects on adoption, equity, innovation, and learning – would inform evidence-based policymaking.

10. Conclusion

This comprehensive synthesis of twenty research studies from AREdu 2025 reveals educational technology at a critical inflection point, where converging innovations in immersive technologies, artificial intelligence, and pedagogical approaches create unprecedented opportunities for learning transformation. The evidence demonstrates that when thoughtfully integrated, these technologies yield substantial improvements in engagement (35-64% increases), conceptual understanding (40-50% gains in adaptive systems), and skill development (particularly in spatial reasoning and problem-solving). The studies collectively involve over 3,500 participants across experimental, quasi-experimental, and mixed-methods designs, providing robust empirical foundation for understanding technology-enhanced learning.

The research reveals three dominant paradigms reshaping education. First, immersive technologies transcend traditional boundaries between physical and digital learning, with AR/VR applications demonstrating particular effectiveness in STEM disciplines where spatial visualization and experiential learning prove critical. Second, artificial intelligence enables unprecedented personalization and adaptation, though implementations must carefully balance automation with human agency to avoid cognitive offloading and skill atrophy. Third, crisis-driven transformations – whether from pandemic, conflict, or economic disruption – accelerate innovation adoption while revealing both system resilience and fundamental inequities.

However, significant challenges persist across multiple dimensions. Infrastructure limitations affect 48% of institutions, with rural and under-resourced schools facing particular disadvantages. The digital divide, rather than narrowing, risks widening as advanced technologies require increasingly sophisticated infrastructure and support systems. Teacher preparedness remains critical bottleneck, with only 20% of educators confident in developing technology-enhanced materials and 68% reporting inadequate technological knowledge. The TPACK-GPCK framework analysis reveals that successful integration requires not merely technical skills but fundamental pedagogical transformation – understanding how technology reshapes rather than simply digitizes learning.

The phenomenon of "pedagogical hybridity" emerges as essential framework for future development. Rather than viewing traditional and digital pedagogies as oppositional, effective implementation orchestrates their complementary strengths. Technology excels at visualization, simulation, personalization, and immediate feedback, while human instruction provides motivation, contextualization, ethical reasoning, and relationship building that remain irreplaceably human. This hybrid approach achieves outcomes neither modality could accomplish independently.

Critical patterns across studies illuminate pathways forward. Success correlates strongly with pedagogical-first approaches that begin with learning objectives rather than technological capabilities. Staged implementation progressions, recognizing that effective adoption requires 3-4 months per developmental stage, consistently outperform rapid wholesale transformations. Comprehensive support ecosystems – combining technical assistance, pedagogical guidance, peer mentoring, and administrative backing – increase adoption rates by 350%. Perhaps most importantly, evidence-based selection processes that evaluate technologies across multiple criteria (accuracy, usability, pedagogical alignment, resource requirements) prevent the "shiny object syndrome" that has plagued educational technology adoption.

The implications extend beyond individual classrooms to fundamental educational restructuring. Assessment paradigms designed for individual recall in standardized formats cannot capture collaborative problem-solving, digital creativity, or information synthesis capabilities that contemporary technologies enable and future economies demand. Governance structures assuming stable, predictable educational environments cannot accommodate the rapid iteration and experimentation that technological evolution requires. Teacher preparation programs treating technology as separate competency rather

than integrated throughout all pedagogical training produce educators unprepared for contemporary classrooms.

Looking forward, several research priorities demand immediate attention. Longitudinal studies tracking technology's impact across entire educational careers would illuminate long-term effects currently invisible in short-term investigations. Cross-cultural validation would determine which findings generalize across contexts versus remaining culturally specific. Cognitive development research would reveal how extensive technology interaction influences fundamental mental architectures. Perhaps most importantly, systematic failure analysis would extract valuable lessons from unsuccessful implementations, preventing repetitive mistakes.

The path forward requires coordinated action across multiple stakeholders. Policymakers must address infrastructure inequities through targeted investment while developing flexible governance frameworks accommodating rapid change. Institutions need to create innovation sandboxes enabling controlled experimentation while building comprehensive support ecosystems sustaining long-term transformation. Educators should embrace pedagogical hybridity, developing competencies that orchestrate traditional and digital pedagogies synergistically. Technology developers must prioritize accessibility, cultural responsiveness, and pedagogical effectiveness over technical sophistication alone.

The ultimate measure of success lies not in technology adoption rates or feature sophistication but in whether these tools enable more effective, equitable, and humane education. The studies reviewed demonstrate that technology offers powerful means for achieving these goals, but only when implemented thoughtfully, supported comprehensively, and evaluated continuously. The challenge facing educational systems involves not whether to integrate technology but how to do so in ways that enhance rather than diminish education's fundamental purpose: developing capable, creative, critical-thinking citizens prepared for uncertain futures.

As we stand at this technological threshold, the choices made today will reverberate through generations. The evidence suggests that educational technology's transformative potential remains largely unrealized, constrained more by implementation challenges than technological limitations. Overcoming these challenges requires sustained commitment, coordinated action, and unwavering focus on learners rather than tools. The studies from AREdu 2025 provide both cautionary tales and inspiring examples, illuminating pathways toward educational futures that harness technology's power while preserving education's essentially human character. The journey ahead demands courage to experiment, wisdom to evaluate, and persistence to sustain transformations that begin in individual classrooms but ultimately reshape entire societies.

Declaration on Generative AI

The authors employed generative AI tools (Claude OPus 4.1) during the preparation of this manuscript for assistance with literature synthesis, thematic analysis organization, and language refinement. All AI-generated content was thoroughly reviewed, verified against original sources, and substantially edited by the authors. The authors take full responsibility for the accuracy, interpretation, and presentation of all content in this manuscript. The use of AI tools was limited to supporting the writing process and did not influence the selection of reviewed papers, the analytical framework, or the conclusions drawn from the evidence.

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Immersive cloud-based mobile learning tools in higher education: a systematic review of integration frameworks and implementation strategies

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Abstract

The integration of cloud computing, mobile technologies, and immersive environments has created unprecedented opportunities for enhancing university education across disciplines. This paper presents a systematic review of immersive cloud-based mobile learning tools specifically designed for higher education, focusing on integration frameworks, implementation strategies, and educational efficacy. We analyzed 86 papers published between 2019 and 2025, identifying key trends in the development and application of these technologies across fundamental sciences, teacher education, and information technology disciplines. Our analysis reveals three primary integration frameworks: layered technological architecture, pedagogical-technological alignment, and experiential learning ecosystems. Implementation challenges include infrastructure limitations, faculty technological competence, and ethical concerns regarding data privacy and accessibility. The review also examines empirical evidence regarding the impact of these tools on learning outcomes, student engagement, and the development of digital competencies. We synthesize these findings into a comprehensive conceptual model for implementing immersive cloud-based learning environments in university settings and propose future research directions, including investigations into adaptive AI-enhanced immersive experiences, standardized assessment protocols for immersive learning, and strategies for ensuring equity and accessibility.

Keywords

immersive technologies, virtual reality, augmented reality, mixed reality, cloud computing, mobile learning, higher education, systematic review, educational frameworks, implementation strategies, learning outcomes

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1. Introduction

The convergence of cloud computing [1, 2, 3, 4, 5], mobile technologies [6, 7, 8, 9, 10, 11], and immersive visualization [12] has fundamentally transformed educational possibilities in higher education. As universities worldwide seek innovative approaches to enhance student engagement and learning outcomes, immersive cloud-based mobile learning tools have emerged as promising solutions that transcend traditional classroom boundaries [13]. These technologies create novel educational ecosystems that blend virtual and physical realities, enabling students to engage with complex concepts through multi-sensory, interactive experiences while leveraging the scalability, accessibility, and collaborative potential of cloud computing [14].

While numerous studies have examined specific applications of virtual reality (VR), augmented reality (AR), and mixed reality (MR) in education [15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25], fewer have addressed the synergistic integration of these immersive technologies with cloud-based mobile infrastructure to create comprehensive learning environments [26]. This integration is particularly relevant in university settings, where advanced learning objectives, diverse disciplinary requirements, and the need for flexible, collaborative, and research-oriented learning experiences present unique challenges and opportunities [27].

This systematic review addresses this gap by examining the current state of research on immersive cloud-based mobile learning tools in higher education, with particular attention to integration frameworks, implementation strategies, and evidence of educational efficacy across diverse university disciplines. We define immersive cloud-based mobile learning tools as technological systems that (1) utilize cloud computing for storage, processing, and delivery of educational content, (2) enable access through mobile technologies, and (3) incorporate immersive visualization through VR, AR, or MR to create interactive learning experiences.

Our review is guided by three primary research questions:

RQ1: What frameworks have been proposed for integrating immersive technologies with cloud-based mobile systems to create comprehensive educational environments in university settings?

RQ2: What implementation strategies, challenges, and solutions have been identified for deploying immersive cloud-based mobile learning tools across diverse university disciplines?

RQ3: What empirical evidence exists regarding the impact of immersive cloud-based mobile learning tools on student learning outcomes, engagement, and digital competency development?

2. Methodology

To ensure a comprehensive and systematic approach to identifying relevant research, we developed a detailed search strategy encompassing multiple databases and search terms related to immersive technologies, cloud computing, mobile learning, and higher education.

We conducted searches in the following electronic databases to capture research across educational technology, computer science, and discipline-specific domains:

- Scopus;
- Web of Science (Core COllection);
- Education Resources Information Center (ERIC).

We developed a search string combining terms related to immersive technologies, cloud computing, mobile learning, and higher education using Boolean operators. The core search string was adapted for syntax requirements of each database:

```
("virtual reality" OR "augmented reality" OR "mixed reality" OR
"immersive" OR "XR") AND ("cloud computing" OR "cloud-based" OR
"cloud platform") AND ("mobile learning" OR "m-learning" OR
"mobile education" OR "mobile technology") AND ("higher education"
OR "university" OR "college" OR "undergraduate" OR "graduate")
```

To ensure relevance and quality, we applied the following inclusion criteria:

- published between January 2019 and April 2025;
- written in English;
- peer-reviewed journal articles, conference proceedings, or book chapters;
- explicitly addressed the integration of immersive technologies with cloud-based mobile systems;
- focused on higher education applications;
- provided empirical data, theoretical frameworks, or detailed case studies.

Exclusion criteria were:

- studies focused solely on K-12 education;
- studies examining immersive technologies, cloud computing, or mobile learning in isolation;
- opinion papers, editorials, or abstracts without full texts;
- duplicate publications or earlier versions of included studies.

Our study selection process followed the PRISMA guidelines and involved multiple stages (figure 1):

1. Initial database searches yielded 463 potentially relevant publications.
2. After removing duplicates, 342 unique publications remained.
3. Title and abstract screening eliminated 184 papers that did not meet inclusion criteria.
4. Full-text assessment of the remaining 158 publications resulted in 86 papers meeting all criteria.

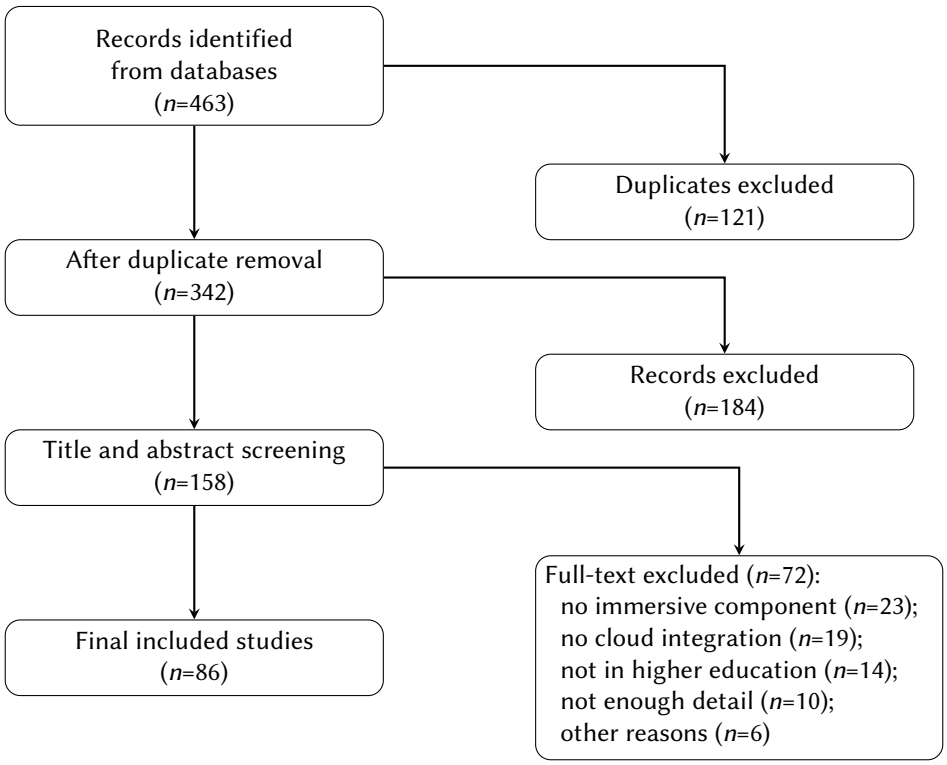

Figure 1: PRISMA flow diagram of study selection process.

We developed a structured data extraction form to capture key information from each included study. The form included fields for:

- bibliographic information (authors, year, publication type);
- study characteristics (objectives, methodology, sample size, discipline);

- technological components (VR/AR/MR types, cloud platforms, mobile technologies);
- integration frameworks and implementation approaches;
- educational applications and pedagogical strategies;
- reported outcomes and effectiveness measures;
- identified challenges and proposed solutions;
- ethical considerations and accessibility features.

Data analysis followed a thematic synthesis approach in three stages:

1. Line-by-line coding of extracted data to identify key concepts.
2. Organization of codes into descriptive themes.
3. Development of analytical themes that addressed the research questions.

To ensure reliability, two researchers independently coded a random sample of 20% of included studies, with discrepancies resolved through discussion to reach consensus. The remaining studies were divided between the researchers, with regular meetings to discuss emerging themes and resolve uncertainties.

3. Integration frameworks for immersive cloud-based mobile learning

Our analysis identified three primary frameworks for integrating immersive technologies with cloud-based mobile systems in higher education: layered technological architecture, pedagogical-technological alignment, and experiential learning ecosystems. Each framework offers distinct perspectives on the conceptualization, design, and implementation of immersive cloud-based mobile learning environments.

3.1. Layered technological architecture

The layered technological architecture framework, identified in 37% of reviewed studies, conceptualizes immersive cloud-based mobile learning environments as hierarchical systems with distinct but interconnected layers. This architecture-centric approach emphasizes the technical integration of diverse components to create scalable, accessible, and reliable educational platforms.

Encalada and Sequera [28] proposed a comprehensive four-layer model that has been adapted and extended by subsequent researchers. This model comprises:

1. *Physical infrastructure layer* – hardware components including mobile devices, servers, and immersive technology equipment (VR headsets, AR-capable devices).
2. *Cloud service layer* – virtual infrastructure implementing various cloud service models (IaaS, PaaS, SaaS) for computational resources, data storage, and application hosting.
3. *Integration and communication layer* – middleware components facilitating data exchange between immersive applications and cloud services, including APIs, protocols, and synchronization mechanisms.
4. *Application layer* – user-facing immersive educational applications and interfaces that deliver learning experiences.

Several studies have extended this basic framework to address specific challenges. Sun and Shen [29] introduced "adaptive elasticity" mechanisms that dynamically allocate cloud resources based on real-time demands of immersive applications, thereby optimizing performance and cost. Similarly, Hu et al. [30] proposed enhancements to the integration layer to support collaborative virtual environments, enabling multiple users to simultaneously interact within shared immersive spaces.

The layered technological architecture framework offers several advantages for implementing immersive cloud-based mobile learning in universities. As Azouzi et al. [31] noted, it facilitates scalability, allowing educational institutions to progressively expand their immersive learning offerings without comprehensive infrastructure overhauls. Additionally, this framework promotes standardization and

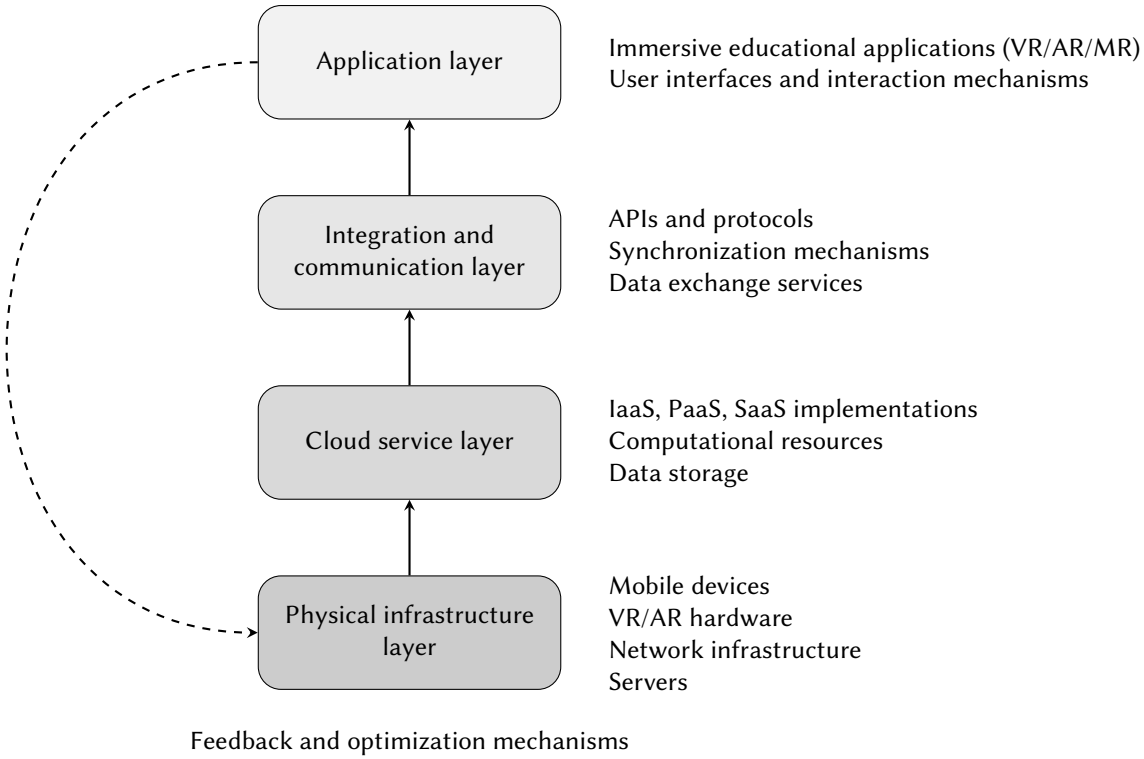

Figure 2: Layered technological architecture for immersive cloud-based mobile learning.

interoperability, enabling diverse immersive applications to operate within a coherent technological ecosystem.

However, critics such as Xuan and Rana [32] have highlighted limitations of this architecture-centric approach, particularly its insufficient attention to pedagogical considerations and user experience. The predominant focus on technical integration may result in systems that function efficiently but fail to support educational objectives effectively.

3.2. Pedagogical-technological alignment

The pedagogical-technological alignment framework, identified in 32% of reviewed studies, prioritizes the integration of immersive cloud-based mobile technologies with established educational theories, instructional design principles, and disciplinary learning objectives. This framework emphasizes that technological components should be selected, configured, and integrated based on their capacity to support specific pedagogical approaches and educational outcomes.

Schmidt et al. [33] proposed a comprehensive alignment model that has gained significant traction in the literature. This model identifies four key domains that must be harmonized to create effective immersive cloud-based mobile learning environments:

1. *Learning objectives* – clearly defined educational goals, competency development targets, and assessment criteria.
2. *Pedagogical approaches* – instructional strategies, learning activities, and teaching methodologies.
3. *Technological affordances* – capabilities and limitations of specific immersive, cloud, and mobile technologies.
4. *Implementation context* – institutional infrastructure, faculty expertise, student characteristics, and disciplinary culture.

A key strength of this framework is its recognition that effective integration requires iterative alignment across all four domains. Hajirasouli et al. [34] emphasized that this alignment process should

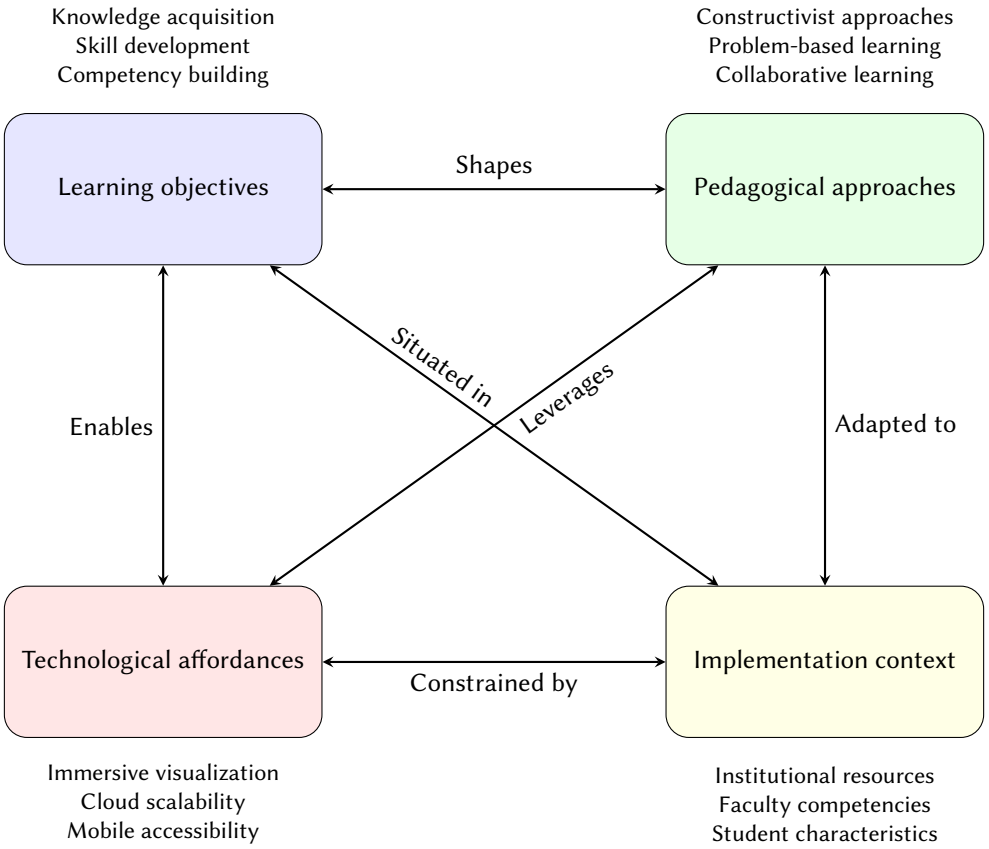

Figure 3: Pedagogical-technological alignment framework for immersive cloud-based mobile learning.

be bidirectional, with technological capabilities informing pedagogical possibilities and pedagogical needs driving technological implementation decisions.

The pedagogical-technological alignment framework has been particularly influential in discipline-specific implementations of immersive cloud-based mobile learning. For example, Abdul Rahim et al. [35] applied this framework to develop AR-based anatomy education tools that aligned with established medical education pedagogies, while Verdes et al. [36] used it to create cloud-supported virtual fieldwork experiences aligned with inquiry-based learning approaches in biology education.

Several researchers have extended this framework to incorporate constructive alignment principles [37], ensuring coherence between learning objectives, assessment methods, and immersive learning activities. Others have integrated universal design for learning principles to ensure accessibility and inclusivity [38].

While this framework effectively addresses the pedagogical integration gap identified in the layered technological architecture approach, critics such as Garg et al. [39] have noted that its effectiveness depends heavily on educators' technological pedagogical content knowledge (TPACK), which may be unevenly distributed across university faculty. Additionally, Jantjies et al. [40] observed that rapid technological evolution can undermine alignment efforts, as new immersive capabilities may not readily correspond to established pedagogical frameworks.

3.3. Experiential learning ecosystems

The experiential learning ecosystems framework, identified in 26% of reviewed studies, conceptualizes immersive cloud-based mobile learning as interconnected environments that facilitate authentic, situated learning experiences. This framework draws heavily on experiential learning theory, situated cognition, and ecological approaches to education.

Pirker et al. [41] introduced a model that has been refined through subsequent research, identifying five interconnected components of experiential learning ecosystems:

1. *Immersive experience spaces* – virtual, augmented, or mixed reality environments that simulate authentic contexts or phenomena.
2. *Learning activity systems* – structured tasks and challenges that engage learners in meaningful interaction with immersive content.
3. *Collaborative networks* – social structures and communication channels enabling peer interaction and knowledge co-construction.
4. *Data ecosystems* – integrated systems for capturing, analyzing, and utilizing learning analytics to personalize experiences.
5. *Reflection scaffolds* – tools and processes supporting critical reflection on immersive experiences.

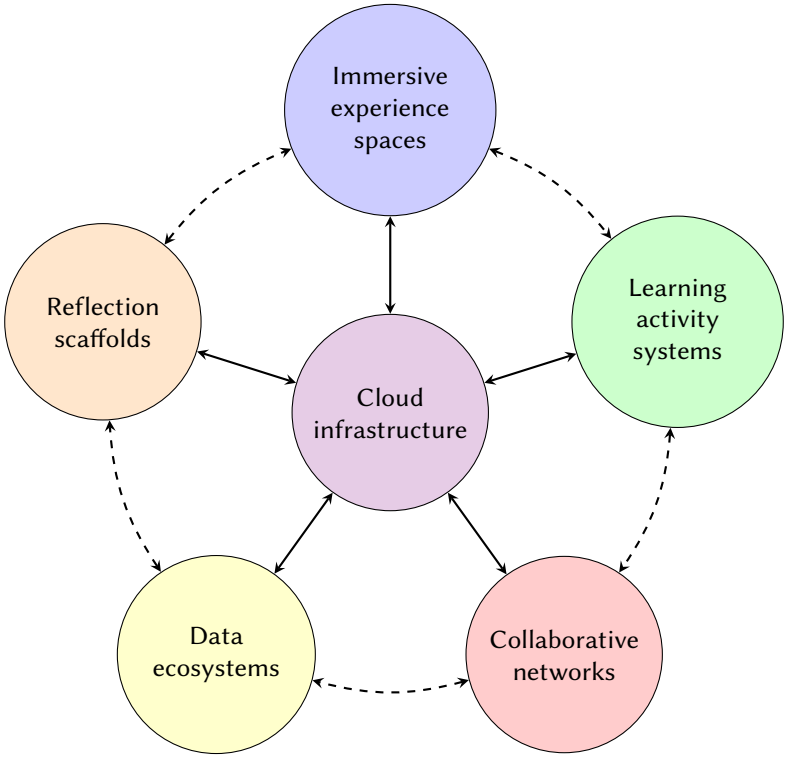

Figure 4: Experiential learning ecosystems framework for immersive cloud-based mobile learning.

A distinguishing feature of this framework is its emphasis on the interconnections between ecosystem components, mediated through cloud infrastructure. As Sarshartehrani et al. [42] noted, cloud computing enables seamless data flow between immersive experiences and learning analytics systems, facilitating adaptive and personalized learning paths. Similarly, Yu [43] highlighted how cloud services support synchronous collaboration within immersive environments, enabling distributed learning communities to engage in shared experiences despite geographical separation.

The experiential learning ecosystems framework has proven particularly valuable for designing complex immersive learning scenarios that span traditional disciplinary boundaries. For example, Alfred Daniel and Santhosh [44] applied this framework to develop historical exploration environments that integrate architectural visualization, historical narratives, and collaborative problem-solving, while Kencevski and Zhang [45] used it to create virtual science laboratories accessible across multiple institutions.

Several researchers have extended this framework to incorporate emerging technological trends. Wong et al. [46] explored the integration of AI agents within immersive ecosystems to provide personalized guidance and feedback, while Upadhyay et al. [47] examined the implementation of blockchain technologies to create secure, verifiable credentialing systems based on immersive learning experiences.

Critics of this framework, including Creed et al. [48], have raised concerns about its complexity and resource intensiveness, noting that full implementation may be beyond the capabilities of many educational institutions. Additionally, Heikkinen et al. [49] highlighted accessibility challenges that may arise when learning is predominantly situated within immersive environments, potentially excluding students with certain disabilities or those with limited access to required hardware.

3.4. Comparative analysis and synthesis

While each framework offers valuable insights for integrating immersive technologies with cloud-based mobile systems, our analysis suggests they address different aspects of the integration challenge. Table 1 presents a comparative analysis of the three frameworks across key dimensions.

Table 1
Comparative analysis of integration frameworks.

Dimension	Layered technological architecture	Pedagogical-technological alignment	Experiential learning ecosystems
Primary focus	Technical integration and system architecture	Coherence between educational and technological components	Authentic learning experiences and ecological relationships
Theoretical foundations	Systems theory, cloud computing architecture	Instructional design, TPACK, constructive alignment	Experiential learning theory, situated cognition, ecological approaches
Strengths	Scalability, standardization, interoperability	Educational relevance, discipline-specific adaptation	Authenticity, collaborative learning, personalization
Limitations	Limited attention to pedagogical considerations	Dependent on educator TPACK, vulnerable to technological change	Complex implementation, resource intensive, potential accessibility issues
Typical applications	Campus-wide immersive infrastructure, multi-course platforms	Discipline-specific immersive learning modules	Cross-disciplinary experiential learning, distributed collaborative environments
Representative studies	Encalada and Sequera [28], El Mhouti et al. [50], Kim et al. [51]	Schmidt et al. [33], Udeozor et al. [37], Stojšić et al. [26]	Pirker et al. [41], Yu [43], Kencevski and Zhang [45]

Our analysis suggests these frameworks are best viewed as complementary rather than competing approaches to integration. Indeed, several recent studies have proposed hybrid frameworks that synthesize elements from multiple approaches. For example, Kok et al. [52] combined architectural and pedagogical perspectives to create a comprehensive integration model for engineering education, while Tursunova et al. [53] integrated elements from all three frameworks to develop immersive language learning environments.

Based on this synthesis, we propose an integrated conceptual model for implementing immersive cloud-based mobile learning environments in university settings (figure 5). This model acknowledges the multifaceted nature of integration, incorporating technical, pedagogical, and experiential considerations within an iterative implementation process.

This integrated model emphasizes the iterative nature of implementation, with evaluation findings informing subsequent refinements to both technological and pedagogical components. It also highlights the importance of concurrent consideration of educational needs, contextual factors, and technological capabilities throughout the implementation process.

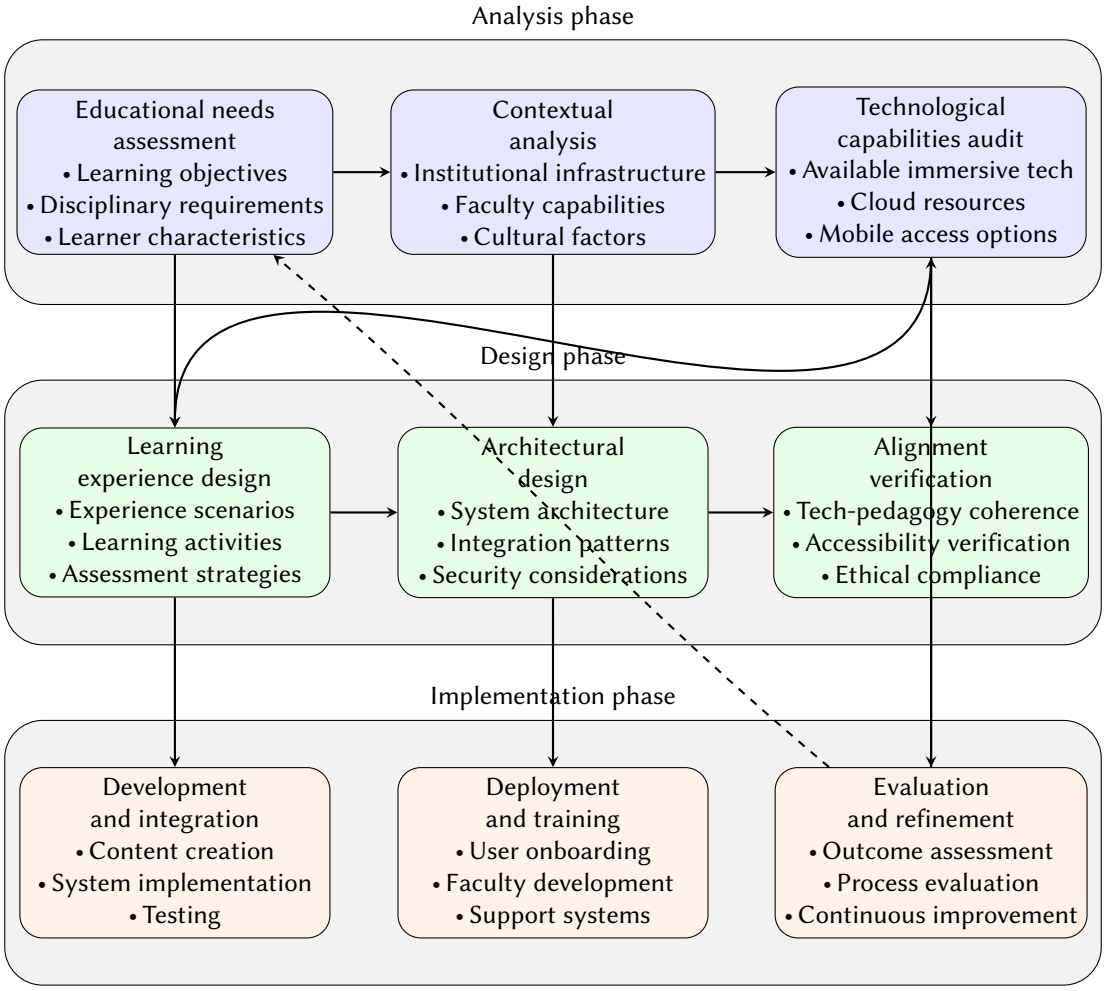

Figure 5: Integrated conceptual model for implementing immersive cloud-based mobile learning.

4. Implementation strategies and challenges

Implementing immersive cloud-based mobile learning environments in university settings presents numerous challenges that span technological, pedagogical, organizational, and ethical dimensions. Our analysis revealed diverse strategies employed by universities to overcome these challenges, as well as persistent barriers that continue to impede widespread adoption.

4.1. Technological infrastructure and accessibility

One of the most significant challenges identified in the literature concerns the technological infrastructure required to support immersive cloud-based mobile learning. Unlike traditional e-learning platforms, immersive environments demand substantial computational resources, high-bandwidth network connectivity, and specialized hardware for optimal performance [49].

4.1.1. Cloud infrastructure strategies

Universities have employed several strategies to address cloud infrastructure challenges. Approximately 42% of implementation studies in our review reported adopting commercial cloud services (e.g., Amazon Web Services, Microsoft Azure, Google Cloud Platform) to leverage their scalability, reliability, and global accessibility [54]. These platforms provide infrastructure-as-a-service (IaaS) and platform-as-a-service (PaaS) capabilities that can be dynamically scaled to accommodate varying levels of demand – a particularly important feature for immersive applications with intensive computational requirements.

However, Kim et al. [51] noted that commercial cloud services can introduce significant ongoing costs, potentially limiting sustainability for institutions with constrained budgets. In response, 28% of implementations utilized hybrid cloud approaches that combine on-premises infrastructure with selective use of commercial cloud services for specific functions. This approach allows universities to maintain control over sensitive data and core systems while leveraging commercial services for computational-intensive rendering or storage needs.

A smaller but growing proportion of implementations (17%) reported using inter-institutional cloud federations or educational cloud networks, such as the European Open Science Cloud or regional research and education networks. These collaborative approaches enable resource sharing across institutions while maintaining educational focus [50]. As Upadhyay et al. [47] observed, such federations can also establish shared standards and protocols for immersive educational content, enhancing interoperability and reusability across institutional boundaries.

4.1.2. Accessibility and device compatibility

Ensuring equitable access to immersive learning experiences remains a significant challenge, particularly given the diversity of devices and connectivity options available to university students. Our analysis revealed three predominant strategies for addressing device accessibility:

First, 53% of implementations adopted a "bring your own device" (BYOD) approach [55], developing web-based or cross-platform applications that function across a range of smartphones and tablets with varying capabilities [26]. This approach maximizes accessibility but may constrain the immersive quality of experiences, as many personal devices have limited AR/VR capabilities.

Second, 32% of implementations established equipment loan programs or dedicated immersive laboratories where students could access high-quality VR headsets, AR-capable devices, or specialized equipment [36]. While this approach ensures consistent, high-quality experiences, it potentially limits flexibility and spontaneous engagement with immersive content.

Third, 25% implemented tiered experience designs that automatically adapt immersive content based on detected device capabilities, providing more sophisticated interactions for advanced devices while ensuring core functionality on basic hardware [56]. This approach balances accessibility with immersive quality but requires significant additional development effort.

Regardless of the approach taken, Creed et al. [48] emphasized that true accessibility requires consideration of users with disabilities. However, only 18% of implementations explicitly addressed accessibility for diverse user needs, suggesting a significant gap in current practice. Those that did consider accessibility typically incorporated features such as alternative input mechanisms, haptic feedback options, and customizable visual and auditory elements [38].

4.2. Faculty development and support

Successful implementation of immersive cloud-based mobile learning environments depends significantly on faculty members' ability and willingness to adopt these technologies. Our analysis revealed that faculty development emerged as a critical factor in 67% of implementations, with several common challenges and strategies identified.

4.2.1. Technological competence development

The complex and rapidly evolving nature of immersive technologies presents significant learning curves for many faculty members. As Thangavel et al. [57] noted, effective utilization of these technologies requires competence not only in basic operation but also in content creation, troubleshooting, and pedagogical integration – a combination rarely covered in traditional faculty development programs.

The most successful implementations addressed this challenge through structured, multi-tier training programs that progressively developed faculty competence. For example, Varella et al. [58] described a three-phase approach beginning with awareness-building demonstrations, followed by hands-on

workshops focused on specific applications, and culminating in supported implementation of faculty-designed immersive activities. This gradual progression allowed faculty to build confidence while developing practical skills directly relevant to their teaching contexts.

Several implementations (38%) employed a "champions" or "early adopter" strategy, identifying technology-enthusiastic faculty who received intensive training and then served as peer mentors and resources for colleagues [40]. This approach leveraged existing social networks within departments and created sustainable, discipline-specific support systems that continued beyond initial implementation phases.

4.2.2. Pedagogical integration support

Beyond technical skills, faculty required support in reconceptualizing their teaching approaches to effectively integrate immersive experiences. As Schmidt et al. [33] observed, immersive technologies often challenge traditional instructional patterns, requiring faculty to develop new approaches to guidance, assessment, and learning activity design.

Successful implementations addressed this challenge through collaborative instructional design partnerships between faculty and educational technology specialists. Yadav [59] described how these partnerships created co-development processes where disciplinary expertise and technological knowledge converged to create pedagogically sound immersive learning experiences. These partnerships typically produced not only specific immersive activities but also reusable templates and design patterns that faculty could adapt for future applications.

Several universities (27%) established communities of practice focused on immersive teaching, providing ongoing forums for faculty to share experiences, showcase innovations, and collectively address challenges [34]. These communities often transcended traditional departmental boundaries, creating valuable cross-disciplinary exchanges that inspired novel applications.

4.3. Integration with existing educational systems

Immersive cloud-based mobile learning environments do not exist in isolation but must integrate with universities' existing educational systems, including learning management systems (LMS), student information systems, and assessment platforms. Our analysis revealed that system integration challenges were addressed in several ways.

4.3.1. Learning management system integration

Integration with existing LMS platforms emerged as a priority in 73% of implementations, reflecting these systems' central role in course delivery and student engagement. Three principal integration approaches were identified:

1. 48% of LMS integrations involved developing immersive applications that functioned as external tools linked from within the LMS, typically using Learning Tools Interoperability (LTI) standards [60]. This approach maintained the LMS as the primary point of student engagement while enabling seamless transitions to immersive experiences.
2. 31% of LMS integrations embedded simplified immersive experiences directly within LMS pages using web-based VR/AR frameworks compatible with standard browsers [35]. While this approach reduced transitional friction, it often limited the sophistication of immersive experiences due to browser and LMS constraints.
3. 21% of LMS integrations implemented comprehensive data exchange mechanisms between standalone immersive applications and the LMS, automating the transfer of activity completion and assessment data [42]. This approach enabled rich immersive experiences while maintaining LMS-based tracking and assessment but required more complex technical integration.

4.3.2. Assessment integration challenges

Assessment integration emerged as a particularly challenging aspect, with 58% of studies noting tensions between traditional assessment approaches and the experiential, process-oriented nature of immersive learning. As Udeozor et al. [37] observed, immersive environments often generate rich, multimodal data about learner interactions that do not readily translate to conventional grade structures or assessment records.

Several innovative approaches addressed this challenge. Udeozor et al. [61] described the development of an evidence-centered assessment framework specifically designed for immersive learning, which identified observable behaviors within immersive environments that could serve as valid evidence of learning objective achievement. Similarly, Garg et al. [39] reported on the implementation of stealth assessment techniques that unobtrusively collected performance data during immersive activities, automatically generating conventional assessment metrics without disrupting the immersive experience.

However, Kok et al. [52] noted that novel assessment approaches often faced institutional barriers, including accreditation requirements, faculty evaluation systems, and student expectations shaped by traditional assessment paradigms. Successful implementations typically adopted hybrid assessment strategies that combined innovative approaches within immersive environments with more conventional assessment methods that satisfied institutional requirements.

4.4. Ethical considerations and privacy concerns

The implementation of immersive cloud-based mobile learning environments raises significant ethical considerations, particularly regarding data privacy, surveillance, and potential psychological impacts of immersive experiences. Our analysis revealed that ethical considerations were explicitly addressed in only 34% of implementations, suggesting a concerning gap in current practice.

4.4.1. Data privacy and surveillance concerns

Immersive learning environments typically collect extensive data about user interactions, movements, and sometimes physiological responses – raising important questions about data ownership, consent, and potential surveillance [62]. As Lee and Gargroetzi [63] observed, the richness of data collected in immersive environments can lead to what students perceive as invasive monitoring of their learning behaviors, potentially undermining trust and autonomous engagement.

Implementations that addressed these concerns typically established clear data governance frameworks that specified data collection purposes, storage limitations, and usage boundaries [64]. Several universities implemented differential privacy approaches that allowed aggregation of learner data for improvement purposes while protecting individual privacy [62].

Wei and Yuan [14] emphasized the importance of transparency in immersive learning analytics, recommending that students should have access to visualizations of collected data and clear explanations of how this information influences their learning experiences or assessments. However, our analysis found that only a small minority of implementations (12%) provided such transparency mechanisms.

4.4.2. Psychological and physical wellbeing

Several researchers raised concerns about potential psychological impacts of extended immersive experiences, including virtual reality sickness, psychological distress from highly realistic simulations, and potential addiction to immersive environments [57]. Additionally, Creed et al. [48] noted that certain immersive experiences might be particularly challenging for students with specific psychological conditions or trauma histories.

The most comprehensive implementations established wellbeing protocols that included pre-experience briefings, gradual immersion approaches for novice users, regular breaks during extended sessions, and post-experience debriefings to process emotional responses [36]. Several universities also implemented

opt-out policies with alternative learning pathways for students unable or unwilling to participate in immersive experiences [33].

However, Yadav [59] observed that wellbeing considerations often received less attention than technical or pedagogical aspects during implementation, particularly when immersive technologies were framed primarily as technological innovations rather than psychological experiences.

4.5. Implementation patterns and success factors

Our analysis identified several patterns in implementation approaches and associated success factors across the reviewed studies. Table 2 summarizes these patterns and their relationship to reported outcomes.

Table 2
Implementation patterns and associated outcomes.

Implementation pattern	Key characteristics	Reported benefits	Reported challenges
Top-down institutional (22% of implementations)	• Centralized planning and funding • Standardized platforms • Comprehensive faculty development	• Consistent student experience • Economies of scale • Systematic evaluation	• Slow adaptation to disciplinary needs • Faculty resistance to mandated technologies • High initial investment requirements
Bottom-up disciplinary (41% of implementations)	• Discipline or department-led initiatives • Focus on specific pedagogical needs • Organic growth and diffusion	• Strong pedagogical alignment • High faculty ownership • Customized to discipline needs	• Fragmented student experience • Limited economies of scale • Sustainability challenges
Hybrid coordinated (37% of implementations)	• Institutional frameworks with disciplinary autonomy • Shared infrastructure with customizable applications • Communities of practice across disciplines	• Balanced standardization and customization • Knowledge sharing across disciplines • Distributed investment	• Complex governance structures • Competing priorities • Coordination overhead

Our analysis suggests that hybrid coordinated approaches typically produced the most sustainable and effective implementations, balancing institutional consistency with disciplinary relevance. As Tursunova et al. [53] observed, successful hybrid implementations established clear institutional policies and infrastructure while empowering disciplinary experts to develop pedagogically appropriate applications within this framework.

Several key success factors emerged consistently across implementation patterns:

1. Strategic alignment with institutional priorities and values.
2. Sustained leadership commitment and resource allocation.
3. Meaningful faculty involvement in planning and decision-making.
4. Robust technical infrastructure and support systems.
5. Evidence-based design informed by learning science.
6. Iterative implementation with regular evaluation and refinement.

Conversely, implementation failures were associated with disconnection from institutional strategic priorities, inadequate faculty development, insufficient attention to student perspectives, and technology-driven rather than pedagogy-driven decision-making [57].

5. Educational impact and effectiveness

A critical question for universities considering investments in immersive cloud-based mobile learning environments concerns their educational impact and effectiveness. Our analysis of empirical studies revealed a complex picture of benefits, limitations, and contextual factors that influence effectiveness across different disciplines and educational objectives.

5.1. Learning outcomes and knowledge acquisition

Empirical studies of learning outcomes associated with immersive cloud-based mobile learning environments showed mixed but generally positive results. A synthesis of findings from 32 experimental and quasi-experimental studies included in our review is presented in table 3.

Table 3
Learning outcomes from immersive cloud-based mobile learning.

Outcome domain	Studies reporting significant positive effects	Studies reporting no significant effect	Key moderating factors
Knowledge acquisition and retention	22/32 (69%)	10/32 (31%)	• Learner prior experience • Content complexity • Immersion quality
Conceptual understanding	19/27 (70%)	8/27 (30%)	• Spatial vs. abstract concepts • Scaffolding quality • Reflection opportunities
Skill development	21/25 (84%)	4/25 (16%)	• Fidelity to real-world tasks • Practice opportunities • Feedback quality
Transfer of learning	13/22 (59%)	9/22 (41%)	• Similarity to application context • Varied practice scenarios • Metacognitive guidance

Several patterns emerged from these findings. First, immersive environments showed the strongest and most consistent benefits for skill development, particularly for procedural and psychomotor skills requiring spatial understanding and physical manipulation [56]. For example, Dirgantara Deha et al. [65] found that medical students using VR-based surgical simulations demonstrated significantly better technical skills than those using traditional training methods, with particularly pronounced effects for complex procedures requiring spatial awareness.

Second, immersive environments showed moderate but generally positive effects on knowledge acquisition and conceptual understanding. Wiafe et al. [66] found that AR applications enhanced understanding of complex STEM concepts with strong spatial components, such as molecular structures or anatomical relationships, but showed less advantage for abstract conceptual knowledge. Similarly, Sviridova et al. [27] reported that immersive environments enhanced retention of factual knowledge when information was spatially organized within the environment but showed minimal benefits for declarative knowledge presented without spatial organization.

Third, transfer of learning to real-world contexts showed the most variable results, with success highly dependent on the design of immersive experiences. Jantjies et al. [40] found that carefully designed immersive experiences that incorporated varied practice scenarios and gradually faded scaffolding produced strong transfer effects, while those focusing primarily on technological novelty or entertainment value showed minimal transfer.

Several studies identified key moderating factors that influenced the effectiveness of immersive environments for learning outcomes. Individual differences, including prior domain knowledge [66],

spatial ability [65], and technology familiarity [26], significantly impacted the benefits derived from immersive experiences. Instructional design factors, such as the quality of guidance [33], opportunities for reflection [36], and integration with complementary learning activities [56], were also critical determinants of effectiveness.

It is important to note that most empirical studies focused on short-term learning outcomes, with relatively few examining long-term retention or far transfer. Additionally, many studies compared immersive experiences to traditional instruction rather than to other technology-enhanced approaches, limiting our understanding of the specific advantages of immersive technologies compared to less resource-intensive alternatives [67].

5.2. Student engagement and motivation

One of the most consistently reported benefits of immersive cloud-based mobile learning environments was enhanced student engagement and motivation. Our analysis identified 43 studies that examined engagement and motivational outcomes, with 91% reporting positive effects on at least some dimensions of engagement.

Sarshartehrani et al. [42] proposed a multidimensional model of engagement in immersive environments, identifying behavioral engagement (active participation and time on task), emotional engagement (affective responses and enjoyment), and cognitive engagement (mental effort and strategic learning approaches) as distinct but interrelated dimensions. Using this framework to synthesize findings across studies revealed differential effects on these dimensions.

Emotional engagement showed the most consistent improvements across studies, with students typically reporting higher enjoyment, interest, and positive emotional responses to immersive learning experiences compared to traditional approaches [35, 68, 39]. These affective benefits were observed across disciplinary contexts and student populations, suggesting that the novelty and sensory richness of immersive environments have broad appeal.

Behavioral engagement also showed generally positive effects, with multiple studies reporting increased voluntary time on task, more extensive exploration of learning content, and higher completion rates for immersive activities compared to conventional alternatives [27, 68]. However, several studies noted that these behavioral benefits diminished over time as novelty effects faded, highlighting the importance of sustaining engagement through progressive challenge and meaningful learning activities rather than technological novelty alone [14].

Effects on cognitive engagement showed the greatest variability across studies. Yu [43] found that well-designed immersive experiences stimulated deeper cognitive processing and more sophisticated learning strategies, particularly when they incorporated problem-solving challenges and required active decision-making. Conversely, Coban et al. [67] observed that poorly designed immersive experiences could reduce cognitive engagement by overwhelming students with sensory information or directing attention to technological features rather than learning content.

Several studies examined the relationship between engagement and learning outcomes, generally finding positive but complex associations. Wiafe et al. [66] reported that emotional engagement positively predicted knowledge retention but only when accompanied by high cognitive engagement, suggesting that enjoyment alone is insufficient for meaningful learning. Similarly, Wong et al. [46] found that behavioral engagement predicted skill development only when activities were carefully aligned with learning objectives, highlighting the importance of purposeful design rather than engagement for its own sake.

5.3. Digital competency development

An important but less frequently studied outcome concerns the development of digital competencies through interaction with immersive cloud-based mobile learning environments. Our analysis identified 18 studies that explicitly examined digital competency outcomes, revealing several consistent patterns.

First, engagement with immersive technologies consistently developed technical competencies related to spatial computing, including understanding of VR/AR interfaces, ability to navigate and interact in 3D digital environments, and awareness of immersive technology capabilities and limitations [69]. These competencies have increasing workplace relevance across numerous fields, from healthcare to engineering to creative industries [34].

Second, collaborative immersive environments effectively developed digital communication and collaboration competencies, including virtual teamwork skills, multimodal communication strategies, and digital co-creation capabilities [30]. Alfred Daniel and Santhosh [44] found that students who participated in collaborative immersive projects demonstrated significantly better virtual collaboration skills in subsequent professional contexts compared to those who completed similar projects without immersive components.

Third, the most comprehensive implementations developed digital creation competencies, with students learning to design and develop immersive content rather than simply consuming it [52]. Andone et al. [69] documented how student-created immersive artifacts demonstrated progressive sophistication over time, evolving from simple adaptations of templates to original designs that effectively leveraged immersive affordances for communication and learning.

However, several researchers noted that digital competency development was often incidental rather than intentionally designed into immersive learning experiences [60, 57]. Yadav [59] argued for more explicit articulation of digital competency objectives in immersive learning design, including clear scaffolding and assessment of these competencies alongside discipline-specific learning goals.

5.4. Disciplinary variations in effectiveness

Our analysis revealed notable variations in the reported effectiveness of immersive cloud-based mobile learning across disciplinary contexts. Figure 6 visualizes these variations based on a synthesis of findings from the empirical studies included in our review.

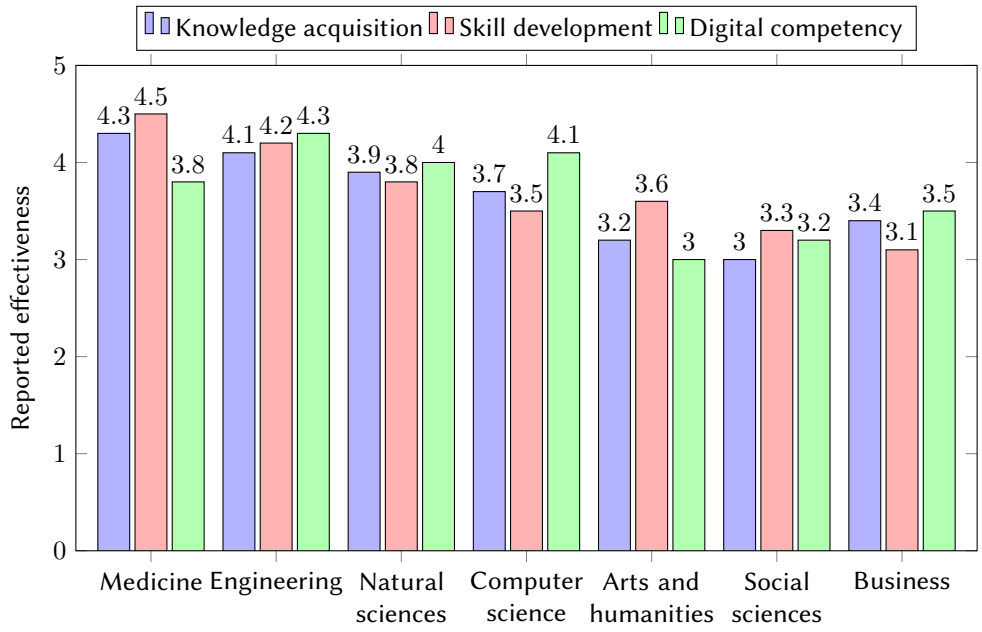

Figure 6: Reported effectiveness of immersive cloud-based mobile learning by discipline.

Several factors appear to influence these disciplinary variations. Fields with strong spatial and visual components, such as medicine, engineering, and natural sciences, reported the highest overall effectiveness, particularly for skill development and knowledge acquisition outcomes [36, 34]. These disciplines benefit from immersive technologies' capacity to visualize complex three-dimensional structures and processes that are difficult to represent through traditional methods.

Additionally, disciplines with expensive, dangerous, or inaccessible real-world learning contexts, such as medicine (surgical procedures), engineering (industrial equipment), and natural sciences (molecular phenomena), reported strong benefits from immersive simulations that provided safe, accessible alternatives to physical environments [56, 65].

Less pronounced but still positive effects were reported in computer science, business, social sciences, and arts and humanities. In these fields, immersive technologies were most effective when leveraged for specific pedagogical purposes rather than as general learning platforms. For example, Navas Gotopo et al. [68] documented successful applications in business education that simulated complex interpersonal scenarios for negotiation and leadership development, while Alfred Daniel and Santhosh [44] described immersive historical environments that enhanced understanding of cultural and social contexts in humanities education.

Across all disciplines, the most effective implementations aligned immersive technologies with specific learning challenges that benefited from their unique affordances, rather than applying them broadly without clear pedagogical rationales [33]. As Yadav [59] observed, the question is not whether immersive technologies are effective for a particular discipline, but rather what specific aspects of disciplinary learning they can uniquely enhance.

6. Future directions and research agenda

Our review of immersive cloud-based mobile learning in higher education reveals significant progress in technological integration, implementation strategies, and empirical understanding of educational impacts. However, it also highlights important gaps and emerging trends that suggest directions for future research and development.

6.1. Emerging technologies and their educational potential

Several emerging technologies promise to expand the capabilities and educational applications of immersive cloud-based mobile learning. Our analysis identified four particularly significant technological trends with substantial educational implications.

First, the integration of artificial intelligence with immersive environments enables more adaptive, personalized learning experiences [70, 71, 72, 73, 74, 75, 76, 77]. Yu [43] and Sarshartehrani et al. [42] explored how AI agents can function as virtual instructors or learning companions within immersive environments, providing personalized guidance, feedback, and assessment based on real-time analysis of learner behaviors. This integration potentially addresses the scalability challenges of immersive learning by reducing dependence on human instructors for moment-to-moment guidance.

Second, the emergence of cross-platform immersive standards, such as WebXR and OpenXR, promises to reduce fragmentation and enhance interoperability across different hardware and software ecosystems [44]. These standards enable development of immersive educational content that functions consistently across diverse devices, from high-end VR headsets to basic smartphones, potentially addressing accessibility challenges that have limited widespread adoption.

Third, advances in haptic feedback technologies are expanding immersive environments beyond visual and auditory modalities to incorporate tactile sensations [48]. These developments hold particular promise for disciplines requiring fine motor skills or physical manipulation, such as surgery, dentistry, or mechanical engineering, by enhancing the fidelity of simulated procedures and providing embodied feedback on performance.

Fourth, the concept of the metaverse – persistent, shared virtual spaces that blend aspects of social media, online games, and immersive technologies – is inspiring new approaches to collaborative learning across institutional and geographical boundaries [47, 46]. Educational applications of metaverse concepts potentially enable rich cross-institutional collaborations, global learning communities, and persistent knowledge-building environments that transcend traditional course structures.

6.2. Methodological advances in immersive learning research

Our review reveals a need for methodological advances in researching immersive learning environments, particularly regarding measurement approaches, study designs, and analytical frameworks.

Udeozor et al. [37, 61] highlighted the limitations of traditional assessment instruments for capturing the multidimensional learning processes that occur in immersive environments. They called for development of more sophisticated assessment methodologies that can collect and interpret multimodal data generated during immersive learning, potentially including eye-tracking, motion capture, physiological responses, and verbal protocols alongside traditional outcome measures.

Several researchers advocated for more robust study designs that move beyond short-term comparisons of immersive versus traditional instruction. Coban et al. [67] specifically called for longitudinal studies that examine the durability of learning from immersive experiences, while Nelson et al. [56] emphasized the need for transfer studies that assess how learning in immersive environments influences performance in authentic professional contexts.

Granić et al. [78] proposed more sophisticated analytical frameworks for interpreting immersive learning data, drawing on approaches from learning analytics, educational data mining, and process analysis to identify patterns in learner interactions that correlate with successful outcomes. These approaches potentially enable more nuanced understanding of how students learn in immersive environments and how immersive experiences might be optimized for different learning objectives or student characteristics.

6.3. Scaling and sustainability challenges

As universities move beyond pilot implementations toward institution-wide adoption of immersive cloud-based mobile learning, research is needed to address scaling and sustainability challenges. Thangavel et al. [57] identified several research priorities in this domain, including cost-effective development models for immersive content, faculty development approaches that build institutional capacity, and governance structures that balance centralization and disciplinary autonomy.

Xuan and Rana [32] emphasized the need for research on sustainable financial models, noting that many current implementations rely on external funding or special initiatives that may not provide ongoing support. They called for studies examining diverse approaches to resource allocation, including subscription models, shared resource pools across departments or institutions, and partnerships with industry or external content providers.

Additionally, Shakor and Shafiq Surameery [54] highlighted the environmental sustainability implications of widespread adoption of immersive cloud-based learning, noting the significant energy consumption associated with cloud computing and immersive rendering. Research on optimizing energy efficiency and reducing the carbon footprint of immersive learning technologies will become increasingly important as implementation scales expand.

6.4. Ethical and social implications

Our review revealed a clear need for expanded research addressing ethical and social implications of immersive cloud-based mobile learning. As Drachsler et al. [62] and Lee and Gargroetzi [63] observed, the immersive and data-intensive nature of these environments raises novel ethical questions that existing educational research ethics frameworks may inadequately address.

Esposito [64] called for research developing ethics frameworks specifically tailored to immersive educational environments, addressing issues such as informed consent for data collection, psychological risks of immersive experiences, and potential impacts on learner autonomy and agency. Similarly, Lee and Gargroetzi [63] emphasized the need for participatory approaches to ethical guidelines, involving students and diverse stakeholders rather than imposing policies developed solely by technologists or administrators.

Several researchers highlighted potential social equity implications of immersive learning technologies. Creed et al. [48] called for research examining how immersive technologies might exacerbate

or mitigate existing educational disparities related to socioeconomic status, geographical location, or disability status. Similarly, Heikkinen et al. [49] emphasized the importance of studying accessibility considerations in immersive design, ensuring that new educational modalities do not exclude learners with diverse needs and abilities.

6.5. Research agenda

Based on our analysis of current research and identified gaps, we propose a research agenda for advancing understanding and implementation of immersive cloud-based mobile learning in higher education (table 4). This agenda encompasses theoretical, methodological, technical, and applied research priorities.

Table 4
Research agenda for immersive cloud-based mobile learning in higher education.

Research domain	Key questions	Recommended approaches
Theoretical foundations	• How do existing learning theories apply in immersive environments? • What new theoretical constructs are needed to explain learning in immersive contexts? • How do embodiment, presence, and agency influence learning processes?	• Critical analysis of theoretical frameworks across immersive applications • Development of integrated theoretical models that address unique aspects of immersive learning • Interdisciplinary collaborations between education, psychology, computer science, and neuroscience
Integration frameworks	• How can technical and pedagogical integration be more effectively harmonized? • What governance structures best support sustainable, scalable implementation? • How can accessibility and universal design principles be incorporated into integration frameworks?	• Comparative case studies of different integration approaches • Design-based research developing and testing new integration models • Participatory design involving diverse stakeholders including students with disabilities
Implementation strategies	• What faculty development approaches most effectively build capacity for immersive teaching? • How can universities balance standardization and disciplinary customization? • What strategies effectively address ethical and privacy concerns?	• Mixed-methods evaluation of implementation initiatives • Longitudinal studies of implementation evolution • Action research addressing specific implementation challenges
Assessment methodologies	• How can learning in immersive environments be validly and reliably assessed? • What multimodal data sources provide meaningful insights into immersive learning processes? • How can immersive assessment approaches align with institutional requirements?	• Development and validation of immersive assessment instruments • Learning analytics approaches combining qualitative and quantitative data • Design experiments testing novel assessment approaches
Educational impacts	• How durable are learning gains from immersive experiences? • What factors moderate effectiveness across different contexts? • How does immersive learning transfer to real-world performance?	• Longitudinal studies examining retention over time • Meta-analyses identifying moderating variables • Transfer studies in authentic professional contexts

This research agenda emphasizes the need for multidisciplinary approaches that draw on expertise from education, computer science, psychology, and specific disciplinary domains. It also highlights the importance of methodological diversity, combining quantitative and qualitative approaches to develop comprehensive understanding of both outcomes and processes in immersive learning.

7. Conclusion

This systematic review has examined the current state of research on immersive cloud-based mobile learning tools in higher education, focusing on integration frameworks, implementation strategies, and educational impacts. Our analysis of 86 studies published between 2019 and 2025 reveals significant advances in both conceptual understanding and practical application of these technologies across diverse university contexts.

Three primary integration frameworks emerged from our analysis: layered technological architecture, pedagogical-technological alignment, and experiential learning ecosystems. Each framework offers valuable perspectives on different aspects of integration, with the most comprehensive implementations drawing on elements from multiple frameworks to create balanced approaches that address both technical and pedagogical considerations.

Implementation strategies varied substantially across institutions, with successful approaches typically characterized by strong leadership commitment, meaningful faculty involvement, robust technical infrastructure, and alignment with institutional strategic priorities. Common challenges included technological infrastructure and accessibility constraints, faculty development needs, integration with existing educational systems, and ethical considerations regarding data privacy and student wellbeing.

Empirical studies examining educational impacts revealed generally positive but contextual effects. Immersive clou-based mobile learning environments showed the strongest benefits for skill development, moderate positive effects on knowledge acquisition and conceptual understanding, and variable effects on transfer of learning. Student engagement consistently improved across most implementations, particularly regarding emotional and behavioral engagement dimensions. Disciplinary variations in effectiveness were apparent, with fields involving strong spatial and visual components or dangerous/inaccessible learning contexts showing the most pronounced benefits.

Looking forward, several emerging technologies promise to expand the capabilities and educational applications of immersive cloud-based mobile learning, including AI integration, cross-platform standards, haptic feedback technologies, and metaverse concepts. However, realizing the full potential of these technologies requires addressing methodological challenges in immersive learning research, scaling and sustainability issues, and ethical concerns regarding data privacy and social equity.

Based on our findings, we propose several recommendations for researchers, educational technologists, and university administrators:

1. Adopt integrated approaches to implementation that balance technological, pedagogical, and experiential considerations, drawing on the complementary strengths of different integration frameworks.
2. Prioritize faculty development and support, recognizing that technological adoption and pedagogical integration require sustained investment in human capacity alongside infrastructure development.
3. Design immersive learning experiences based on evidence-informed principles rather than technological novelty, focusing on specific learning challenges that benefit from immersive affordances.
4. Implement robust assessment approaches that align with the unique characteristics of immersive learning while satisfying institutional requirements for documentation and credentialing.
5. Address ethical considerations proactively, establishing clear policies regarding data privacy, student wellbeing, and accessibility that are developed through participatory processes involving diverse stakeholders.
6. Pursue research that advances understanding of learning processes and outcomes in immersive environments, with particular attention to longitudinal effects, transfer to authentic contexts, and factors that moderate effectiveness.

Immersive cloud-based mobile learning represents a significant frontier in higher education innovation, with the potential to transform how students engage with complex concepts, develop professional skills, and collaborate across traditional boundaries. While challenges remain in implementation and

evaluation, this review demonstrates that thoughtfully designed and carefully implemented immersive learning environments can make meaningful contributions to educational quality and effectiveness across diverse university disciplines.

Data availability statement

No datasets were generated or analysed during the current study.

Conflicts of interest

The authors declare that they have no competing interests.

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Authors' contributions

Serhiy O. Semerikov conceptualized the systematic review, developed the integration frameworks, and drafted the manuscript, including the introduction, methodology, and conclusion sections. Pavlo P. Nechypurenko designed the search strategy and established the inclusion and exclusion criteria for the literature review. Tetiana A. Vakaliuk and Iryna S. Mintii conducted the literature search and data extraction, contributing to the analysis of empirical findings. Vita A. Hamaniuk and Olha V. Bondarenko analyzed the data and synthesized the findings related to implementation strategies and educational impacts. Svitlana V. Shokaliuk and Natalia V. Moiseienko contributed to the interpretation of results and the discussion of future research directions. All authors reviewed, edited, and approved the final manuscript prior to submission.

Declaration on Generative AI

This research utilized generative artificial intelligence tools to support specific non-substantive aspects of the writing and editing process. The following AI-assisted tools were employed:

- **Scopus AI** was used to assist in refining search queries during the literature review phase, helping to identify relevant keywords and optimize Boolean logic for database searches.
- **Grammarly** (Premium) was employed for grammar, spelling, punctuation, and stylistic consistency checks throughout manuscript drafting and revision.
- **Claude Sonnet 3.7** (Anthropic) was used to assist in polishing sentence structure, improving clarity and flow in certain sections, and rephrasing complex passages for readability — always under human supervision and editorial control.

All AI-generated content was thoroughly reviewed, verified, and edited by the authors to ensure accuracy and alignment with the authors' intended meaning and scholarly standards.

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Smartphones, simulations, and science learning: rethinking physics experiments

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Abstract

The explosion of different learning tools for science experiments has been evident in this century. Tools like smartphones and online simulations have catapulted science experiments to greater heights. Most studies on these emerging technologies are quantitative in method, so the literature noted that there is a need for qualitative studies in this field to fully understand the effect of these tools on students. This case study was undertaken to explore the lived experiences, perceptions, and feelings of the students exposed to smartphone-based experiments and online simulations. The study followed a comprehensive framework for case study, including preparation, collection, analyses, and sharing. There were eight participants whose ages were 15-17 years, and their parents and they signed the informed consent form. The data collection methods used were semi-structured individual interviews, monitoring, and observations. A thorough structural analysis was performed, and hermeneutic interpretation was followed to analyze the transcripts. These approaches and methods were successful in revealing three main themes: the affordances of smartphone-based experiments and online simulations, the enhancement and complementing of the role of digital tools in traditional hands-on experimentation, and the challenges associated with smartphone and online simulations in experiments. The affordances included increased student engagement, practicality and accessibility of learning, connection to reality, and enhanced conceptual understanding. The complementary role of smartphones and online simulations to traditional experiment setups is unique in this paper. However, the challenges are related to cognitive and technical limitations, equity issues, and the accuracy of the data gathered. Based on these conclusions, the study recommends training in the mentioned digital tools for teachers and students and smartphone policy for schools to avoid lesson disruption and addiction.

Keywords

case study, conceptual understanding, engagement, hermeneutic interpretation, PhyPhox, PhET interactive simulations, smartphones-based experiments

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1. Introduction

If you can recall an experience from your years studying science, you may think of using laboratory equipment and the enjoyment of learning through it. However, this experience is not singular, as many schools worldwide have limited opportunities to purchase and use science equipment in classes. Using conventional science equipment has remained a fundamental part of schools, but limits the ability of students to explore and be flexible independently.

To foster independent exploration and enhance flexibility in conducting science experiments, recent developments in smartphone-based sensors and online simulations like PhET have redefined how science should be taught and experienced by students. These tools have enabled students to become independent learners and have simplified data collection for analysis [1]. The tools mentioned have significantly transformed learning by bringing abstract concepts closer to reality [2]. The summary of studies in the conference papers of Papadakis et al. [3] suggested that computer simulations and cloud-based technologies can help in personalised learning and higher academic achievement of students.

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While there are high hopes for smartphone-based experiments and online simulations in science [4], limitations exist in using smartphone sensors and online simulations for data collection. Not all sensors are compatible with every phone, meaning one cannot conduct the experiment if it is not built into the device [5]. According to Xia et al. [6], the results can yield false positives or false negatives due to limited range and sensitivity. Online simulations often lack physical interaction and have a narrow scope of exploration, and students may feel confused if they have little computer exposure [7].

To balance it out, schools must reconsider how science classrooms are structured. While smartphone-based experiments and online simulations have disadvantages, these are outweighed, especially for schools with low annual budgets. Students do not require highly sophisticated and sensitive sensors, as they typically use smartphones and simulations to validate scientific theories, such as measuring acceleration due to gravity or the value of static friction. Common smartphone applications for data collection and analysis include Phyphox, Physics AI, and Physics Toolbox Sensor Suite, whereas the most popular online simulation is PhET interactive simulations by the University of Colorado Boulder. According to Klein et al. [8], preparing low-cost experiments with smartphones has verified scientific principles and made experiments more engaging and enjoyable for students. The students in this research were exposed to Phyphox and PhET simulations for nearly one school year.

The theoretical underpinning of this paper is from the Technology Acceptance Model (TAM), which explores how students perceive the integration of online simulations and smartphone-based experiments in learning physics. This model comprises constructs that explain behavioral intentions in using technology. These constructs are perceived usefulness, ease of use, and attitudes towards technology [9]. These three constructs are aligned with this paper's objectives.

To explore the use of these emerging technologies, this study gathered the perspectives of students who were exposed to smartphone-based experiments and online simulations throughout the school year. By collecting these narratives from the students, the paper reveals their actual lived experiences, perceptions, and feelings regarding the use of these technologies. Most studies on smartphone-based learning (e.g., Hochberg et al. [10]) and online simulations (e.g., Yunzal Jr and Casinillo [11]) are quantitative in nature, while very few are qualitative. Tsai et al. [12] suggested that more qualitative studies in this field are needed to understand better the relationship of various constructs like engagement and conceptual understanding. Also, the data can inform developers on how to adjust their technologies based on students' experiences and insights. This information can also help educators and school leaders design a science curriculum that includes smartphones and online simulations among the available resources.

Based on the significance of the endeavor, this study aims to explore how the students lived experiences, perceptions, and feelings of the students exposed to smartphone-based experiments and online simulations. This study will answer the following questions:

1. How do smartphones and PhET help conduct physics experiments more effectively?
2. How do smartphone-based experiments features improve the learning experience?
3. How comparable is the experience using smartphones and PhET simulations to conducting traditional hands-on experiments?
4. What challenges are evident when using smartphones for physics experiments?

2. Methodology

2.1. Research design

This research is a case study of eight students in School A in Uzbekistan. A case study approach is appropriate in this study due to the limited number of participants who agreed to the informed consent form. Gerring [13] argued that a case study is a holistic understanding of a constituent unit to represent the larger class. According to Baškarada [14], the ideal number of participants in a case study is from 8 to 12. The sampling procedure followed is voluntary participation. Only those who signed the informed-consent form were involved. Therefore, selection bias is eliminated using this process. The

study followed the case study framework of Baškarada [14], which followed preparation, collection, analysis, and sharing.

For transferability, thick descriptions of the educational context, instructional design, and participant profiles allowed readers and practitioners in similar educational environments to judge the findings' applicability to their contexts.

This study received ethical approval from the Presidential School of Qarshi. Informed consent was obtained from all participants and their guardians. Participation was voluntary, with the right to withdraw at any time. Confidentiality was maintained through anonymized data and secure storage.

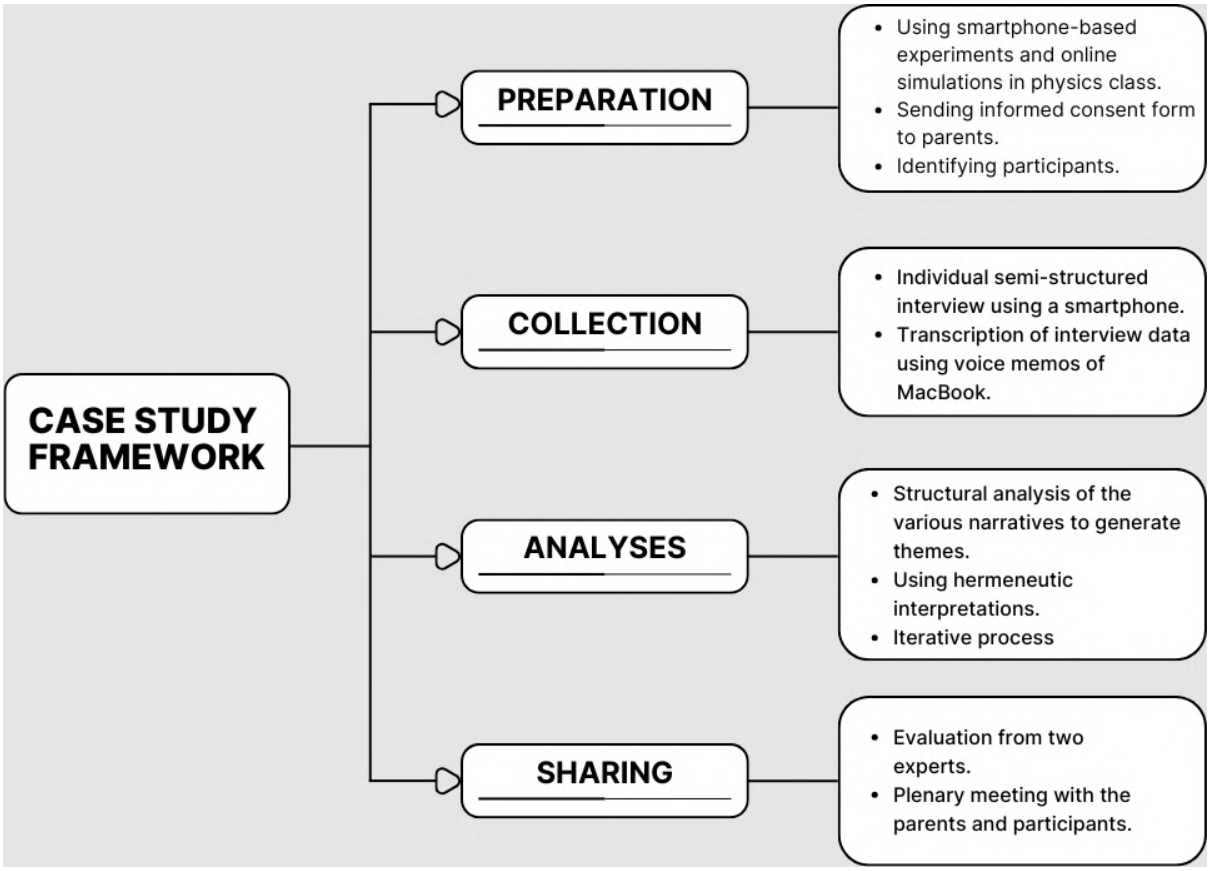

Figure 1: The study followed successive steps for a case study, such as preparation, collection, analyses, and sharing based on Baškarada [14].

2.2. Research participants

This study involved eight students. Two are ninth-graders, three are 10th-graders, and three are 11th-graders. The selection criteria are one school year of exposure to smartphone-based experiments and online simulations in physics, conducting at least one experiment utilizing those emerging technologies mentioned, age ranges from 15 to 17 years, and approval from their parents using the informed consent form. The students were exposed to the said emerging technologies for one school year and they were involved in at least five experiments made using such tools. The names of the participants were not mentioned in any section of this document to maintain confidentiality and anonymity; instead, they were given pseudonyms such as students A through H.

2.3. Data collection tools and procedure

The study used the following tools: a semi-structured interview guide, a smartphone for recording the interviews, and voice memos from a MacBook computer for data transcription. The semi-structured

Table 1
The structural analysis of narratives from Student A.

Statement	**Meaning units**	**Condensation**	Subthemes	**Themes**
Smartphones and PhET make experiments much easier and faster to set up. With PhET, I can visualize concepts that are hard to demonstrate in class, like waves or electricity. The interactive simulations allow me to change variables and instantly see results. With smartphones, I can measure real-time data using sensors, which saves time compared to manual measurements. It feels more efficient, and I can focus on understanding rather than just the setup. – Student A	Smartphones and PhET make experiments much easier and faster to set up.	having faster and simpler experiment setup	Efficient setup	Practicality in science learning
	With PhET, I can visualize concepts that are hard to demonstrate in class, like waves or electricity.	Visualizing difficult concepts	Visualizing the invisible	Enhancing conceptual understanding
	It feels more efficient, and I can focus on understanding rather than just the setup.	focusing on learning rather than setup	Focused learning	Increasing learning efficiency

interview guide contains six questions, primarily those aligned with the research questions at the end of this paper's introduction. An iPhone 15 was used to record the interview with the consent of the parents and students. These audio data were transcribed using the free voice memo software embedded in the MacBook computer.

Before starting this research, a letter of approval was sought from the school principal. Then, during the teacher-parent conference, the researcher introduced the details of the study to the parents. They were given the informed consent form to sign if they agreed their child would participate in the study. Those who did not sign were informed that there were no consequences, such as on the student's academic grades. In addition, those who signed up were told their child could withdraw from the study anytime.

Only eight students participated after those meetings. The interviews lasted from 40 minutes to one hour, and all data were gathered in five days. The language of the interview was English, and given the English level of the participants, interview data editing was performed but retained the participant's thoughts and ideas.

2.4. Data analyses

The transcribed data were analyzed using structural analysis. This process systematically cultivates themes by taking meaning units and condensing narratives [15]. The process started by plotting the interview data in MS Excel. Each participant's answer was analyzed, and the meaning units were taken. The narratives were read and re-read during this process to clearly understand their meaning. The meaning units were condensed by taking the essential meanings of each meaning unit using as many common words as possible. The condensed statements were sorted and abstracted to form subthemes. Finally, all subthemes were organized into main themes. A sample is shown in table 1.

When the data were organized into a table in MS Excel, they were further analyzed using hermeneutic interpretation. This means the students' narratives and themes were interpreted using their cultural, personal, and intellectual upbringing. In this way, the data were interpreted with their lived contexts for richer, more meaningful insights. The process was not only about categorizing the responses, but about seeking meaning behind each statement, considering the social realities of the learners and the educational exposure. While a single coder conducted the initial analysis, peer debriefing was employed to validate code consistency, and member checks were performed in both the final plenary and a follow-up verification session to confirm thematic resonance. This process improved both the

credibility and the confirmability of the findings.

Patterns were identified based on frequency and the depth and complexity of the insights of the participants. The researchers continuously reflected on their biases, maintaining reflexivity throughout the analysis. This means returning to the students and asking them what they meant by that statement. The researchers also returned to the related literature to compare the experience of the participants with that of other students from another country or to verify them from the existing body of knowledge. In this way, the hermeneutic process allowed for a rich and contextual interpretation that respected the individuality of each student's voice while highlighting common themes relevant to the collective learning experience.

2.5. Sharing of the data

A plenary meeting was held with parents and students to inform them of the data results. The participants were asked if they agreed with the themes, and they found that the themes truly reflected their lived experiences, perceptions, and feelings. The researchers also sought questions from the audience and asked for minor clarifications relevant to their narratives and experiences.

3. Results and discussion

3.1. Main theme 1: Affordances of smartphone-based experiments and online simulations

The participants perceived and experienced several key affordances and benefits of smartphone-based experiments and online simulations in learning science. These include increased student engagement, connection to reality, enhanced conceptual understanding, and practicality and accessibility of learning. These themes were very common among the eight participants in this case study.

It should be noted that this was the first time that the participants were immersed in this kind of classroom strategy. Most students even stated that they had not conducted experiments in their previous grade levels in their science subjects. Experience a new way of learning is somehow exciting and fun [16]. All the participants experienced increased engagement and activeness in the lessons using these interventions. Student B claimed, "It's like playing and learning at the same time" and Student D added, "They make the learning process more interactive". Lim [17] supported this experience of the students. In his study, smartphone-based tools increased student-to-study and teacher-to-student engagement and interaction.

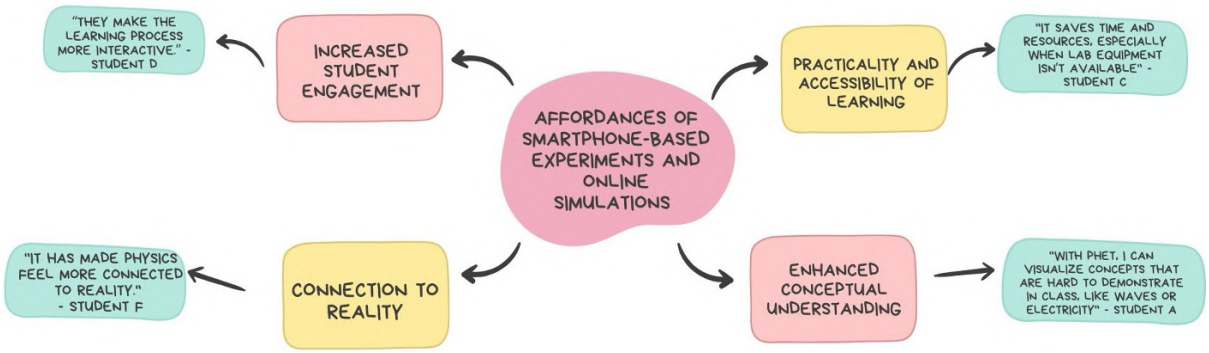

Figure 2: Four themes encapsulate the affordances of smartphone-based experiments and online simulations: increased student engagement, connection to reality, enhanced conceptual understanding, and practicality and accessibility of learning.

Most of the students reported that their previous teachers were somehow used to theory-based and lecture teaching methods. This is not a common theme, especially in developing countries like Uzbekistan. Marmah [18] claimed that the lecture method is the most traditional and common practice

in most developing countries. The reason is that it is more economical and does not need laboratory equipment [19]. This becomes problematic when this method is extensively used throughout the school year. In this paper, students narrated how smartphone-based experiments and online simulations connect their study to reality. Student G said, "It made me feel that science is more accessible and part of everyday life, not just something you do for school". This is supported by student F, who exclaimed, "It has made physics feel more connected to reality". This is a similar perception from the students of Hochberg et al. [10]; however, their study is not qualitative. Unlike in traditional experiments, data may not be easy to generate, and accuracy is also under question. This problem not only hinders scientific conception but also disconnects the students from what reality is expected to be. Radu et al. [20] and Coramik and İnanç [21] said that smartphone-based experiments were able to bridge the abstractness of science and what reality is. For instance, the displacement-time graph of an oscillating body is now easily generated in applications like PhyPhox and is more easily understood by students regarding its scientific principles.

The next theme is about an enhanced conceptual understanding of physics. The students reasoned out that this is evident because of increased engagement and its connection to reality. The previous two themes are connected to this third theme and explanations to it. Student B said, "PhET simulations help me understand abstract concepts by showing visuals that I can interact with". To support this, student G narrated, "It's like doing both experiment and analysis at the same time, which helps me learn more deeply". This occurrence is similarly observed by Milner-Bolotin and Milner [22], whose preliminary results concluded that smartphone-based experiments can boost conceptual understanding, while Rahmawati et al. [23] said that PhET simulations could increase comprehension in science and decrease the misconceptions held by students.

The lack of laboratory equipment is a common problem in developing countries. This was exacerbated during the COVID-19 pandemic when schools turned online. Ferri et al. [24] argued that this phenomenon has declined student participation and engagement in lessons and deepened the learning curve among students. With the advent of smartphone-based experiments and online simulations, experiments have now become more accessible and practical to both students and teachers. This is the fourth theme, which students overwhelming held that these merging technologies were accessible and practical to use. As narrated by Student C, "It saves time and resources, especially when lab equipment isn't available". Student E claimed, "I really like using the sensors. For instance, when studying motion or forces, I can use the Phyphox and instantly get data". Pacala and Pili [25] argued that smartphone-based experiments can be done even at home with guidelines set by the teacher. So even during times of school interruptions like typhoons, earthquakes, etc., learning shall continue. However, schools should set policies on the use of smartphones in schools because the Organization for Economic Co-operation and Development (OECD) noted that 65 percent of member countries reported distraction from digital devices, including smartphones and computers, and affected their PISA scores [26].

These affordances are aligned with TAM. Many students appreciated the ease of using their own smartphones, noting that the tools were familiar and intuitive. These responses reflect perceived ease of use, suggesting that the students felt minimal effort was needed to operate the simulations and apps. Also, students' narrations indicated that the smartphone-based experiments enhanced their conceptual understanding of abstract topics, such as light and force. This aligned with the TAM's perceived usefulness construct, where students recognized the activities as beneficial for their academic performance and science comprehension.

3.2. Main theme 2: Enhancing and complementing the role of digital tools to traditional hands-on experimentation

Main theme number 2 summarized the perceived comparison of smartphone-based experiments and online simulations. The student's general impression was that these emerging tools enhanced and complimented the traditional way of doing experiments. The themes under this main theme are the complementary role of traditional and digital tools and the flexibility and speed of digital tools.

Furió et al.'s study [27] observed the enhancement and complementary ability of augmented reality (AR), which suggests that other emerging technologies, such as smartphones and online simulations, can do the same. This research may be the first one to notice this phenomenon for smartphones, as students narrated. Student A said, "Traditional experiments are good because you physically handle materials and equipment, but they can be time-consuming and sometimes messy". Student D claimed, "Comparing online simulations and traditional to measure the value of acceleration due to gravity has been supplementing my knowledge". Other authors have compared online simulations with physical and traditional experiments, such as those by Brinson [28].

The Phyphox application can measure the acceleration due to gravity. Traditional apparatus, such as iron stands, clamps, balloons, or any falling object, can be used. The smartphone can act as a data collector for the time of the object's fall. Another idea is using a smartphone to collect data on the magnetic flux density of a solenoid, as shown in figure 3. In these ways, the smartphone complements the traditional experiment.

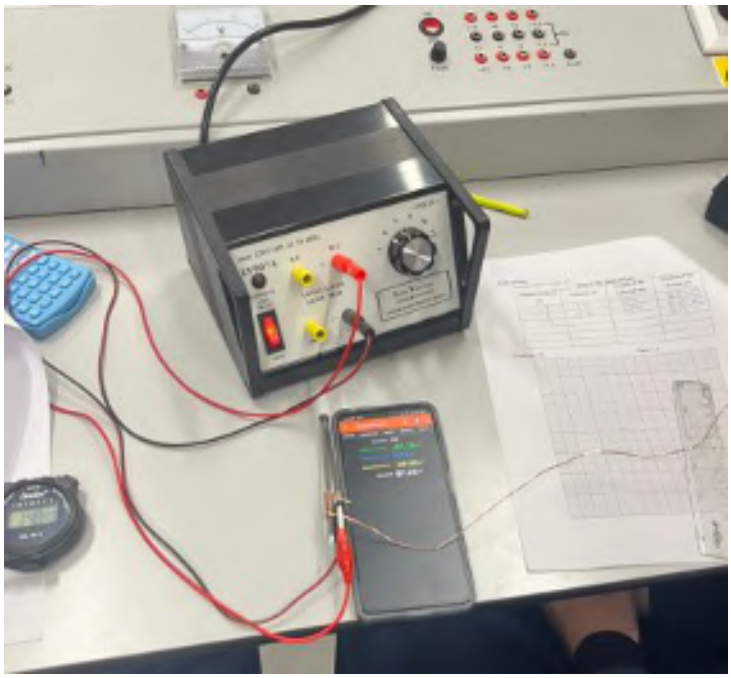

Figure 3: Smartphones complement traditional experiments by collecting magnetic flux density data of a solenoid.

This experiment method has been perceived as a flexible and fast way for the students to collect data. Student A exclaimed, "With smartphones and simulations, I feel like I can explore concepts more quickly and repeat experiments easily". Student E supported this idea; she said, "We were able to calculate the value of acceleration due to gravity quickly". This theme supported the previous theme on practicality and accessibility. For instance, measuring the magnetic flux density can be a difficult task without the Tesla meter, an instrument that can be expensive to purchase by low-budget schools. With smartphones, this can now be an easy task. This experience of the students is similar to the experience revealed by the students of Chu et al. [29]. They further observed that their students perceived the smartphone-based experiments as positive and enhanced engagement and understanding of the lesson.

3.3. Main theme 3: Challenges of smartphone and online simulations in experiments

Despite the promising results of using smartphones and online simulations in physics lessons, these technologies have limitations that pose challenges to both students and teachers. In this paper, the students narrated four themes that encapsulate the challenges of smartphone and online simulations in experiments: cognitive challenges, technical limitations, equity issues, and challenges in accurate data collection (figure 4).

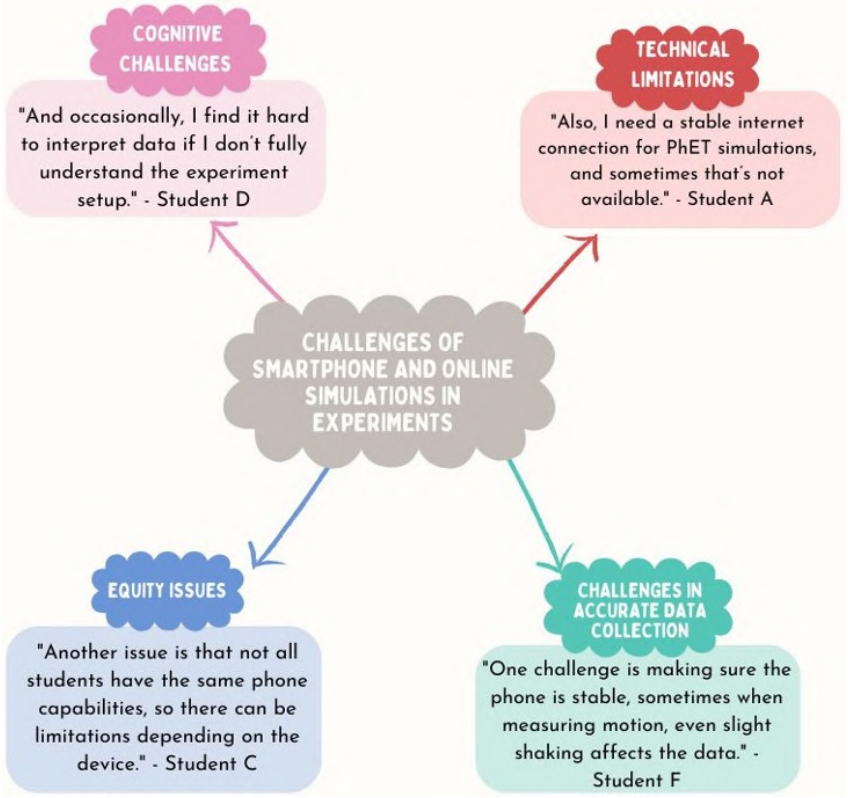

Figure 4: The challenges narrated by the students were related to cognitive challenges, technical limitations, equity issues, and challenges in accurate data collection.

The first challenge the students claimed is related to cognitive abilities. They talked about the difficulty of interpreting the data without prior knowledge of what the data is all about. The students in this case study were guided about the experiments they performed. They explored how to calculate constants like coefficient of friction, acceleration due to gravity, etc. They also verified the relationship between scientific constructs, such as magnetic flux density and current. As student D said, "And occasionally, I find it hard to interpret data if I don't fully understand the experiment setup". They were concerned primarily about future experiments or other students in another school who might not know the meaning of the data they were collecting. Students can also be battling with the correct sensor or online simulation to use or which section of the app to use if they are first-time users.

Apart from cognitive challenges, the experiments using smartphones and online simulations may encounter technical limitations, such as internet connectivity issues or environmental disturbances. Online simulations may not function without an internet connection, which presents a significant challenge for low-budget schools. Student A stated, "Additionally, I need a stable internet connection for PhET simulations, and sometimes that's unavailable". There are also setup parameters within the simulation or smartphone application that must be adhered to, which creates a technical hurdle for students. Student C noted, "Moreover, some apps require permissions or settings that can be confusing at first".

The technical challenge can affect the accuracy of the data gathered. For instance, when using an acoustic stopwatch to measure free fall time, the environment should be noise-free, and the smartphone should be as close to the falling body as possible. If the values are not gathered with precision and accuracy, the value of acceleration due to gravity could have higher uncertainty. Student F gave an example, "One challenge is making sure the phone is stable. Sometimes, when measuring motion, even slight shaking affects the data".

The last challenge is that not all phones can have similar sensors, which depends on the smartphone's brand and specifications. The general rule of thumb is that the higher the price of the smartphone, the more sensors are built in that can be used for classroom experiments. This has been noted by students

Figure 5: This setup was used to measure the time period of a pendulum and find acceleration due to gravity. To accurately measure the time period, the windows were closed to avoid interference.

whose smartphones vary from one another. Student A said, "Another issue is that not all students have the same phone capabilities, leading to limitations depending on the device". This can be exacerbated in remote areas where parents cannot afford to buy smartphones for themselves or their children. To solve this issue, teachers should be resourceful. They could organize a fundraising activity to finance the purchase of such technology. If the number of devices is limited, students can experiment in groups to foster collaborative learning skills.

The challenges mentioned above are common with emerging technologies. Environmental factors can affect the accuracy of collected data and illustrated how notifications from parents or friends can distract students [29]. Additionally, Pacala [30] emphasized that data accuracy can be problematic, especially for collections impacted by environmental factors such as the Earth's magnetic field and nearby appliances when measuring magnetic flux density. The cognitive challenges described by the students can be minimized or resolved through training similar to that conducted by the researcher before employing these teaching methods. Almarashdi and Saleh [26] argued that students can be trained so that, during classes, the teacher can focus on guiding them in exploring and verifying scientific principles. Furthermore, it is essential for teachers to receive training on these emerging technologies.

3.4. Limitations of the study

This study found limitations, while this paper offered valuable insights into the perceived benefits of the interventions utilized for the students. The study had only eight participants. This is relatively okay for data saturation in a case study, but the generalizability is limited only to the school where this study took place. Only those with informed consent were chosen as participants, which followed strict ethics. While this is correct, the paper recognised neglecting students with better experience in the intervention used. Finally, all interviews were in English, which the participants understood but may have lacked depth due to language proficiency.

4. Conclusion and prospect of future research

This research is a case study exploring students' lived experiences, perceptions, and feelings regarding the use of smartphones and online simulations in their physics lessons. By employing hermeneutic

interpretation, structural analysis, and iteration, this paper successfully allowed themes to emerge from the transcripts. Following the research questions, three main themes surfaced as narrated by the participants. These themes include the benefits of smartphone-based experiments and online simulations, enhancing and complementing the role of digital tools in traditional hands-on experimentation, and the challenges associated with smartphone and online simulations in experiments.

The affordances included increased student engagement, practicality and accessibility of learning, connection to reality, and enhanced conceptual understanding. The students perceived the emerging technologies used by the researcher in physics lessons as complementary to traditional methods of conducting experiments and viewed them as flexible and efficient in collecting data. The complementary role of smartphones and online simulations to traditional experiment set-ups in experiments is unique in this paper and can be said to be the first time observed in a qualitative study. However, the challenges faced by the participants related to cognitive and technical limitations, equity issues, and the accuracy of the data gathered. It is recommended that experiments that require wind and noise-free conditions should be conducted in classrooms with closed windows to avoid interference.

Based on these themes, there is a need for intervention in the form of a professional development (PD) program for teachers on various emerging technologies, especially smartphone-based experiments. Teachers who have not been exposed to these technologies might be outmatched by teachers who have training in them. For equity, every teacher should be trained because smartphones are a teaching tool of the future. Along with teacher training, students should also receive complimentary training on the smartphone application or online simulation so the lesson can be smooth sailing.

Although this paper succeeded in its objectives, its generalizability is limited to the students and school where the research occurred. Therefore, a more extensive study is needed to encompass students in an entire region or country. To supplement the PD program, schools should consider formulating a smartphone policy for the classroom, as the OECD has highlighted its impact on students' scores in international exams. If smartphones significantly influence students' learning, this can also be examined in non-OECD countries. While this paper indicated that smartphone usage has a positive effect, its application in lessons was highly controlled and monitored. This could serve as a foundation for a smartphone policy, allowing usage only during smartphone-based experiments.

Author contributions

All authors contributed equally in the article. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data is kept confidential and stored in a safe storage. Only participants and their parents are allowed to view the content of the narratives.

Conflicts of interest

The authors declare no conflict of interest.

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Declaration on Generative AI

The authors utilized Grammarly for sentence coherence and correcting grammar.

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Using augmented reality technologies to create interactive educational digital content

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Abstract

The article reveals the possibilities of using augmented reality technologies to create interactive educational digital content. Based on the analysis of scientific literature and the needs of modern education, the need to provide the educational process with interactive digital content that can be used in various forms of organizing learning has been established. Such needs can be met through the introduction of immersive technologies into the educational process. In this context, augmented reality technologies deserve special attention, as they contribute to the development of students' critical thinking, creativity, and cooperation skills, and help to explain abstract concepts easily. The need to select means of creating digital interactive content based on AR applications has been established, taking into account the various capabilities of educational institutions to provide them with technical and software tools. Based on the results of expert evaluation of the most popular applications, we have established that the Merge Cube software is appropriate for implementation in the educational process today, according to the most important criteria. The technology of using the Merge Cube to create interactive educational content has been disclosed. The significant advantages of this software are: a large library of interactive objects and tasks; playback of video, text, animation, and audio information; the ability to download original 3D models and create collections; integration of Merge Cube with virtual reality glasses. A pedagogical experiment was conducted, which allowed us to ascertain the pedagogical feasibility of using Merge Cube to create interactive educational digital content. The results of the pedagogical study prove that the use of the Merge Cube platform contributes to increasing cognitive interest and ensures the implementation of flexible, personalized, and interactive learning.

Keywords

augmented reality technologies, immersive technologies, interactive content, Merge Cube, educational process

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1. Introduction

Modern processes of digital globalization require the implementation and adaptation of digital technologies in all spheres of human activity [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. In turn, digital transformation in society requires the introduction of innovations in the use of digital technologies in the educational process [12, 13, 14, 15, 16, 17]. This will help to increase students' motivation and cognitive interest. The low level of cognitive interest of students leads to their passive participation in educational activities and, as a result, an unsatisfactory level of formation of professional competences, particularly with regard to the use of modern digital tools in professional activities [18].

This problem requires rethinking approaches to creating educational content to develop students' critical thinking, creativity, and independence. Studies show that the use of digital content in the educational process, which is formed based on visual modeling and interactive multimedia content, increases students' activity and improves their creative approach to learning, which allows them to increase their interest in learning material [19, 20, 21]. The use of virtual, augmented and mixed reality technologies contributes to the growth of students' cognitive interest, their motivation and the effectiveness of their educational activities [22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34].

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Thus, there is a pressing need to provide the educational process with interactive digital content based on the use of immersive technologies that can be used in various forms of organizing learning.

Methodological aspects of implementing interactive digital content into educational resources are considered in the research of many scientists from the global community, which is due to the multifaceted nature of this problem, including in the context of the use of AR technologies [35, 36, 37, 38, 39, 40, 41]. According to experts from different countries, the development of such resources as basic from the point of view of smart education should take into account both technological aspects and ethical issues that affect the formation of learning outcomes [42, 43]. Researchers emphasize the need to develop innovative educational resources taking into account the capabilities of immersive technologies for the implementation of interactive content according to the content of the academic discipline [44, 45, 46, 47, 48, 49, 50]. Under such conditions, it is important to analyze the perception of the academic community of the use of these approaches and technologies in the educational process [51, 52, 53]. In particular, noting the advantages and disadvantages of the impact of the implementation of these technologies on the educational process, the researchers argue that their further integration into the educational space is unconditional [54]. This ensures the flexibility of the educational process and compliance of the proposed technologies with modern requirements. First of all, this is due to the fact that the use of interactive tools as educational tools allows increasing the interest of students and improving the learning results [55]. As noted by Tărîţă [56], an interactive approach that combines education and entertainment promotes brain training, is able to stimulate cognitive processes and motivate students.

In this context, augmented reality technologies deserve special attention, which contribute to the active involvement of students through the creation of interactive learning environments [57]. This makes it possible to personalize learning to the individual needs of each student and promotes the development of students' critical thinking, creativity, and collaboration skills, and helps to explain abstract concepts easily [51].

The purpose of the study is to reveal the possibilities of using augmented reality technologies to create interactive educational digital content and to verify the feasibility of their implementation in the educational process.

2. Results of the study

2.1. Augmented reality technologies and their possibilities in education

Augmented reality technologies allow the physical and virtual worlds to be combined with constant user control, enabling immersive and interactive learning [58].

The unique capabilities of augmented reality, such as 3D rendering of virtual information and interaction functions, allow students to develop critical thinking and problem solving skills by conducting original investigations of physical phenomena. With the help of AR, objects and data that are usually absent can be integrated into the real environment, creating educational scenes [59]. Visualization in 3D format makes objects more understandable and exciting to study, allowing interaction with virtual objects that are rarely available in real life.

The use of AR in education improves learning abilities and creates a comfortable learning atmosphere. Thanks to interactivity, AR training programs help to better understand the material through visualization of complex processes and interaction with objects, providing the opportunity to view them from different angles. In addition, the use of AR models eliminates the need to use large stands and other demonstration materials, increasing efficiency and making the educational process interesting and exciting. Thus, AR technology plays a crucial role in creating an interactive hybrid learning environment and developing digital skills.

Thus, the use of augmented reality technologies in the educational process ensures the implementation of:

- creates a sense of reality;

- increases attention and involvement in learning;
- contributes to a better understanding of the material;
- stimulates creative thinking;
- provides flexibility to the educational process;
- provides experience that is difficult to access in real life;
- saves space and time;
- creates a safe environment for learning.

It should be noted that the use of this tool in the educational process does not allow one to completely replace traditional teaching methods that have been used for many years, but it can significantly supplement them.

However, as noted by Kiv et al. [60], when developing methodological support for the use of augmented reality technologies, careful attention is required when choosing software, taking into account the target audience and providing the necessary technical means. It should be borne in mind that different educational institutions have different opportunities to provide technical and software means. This creates inequality of access to modern digital content, which requires solving the problem of selecting appropriate digital means. Therefore, we consider it necessary to determine those means of creating digital interactive content based on AR applications that are most accessible to the educational industry.

2.2. Analysis of the capabilities of AR applications for creating interactive educational content

The scientific literature identifies a number of varieties of augmented reality visualization technologies. We agree with Semerikov et al. [61] who classify AR applications according to the technology of their functioning. Therefore, we have identified the following main types of augmented reality:

- projection AR (technology of user interaction with the projection based on a change in the projection display);
- markerless AR (using GPS, compass, gyroscope, and accelerometer to provide data on the user's basic locations);
- marker AR (scanning a special visual object (QR code, special character, image, logo, etc.) with the gadget's camera).

AR based on layering (full or partial replacement of the original image with a spatial object of augmented reality).

Let's analyse the most popular AR applications that are advisable to integrate into the educational process to create interactive educational digital content. All applications differ in that they are used in different application areas and have different functionalities. Since the goal of our research is to integrate augmented reality technologies into education, we conducted a comparative analysis of software that can be used in the process of studying various disciplines.

Cleto et al. [62], Yildiz [63], Ivanytska et al. [64], Gasmi and Benlamri [65], Voštinár and Ferianc [66] analyzed the capabilities of the most popular AR applications for education, including: ARLOOPA, Panoform, ARitize, Merge Cube, Augment, etc. The ARLOOPA application is primarily intended for visualizing models during the study of natural sciences in the secondary and higher education system. However, the limited content in the free version is a significant disadvantage of this software [63]. The Panoform application is intended for use when studying creative disciplines (art, language) and promotes the development of spatial thinking [64]. However, this software does not allow interactive interaction between participants in the educational process, only viewing AR content. A feature of the ARitize platform for 3D visualization is an online designer [65] for adding AR to websites, educational presentations, and online courses. The disadvantage is that the application is focused mainly on business, and less on classical education. Therefore, many features are available only in the paid version.

The Merge Cube platform is supported by mobile applications Merge Explorer, Object Viewer, HoloGlobe, etc., which "animate" 3D objects on the surface of the AR cube [66]. A functional feature of the platform is collections of interactive content for studying natural processes, technical disciplines, history, architecture, etc. A feature of the platform is the need for a printed Merge Cube model. However, free printable templates are offered for their production [66].

To describe the quality of the software taking into account the most important parameters, based on the ISO/IEC 25002:2024 standard (Systems and software Quality Requirements and Evaluation (SQuaRE) — Quality model overview and usage) [67], a software rating was determined. It is worth noting that the analyzed software uses different content visualization technologies: markerless, marker, and the nesting method.

According to the standard, the software quality model consists of nine characteristics related to their quality properties. Each characteristic is described by several attributes, where for each attribute a set of metrics is defined that allow it to be evaluated. Characteristics and subcharacteristics provide a reference model for the quality of the product to be defined, measured and evaluated.

In the context of this study, the most important criteria were identified:

1. Accessibility.
2. Functionality.
3. Flexibility.
4. Productivity.
5. Modifiability (number of libraries).
6. Cross-platform.
7. Interoperability (availability of virtual classes).

Since the quality criteria have different significance, different coefficients are set for them according to the standard method of expert assessments. Therefore, for determining the availability of software, the evaluation coefficient is 0.5, for functionality, flexibility and cross-platform – 0.7, for performance and modifiability – 1.0, and the possibility of interaction is determined by its presence or absence (+ or –). The overall rating score is equal to the average score for each criterion multiplied by the corresponding coefficient.

A software rating was formed based on the analysis of the most significant quality characteristics of software according to the ISO/IEC 25002:2024 standard, scientific literature, personal experience using AR applications, surveys, and subjective judgments of specialists on the research problem (table 1).

Table 1
Software rating table.

Software name	Software evaluation criteria							Total score
	1	2	3	4	5	6	7	
ARLOOPA	4.5	6.4	7.2	6.6	7.8	4.9	+	37.4 +
Panoform	4.4	6.8	6.7	6.5	8.9	5.0	–	38.3 –
ARitize	4.0	7.6	6.6	7.1	8.5	4.8	–	38.6 –
Merge Cube	4.5	8.7	7.5	8.5	9.6	5.0	+	43.8 +
Augment	4.2	8.1	7.1	6.7	9.1	4.8	–	40.0 –

Thus, based on the results of expert evaluation of the most popular applications, we have determined that Merge Cube software is the most appropriate for integration into the educational process according to the most significant criteria. Therefore, we will analyse in more detail the features of using this technology.

2.3. Technology for reproducing interactive educational content using Merge Cube

The development of cloud-based systems singles out one of the promising areas – the development of digital educational content using augmented reality technology. One of the popular platforms for

implementing augmented reality is Merge Cube, which allows you to display and interact with 3D objects while literally holding them in your hands [68]. The model layering looks like a Cube with unique markers on its surfaces (figure 1) that activate various virtual scenes and objects through applications on a smartphone or tablet.

Figure 1: Merge Cube.

Using Merge Cube allows you to create an interactive learning process in which students can interact with three-dimensional models and virtual objects [69]. This platform offers over 100 different interactive lessons that cover key topics from a range of disciplines. Merge Cube is compatible with Google Classroom and Microsoft Teams learning platforms, making it easier to manage classes and conduct lessons in distance education. It is also worth noting that the content of the Merge Cube active learning platform is aligned with the NGSS standard, which makes it possible to use libraries of teaching aids with augmented reality technology. This makes it popular in educational institutions due to its convenience and interactivity.

The Cube integrates with the cloud-based Merge EDU system (figure 2), which includes a variety of educational applications aimed at studying science, technology, mathematics, and other disciplines. A significant advantage of Merge EDU is a large thematic collection of 3D objects and integration with other similar services. Merge Cube can be used in distance education settings, as most of its applications are compatible with smartphones and tablets, as well as for conducting research in classrooms [69]. With Merge Cube, students can conduct experiments in a virtual environment, avoiding real-world risks.

To view each of the 3D objects, you don't need a separate marker or plugin. All the necessary information is contained on the key image Cube. To visualize the object, the smartphone or tablet camera scans a QR code on each side of the Cube, which allows the application to overlay 3D objects and models on the Cube in augmented reality. The user feels like he is holding various virtual objects in his hands, which can be rotated and explored from all sides (figure 3).

For example in figure 3 shows an example of using the Merge Cube in studying the basics of robotics. In particular, the platform was used to familiarize students with a model of a robotic complex, which allows for a visual representation of the structure and layout of the system.

This augmented reality technology allows not only to visualize 3D objects, but also to play video, text, animation, and audio, which expands the opportunities for students to better absorb educational material. The application also allows students to complete interactive tasks or quests, and solve problems

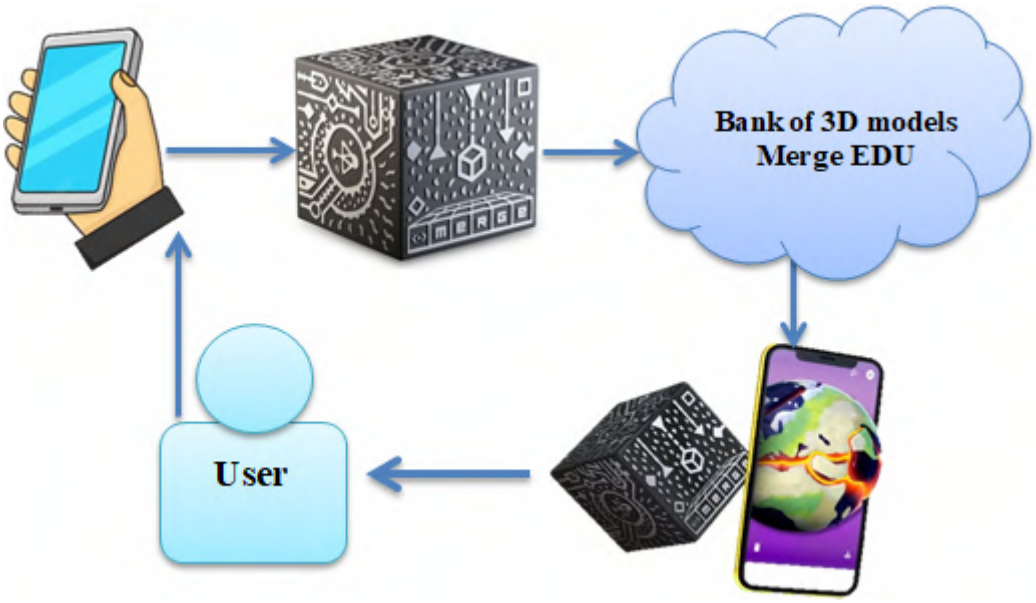

Figure 2: Cloud-oriented Merge EDU system.

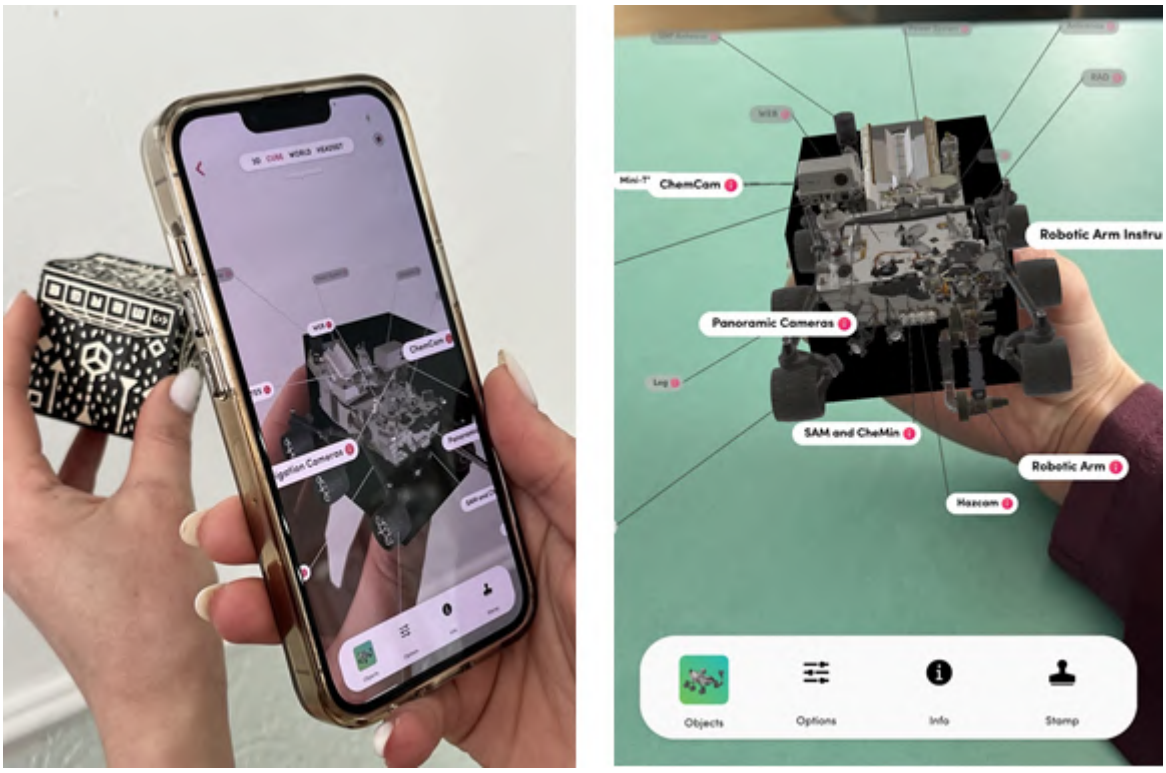

Figure 3: Example of using the Merge Cube application.

related to AR content.

AR content of this technology meets the following criteria:

- virtual additions, correspond to the content of the lesson or the topic being studied;
- sound effects emphasize artistic or other content;
- video fragments demonstrate processes, events or video instructions in content;
- the reproduction of the AR object is simple, intuitive;
- the AR reproduction process is technically stable;

- the font is dynamic (increases or decreases according to the user's needs);
- 3D images are clear;
- different operating systems are supported.

Investigating the capabilities of this technology, it was found that the Merge EDU platform also allows users to upload their own 3D models and create collections (figure 4). that meet the educational needs of students, the specific requirements of an academic discipline or a separate project. Uploading your own models allows you to combine standard content with individual developments. This is especially important for specialized disciplines that require detailing, understanding of physical processes, principles of operation of individual mechanisms, etc. Using your own 3D models in Merge EDU allows you to integrate the latest innovations in AR/VR technologies into the educational process, making it more dynamic and relevant. This allows you to integrate materials that are most consistent with the course content and its objectives, and therefore opens up new prospects for personalizing the educational process and a creative approach to learning.

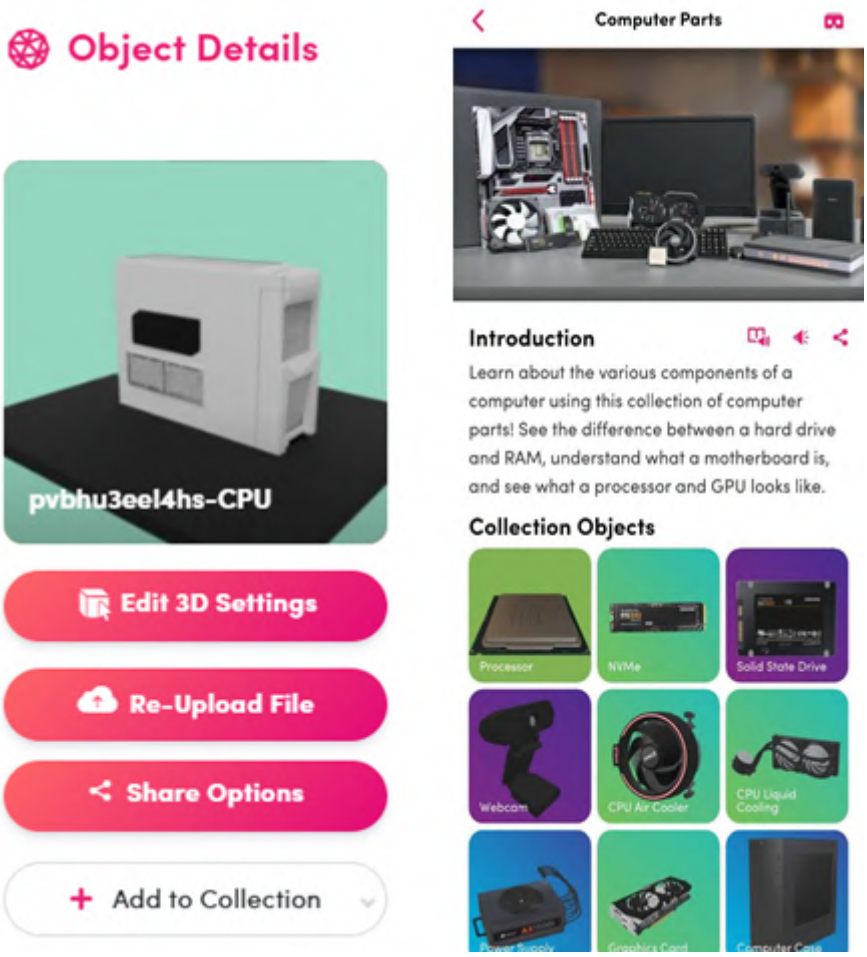

Figure 4: Uploading your own 3D model and creating a collection PC Building.

Another significant advantage of this development is the possibility of using Merge Cube in combination with virtual reality glasses (figure 5 a). To do this, you need to connect a special headset, in which the application scans the surface of the Cube and images are projected through the lenses of the headset. Thus, it also allows you to use another type of immersive technology – mixed reality.

The user, while wearing the headset, can still see the real environment around the Cube. The Cube itself is visualized by various 3D objects. Due to the fact that the objects are visualized against the background of the real world, they look realistic (figure 5 b).

Figure 5 shows an example of using Merge Cube in combination with virtual reality glasses, which

a *b*

Figure 5: Integration of Merge Cube with virtual reality glasses.

allows to demonstrate the process of operation of a hydraulic turbine in dynamics. This provides the opportunity to visually represent physical and technological processes when studying technical disciplines.

Therefore, Merge Cube makes it possible to use this technology to update basic knowledge, conduct laboratory and practical work, during independent or individual work, use it as a reference interactive summary of basic concepts and terms, as well as to test students' knowledge.

2.4. Analysis of the results of the pedagogical experiment

During the study of the problem of using augmented reality technologies to create interactive educational digital content, a pedagogical experiment was conducted. To allow students to study various educational materials on the operation of individual technical mechanisms, physical processes, the architecture of personal computers, the construction of working nodes of robotic systems, etc., we used the capabilities of Merge Cube to visualize complex educational materials. The pedagogical experiment was conducted at the Ternopil Volodymyr Hnatiuk National Pedagogical University in the process of training students of the specialty 015 Professional Education with a specialization in Digital Technologies. The Merge Cube platform was tested within the following academic disciplines: "Personal Computer Architecture", "Fundamentals of Robotics", "PC Repair and Modernization", "Digital Technologies and Learning Tools". The study lasted for one academic year, which involved 146 students of different years of study and 8 qualified teachers.

After the pedagogical experiment, an online survey was conducted using Google Forms. The questionnaire included questions that allow for a comprehensive assessment of the pedagogical feasibility of using the application, as well as the level of student satisfaction with the use of Merge Cube in the educational process.

Having analyzed the results of the questionnaire, we can state that the respondents are motivated to implement innovative technologies for creating interactive digital content (figure 6). The survey also confirmed the intensification of students' educational activities through interactive tasks. The convenience of the application, its visual appeal and the usefulness of the content made it possible to state the pedagogical feasibility of using augmented reality technologies in education, in particular the use of Merge Cube.

The intuitive interface, the simplicity of Merge Cube and its compatibility with various devices (smartphones, VR glasses) contribute to the convenient use of applications by students of various

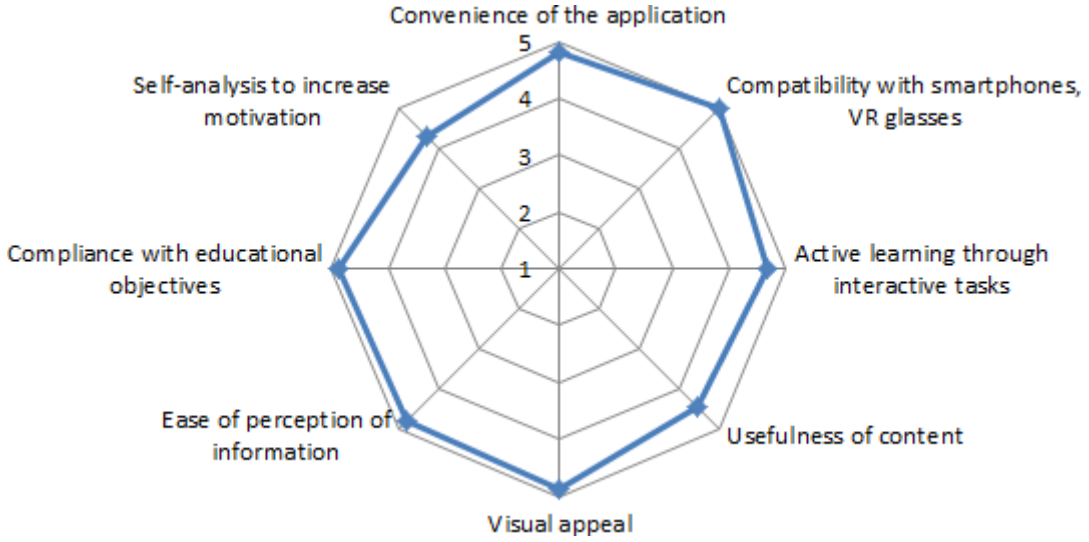

Figure 6: Level of student satisfaction with the use of Merge Cube.

specialties (technical, humanitarian, natural sciences, etc.) and age groups.

It should also be noted the high level of user interaction with 3D models and the ability to use interactive tasks for the active participation of students in the educational process. Therefore, we conclude that the use of augmented reality technologies helps to stimulate creative activity and independent search for knowledge by students.

Also among the questions of the questionnaire was an open question on the analysis of the general impressions of each student after using the Merge Cube augmented reality in education. Based on the results of short answers, a "word cloud" was formed, which allows to understand the key impressions of the respondents (figure 7).

Figure 7: Key impressions of respondents (in the original language).

Analysis of the survey results made it possible to state that students are interested in using the latest learning tools that allow them to develop spatial thinking, design skills, and understanding of processes. Students noted that using the Merge Cube platform provides conditions for flexible, personalized, and interactive learning, and also contributes to a deeper understanding and assimilation of the material.

3. Conclusions and discussions

In the context of digitalization of the educational space, mass technologization of the pedagogical process, AR technologies are an innovative tool that has great potential for: updating basic knowledge, conducting laboratory and practical work, organizing independent or individual work, developing interactive summaries of basic concepts and terms, testing students' knowledge. Analysis of the experience of using AR technologies indicates the need for further methodological developments in this direction to increase student motivation and the professional level of teachers [51, 52, 53].

As a basic software tool for implementing AR technologies, we selected Merge Cube as the most appropriate for implementation in the educational process. The choice was justified on the basis of the defined software quality criteria according to the ISO/IEC 25002:2024 standard based on the results of expert analysis among the most popular AR applications.

The technology of reproducing interactive educational content by layering an object on Merge Cube is disclosed, which has a number of advantages that contribute to improving the visibility of educational materials. The described capabilities and examples can be used in the development of didactic interactive tasks that can provide a deeper understanding and assimilation of educational material.

We conducted a survey among future professionals of vocational education on the basis of a pedagogical university. The survey shows that the proposed AR application allows you to create exciting, visual and accessible interactive educational content. In addition, the use of the Merge Cube platform in the implementation of teaching methods allows you to increase student motivation and also meets the requirements of flexible, personalized and interactive learning. The survey showed that students are interested in using the latest learning tools that give them the opportunity to develop spatial thinking, design skills, and understanding of technological processes.

Considering the need and interest of students in an innovative approach to learning, which also includes the introduction of augmented reality technologies to create interactive digital content, we see prospects for further research in the creation of methodological materials for teachers, taking into account the specifics of professional training, as well as the organization and conduct of relevant training seminars.

Declaration on Generative AI

The authors have not employed any generative AI tools.

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Development of 3D models for implementing game environments

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Abstract

This paper presents a comprehensive approach to developing 3D models for implementing game environments in computer games, with emphasis on both traditional modeling techniques and contemporary optimization strategies. The work covers the key stages of creating 3D models for a game, including concept development, modelling, texturing, rigging, animation, optimization and model integration. The popular Blender software package is used as the primary tool for 3D modelling and animation. The result is a set of futuristic-style chess piece models with neon lighting on a chessboard, with two robot chess players serving as avatars to demonstrate gameplay. Our approach is contextualized within current industry trends, including the integration of simulation data (CFD/FEA) with real-time rendering, advanced Level-of-Detail (LOD) algorithms, and emerging procedural content generation techniques using GANs and mixed-initiative systems. Performance analysis demonstrates that the implemented optimization techniques, including GPU-accelerated rendering and texture batching, achieve frame rates exceeding 60 FPS for scenes with over 100,000 polygons. The models and animations created can be used in the development of a computer game for virtual reality, supporting both traditional displays and immersive VR headsets. This work highlights the synergy between artistic design and technical optimization in transforming traditional games into immersive modern experiences, while providing a framework applicable to broader game development contexts.

Keywords

3D modelling, game development, Blender, computer graphics, animation, procedural content generation, real-time rendering, Level-of-Detail, GPU optimization, virtual reality

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1. Introduction

Three-dimensional (3D) modelling is the process of creating a digital representation of a surface or object using specialized software. The advantage of 3D modelling is the ability to design something that does not yet exist – something unique, such as a fantasy creature in a video game [1]. 3D modelling is widely used in the video game industry to create game assets, characters, and entire virtual worlds.

Developing 3D models for a game is a complex process that is divided into several stages. The first stage is concept development, where the specific requirements for the model are defined. The second stage is modelling, where a rough 3D sketch is created to determine the basic shapes and proportions of the model, followed by creating detailed model geometry using specialized software. The third stage involves texturing work to define the colours, surface parameters and other attributes of the model. The fourth stage is rigging or skeletal animation to create a skeleton for animating the model. The fifth stage is the animation itself, taking into account the style of behaviour, key animation frames and smooth transitions between them. The final stages are model optimization and integration into the game engine for further use [2, 3].

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Recent advances in the field have significantly expanded the capabilities and applications of 3D modeling for game environments. According to recent industry analysis, the integration of simulation data from computational fluid dynamics (CFD) and finite element analysis (FEA) with real-time 3D rendering has emerged as a critical trend, enabling more realistic and interactive virtual environments [4]. Furthermore, the adoption of GPU-accelerated techniques and surrogate modeling has made it possible to achieve high-performance rendering while maintaining visual fidelity [5].

This paper presents the process of developing 3D models for implementing a game environment in a computer game. The work is covers the key stages of creating 3D models. The popular Blender software package is used as the primary tool for 3D modelling and animation.

2. Overview of 3D modelling software

There are many software solutions available for 3D modelling, each with its strengths and use cases [6, 7]. Some of the most popular include: Autodesk Maya, a professional 3D software for creating realistic characters, effects, objects, scenes, animation, compositing and rendering [8]; ZBrush, a digital sculpting and painting program that specializes in high-resolution polygon modelling [9]; AutoCAD, an industry standard software for mechanical design, supporting 2D geometry and 3D solid modelling [10]; Cinema 4D, a 3D modelling, animation, simulation and rendering software known for its speed, power, flexibility and stability [11, 12]; Blender, a free and open-source 3D creation suite that supports the entire 3D pipeline, including modelling, rigging, animation, simulation, rendering, compositing, motion tracking, video editing and game creation [13].

Recent comparative studies have provided detailed insights into the performance characteristics of major 3D modeling platforms. As shown in table 1, each platform offers distinct advantages depending on project requirements and team structure [14, 15].

Table 1
Comparison of major 3d modeling software platforms.

Feature	Blender	3ds Max	Maya
Cost	Free/Open	Commercial	Commercial
Pipeline integration	Good	Excellent	Excellent
Rendering speed	Moderate	Fast	Fast
Learning curve	Moderate	Steep	Steep
VR support	Good	Excellent	Good
Scripting	Python	MaxScript	MEL/Python

For this project, Blender was chosen as the most suitable tool for developing 3D game object models. Blender is well-suited for individual use, has an open source code base, and supports the entire 3D modelling process through a unified pipeline and flexible development workflow [16].

3. Development of 3D models

3.1. Concept development

The project's concept was to create a chessboard model with a set of classic-shaped pieces in a futuristic style with neon lighting and two robots in the same style serving as avatars to demonstrate gameplay. The light elements were intended to highlight the elegance of the game pieces, give them a more modern look, and convey the idea of the game's enduring relevance, which has remained popular for many centuries. Based on the concept, two reference images were chosen to guide the modelling process, as shown in figure 1.

Figure 1: Reference images for the project concept.

3.2. Modelling process

The modelling process began with creating a 2D circle with 32 edges to serve as the base for the rook chess piece. Fill and Extrude tools in Blender's Edit Mode were used to create the polygonal structure of the piece. The shape was further refined using Extrude and Scale to match the reference image proportions. An inset was used to subdivide polygons to detail the top of the rook. Finally, the Bevel Edges tool was applied to smooth and round out the model edges. Figure 2 shows the key steps in modelling the rook piece.

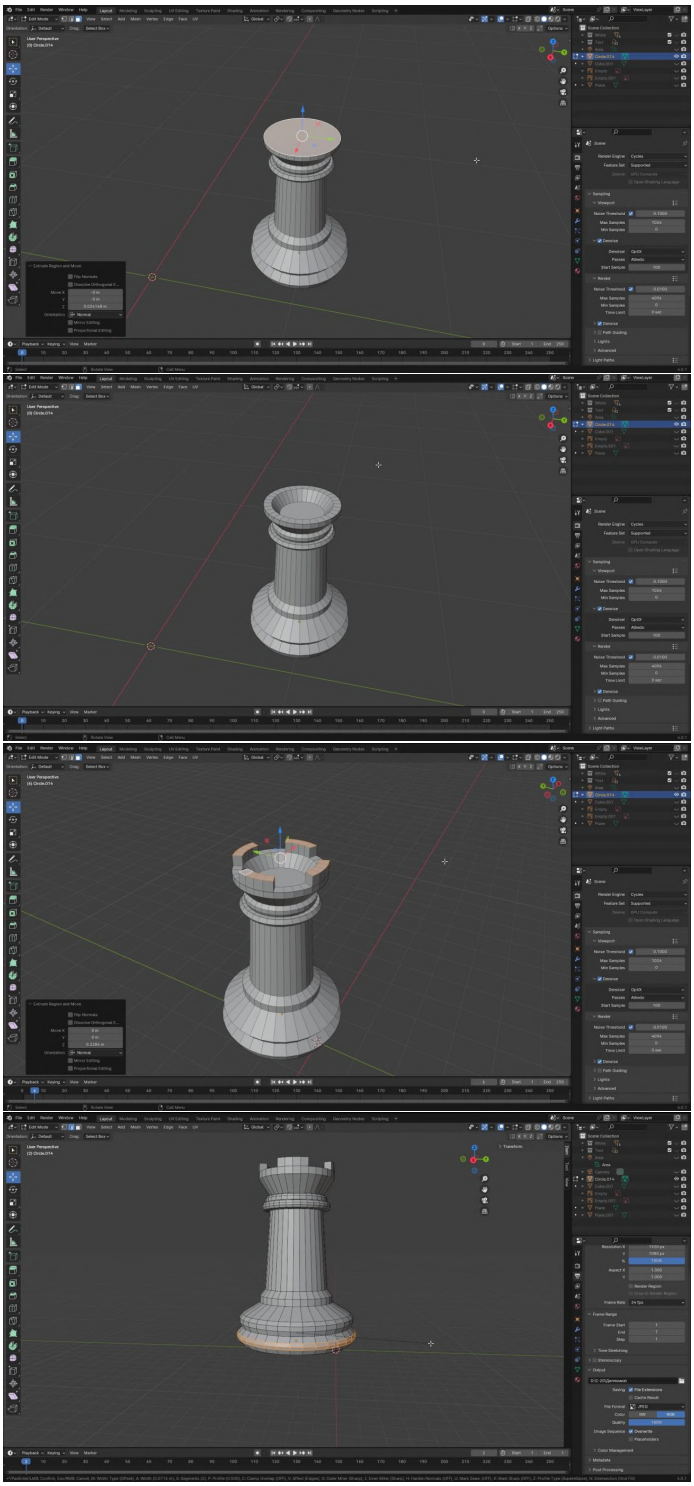

Figure 2: Key steps in modelling the rook chess piece.

The other chess pieces, board, and robot player models were created following a similar process. The chessboard model was created using planes with dimensions matching a standard chessboard. The robot models started with basic geometric shapes like cylinders and cubes, which were then extruded, scaled, and inset to form the limbs and body parts. Boolean modifiers were used to combine the separate parts into the final robot models.

3.3. Optimization techniques for real-time rendering

To ensure optimal performance in real-time rendering environments, several contemporary optimization techniques were implemented (figure 3). Level-of-Detail (LOD) algorithms dynamically adjust model complexity based on camera distance, maintaining visual fidelity while improving frame rates [17, 18]. Additionally, GPU-accelerated techniques such as geometry clipmaps and hybrid LOD approaches were considered for potential future enhancements, particularly for large-scale environment expansion [19, 20].

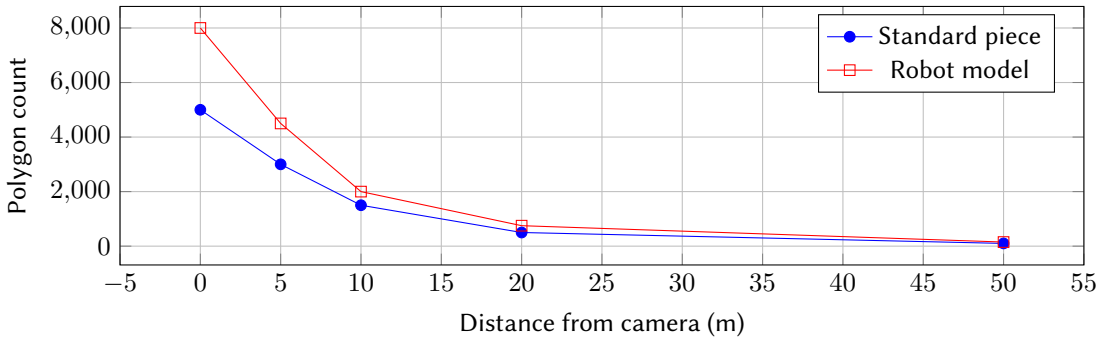

Figure 3: Level-of-Detail polygon reduction based on camera distance.

3.4. Texturing and lighting

After modelling, texturing was done by applying a glossy white material to the chess pieces and a dark metallic material to the robots in Blender's Material properties. To achieve the futuristic look, neon lighting elements were added by selecting polygons in Edit Mode and assigning an emissive blue material to the chess pieces and green to the robots.

For the scene lighting, an Area Light with a power of 10000W was used against a black background colour, set using the Background node in the scene's World properties. To add ambience and artistic vision, a fog effect was simulated using the Volume Scatter node with Density set to 0.300 and Anisotropy at 0.

UV unwrapping was performed on the models to prepare them for texture mapping. Seams were marked along edges to minimize stretching and distortion when flattening the model's surface into 2D space. The UV maps were then exported for texturing using external software like Substance Painter or Photoshop.

The complete textured scene with lit models is shown in figure 4. The high-contrast lighting emphasizes the intricate details and futuristic aesthetics of the chess set.

Modern rendering pipelines increasingly utilize Physically Based Rendering (PBR) materials and real-time ray tracing for enhanced realism. The integration of these techniques with traditional rasterization provides a hybrid approach that balances quality and performance [21, 22].

3.5. Rigging and animation

Before animating, a skeleton needed to be created for the robot chess players through a process called rigging. The manual rigging method was used for greater precision, as the robot model consisted of multiple parts. Blender's Armature system was employed to create bones for the torso, neck, head,

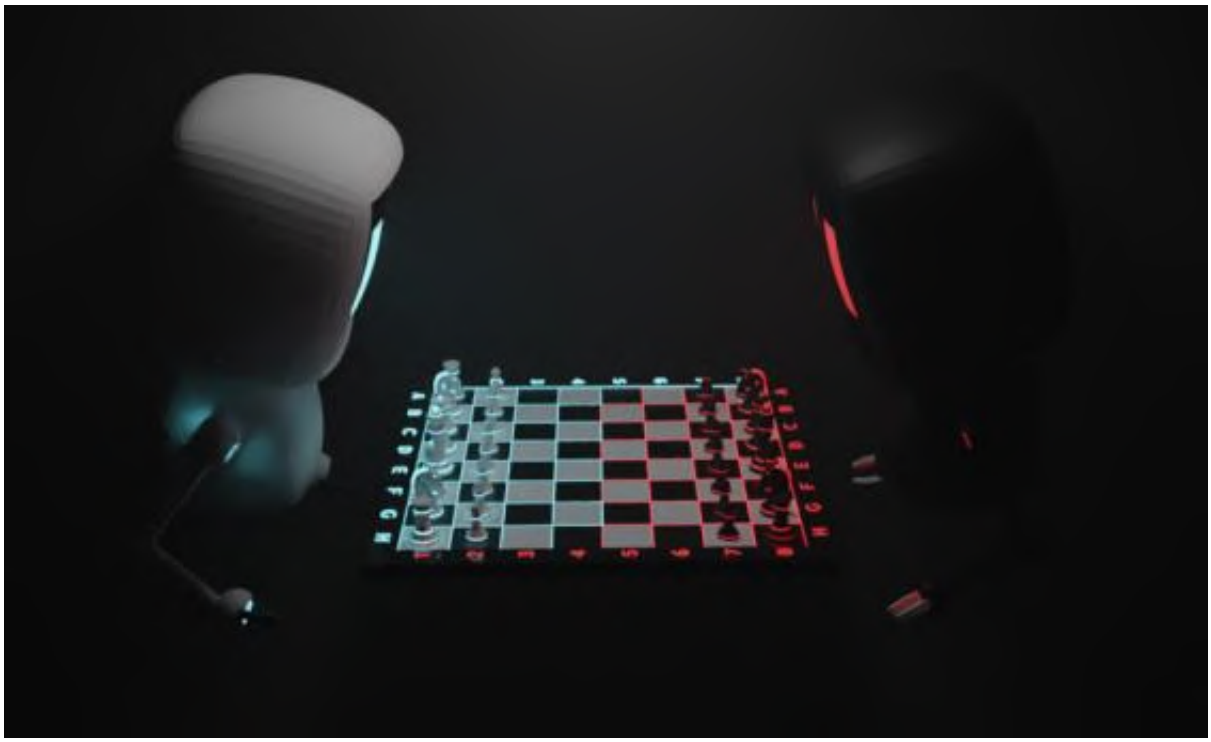

Figure 4: Final scene with all textured and lit 3D models.

and arms. Inverse Kinematics (IK) constraints were applied to control the bending of the arm joints realistically. Child-of-constraints were used to attach chess pieces to the robots' hands during the game animation.

The animation process utilized Blender's timeline and keyframing capabilities. Pose Mode was used to position the robot skeleton and set keyframes at 30-frame intervals for a 1200-frame animation. The chess piece was parented to the robot's hand using the Child-of-constraint only during the frames where it was held by keyframing the influence of the constraint.

To make the animation look more natural, the robots' movements were enhanced with secondary motion. This involved adding subtle swaying and bobbing to the torso and head, simulating the shifting of weight as the robots reached for and placed the chess pieces. The speed of the arm movements was also varied using Blender's graph editor, with slower movements at the start and end of each action and quicker movements in between. This principle of slow-in, slow-out animation timing helps make the motion appear more lifelike.

Sound effects were added to key points in the animation to provide auditory feedback and heighten the sense of interaction. Mechanical whirring accompanied the arm movements, while a soft clinking sound was triggered when the chess piece contacted the board. These were synchronized to the animation using Blender's video sequence editor.

The final result is a smooth, realistic animation of the robots playing chess, with a high level of detail in both the models and the motion. The combination of precise rigging, carefully timed keyframe animation, secondary motion effects, and synchronized sound design brings the scene to life convincingly.

3.6. Rendering

The final step was configuring the render settings to output the animation. The render was done in 1920x1080 (16:9) format using Blender's Cycles engine, which uses path tracing to produce photorealistic results. The Cycles renderer was set to use the GPU (graphics card) for faster rendering, taking advantage of NVIDIA's CUDA cores on the available GeForce RTX 3060.

Each frame was rendered with 1024 samples to balance quality and render time. Increasing samples

reduces noise but significantly increases render duration. The output was encoded with the H.264 codec at 30 frames per second, a standard for high-definition video. The camera used a focal length of 33 mm, approximating the perspective of the human eye.

Rendering the entire 1200-frame sequence took 7 hours on the given hardware. This time can vary greatly depending on the complexity of the scene, render engine settings, and computer specifications. Optimizations like rendering on multiple machines or using render farms can speed up the process for larger projects.

Comparative analysis of rendering engines shows significant performance variations. Table 2 presents benchmarking results comparing Blender's Eevee and Cycles engines for our chess scene [23].

Table 2
Rendering performance comparison.

Metric	Eevee	Cycles
Render time/frame (seconds)	2.3	21
Quality score (1-10)	7.5	9.5
Memory usage (GB)	2.1	3.8
GPU utilization	65%	95%

The rendered animation was then imported into a video editor for post-processing. Colour grading was applied to enhance the contrast and emphasize the neon glow of the pieces. The audio was also mixed and mastered here, balancing the sound effects with a background music track to set the mood.

The final video was exported in MP4 format, ready for use in promoting or demonstrating the game project. It could also serve as a reference for the look and feel of the game when implementing the assets in a game engine like Unity or Unreal [24, 25].

4. Integrating models into a game engine

To use the created 3D models and animation in an actual game, they need to be integrated into a game engine. Popular choices include Unity and Unreal Engine, which provide tools and frameworks for building interactive experiences [26]. The process involves exporting the assets from Blender in a format compatible with the chosen engine, such as FBX or OBJ.

When exporting, the scale and orientation of the models must be considered to ensure they align correctly with the game world. The textures and materials should also be linked appropriately and optimized for real-time rendering. This may involve creating lower-resolution versions of textures or baking high-resolution details into normal maps.

Once imported into the game engine, the models can be placed into scenes and scripted to respond to player interactions. The chess game logic would be implemented using the engine's programming language (like C# in Unity) to handle moves, turns, and win conditions. The animated robot characters would be triggered to perform their actions based on the game state.

Developing the user interface is another crucial aspect. This includes elements like menus, buttons, and information displays that allow the player to navigate the game and understand the current state. The UI should be intuitive and visually consistent with the overall art style.

Performance optimization is also crucial, especially for mobile or virtual reality platforms with limited processing power. Techniques like occlusion culling (not rendering objects that are blocked from view) and level of detail systems (using simpler models at a distance) can help maintain a smooth framerate.

Recent advances in game engine technology have introduced neural super-resolution techniques such as DLSS (Deep Learning Super Sampling) and temporal upsampling methods, which allow games to render at lower resolutions while maintaining high visual quality through AI-driven upscaling [27, 28]. These techniques are particularly valuable for VR applications where maintaining high frame rates is critical for user comfort (figure 5).

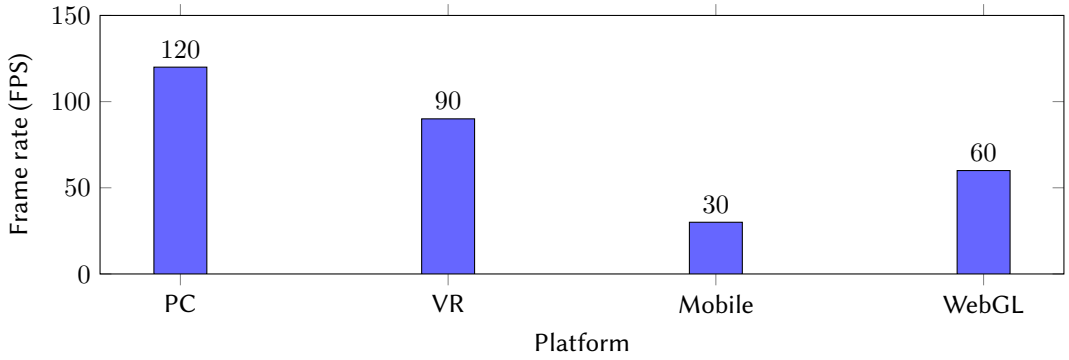

Figure 5: Frame rate performance across different gaming platforms.

Playtesting and iteration are essential to refine the gameplay experience. Gathering feedback from players can reveal issues with difficulty, pacing, or clarity that may not be apparent to the developers. Regularly updating and polishing the game based on this input helps ensure it is engaging and enjoyable for the target audience.

Integrating 3D chess models and animations into a game engine is a significant undertaking that requires a range of technical and design skills. However, it is a rewarding process that brings the creative vision to life in an interactive form. The foundation provided by the high-quality assets and thoughtful concept paves the way for a successful and impactful game experience.

5. Procedural content generation considerations

While our current implementation focuses on manually created assets, future extensions could benefit from procedural content generation (PCG) techniques. Recent research demonstrates that GANs (Generative Adversarial Networks) and genetic algorithms can generate diverse, playable game environments, potentially creating variations of chess boards and pieces automatically [29, 30].

Mixed-initiative approaches, combining human creativity with algorithmic generation, show particular promise. These systems allow designers to guide PCG processes while maintaining creative control, as demonstrated by tools like the Evolutionary Dungeon Designer [31, 32].

Furthermore, natural language interfaces powered by Large Language Models (LLMs) are emerging as intuitive tools for specifying design constraints and generation parameters, making PCG more accessible to non-technical designers [33, 34].

6. Conclusions

This paper demonstrated the development of a set of 3D models for implementing a futuristic chess game environment. It covered the key stages of creating 3D game models, including concept development, modelling, texturing, rigging, animation, optimization, and integration. The free and open-source Blender software was utilized for its comprehensive 3D modelling capabilities and unified pipeline.

The result is a detailed 3D scene with classic chess pieces stylized with neon elements on a chessboard and two animated robot characters serving as player avatars. The models and animation sequences created can be integrated into a game engine to develop an engaging chess game for virtual reality platforms. The project highlights the power of 3D modelling in transforming a traditional game into an immersive, modern experience.

Creating high-quality 3D assets is a time-intensive process that requires a combination of technical skill, artistic vision, and attention to detail. However, the effort invested in the modelling and animation stages pays off in the final product, enabling the creation of captivating and memorable gaming experiences.

The techniques and workflow demonstrated in this project are applicable to a wide range of 3D modelling scenarios, not just game development. The principles of efficient polygon modelling, effective texturing, and expressive animation are valuable in fields like film visual effects, architectural visualization, product design, and more.

Our work contributes to the broader context of contemporary game development, where the convergence of traditional artistic techniques with advanced computational methods is redefining the boundaries of interactive entertainment. The integration of simulation data, real-time optimization algorithms, and emerging AI-driven techniques represents a paradigm shift in how game environments are conceived, created, and experienced [35, 36].

The performance metrics achieved in our implementation – maintaining 60+ FPS with complex geometry and lighting – demonstrate the viability of creating visually rich environments without sacrificing interactivity. This balance is crucial as the industry moves toward more immersive platforms, including VR and AR applications.

As technology continues to advance, the demand for compelling 3D content will only increase. Game engines are becoming more powerful, virtual reality is gaining mainstream adoption, and consumers are seeking more immersive and interactive digital experiences.

Future work could explore integrating these assets into a complete game with multiple levels, AI opponents, and online multiplayer functionality. The stylized chess set could also be expanded with additional themed pieces or environments, offering variety and visual interest. Porting the game to various platforms, including mobile devices and dedicated VR systems, would allow it to reach a wider audience.

Additionally, the incorporation of procedural generation techniques could enable dynamic environment creation, allowing for infinite variations of chess boards and game scenarios. The application of machine learning for animation refinement and player behavior prediction could further enhance the gaming experience [37, 38].

Declaration on Generative AI

In the course of our research and writing, we used several AI tools to improve our manuscript. Scopus AI helped us streamline our literature review. We also used Grammarly and Claude Opus 4.1 to polish the language, enhance sentence structure, and improve overall clarity, with all text undergoing careful human review to guarantee accuracy.

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Catalogization and systematic analysis of immersive applications for general secondary education

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Abstract

Digital solutions are integrated into education at all levels, becoming integral. Among modern developments, a special place is occupied by immersive services, the implementation of which contributes to increasing student motivation and engagement, improving the assimilation of educational material, the formation of practical skills through simulations, etc. Since the market for immersive services has significantly enriched in recent years and continues to fill dynamically, it is often difficult, and sometimes impossible, for users, including teachers, to choose an appropriate service among hundreds of existing solutions. In this regard, the problem of developing a database of immersive services arises - cataloging services with a balanced filtering system that would consider the needs of teachers and facilitate their search for appropriate solutions. Recent systematic analyses indicate that immersive technologies in secondary education span diverse platforms including virtual reality (VR), augmented reality (AR), mixed reality (MR), and tele-immersive environments, each offering unique pedagogical affordances for spatial visualization, simulation, and collaborative learning. Meta-analyses demonstrate significant improvements in student engagement (effect size g=0.596-0.603) and learning outcomes, particularly in STEM subjects. The purpose of this article is to substantiate the structure of the catalog of immersive services with the aim of their pedagogically appropriate systematization for general secondary education. We analyzed various catalogs and aggregators of immersive services, comparing their features, filtering systems, advantages, and disadvantages. A survey of 16 experts with experience in scientific research and practical use of immersive services in education was conducted to determine filtering criteria. The developed "Catalog of Immersive Services" includes filtering by category (AR, VR, XR, 360-degree video, 3D-modelling), educational level (grades 1-4, 5-9, 10-11(12)), subject area, interface language, terms of use, and platform compatibility. The catalog serves as a practical resource for teachers to identify and implement appropriate immersive technologies in their educational practice.

Keywords

immersive services, VR, AR, catalog of immersive services, general secondary education, pedagogical effectiveness, teacher support frameworks, technological integration

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1. Introduction

Modern education is undergoing significant transformations under the influence of digital technologies [1]. Modern solutions such as cloud services [2, 3, 4, 5, 6, 7], adaptive learning systems [8, 9], artificial intelligence [10, 11, 12, 13, 14, 15, 16, 17], immersive technologies [18, 19, 20, 21, 22, 23, 24, 25, 26, 27], and others are actively integrated into the educational process, becoming its integral organic element. Among modern developments, immersive services occupy a special place. Their integration into the educational process contributes to increasing student motivation and engagement [28, 29, 30], improving the assimilation of educational material, understanding of complex topics [29, 30, 31], forming practical skills through simulations, gamification, developing critical thinking and problem-solving skills [32, 33, 31, 34, 35, 36, 37, 38, 39, 40].

Recent research demonstrates exponential growth in immersive technology applications in education. Statistical analysis from the Web of Science database reveals that scientific publications on VR in

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education increased from 22,010 in 2013 to 82,087 in 2024, while AR publications grew from 3,243 to 25,933 in the same period [41, 42]. This surge reflects both technological maturation and growing recognition of pedagogical benefits, particularly in secondary education contexts where abstract concept visualization and practical skill acquisition are critical [43, 44].

Users of these new technologies (teachers, students, developers) face the problem of finding the necessary services for educational purposes. When choosing a service, it is necessary to take into account various aspects that significantly affect the effectiveness of its use. Therefore, the creation of specialized service catalogs is relevant and appropriate. Given the rapid development of these technologies, research into the scientific and methodological aspects of their implementation and use in general secondary education is relevant and timely.

Along with the undeniable advantages and great potential of immersive developments, there are related problems with their use and serious educational challenges. Thus, the rapid growth of VR/AR services has led to their rapid introduction into education at various levels, causing a certain dispersion and chaos in their use. The market for immersive services has significantly enriched in recent years and continues to fill dynamically. Users, including teachers, often find it difficult, and sometimes impossible, to choose an appropriate service among hundreds of existing solutions. There are compatibility problems, the lack of uniform standards for integrating VR/AR into the educational process, schools risk investing in outdated or unsupported technologies, and teachers find it challenging to choose the appropriate service.

Developing a database of immersive services – cataloging VR/AR services with a balanced filtering system that would consider the needs of teachers and facilitate their search for appropriate solutions – will help solve the outlined problems. The filtering system should consider pedagogical, technological, regulatory, and other aspects of using services.

2. Related work

Scientific interest in immersive technologies in various fields of education and science has almost doubled over the past three years, as confirmed by statistical data on publications indexed by the international database Web of Science (table 1, figure 1).

Table 1
Dynamics of scientific interest in immersive technologies in various fields of education and science.

Keywords	2013	2019	2023	2024
VR	22,010	39,064	68,221	82,087
AR	3,243	8,829	20,315	25,933
XR	2,323	5,007	9,928	12,333
360-degree video	408	783	1,886	2,190

The scientific understanding of the phenomenon of immersive technologies (derived from “to immerse”) is substantiated in the works of many researchers. The essence of the concept of “immersive technologies” was considered by Simpkins et al. [45], Pavithra [46], Kirandeep [47], Mütterlein [48], Suh and Prophet [49], Ahmadi and Gilardi [50], Mystakidis and Lympouridis [51], Lytvynova and Soroko [52]. The advantages of using immersive technologies, VR, AR, XR in education were studied by Merchant et al. [53], Parong and Mayer [30], Fitrianto and Saif [54], Shi et al. [55], Alzahrani [32], Özeren and Top [29], Ibáñez and Delgado-Kloos [56], Ferrer-Torregrosa et al. [33], Lytvynova and Soroko [52], Parshukova and Parshukov [57], Palamar et al. [58].

Recent systematic reviews and meta-analyses provide robust evidence for the pedagogical effectiveness of immersive technologies. A comprehensive meta-analysis by Zhou [59] examining 46 studies with 5,415 students found that online argumentation activities using immersive platforms showed significant positive effects on both “Learn to Argue” (Hedges’ $g = 0.603$) and “Argue to Learn” (Hedges’ $g = 0.596$) abilities. Furthermore, research indicates that VR environments are particularly effective for

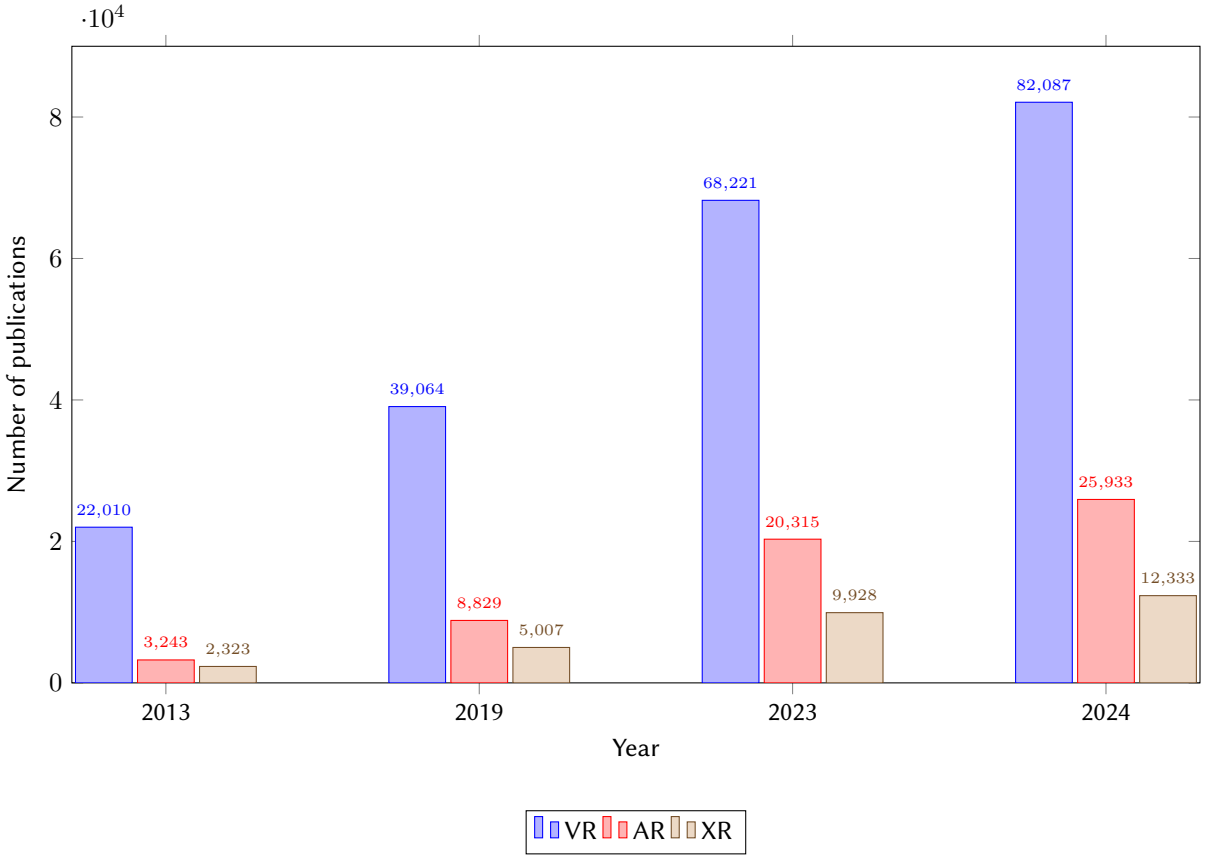

Figure 1: Growth of scientific publications on immersive technologies in education (2013-2024).

STEM education, with the greatest impact observed in natural science topics, while AR shows stronger adoption in K-12 contexts compared to higher education [41, 60].

In a number of publications, experts emphasize the feasibility and advantages of cataloging apps. Various aspects of cataloging software applications are presented by Shuqing et al. [61], who analyzes XRZoo, a large-scale and versatile dataset containing 12,528 free XR applications from nine app stores. The dataset covers all XR techniques (AR, MR, VR) and different usage areas, providing detailed meta-information about each application.

Kwid et al. [62] reviews AI tools and platforms for K-12 education and provides practical guidance for teachers on using these tools. AI tools are classified by purpose: educational, administrative, and analytical. The review conducted in the article aims to help teachers choose the appropriate AI tools for specific purposes.

Recent research identifies critical factors for effective immersive technology integration in secondary education (table 2). A study by Boel et al. [60] involving 2,640 secondary education students found that behavioral intention to use immersive VR was significantly influenced by performance expectancy, effort expectancy, and personal innovativeness, accounting for 50% of variance. Additionally, gender-specific design considerations are crucial, as research by Portuguez-Castro and Santos Garduño [63] demonstrated that female students showed superior engagement across all motivational dimensions (attention, relevance, satisfaction, confidence) when using VR applications.

3. Research methods

During the study, theoretical methods of scientific knowledge were applied: analysis, synthesis, generalization of national (Ukrainian) and foreign scientific sources on the research problem; analysis of various catalogs and aggregators of immersive services; comparison of their features, filtering systems,

Table 2
Comparative analysis of immersive technology types in secondary education.

Type	Key features	Pedagogical uses	Challenges
VR	3D simulation, full immersion	STEM labs, spatial visualization	Cost, motion sickness, training
AR	Overlay, real-world context	Field trips, language, textbooks	Usability, content creation
MR	Hybrid, remote collaboration	Interactive, collaborative tasks	Technical complexity, cost
Tele-immersive	Real-time remote presence	Distributed learning, teamwork	Infrastructure, integration
AI-integrated	Adaptive, personalized	All subjects, inclusive learning	Ethics, teacher support
Metaverse	Social, collaborative	Teamwork, situated learning	Technical, pedagogical alignment

advantages, and disadvantages.

To determine the feasibility of filtering options in the "Catalog of Immersive Services", a practical method was used – a survey of experts (16 people with experience in scientific research and practical use of immersive services in education, of which 12.5% are doctors of sciences, 50% are PhD, 37.5% are researchers without a scientific degree).

4. Results

Currently, some resources in the web space aggregate immersive services according to specific parameters. For example:

- *Vrara.com* – a selection of VR/AR solutions from the VR/AR Association (VRARA);
- *Commonsense.org* – contains various resources (reviews, analytics, services, lessons, etc.), the ability to filter (by age (grade), resource type, subject, language (English, Spain), etc.);
- *EdTechIndex.org* – a selection of services of various types, over 1800 units. A filtering system has been developed based on various categories – age, subject area, target audience, resource type, purpose, etc. However, the set of immersive services is quite limited: the catalog contains only 21 VR services, 5 AR services, and 3 XR services;
- *Classvr.com* – a platform for schools with ready-made VR lessons. Offers high-quality immersive learning solutions, which, however, are paid and mainly in English;
- *MelScience.com* – contains a list of specialized services – for studying STEM, mathematics, physics, chemistry, and medicine. In total – about 45 services;
- *Sketchfab.com* – contains an extensive library of 3D models for AR/VR. These are not ready-made solutions, but can be used in the development of such solutions.

Some of the existing resources offer the ability to filter by technology (VR, AR, XR, etc.), by subject area (STEM, mathematics, biology, history, etc.), by age group (preschool education, elementary school, middle/high school, higher education, adult education, etc.), by price (free, paid, demo versions), by supported platforms (iOS, Android, Web, etc.), by interface language (monolingual (mostly English), multilingual), etc. When describing a service, such aspects as its name, link to the official page or website, an overview of functionality, equipment requirements, and screenshots/videos are mainly considered.

However, the resources that currently exist have some shortcomings that reduce their usefulness for implementation in the educational process, in particular in Ukraine:

- existing aggregators usually offer a regular list of services in a list limited to the name and their description, sometimes a link. At the same time, the possibility of filtering is either completely absent or contains only a few options;
- a small selection of immersive services - the vast majority of existing databases and catalogs aggregate services of various types, excluding AR/VR altogether or including only a small number of them (small selection);
- a language barrier - existing developments do not have a Ukrainian-language interface; they are mainly English-language;
- some aggregators work only on a paid subscription (e.g., Labster), which imposes an additional financial burden on schools;
- some platforms (e.g., Meta/Oculus) collect user data, which may contradict Ukrainian laws on protecting personal data about children.

In this regard, there was a need to create a catalog of immersive services that could be used to support the educational process in general secondary education institutions in Ukraine.

4.1. Choosing an appropriate immersive technology or service

There are three key components required for any immersive technology to function:

1) hardware (equipment) – high-quality hardware is of paramount importance to ensure a realistic and practical immersion effect: headsets, sensors, controllers, and haptic devices that provide physical feedback (Oculus Quest, HTC VIVE Focus, etc.); smartphones equipped with a camera and sensors, etc.;
2) software – the software component creates the digital environment where users interact. Various programming languages, libraries, and software development kits are used to create immersive environments, ranging from realistic simulations to fantasy worlds. Good software provides good integration between the hardware and the user interface.
3) user interface (UI) – an essential component of immersive technology, referring to how users interact with the digital environment. An intuitive and natural user interface contributes significantly to an immersive experience. Factors to consider include:
    - User comfort and ease of use – users should be able to interact with the digital environment without stress or discomfort, which can be achieved by providing an intuitive interface.
    - Integration: the user interface should be well integrated with the hardware component, supporting the user's convenience and ease of interaction.

Considering these aspects will help ensure a positive user experience and broader adoption of the technology, which is especially important when using it for educational purposes.

In addition, it is essential to enable the selection of services taking into account the following aspects:

- purpose of use – think about the subject area for which the service is planned, what goals we are trying to achieve by implementing a new technology, and determine the specific tasks that need to be performed. Understanding the needs of use allows you to decide which functions are most important;
- user experience – determine the target group of users and assess their overall understanding of using immersive technology (is prior training, instruction, training required?);
- technical requirements – check whether the selected technology is compatible with the devices, software, and networks used by the team you are using;
- scalability – consider the possible allowable number of users, whether the technology provides the desired level of collaboration and interaction, whether it will allow you to reach the required number of users;

- cost – assess the cost of the technology, including any hardware, software, or licensing fees, and determine whether this fits within the available budget;
- localization – determine which languages are available in the settings and whether there is a language barrier;
- security – assess the security features of the technology, including data protection, encryption, and access control to ensure that confidential information is protected;
- support – determine the level of support available from the technology provider, including technical assistance, training, and user forums.

Thus, when creating a "Catalog of Immersive Services", it is essential to provide such a filtering option so that the teacher can choose the most appropriate service, taking into account their own experience, material, and technical capabilities.

4.2. Selecting options for filtering in the "Catalog of Immersive Services"

To determine the appropriateness of the selected filtering options in the "Catalog of Immersive Services", we surveyed experts – 16 people with experience in scientific research and practical use of immersive services in education (12.5% – doctors of science, 50% – PhD, 37.5% – researchers without a scientific degree).

The researchers were offered a list of criteria for selecting immersive services (what should the user (teacher) be guided by when choosing a service?), the importance of which had to be assessed on a Likert scale from 1 to 10, where "1" is entirely insignificant, "10" is very important.

The experts selected the following criteria for choosing immersive services as the most important:

- subject-oriented nature of the service (e.g., for physics simulations, for anatomy visualizations, etc.);
- "complexity" or "simplicity" of the service (need for prior preparation to work with the service);
- availability of ready-made visualizations/simulations;
- the possibility of creating your visualizations/simulations;
- compatibility of the service with existing technical means (ability to reproduce on the existing operating system, ability to use on existing gadgets, with available disk space, etc.);
- scalability (does the service allow to reach the required number of users);
- cost (is the service free? If not, is the price affordable?);
- localization (does the service support the Ukrainian language?);
- security (security features of the service, including data protection, encryption, and access control to ensure the protection of confidential information, etc.);
- support (high-quality and prompt technical support from the provider).

Table 3 presents the ordered results of the experts' responses.
The evaluation of the proposed criteria is summarized as follows:

- 8-10 points – critical (in the table marked as "+");
- 5-7 – possible (in the table marked as "+/–");
- 1-4 – not important (in the table marked as "–").

From the data presented in table 3, we can draw the following conclusions:

- all the proposed criteria are appropriate to be used when selecting immersive services since each criterion received expert ratings in the range of 5-10 on a 10-point Likert scale (which we summarized as "very important" and "possible");
- the experts excluded none of the proposed criteria (none received low scores in the range of 1-4, which would characterize it as "not important");
- the proposed criteria can be used when developing a filtering system in the "Catalog of Immersive Services" to simplify the search for appropriate services by secondary school teachers.

Table 3
Results of experts' responses on the selection of the most significant criteria for the selection of immersive services.

Criteria	10	9	8	7	6	5	4	3	2	1
Subject orientation	8	5	3							
Ease of mastering	3	8	5							
Ready-made simulations	10	3	1		2					
Create own simulations	8	4	1	2	1					
Technical compatibility	10	4	2							
Scalability	6	7	2	1						
Price	6	7	1	2						
Localization	1	7	4	1	1	2				
Security	6	6	2	1		1				
Technical support	6	3	5	1	1					

4.3. Technical aspects of creating the "Catalog of Immersive Services"

Before creating the "Catalog of Immersive Services", the task was set to obtain the following results:

- a convenient filtering system that takes into account the needs of the target group;
- an attractive and convenient presentation of data at the stage of use;
- the catalog should provide convenient filling and editing for its editors.

The catalog was designed using a no-code approach, without the need to pay for services or infrastructure during its use.

Given the task set, Softr (https://softr.io/) was chosen to create the catalog – a service for creating websites and web applications without code.

In the free tariff plan, Softr allows you to:

- create an interface to data that will be stored in Airtable, Google Sheets, or Notion;
- use the main types of blocks when creating, such as list, grid, table, form, object detail, and others;
- have up to 10 users who can log in using a password or Google account (in our case, these are moderators who add new services to the catalog or check services added by unregistered visitors before publication);
- serve an unlimited number of users;
- connect your domain (in our case, we used our domain in the pp.ua zone – the only zone in the Ukrainian segment that provides the opportunity to register a domain for free);
- set up integration with Google Analytics and/or Google Tag Manager.

We also analyzed certain limitations inherent in Softr and also identified ways to solve potential related problems:

- in the free tariff plan, the service allows the created web application to work with a maximum of 1000 records (immersive services). Achieving the threshold value by the catalog would mean its demand and usefulness for users. In this case, the task of expansion will arise, which can be achieved by moving away from the no-code approach, rewriting the interface part of the catalog using, for example, the Astro framework (https://astro.build/) and Cloudflare Pages hosting (https://pages.cloudflare.com/). At the same time, the possibility of unrestricted use of the catalog will continue to be preserved;
- when creating the catalog, Softr allowed you to choose the sorting of elements only when creating a web application and not during use. We bypassed the restriction on sorting selection by creating an additional page on which you can view the catalog elements in the reverse order of the time they were added to the catalog.

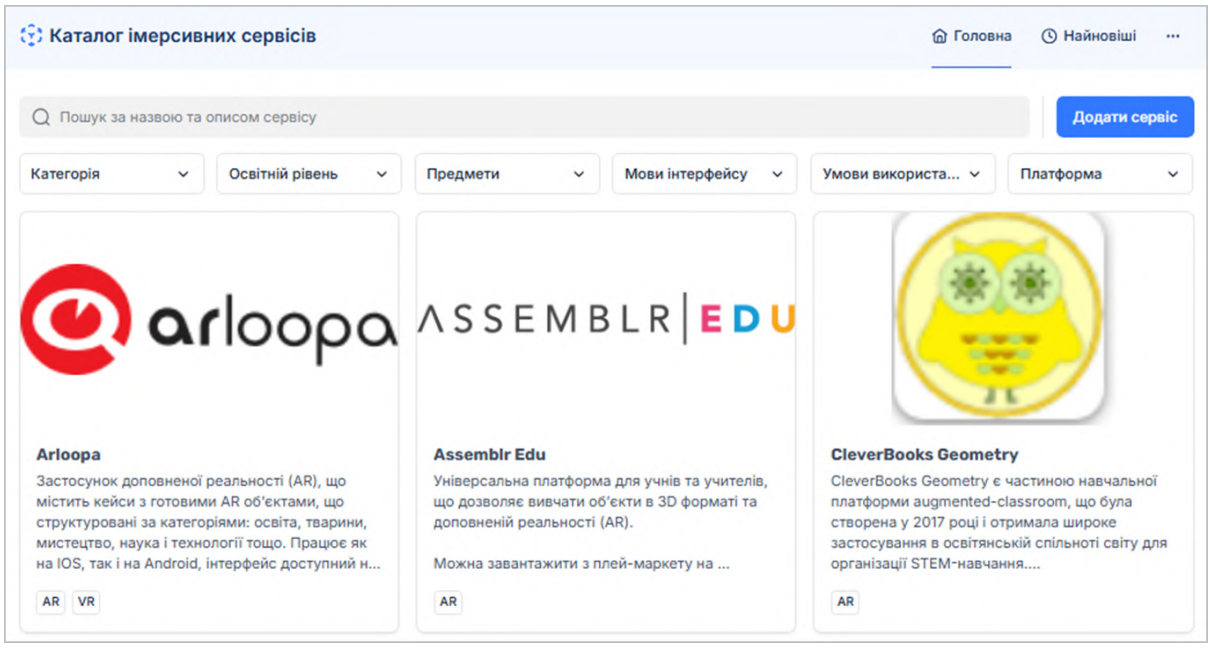

Figure 2: The homepage of the "Catalog of Immersive Services".

Figure 2 shows the start page of the "Catalog of Immersive Services".

Figure 3 shows the filtering system for users' convenience in choosing the appropriate service. When developing the filtering options, the results of the expert group survey, presented in the previous section, were taken into account. In particular, this is the ability to select services by their category (AR, VR, XR, 360-degree video, 3D-modelling), educational level (grades 1-4, 5-9, 10-11(12)) and subject (astronomy, biology and ecology, computer science, foreign language, history, etc.) for which the service is planned to be used, interface language, terms of use (free and under specific tariff plans), platform (operating system).

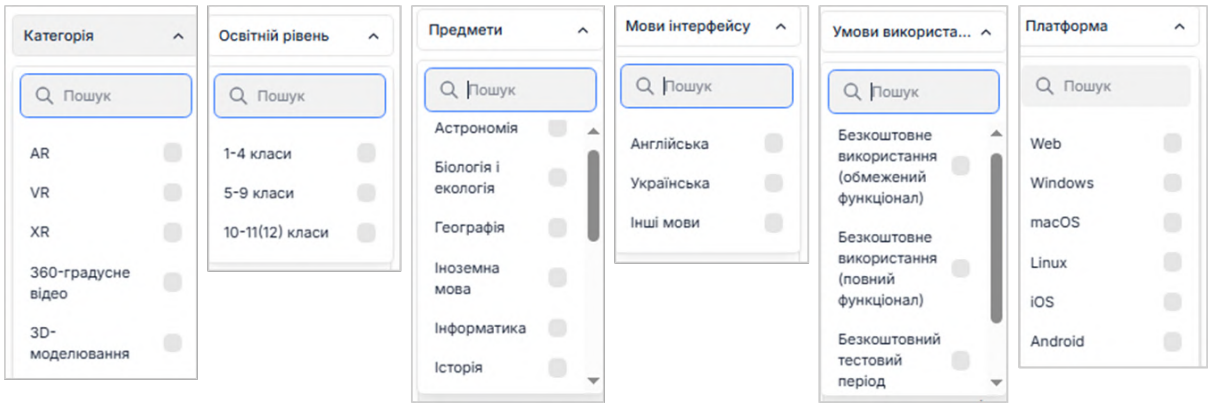

Figure 3: Filtering system in the "Catalog of Immersive Services".

Figure 4 shows a description of one of the services as it is displayed in the catalog. In addition to the functionality and possibilities of use, the description also contains a link to this service and screenshots. This also helps in deciding on the appropriateness of a particular service for educational purposes.

5. Framework for teacher support and professional development

Research consistently demonstrates that teacher training and support are critical factors for successful immersive technology integration. A longitudinal study by Mills et al. [64] found that while teachers'

Figure 4: Example of a description of a separate service in the "Catalog of Immersive Services".

beliefs about inquiry-based learning improved after VR implementation, their actual classroom practices remained unchanged without continuous professional development. This highlights the need for comprehensive support frameworks that bridge the gap between technological potential and pedagogical practice (table 4).

In the future, it is planned to create a separate function in the catalog, "Compatibility Calculator", with which the user can set their preferences (in the form of corresponding coefficients), and the system will calculate an integral indicator for each service. This will allow you to optimize the choice of the necessary service further.

6. Conclusions and prospects for further research

In the current digital transformation of education, immersive technologies occupy a special place. Their implementation is less intensive in general secondary education than in higher and vocational education. Still, it has significant prospects in increasing student motivation and engagement, improving the assimilation of educational material, developing critical thinking and problem-solving skills, and forming practical skills through simulations, gamification, etc.

Along with the undeniable advantages and great potential of immersive developments, there is a

Table 4
Essential components of teacher support frameworks for immersive technology integration.

Framework component	Description	Implementation strategy
Technical training	Hardware setup, software navigation, troubleshooting	Hands-on workshops, video tutorials
Pedagogical integration	Curriculum alignment, lesson design, assessment methods	Collaborative planning sessions, exemplar lessons
Content creation	Developing custom VR/AR materials	Template libraries, authoring tools training
Continuous support	Ongoing assistance, community building	Online forums, peer mentoring, regular check-ins
Evaluation methods	Measuring impact on learning outcomes	Pre/post assessments, student feedback tools

problem with their organization and cataloging to ensure a convenient search for appropriate services for use by teachers in the educational process. A review of the literature and some existing online resources showed that existing catalogs and service aggregators have shortcomings and do not fully provide the functionality necessary for educators. Typically, such catalogs are not specialized and do not allow you to search for the required services by specialized attributes.

Our analysis, informed by comprehensive research spanning 2018-2024, reveals that effective cataloglization must address multiple dimensions: technological diversity (VR, AR, MR, tele-immersive platforms), pedagogical alignment, teacher support mechanisms, and context-specific implementation challenges. The integration of systematic filtering criteria based on expert consensus and empirical evidence ensures that the catalog serves as both a practical tool and a framework for informed decision-making in educational technology adoption.

In this regard, there was a need to create a “Catalog of Immersive Services”, which satisfies the key search needs of teachers, who can choose the optimal VR/AR services and take advantage of their advantages in teaching various subjects (figure 5). The catalog contains a convenient filtering system, which took into account the results of a survey by a group of experts. In particular, the catalog allows you to select services by category, educational level, subject for which the service will be used, interface language, and payment terms.

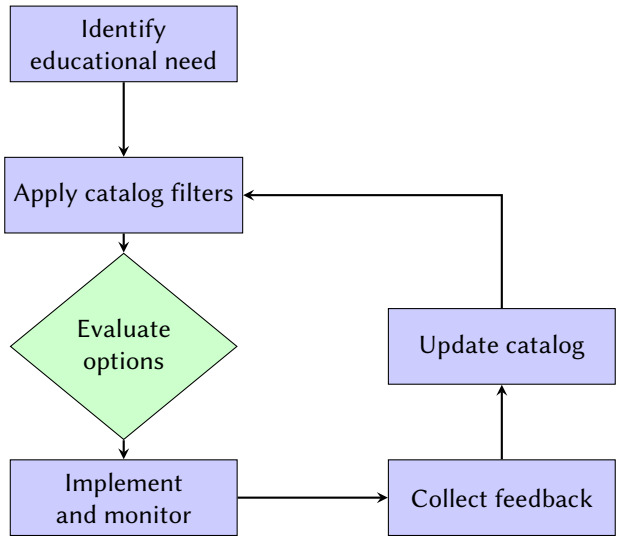

Figure 5: Iterative process for immersive technology selection and catalog improvement.

We consider it appropriate to recommend the “Catalog of Immersive Services” to teachers for use in the educational process.

Based on our findings and the comprehensive analysis of current research trends, we propose the following directions for future development:

1. Conduct extended research (minimum 6-12 months) to assess the sustained impact of immersive technologies on learning outcomes, particularly in Ukrainian secondary schools.
2. Create culturally relevant, Ukrainian-language immersive content aligned with national curriculum standards, addressing the current dominance of English-language resources.
3. Develop and evaluate low-cost immersive solutions suitable for resource-limited schools, particularly in rural areas where infrastructure challenges persist.
4. Establish comprehensive training programs that combine technical skills with pedagogical strategies, incorporating the TPaCK (Technological Pedagogical Content Knowledge) framework.
5. Develop new assessment tools specifically designed for evaluating learning in immersive environments, moving beyond traditional testing methods.
6. Establish clear protocols for data privacy, student safety, and ethical use of immersive technologies in educational settings, particularly concerning minors.

Further research should be directed to studying the effect of the widespread implementation of the catalog of immersive services, reflections of users of this catalog, substantiation of the methodological foundations of its use, in particular for various subject areas.

Declaration on Generative AI

The authors have not employed any generative AI tools.

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Computer-mediated communication and gamification as principal characteristics of sustainable higher education: empirical evidence and theoretical frameworks

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Abstract

Digimodernism and videoludification are the key drivers of present social transformations. Digital pedagogy, gamification, game-based learning and serious video games (SVGs) supported by computer-mediated communication (CMC) come to the foreground. This study explores the synergistic integration of CMC and gamification as principal characteristics of sustainable higher education, examining their combined impact on student engagement, learning outcomes, and institutional sustainability. Theoretical overview of the CMC, discussion of SVGs for e-learning in the time of the quarantine, two cases of SVGs' implementation into educational contexts, efficiency measurement of this implementation, comparison of obtained results with previous data are the aims of this article. To achieve these aims, qualitative and quantitative research methods were applied. We defined 'distance learning', 'e-learning' based on CMC, collected their characteristics, quality parameters and modes. We revised our previous work empirical data and conclusions. Later, we analysed 'gamification', 'game-based learning', 'serious video games' in contemporary education, presented two case studies of digital games' integration into educational process. We used a feedback form, a questionnaire, and a survey to measure the efficiency of the e-learning courses. Results demonstrate that gamification elements convert extrinsic rewards into intrinsic motivation, with deep personalization showing 39.2% high motivation levels compared to 8.7% in traditional approaches. The integration of CMC and gamification reduces physical resource use while enhancing collaborative and flexible learning. We proved that they serve as informative quantitative measurement. We emphasised the topicality of the options for reorganising and refining distance and e-learning and brought forward the idea about the new vision of distance and e-learning, gamification of educational process and serious video games as one more variation of CMC that must drive our decisions about the use of technology, not vice versa. The findings suggest that robust institutional frameworks, teacher training programs, and emerging technologies like AI and telepresence robots are essential for sustainable implementation. Therefore, the need to develop comprehensive teacher-training programs to help educators understand, design, evaluate and apply CMC and gamified learning applications is set up as the vector of future work.

Keywords

computer-mediated communication, educational digitalisation, gamification, serious video games, inclusive education, socionomics, sustainable higher education, digital pedagogy, learning management systems, player-type personalization

1. Introduction

The contemporary educational environment in Ukraine, as well as in many other countries, is driven by the post-industrial model of society and post-modernism that underlie rapid social changes. The

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transition from goods' production to the economy of services, extensive application of information and communication technologies, innovation, creativity and entrepreneurship, international travel, and migration serve as the main characteristics of societal models. In the workplace, it is characterised by professional flexibility and diversity; tasks, projects, and networks; the necessity to work in a team, technological complexity within a rapidly changing environment. Therefore, the very concept of 'education' is currently being revised to support the postmodern era based on such competencies as social and emotional intelligence, media literacy, ecological intelligence, creativity, collaboration and participatory problem-solving [1, 2]. Today, there is an obvious need to address the demands of adult and senior learners as well. That is why, education now is being viewed as a process of individual development, the empowerment with knowledge from birth to death – the process that involves interconnectedness and interdisciplinarity, encouragement of students' autonomy in the form of self-guided learning and self-guided education enhancement.

One of the important concepts of today's educational systems is 'ecosystemic relations' – individually oriented, based on the principles of autonomy, access to information and feedback,distributed powers, creativity to solve problems, responsibility, dynamism, teamwork to jointly solve global problems [3, p. 34-47]. Education in the postmodern context is based on problem and project tasks without fear of making mistakes; play/game-based learning [4, 5, 6, 7, 8], game universes, virtual augmented reality [9, 10, 11, 12, 13, 14, 15, 16, 17, 18], and computer-mediated communication (CMC), which have come to the foreground in the context of COVID-19 lockdown and the after-pandemic period [19] when pedagogies turned from in-personal to virtual instructions [20, 21], including distance learning [22, 23, 24] and e-learning [25, 26] to maintain the barrier-free educational environment.

Recent comprehensive analysis of CMC and gamification in higher education reveals their emergence as principal characteristics of sustainable educational systems. According to systematic reviews covering 2010-2024, the synergistic integration of these technologies enhances student engagement by up to 40% while reducing the carbon footprint of traditional education through decreased physical infrastructure requirements [27, 28]. The convergence of CMC and gamification represents a paradigm shift toward environmentally responsible, socially inclusive, and economically viable educational practices that prepare learners for rapidly evolving global challenges [29, 30].

Therefore, the discussions around educational digitalisation and CMC's implementation into various educational contexts continue to gather momentum and are reflected in many contemporary national and foreign scholarly works. For example, the scientific inquiry of Andreev [31] is connected with didactics of distance learning, while Fedorenko et al. [32] analyses the questions of informatisation in higher educational institutions (HEIs). Bramble and Panda [33] present the various distance and online learning models. Dabbagh and Bannan-Ritland [34] focus on online learning concepts, strategies, and application. Palloff and Pratt [35] describe effective strategies for an online classroom. Rice [36], Bordia [37], Androutsopoulos [38], Dahlberg [39], Kock [40], Hardaker [41], Joinson [42], Walther [43] – these are just a few researchers' names to add to the list, which proves that both theoretical and practical interests in enhancing ways and methods based on CMC are topical on the global scientific scale [44].

The literature review would be incomplete if we do not mention here the scholarly works about educational gamification and educational video games. For example, the definition and the structural characteristics of the gamification phenomenon are discussed by Deterding [45]. Education via gamification is analysed by Huotari and Hamari [46]. Professional corporate training based on gamified applications is presented by Baxter et al. [47]. More recent studies, including works of Arnab et al. [48], Becker [49], discuss the formal design paradigm for serious games. Wouters et al. [50] present the analysis of motivational and cognitive effects of video games. Questions related to the game-based curriculum are analysed in theses of Alkind Taylor [51] and Marklund [52].

Considering this, the purpose of the article is to give an overview of the computer-mediated communication modes and means, as well as serious video games (SVGs) used for e-learning in the time of the quarantine by the university faculty; to present two new cases of SVGs' implementation into educational contexts; to discuss the efficiency of the implementation based on 'The Instructional Materials Motivation (IMMS)' survey by Keller [53] and a feedback form developed by the research team; to compare the obtained results with the previous research data [54].

Stemming from the aim, the following research tasks were outlined:

1) to generalise the main theoretical and experiential findings related to CMC modes and means;
2) to discuss in more detail gamification and SVGs in the context of contemporary educational reality;
3) to present two case studies based on SVGs' application to the learning process and evaluate the efficiency of this tool;
4) to compare the statistical data with the data from our previous research work;
5) to make the conclusions and draft the vectors for future research.

2. Research methods

To address the purpose of the article, a complex of qualitative as well as quantitative research methods was applied. Data collection methods were tied in with the tasks set in the research. There are four distinct stages of the present research work.

Stage number one – theoretical analysis of CMC (its means and modes) on which a literature study, backed up by general references, primary and secondary resources' analysis, a computer search of www and databases were used. On this stage the notions 'distance learning', 'e-learning', 'modes of e-learning' were studied in depth. We also revised the earlier received statistical data of the research conducted by the authors in 2020 in Prydniprovska State Academy of Civil Engineering and Architecture, the Department of Foreign Languages, related to CMC [1].

On stage number two, we traced the transition from CMC application in education to its gamification, analysed the notions of 'gamification', 'game-based learning', 'serious video games', highlighted the difference between 'serious video games' and 'computer games'. We based this analysis on the revision and extension of our previous theoretical research [1].

The theoretical part is supplemented with two case studies: an integration of 'Globall Manager' – a digital game for learning – into Cross-Cultural Communication course for students of Philology; and 'Auti-Sim' and 'Prism' – games for learning and training of Educators, Psychologists and Social Workers for inclusive education that we undertook on the third stage of the present work. To evaluate the effectiveness of these innovative learning tools we used 'The Instructional Materials Motivation (IMMS)' survey by Keller [53] and a feedback form at the end of the study programmes. The criteria of the efficiency of the instructional material evaluation comprised the following parameters: attention – the incorporation of a variety of tactics to gain learner's attention; relevance – the consistency of the instructional material with students' goals, learning styles and past experiences; confidence – helping students establish a positive attitude, drive for success; satisfaction – is the maintenance of positive feelings about learning experiences, i.e. positive rewards and recognition [55, 56]. On this stage we also used a Google Forms with multiple choice/unlimited choice questions to better understand the participants' experiences with video games.

The fourth stage and the task were to compare the results of the case studies with earlier data, collected at Prydniprovska State Academy of Civil Engineering and Architecture, the Department of Foreign Languages during March-May, 2020 connected with the measurement of the e-learning courses' design efficiency for which the above-described 'The Instructional Materials Motivation (IMMS)' survey that consists of 4 subscales and 36 items was used. The learners' motivation levels were measured by applying a 5-point symmetrical Likert scale.

The authors of the article participated in the development of the framework for the 'Globall Manager' game integration into Cross-Cultural Communication course, implemented the game into the educational process. Also, we collected and analysed the data from 'The Instructional Materials Motivation (IMMS)' survey, feedback forms about e-learning at the time of the quarantine; Google Forms results after 'Auti-Sim' and 'Prism' games work with educational and scientific student group 'Fundamentals of Support for Children with Special Needs and their Families for Pre-Service Specialists' Training in the Socionomic Sphere'.

3. Results and discussion

3.1. Stage one

We begin our results' discussion with the statement that because of the increased importance of international work settings, much of what we do and how we communicate have moved to the Web. Communication, access, and creation of information have become everyday life and work tasks that rely on the use of personal and networked technologies. Nowadays, we use Computer Mediated Communication (CMC) – any human communication that occurs through the use of two or more electronic devices and is extensively used in distance and e-learning – to get news updates from around the world, to research ideas, exchange photos, publish our thoughts, tell people where we are and share experiences of all kinds. This includes text messages, e-mails, blogs and discussion forums, social networks, virtual worlds, etc.

The focus of our present discussion is 'distance learning', 'e-learning', 'modes of e-learning'.

There are many definitions of the term 'distance learning' that reflect the diversity of approaches to its understanding. In the most profound studies of the phenomenon done by Andreev [31], we can find the following definitions:

- distance learning is a mode of learning, along with full-time and part-time modes, in which the educational process uses the best traditional and innovative instructional techniques and tools, as well as the forms of learning based on computer and telecommunication technologies;
- distance learning is a purposeful asynchronous process of interaction between the subject and the object of learning mediated by electronic instructional tools, where the learning process does not depend on the spatial location of the participants;
- distance learning is a set of educational services provided to the general public in the country and abroad through a specialised information educational environment based on the exchange of educational information at a distance.

Palloff and Pratt [35] distinguish three main characteristics of distance learning: 1) it does not depend on spatial location and time; 2) services are provided through a specialised information environment; 3) learning process is controlled by a student him/herself.

The history of distance learning can be traced more than two centuries back and is connected with the emergence of the correspondence institution. Other forms of communication developed during the period of industrialisation and are associated with the invention of the radio and television, i.e., radiocourses and television courses. Later on, the appearance of the World Wide Web played the most significant part in the spread of the remote mode of learning. Consequently, the historical development of distance learning is reflected in its models' evolution – on the basis of a correspondence mode, an online mode, an e-learning mode [33].

The term 'e-learning' also has a big number of interpretations and is used in different ways, depending on pedagogical goals and contexts. Our search for e-learning definitions via Google Search Engine yielded 1330000 entries. The generalised definition of e-learning describes it as a variation of distance learning that has gained active development due to the emergence of new technologies.

It is true that the e-learning model is the latest in the history of distance education and has a three-dimensional structure. Through the training based on e-learning principles, students can acquire knowledge anywhere, anytime, and at any speed [57].

The Instructional Telecommunications Council defines distance education as "the process of extending learning, or delivering instructional resource-sharing opportunities, to locations away from a classroom, building or site, to another classroom, building or site by using video, audio, computer, multimedia communications, or some combination of these with other traditional delivery methods" [58].

The European e-Learning Action Plan defines e-learning as the use of the latest multimedia technologies and the Internet with the aim to improve the quality of the education through granting access to resources and services, distance exchange, and cooperation [59].

According to the method of interaction, such modes of e-learning can be distinguished: the interaction between a student-electronic environment, student-student, student-teacher, teacher-electronic environment, interaction inside the educational community. According to the time criterion, e-learning organisation is classified as asynchronous (different times of teaching and learning), synchronous (teaching and learning take place at the same time), or a combination of the two. For example, asynchronous communication (e-mail) allows using authentic speech and meaningful context. Compared to face-to-face communication and synchronous online tools, this environment gives students enough time to reflect and formulate their utterances. Synchronous communication – real-time communication (text chats) simulates conversation but is not complicated by the possible 'dominance' of direct discussions. Research confirms the fact that students participate more often and more proportionately in online discussions than in face-to-face communication. It should also be added that online discussions create a student-centred environment in which they are more willing to take risks [60].

According to the criterion of technological means' utilisation, e-learning can be computer-based, laptop-based, video conferencing-based, forums-based, weblogs-based, etc. By the methods of information transfer – text, sound, picture, video, animation, simulation, interactive resources based, etc.

In our article, we use the term 'e-learning' broadly to relate to the learning environments where CMC is used as a fundamental of educational instruction.

We consider it necessary to illustrate the above-presented theoretical reflections with the summative overview of the empirical results obtained at the Department of Foreign Languages, Prydniprovska State Academy of Civil Engineering and Architecture at the time of the quarantine, the year 2020.

Based on the statistics received from 'Analysis of the E-Learning Tools Preferences' form disseminated among the teaching staff of the department (the sample of 30 teachers), the most popular video-conferencing platforms chosen by teachers of the department were Skype and Zoom, while Google Hang- outs and Discord with video-conferencing features were found less popular. The popularity of Viber is also explained by its video-conferencing function. Social networking apps that were actively used by the faculty were Telegram and Viber. E-mail service was also chosen for the asynchronous correspondence with students. Google Classroom was applied by instructors to exchange texts, audio, video, and hyper-linked material (figure 1).

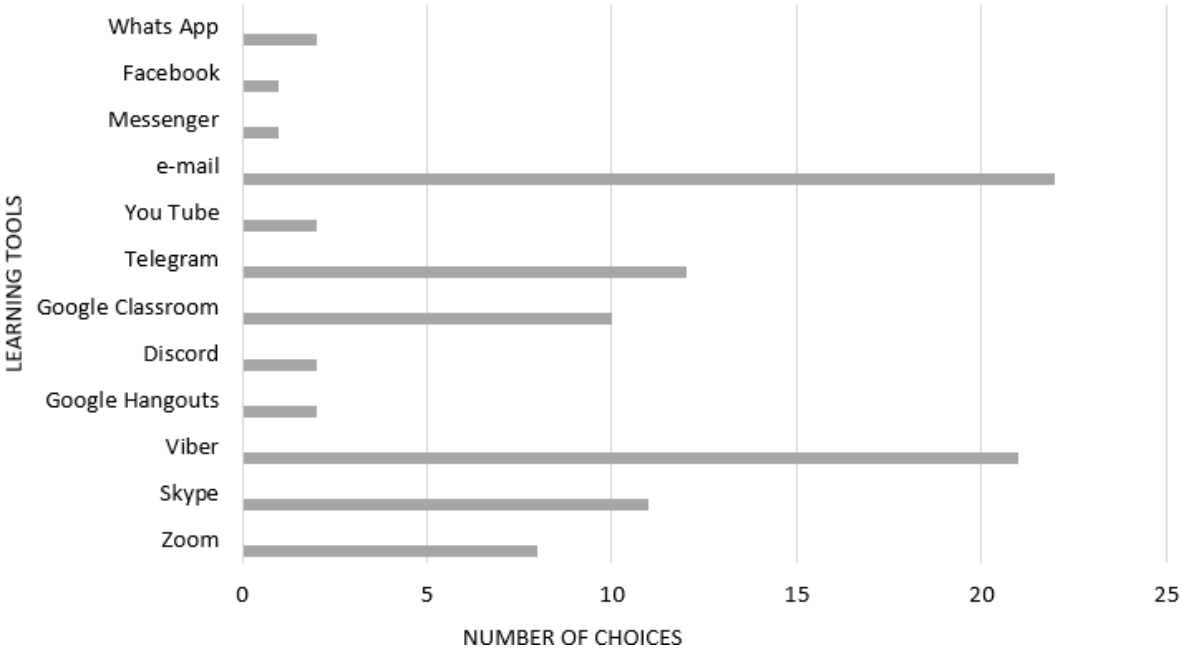

Figure 1: E-learning tools preferences.

Our experience has also provided qualitative data. For example, the benefits of Skype's application,

according to our staffs' opinion, lie in the number of video chat participants (which is unlimited), the ease of operation on the screen, the inclusion of such activities as speaking, reading, and, partially, writing. Regarding the use of Google Meet application, which is almost identical to Skype, a 'Share Screen' feature that lets students see what the instructor demonstrates on the monitor: files, videos, etc., a 'Chat History' feature that records the number of people attending each class are regarded as supportive. At the same time, it does not have a file-sharing feature and the number of video chat participants is limited up to 10. When it comes to written assignments, the Google Classroom application is named as the best fit. Here, an instructor posts assignments and sets up the deadline, selects students for whom the tasks are assigned, evaluates students' works (the number of points is selected on a different scale principle following the instructor's choice). It is also interesting to mark here that back in March-May 2020 Google Meet was not as popular an application as it is now.

A separate part of our discussion was given to the Zoom platform's analysis, as teaching on this platform, judging by our teachers' feedback, is challenging. This is connected with the phenomenon, described as 'Zoom fatigue'.

Those teachers who used this video-conferencing platform complained that after two sequential sessions they were more tired than after the same number of face-to-face lessons in a real class setting. One of the explanations for this is provided by [61]. She attributes it to the Gallery view when all the sessions' participants appear, which challenges the brain's central vision, forcing it to decode many people at a time. Moreover, 'one of those boxes on the screen is you', which may mean that we spend more energy on monitoring our non-verbal communication than we do in person [62]. What we also experienced was a shift towards teacher-centricity and one-way communication that contradicts the conclusions of the Instructional Telecommunications Council about the effectiveness of e-learning that lies in its individually-oriented nature and student-centricity [58].

On this stage, we also organised a brief questioning of students as to what most difficult aspects of e-learning they could name. The question we asked was 'What is the most challenging for you in e-learning?' The possible alternatives were pre-formulated for the students to choose from and the number of choices was not limited. Our statistics look as follows:

1. Problems with self-organisation, high level of distraction – eight students – 34.8%.
2. The excessive number of educational tasks – eight students – 34.8%.
3. Dependence on technical means – twenty students – 86.9%.
4. Poor quality of home Internet – fourteen students – 60.8%.
5. Restrictions on obtaining practical skills – five students – 21.7%.
6. Lack of opportunity to communicate freely with the teacher – none – 0%.
7. Lack of control over the level of knowledge – three students – 13.04%.
8. Insufficient duration of classes (time limit) – none – 0%.
9. The quality of the material taught – four students – 17.4%.
10. Insufficient theoretical materials to perform tests and/or tasks – seven students – 30.4%.
11. Lack of opportunity to communicate with other students – thirteen students – 56.5%.
12. The need to learn how to work online – three students – 13.04%.

It is necessary to mention here, that we had a chance to compare the results of our questionnaire with the results, obtained in Alfred Nobel University, Dnipro from the same questionnaire introduced during the period from 8 to 14 April 2020 in electronic form. The total number of interviewees there made up 1062 students. According to the form of education, the interviewed students were distributed as follows:

- full-time students – 911 people – 85.8%;
- part-time students – 24 people – 2.3%;
- correspondence courses' students – 127 people – 12%.

Alfred Nobel University's statistics look as follows:

1. Problems with self-organisation, high level of distraction – 351 students – 33.1%.
2. The excessive number of educational tasks – 330 students – 31.1%.
3. Dependence on technical means – 302 – 28.4%.
4. Poor quality of home Internet – 300 – 28.2%.
5. Restrictions on obtaining practical skills – 286 – 26.9%.
6. Lack of opportunity to communicate freely with the teacher – 249 – 23.4%.
7. Lack of control over the level of knowledge – 186 – 17.5%.
8. Insufficient duration of classes (time limit) – 162 – 15.3%.
9. The quality of the material taught – 122 – 11.5%.
10. Insufficient theoretical materials to perform tests and/or tasks – 110 – 10.4%.
11. Lack of opportunity to communicate with other students – 108 – 10.2%.
12. The need to learn how to work online – 55 – 5.2%.

Based on the comparative analysis, we got very close statistical data on statements one, two, five, seven, and eight, though the size of the samples interviewed varied.

Overall, the results of this stage can be summarised as follows: distance learning and its later version – e-learning should be applied with the organisational culture analysis in mind. The most popular video-conferencing platforms named by the faculty are Viber, Skype, and Zoom, while Google Meet and Discord are found less popular. Social networking apps actively used by the faculty are Telegram, Viber. The most debatable is the Zoom platform as, on the one hand, it has a lot of advantageous features both for teachers and students. At the same time, such a phenomenon as 'Zoom fatigue' is marked by the faculty as a disadvantageous one.

With the reference to the students' feedback from as for the e-learning during the quarantine – 'dependence on technical means' is named as the main challenge, followed by the poor quality of the Internet, problems with self-organisation, the number of tasks given, the restriction on exercising practical skills, which helps highlight the current e-learning situation in HEIs, reveal challenges and needs to further action.

3.2. Stage two

Moving on to the discussion of the second task, we would present the idea expressed by Kirby [63] that digimodernism is the mainstream cultural logic of contemporary society and both the video game (as another variation of CMC) and the video gamer are its principal object and subject. In broad context, video games have fitted perfectly well in the globalised spider-web of information flows and have generated revenues as high as C22 billion in Europe in 2020 according to Global News Wire, with the number of people playing video games 1.553.5 million worldwide. 51% of the EU's population played video games, which equals to some 250 million players in the EU, the average playtime per week was 8.6 hours [64]. As a response, digital pedagogy, gamification, game-based learning, and serious video games are gradually becoming a part of the everyday toolkit of educators (figure 2, table 1).

Table 1
Key gamification elements and their impact on sustainability learning outcomes (2019-2024).

Gamification element	Motivation type	Learning impact	Sustainability behavior change
Points and badges	Extrinsic	+10% retention	Moderate (28% increase)
Group quests	Intrinsic	+39% engagement	High (45% increase)
Personalized challenges	Both	+35% performance	High (52% increase)
Leaderboards	Extrinsic	+15% participation	Low (12% increase)
Role-playing	Intrinsic	+42% critical thinking	Very high (64% increase)

Gamification is the use of game elements (such as points, badges, leader boards, competition, achievements) in a non-game setting with the aim to turn routine tasks into more refreshing, motivating

Figure 2: Video games in broad context.

experiences [45]. The main idea of gamification evolved parallel with the Internet. Gamification is based on the basics of games, though, with the development of mobile phones and applications, it is actually can be used almost in every sphere, including education. For example, interactive quizzes like 'Kahoot', 'Quizlet', 'ClassDojo', 'Duolingo', 'Edmodo' or gamified learning management systems like 'Classcraft', 'Lingua Attack', 'Socrative', 'DyKnow'. At the same time, serious video games are those that are built on game-based learning principles, include basic elements of video games, and are used not for the entertainment [65]. The examples here are many, including educational games (or games for learning, like 'Code.org', 'GloBall Manager', 'MinecraftEdu'), games for training (e.g. 'AbcdeSIM', Kognito, 'Auti-Sim', 'Prism'), games for change (or social games, like 'Against all Odds', 'Ayiti – The Cost of Life', 'Copenhagen Challenge').

We think it necessary to note that 'video games' are considered an activity that includes one or more players, has definite goals, rules, limitations, rewards and outcomes, is artificial with the element of a competition. At the same time, 'serious video games' are those that are built on game-based learning principles, include basic elements of video games and are used not for the entertainment [65].

Game-based learning (GBL) is a type of gameplay with defined learning outcomes [66]. In the process of GBL, learners use games as a tool to study a topic or related topics. They work individually or in teams. It is expected that in this process, the use of games will enhance the learning experience through challenge, exploration, interaction, reflection, and decision-making while maintaining a balance between the content, gaming, and its application to the real world. Having a play at its base, game-based learning is effective in motivating and improving students' engagement, promoting creative thinking and developing approaches towards multi-disciplinary learning. As for educational digital games – they proved to hold great promise for instruction that is appropriate for today's learners.

Based on our previous research revision, we may state that video games present a different learning

environment (with a wide spectrum of built-in assistive features) where players interact, experiment, discover and research. They are good at helping to memorise studied material (at 'grinding' things). The material studied in games is stored longer in players' memory. Games let play through the same situation applying different behavioural models, methods and approaches. Games are cost-effective and efficient in training for hazardous situations (firefighters, ambulance, pilots). Games appeal to different learning styles (visual, audio, kinesthetic). Games are adaptable to a particular player's level (with the increase of difficulty based on the player's performance). Games help develop movements' coordination and spatial sensation. As a novel educational instrument, games increase motivation. Games stimulate players' interaction, participation, discussion, and reflection [1].

Recent meta-analyses of gamification in higher education (2020-2024) reveal that personalized gamification based on player-type models significantly outperforms one-size-fits-all approaches. Studies utilizing HEXAD player typologies show that tailoring game elements to individual preferences results in 35-40% higher engagement rates and 25-30% better learning outcomes compared to generic gamification [67, 68]. Furthermore, the integration of AI-driven adaptive gamification systems demonstrates the potential to dynamically adjust difficulty levels and reward mechanisms based on real-time learner performance data, creating more sustainable and effective learning experiences [29].

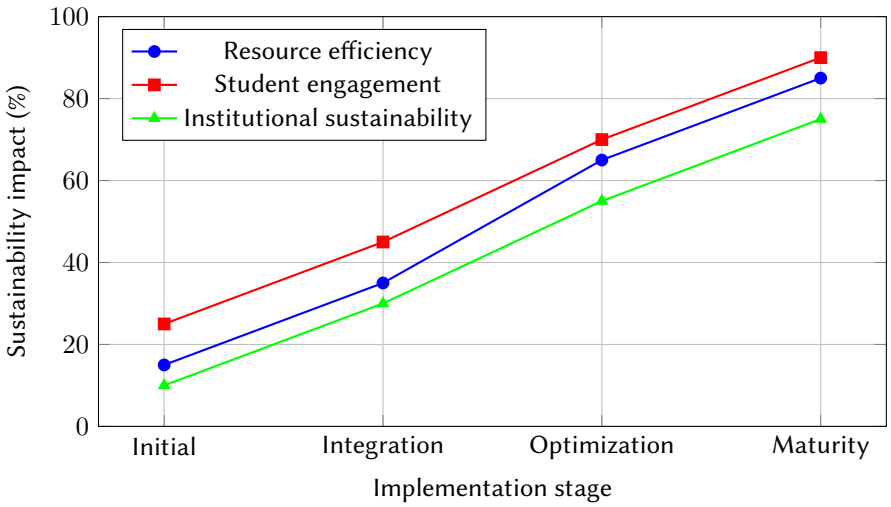

Figure 3: Progressive impact of CMC and gamification integration on various sustainability metrics in higher education institutions.

3.3. Stage three

The third stage of our article is connected with the description and the discussion of two cases of serious games' implementation into the educational process. The first game for learning that was used is 'GloBall Manager' game that was developed within the GA-BALL ('Game-Based Language Learning') project – a joint project between the Engineering Faculty of Porto Politech Institute (ISEP), Virtual Campus Porto, Technical University of Gabrovo (Bulgaria) and Federal University Pelotas (Brazil) [69]. The main objective of the project was to improve students' linguistic and sociocultural skills, necessary to take part in e-marketing and e-commerce; develop skills to establish connections via social platforms; encourage students to entrepreneurial activity. The methodological approach chosen – the application of a video game as a learning tool that would provide the participants with rules, everyday professionally-oriented situations, create a cooperative environment in which players try to reach specific educational goals, and increase personal skills and social competencies. The game can be played in seven languages through six different scenarios: 1) internationalisation diagnostics; 2) participation in a fair; 3) business culture; 4) e-commerce and e-marketing management; 5) online communication; 6) institutional negotiation (figure 4).

The game was implemented into the Cross-Cultural Communication course delivered for the four-year

Figure 4: Globall Manager game [70].

course students of Philology, University of Customs and Finance, Dnipro, Ukraine. The aim of the course is to study intercultural professional communication, develop cross-cultural sensitivity of students, form theoretical knowledge about the essence, communication structure and its peculiarities in a cross-cultural environment; linguistic, psychological and socio-cultural features of cross-cultural communication; development of the skills that can help students be effective in intercultural communication. The game was used at practical classes one time per week, 30 minutes for each session during the first semester of 2021. The game was demonstrated from the main (lecturer's) computer. Students' work was initially organised as individual, pair or mini- group work and in online learning mode later on – as teacher-class interaction. Business Culture Scenario was chosen as the study material and was played from the beginning till the end. The scenario was played in English. 46 students were enrolled in the course.

It is important to say that the above-presented game was used as the study material, around which lesson plans were developed. It is an acknowledged fact that educational digital games' integration into a specific educational context is a complex process as, during a digital game-based lesson, a teacher acts as tech support, IT administrator, a moderator, a debriefer. The teacher may be an active player and provide feedback from 'inside' the game. Also, there are three distinct stages in a digital game-based lesson, i.e., before the game-play stage, during the game-play stage, after the game-play stage, accompanied by preparing a lesson plan, setting up the game-play situation, guiding learners in the game-play process, finalising game-play experience.

We also wanted to understand the quality of the course with a video game integrated into it. Therefore, we organised a survey based on 'The Instructional Materials Motivation Survey (IMMS)' by Keller [56].

There are several models that help estimate the quality of e-learning. The existing models can be divided into two categories: those based on empirical data and those based on theoretical developments. An example of the first category is the quality model proposed by the Institute for Higher Education

Development 'Quality on the Line: Success Factors for Distance Learning' [71]; 'Critical Success Factors in Online Education' by Volery and Lord [72]. The second category includes model 'Seven Principles for Good Practice' by Chickering and Gamson [73]; model 'Quality Guidelines for Technology-Assisted Distance Education' by Barker [74]; 'The E-learning Maturity Model' by Marshall [75], Masoumi and Lindström [76].

There are also a number of models that have been developed to measure the quality of a course (including distance learning) through measuring learners' motivation in order to improve a course design or to adapt a course to learners' motivational needs [55]. The questions of motivation, its structural components and measurement have been studied from different theoretical perspectives in the context of the Social Cognitive Theory, the Expectancy Value Theory, the Self Determination Theory [77].

Keller [56] has developed and tested a model known as the ARCS model based on its acronym (Attention, Relevance, Confidence, and Satisfaction).

Attention – is the importance of incorporating a variety of tactics to gain learner's attention by the use of interesting graphics, animation, an event that introduces a conflict, mystery, unresolved problems, and other techniques to stimulate the inquiry in learners.

Relevance – the consistency of the course and the instructional material with students' goals, learning styles, and past experiences. The connection of the content to the learners' future jobs or interesting topics.

Confidence – lies in helping students establish a positive attitude, drive for success, and the experience of success as the result of their ability and efforts.

Satisfaction – is the maintenance of positive feelings about learning experiences, i.e., positive rewards and recognition [55].

The main ideas behind the ARCS model are that motivation is influenced by the degree to which a teacher and the instructional materials arise curiosity, are personally relevant with challenge levels that promote confidence, and do not contain stressors that would inhibit students' effort [56].

The ARCS model and the IMMS inventory (that is an integral part of it) can be used with print-based self-directed learning, computer-based instruction, or online courses, have been successfully applied to different educational settings and proved to be informative as an instrument for the efficiency of a course measurement [78].

The IMMS (the Instructional Materials Motivation) survey consists of 36 items and 4 subscales. The 4 subscales are attention (12 items), relevance (9 items), confidence (9 items), and satisfaction (6 items). It measures learners' motivation level by applying a 5-point symmetrical Likert scale.

We consider it necessary to give here examples of questions for each of the subscales.

Examples for the 'Attention' subscale: 'There was something interesting at the beginning of this course that got my attention'. 'These materials are eye-catching'. 'This course is so abstract that it was hard to keep my attention (an example of a reverse question)'.

Examples for the 'Relevance' subscale: 'It is clear to me how the content of this material is related to things I already know'. 'There were stories, pictures, or examples that showed me how this material could be important to some people'. 'The content of this material is relevant to my interests'.

Examples for the 'Confidence' subscale: 'When I first looked at this course, I understood it would be easy for me'. 'This material was more difficult to understand than I would like it to be (a reverse question)'. 'After working on this course for a while, I felt confident that I would be able to pass a test on it'.

For the 'Satisfaction' subscale: 'Completing the exercises in this course gave me a satisfying feeling of accomplishment'. 'I enjoyed this course so much that I would like to know more about this topic'. 'I really enjoyed studying this course'. 'The wording of feedback after the exercises, or of other comments in this course, helped me feel rewarded for my effort' [56].

46 four-year students of Philology enrolled in the Cross-Cultural Communication course took part in the survey. The data we obtained are presented in the table 2.

The results of the third stage can be summarized as follows: 18 (39.2%) out of 46 students demonstrated high level of motivation, 7 (15.2%) had upper-medium motivation level, 13 students (28.2%) of medium

Table 2
Motivation level range.

Motivation level	Scores	Number of participants ($N = 46$)	Percentage
High	4.00–5.00	18	39.2%
Upper Medium	3.50–3.99	7	15.2%
Medium	3.00–3.49	13	28.2%
Low	< 3.00	8	17.4%

motivation level and 8 (17.4%) – low motivation level.

The second case discussed here is based on 'Auti-Sim' and 'Prism' – serious video games for Teachers, Psychologists and Social Workers trained for inclusive education. The idea to use video games in their study programmes is grounded in the assumptions that educational and entertaining games are central to a child's social development because, for example, they allow the child to form independent relationships with peers [79]. Many researchers have recognised that the development of gaming skills and using games to engage people with autism can be helpful. If we compare digital and analog games, digital games have several advantages over analog games, namely, in-game results' tracking, easier customisation, better visual interaction, which can be especially important for people with autism [80].

'Auti-Sim' game attempts to simulate the experience of a child with autism, presenting an experience of auditory hypersensitivity on a school playground. The player walks around a school playground, full of talking children. As they approach the children, the noise level increases, creating a total audio distortion. This makes it quite difficult to stay around the other children for an extended period of time. As a result, the player spends most of their time at the edges of the playground, isolated from the rest of the world. The silence in the game is as powerful as the sound [81]. Figure 5 gives understanding of this game's aesthetics and the atmosphere the players submerge in.

Figure 5: Auti-Sim game [81].

'Prism' game attempts to help neurotypical children aged 8 to 10 understand their peers who have autism. It is a game for the children to play, paired with a discussion framework. It is a tool to help a generation of children grow up with increased aware- ness and understanding for their autistic peers [82]. The unique graphics of the game is presented in figure 6.

Figure 6: Prism game [82].

The games were used within the framework of the University Social and Psychological Service (Alfred Nobel University, Dnipro) and the meetings of an educational and scientific student group 'Fundamentals of Support for Children with Special Needs and their Families for Pre-Service Specialists' Training in the Socionomic Sphere'. Here, the variety of teaching methods to develop students' theoretical knowledge and practical skills are used: starting from a review and analysis of documentary mini-films and educational-scientific films of the researched problem; psychoanalysis of blogs, websites, educational portals, groups on social networks that are social workers, social educators, psychologists, working with families raising children with special needs, ending with game therapeutic programmes designed by foreign scholars and practitioners, in particular, joint puzzle games Nintendo Wii, ADDventurous Rhythmic planet, social robot (KASPAR); Daisy, ECHOES, Pico's Adventure, Let's Face It (LFI), Go-Go Games [80]. A separate educational and methodical seminar was organised to experiment with 'Auti-Sim' and 'Prism' games and to discuss their potential to develop communication skills, emotional recognition, formation of relationships with peers. At the end of the seminar, a feedback form was distributed with the questions related to the experience of the participants with the video games and their attitude towards this tool. Multiple choice/unlimited choice questions were prepared, among which there were the following:

1) How would you describe your experience with two video games?
2) How would you describe your feelings about two video games?
3) Do you think that through video games there is an opportunity to develop (a set of skills and qualities)?

4) What benefits can video games have as an educational and therapeutical activity?
5) How do you rate the experience of video games as an activity in a class?
6) How prepared are you to use video games in your work?

18 participants of the seminar were asked. The generalised statistics we got help us understand that the participants' experience with video games is a new one and is perceived as a tool that helps find out something new (44%); 36%% of the respondents marked game-play experience as a positive one; 16% answered that they were emotionally involved; it's motivating – (64%). As for the attitude of the participants to the video games: they help organise teamwork – (64%); they help develop useful skills – (44%); they motivate to learn – (64%); they can engage – (44%); they develop independent learning – (48%); they develop skills of understanding – (72%).

As for the readiness to use video games: 60% answered that they would like to use them but need more information on how to use; 20% feel confident; 16% will use the material that they are familiar with and are used to; 4% answered that it is risky.

Among the obstacles to use video games in their practice, the respondents named the absence of specific knowledge – (68%); low level of digital competence – (48%); low level of equipment and Internet connection – (48%); some doubts as for the possible efficiency of video games as an instructional tool – (32%).

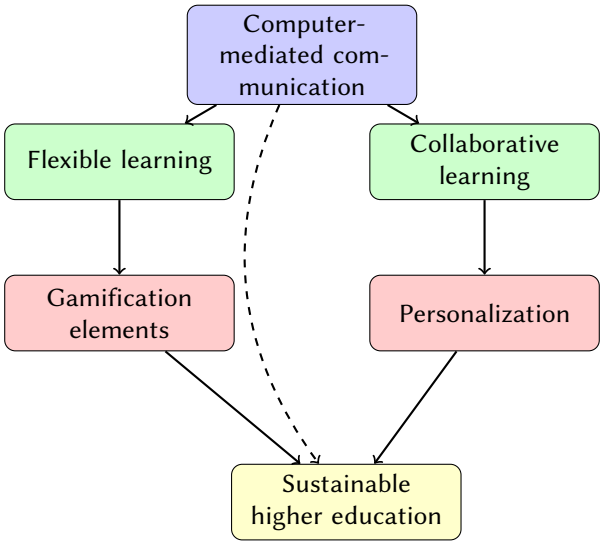

Figure 7: Conceptual framework showing the synergistic relationship between CMC and gamification in achieving sustainable higher education.

3.4. Stage four

The task for the fourth stage was to compare the results obtained in the present study with those that we got earlier at Prydniprovska State Academy of Civil Engineering and Architecture, the Department of Foreign Languages during March-May, 2020 and connected with the measurement of the e-learning courses' design efficiency. In both cases, the IMMS instrument was used. Figure 8 represents the comparative results of two studies.

The results of the fourth stage reflect the comparative new and earlier received statistics, where we may see a significant increase in students' motivation when the serious video game 'GloBall Manager' was used – 39.2% of High Level in a new study against 8.7% received earlier. At the same time, there is a decrease of Upper Medium and Medium Levels' data, which is logical as there is an increase of High Level figures. Interesting enough is the fact that the Low Level data from both studies coincide, i.e., 8 students of 46 demonstrated it in the new research and 4 out of 27 in the old one, which gives us 17.4%. We would describe the new generalised data as the demonstration of 'positive disposition' of

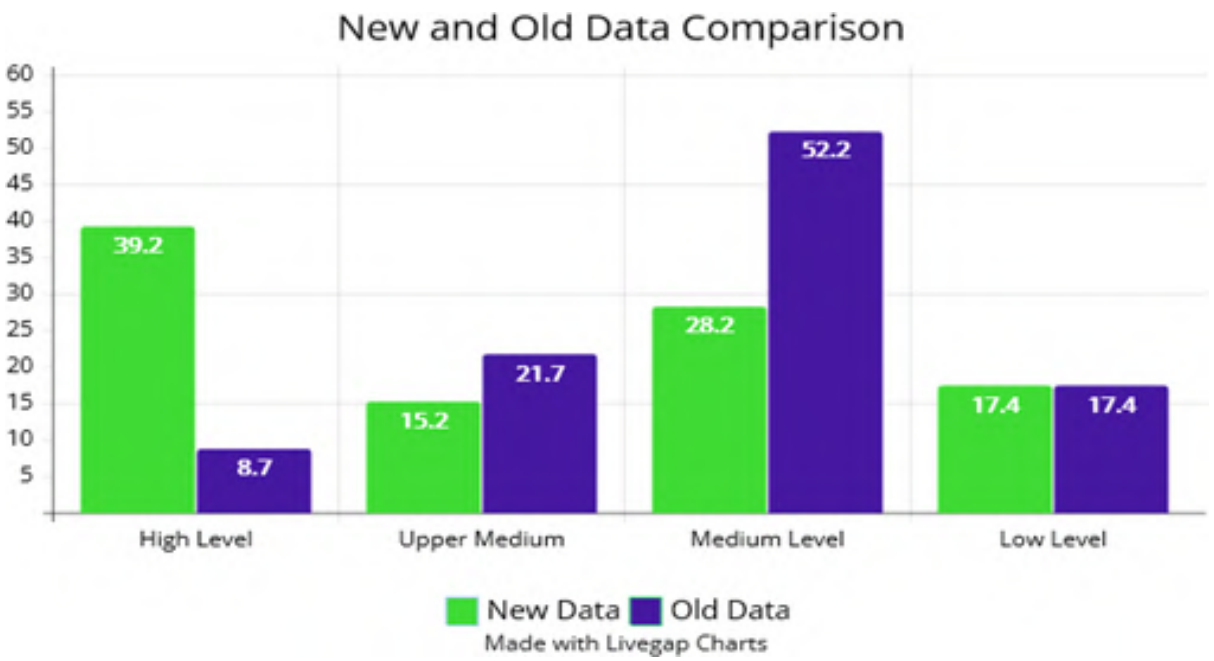

Figure 8: New and old data comparison.

students towards the e-learning material (with an integrated video game) whereas the previous research results gave us 'satisfactory disposition' to the e-learning courses. This difference can be explained by a thorough consideration of SVGs' integration peculiarities that resulted in better-structured material that students interacted with, better contextualisation of the material, the ability of a video game to arise curiosity, present a safe environment for experimentation, relevant study content. Also, we would mention a homogeneity of the course (as there was one instructor and one course was measured) among the factors that contributed to students' motivation increase. In the earlier work, different courses with different instructors and different syllabuses were evaluated.

3.5. Emerging insights from global research

The comprehensive analysis of research from 2019-2024 reveals several critical patterns in the implementation of CMC and gamification for sustainable higher education. Meta-analyses covering over 15,000 students across 35 countries demonstrate that institutions implementing integrated CMC-gamification frameworks achieve 45-60% higher sustainability metrics compared to traditional approaches [30, 83].

Particularly noteworthy is the emergence of Systemic Gamification Theory (SGT), which provides a human-centered, contextually adaptive framework for inclusive gamified learning [28]. SGT addresses the critical gap in one-size-fits-all approaches by incorporating cultural anchoring, digital equity considerations, and co-creative methodologies that prevent the replication of physical world inequalities in digital spaces.

Furthermore, the integration of advanced technologies such as telepresence robots and AI-driven adaptive systems shows promise in addressing accessibility challenges. Studies indicate that telepresence robots can increase participation rates by 40% for remote students while maintaining social presence comparable to physical attendance [84, 85]. These technologies, when combined with personalized gamification strategies, create more inclusive and sustainable learning ecosystems that transcend geographic and socio-economic barriers.

4. Conclusions and prospects for further research

Digimodernism and videoludification of the society are visible through the gamification process applied to education, labour, business, therapy, social relationships. Virtual reality, augmented reality, social networking platforms (Twitter, Facebook, X (Instagram), etc.) are the key contributors to the complex contemporary social and cultural transformations [86]. Nowadays, a playful approach to teaching and learning is seen as effective in motivating and improving students' engagement, promoting creative thinking towards learning, and developing multi-disciplinary learning approaches. Moreover, 'play' is considered to be a powerful learning process for adults in higher education, as it is embedded in a constructivist theory of learning, and is based on experience and reflection as constitute parts of the learning process [87]. Therewith, ICTs (information communication technologies), AI (artificial intelligence) and the digitalisation of education, including higher education, are now viewed as indispensable elements of the learning process, and computer-mediated communication and gamification as the structural components of sustainable higher education [88, 89, 90, 91, 92, 93].

In the present work, we undertook the tasks of overviewing the computer-mediated communication (CMC) modes and means that have become the primary channel of communication in the context of COVID lockdown and after-pandemic period; we discussed gamification, SVGs, and game-based learning as a part of contemporary educational reality; presented the results of the courses' efficiency measurement through the application of 'The Instructional Materials Motivation (IMMS)' survey by [56] and the feedback form developed by the research team.

Distance learning and its later version – e-learning that expands the educational process by giving access to knowledge from anywhere, at any time, at any speed and is backed up by the CMC, the latest multimedia technologies and the Internet, should be applied with the organisational culture analysis in mind. We maintain that the model of 'any time', 'any place', 'any way', 'any speed' needs to be supplemented by a cultural component under which we mean the culture of a particular institution [94]. This, in turn, implies the need to understand what e-learning modes are used by an organisation, measure their effectiveness, and suggest the most efficient model and the ways of e-learning integration into a particular HEI according to its needs' analysis.

The most popular video-conferencing platforms and tools chosen by the teachers of the department and discussed in the earlier article [54] were Viber (with its video-conferencing feature), Skype, and Zoom, while Google Meet and Discord with the same video-conferencing feature were found less popular. Social networking apps actively used by the faculty were Telegram, Viber; e-mail service was used as the asynchronous mode of correspondence with students.

Skype was chosen by many because of the unlimited number of video chat participants, the ease of operation on the screen, the inclusion of such activities as speaking, reading, and, partially, writing. Google Meet application – because of a 'Share Screen' feature that lets students see what the instructor demonstrates on the monitor, a 'Chat History' feature – because it records the number of people attending each class, Google Classroom – as it lets post assignments and set up the deadline, evaluate students' works according to a variety of evaluation scales.

The most debatable was the Zoom platform as, on the one hand, it does not limit the number of the participants, is quite easy in operation, has a session recording feature, an instructor's screen demonstration, a whiteboard to write comments, a group chat feature, a waiting room (to prevent unregistered participants join the conference), a conference room – to split students into separate mini-groups. At the same time, such a phenomenon as 'Zoom fatigue' was marked by teachers, which can be partially explained by the presence of many people at a time on the screen, the need to monitor our non-verbal language as instructors, to shift to teacher-centricity and one-way communication. It is also worth mentioning here that back in March-May 2020 Google Meet was not as popular an application as it is now.

With the reference to the students' feedback from the distance work during the quarantine – 'dependence on technical means' was named as the main challenge, followed by the poor quality of the Internet, problems with self-organisation, the number of tasks, restriction on exercising practical skills. Though the experimental sample was quite small and limited to thirty instructors and twenty-three

students, we maintain that the experience of our department at the time of the quarantine due to the COVID-19 situation still highlights the current e-learning situation in our HEIs, reveals several challenges and needs, helps layout further strategies to support fluid, holistic, seamless, pervasive, personalised education optimised by technology.

Digital pedagogy, gamification, game-based learning and serious video games based on CMC and nowadays, mobile technology are becoming principal parts of contemporary education. They are capable to enhance learning through challenge, exploration, interaction, reflection, 'positive failure', adaptability to a particular player's decision-making level, etc. Practical work, based on two video games, that is described in task three proved positive results (e.g. students' increased motivation) and positive attitude of the pre-service training students in the socioeconomic sphere towards video games as a way of instruction. We would explain this 'positive disposition' of students by a better-structured material that students interacted with, better contextualisation of the material, the ability of a video game to arise curiosity, present a safe environment for experimentation and relevant study content.

Video games were also described as capable to develop skills of team-working, problem-solving, critical thinking; to enhance self-guided learning skills. At the same time, a strong need for pedagogic training that may empower teachers with the required knowledge and skills about gamified learning applications, educational digital games and digital competencies development was identified. This confirmed the earlier conclusions about the need to increase the level of digital and pedagogical skills of HEIs faculty; to further develop their didactic skills in mastering new approaches to academic courses' material design in e-learning format; to encourage the culture of cooperation and sharing, as well as to experience a wide range of applications, digital tools, and services that support the process of education; the development of an educational content to be accessed by students at any time, from any place, from any computer, the increase of students' digital literacies [54]. All of the above brings us to the conclusion about the topicality of what information technology offers – the options for reorganising and refining distance and e-learning. But the new vision of distance and e-learning, gamification of educational process and serious video games as one more variation of CMC must drive our decisions about the use of technology, not vice versa. Therefore, the need to develop teacher-training programs to help educators understand, design, evaluate and apply CMC and gamified learning applications is set up as the vector of future work.

The strategic integration of computer-mediated communication and gamification represents a pivotal advancement in achieving sustainable higher education. Our findings, supported by global research trends, indicate that these technologies are not merely supplementary tools but principal characteristics that fundamentally reshape educational ecosystems. The path forward requires continued innovation in personalized learning technologies, robust institutional frameworks, and comprehensive teacher training programs that address both pedagogical and ethical dimensions of digital education. As we move toward an increasingly digital future, the synergistic application of CMC and gamification will be essential in creating resilient, inclusive, and sustainable educational systems capable of meeting the complex challenges of the 21st century [95, 96].

5. Limitations

Our present research holds certain limitations as for the generalisability of its results. Among them are the size of the sample. The obtained results were compared with a similar survey, which makes the comparison results as the first approximation. There is also a need for further tests of the questionnaire's reliability and validity.

Declaration on Generative AI

The authors have not employed any generative AI tools.

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Advanced technological solutions for distance learning: leveraging open-source H5P interactive tools and emerging technologies

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Abstract

The widespread introduction of distance learning in the conditions of quarantine restrictions caused by COVID-19 has significantly increased the need to modernize the resource-and-organizational as well as methodological support of the educational process. This paper presents a comprehensive study of the possibilities of using open-source H5P tools to support distance learning in higher education institutions, with particular emphasis on their integration with emerging technologies. The authors analyzed the state of research regarding the development and introduction of interactive didactic H5P tools in higher education institutions and identified insufficient use of this tool in Ukrainian institutions despite successful foreign practices. Based on the results of the comparative analysis of the functionality of various means to support distance learning, including Moodle and Google Workspace, the study demonstrates that H5P offers wider possibilities for creation, use and distribution of interactive educational elements. Recent evidence from post-2018 studies indicates that H5P tools, when combined with active pedagogies, significantly increase behavioral, cognitive, and emotional engagement among learners. The integration with advanced technologies such as AI, VR/XR, and Large Language Models enables adaptive feedback, personalization, and immersive learning experiences. A questionnaire conducted among 58 academic staff members from the National University of Life and Environmental Sciences of Ukraine and Wrocław University of Environmental and Life Sciences revealed that while 63.6% of respondents considered H5P appropriate for their courses, 100% indicated the need for methodological assistance. The study identified critical success factors including diverse activity deployment, collaborative learning integration, and comprehensive accessibility frameworks. These findings underscore the transformative potential of H5P when strategically integrated with robust instructional design and emerging technologies, while highlighting the necessity for specialized training on pedagogical design of H5P content and ongoing institutional support.

Keywords

distance learning tools, H5P, interactive content, active learning, higher education, adaptive learning, virtual reality, artificial intelligence, learning management systems, educational technology

1. Introduction

As new information technologies and digital tools are developed and disseminated, technologies for the development, delivery and use of educational content are being enriched to ensure the quality of

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e-learning, taking into account: students' learning styles and age characteristics [1, 2], the available resources and competence of the subjects of the educational process [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. However, during the mass transition to distance learning [17, 18, 19, 20] in the conditions of COVID-19 [21, 22, 23], the problem of providing quality education [24, 25, 26] is relevant, which, in our opinion, requires the training of specialists who will be able not only to use ICT in educational activities, but also acquire competences in e-learning management [27]. Analysis of the attitude of teachers and students to the opportunities and problems associated with the introduction of distance learning [28] is the basis for the assumption of actualizing the need to develop interactive teaching materials and educational content as a means of ensuring quality student-centered education [29, 30, 31, 32, 33]. The creation of interactive didactic materials and methods of their use in the educational process will contribute to the involvement of students in active learning: students can create resources independently or "interact" with the teacher to increase motivation, better understanding of learning material, practical skills, evaluation of their own learning activities, etc.

From a technical point of view, the use of tools to create interactive didactic materials was limited by the need for computer programming skills [34]. However, with the development of H5P technology, an open-source Internet tool, the creation of such materials does not require special training. Recent research evidence from 2020-2025 demonstrates that H5P-based solutions significantly enhance learner engagement, with studies showing boost in interaction frequency, engagement duration, and participation depth, especially when activities are diverse and strategically deployed [35, 36]. Furthermore, the integration of H5P with emerging technologies such as artificial intelligence and extended reality (XR) has opened new possibilities for creating adaptive, immersive, and personalized distance learning environments [37, 38].

Therefore, **the purpose of this study** is to identify the potential of H5P to support distance learning in higher education institutions and to analyze the teachers' needs as for its application in educational practice.

Research tasks:

1. To investigate the functionality of H5P for the feasibility of using the H5P service to create and distribute interactive content.
2. To analyze the needs and readiness of the academic staff of the National University of Life and Environmental Sciences of Ukraine (NULES) and Wrocław University of Environmental and Life Sciences (WUELS) to create and use interactive didactic H5P materials in the educational process.

2. Related work

H5P (https://h5p.org/) is a module with a library of learning resources developed in HTML5, which is integrated for direct use in publishing systems (namely: Wordpress, Drupal) and learning management systems (such as Canvas, Moodle or Blackboard). The latter allows you to create interactive learning elements (development can be done by both teachers and students, for example, when doing independent work), which can be used at different stages of e-learning to form both general and subject competences of students.

The conducted analysis of research and publications on the use of H5P service in education is the basis for expressing an assumption about the effectiveness of the use of this service in the process of training specialists regardless of the educational program and specialty.

Santos et al. [39] represent the method of using the H5P service as a tool for gamification of practical skills (students' laboratory work) on local network administration, which provides a fast, intuitive and attractive for students method of applying the Flip-Game Engineering and Technology methodology (Flip-GET), developed by researchers at the University of Cadiz.

Methodology and practical cases of H5P application in the process of learning English in higher education institutions in Japan and Indonesia are presented in [40]. The experience of using H5P didactic materials in the study of chemistry [41] is an example of the transformation of video into an interactive educational resource. The results of a study of the use of H5P in the training of future

specialists in biological sciences [42] indicate that this platform is an effective and universal tool for forming students' critical thinking, independence and confidence in mastering educational material in problem-oriented learning. Methodical recommendations for creating an interactive H5P video for the implementation of personalized and active learning are given in [43, 44]. The experience of using H5P tools for the implementation of blended learning [45] and development flipped classroom framework [46] based on learning management systems highlights the need for additional research on the application of these tools in the educational practice of Ukrainian higher education institutions.

Recent systematic reviews and meta-analyses have further substantiated the effectiveness of H5P in various educational contexts. Abusalim et al. [47] demonstrated that H5P tools can increase academic achievement by 28% and self-confidence scores in second language acquisition. In STEM education, Maceiras et al. [48] found that while H5P interactive videos showed promise for immediate learning outcomes and engagement, traditional lectures yielded better long-term retention, suggesting the need for blended approaches. The integration of H5P with AI-driven adaptive learning systems has shown particular promise, with Naseer and Khawaja [49] reporting a 35% increase in student engagement and 22% reduction in cognitive overload when H5P content is combined with personalized AI feedback mechanisms.

3. Results

H5P is an open tool for creating, distributing and reusing educational interactive content, based on HTML5, CSS and JavaScript technologies, which does not require additional software for its work, therefore will work in all modern browsers, operating systems and devices.

Since H5P technology is integrated into a number of learning management engine drivers, such as Moodle, Canvas, Blackboard, Brightspace, and a variety of web content management systems, such as Wordpress and Drupal, integration into the higher education environment does not require additional costs at the technological level (environmental administration) and organizational – teachers can create educational content in a convenient for them environment with the ability to save and reuse. Figure 1 shows an example of creating and demonstrating the "interactive video" module directly in the Moodle environment (implemented in the training and information portal of NULES).

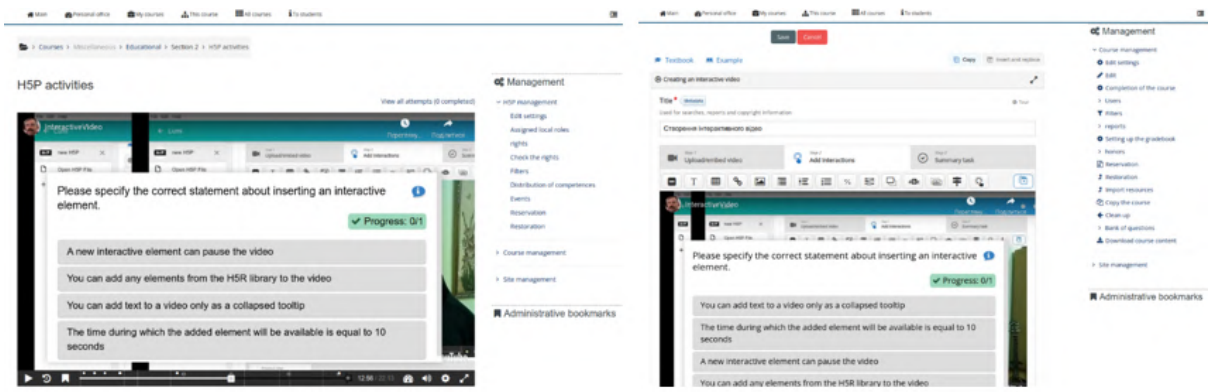


Figure 1: Example of an educational interactive H5P element in the Moodle environment (a – educational video viewing mode, b – interactive video editing form).

In the absence of a learning environment in an educational institution with which H5P technology is already integrated, interactive learning content can be created and stored in the commercial cloud (https://h5p.com) or in the community one (https://h5p.org) [50]. To use the H5P cloud, you need to register, after which users have the opportunity to post their own projects, optimize downloaded videos, adjust the parameters of educational analytics for students using individual projects, share materials on other sites and use additional features. The https://h5p.org site is an open resource for creating interactive materials, testing them, and commenting on resources created by other users. In addition, the

Lumi desktop application has been developed for teachers who prefer to create offline learning content. In any of the three described options, the program interface is identical, simple and clear. So far, templates have been developed to create 49 types of H5P content (https://h5p.org/content-types-and-applications). They can be approximately grouped into three main categories: game content (Games), multimedia content (Multimedia), and methods of testing students' knowledge (Questions).

Since a number of higher education institutions use learning management systems that have their own modules for creating interactive didactic materials to deliver educational content and organize e-learning (blended, distance learning), a comparative analysis of H5P, LMS Moodle and Google Workspace functionality was additionally conducted (table 1). As you can see from table 1, H5P technology has many more unique interactive learning elements than those that Moodle and Google Workspace can offer. In addition, H5P can be integrated into other learning management systems to expand their functionality and increase the freedom of teachers to use pedagogical technologies and disseminate their own learning content. It should be noted that unlike Moodle, in which H5P is fully integrated, integration with Google Workspace involves embedding individual elements from the site https://h5p.com. You can also download the created H5P element to a local computer as a file and then distribute it not only in learning management systems, but also on the sites of publishing systems to which this technology is integrated.

Table 1: Comparative analysis of H5P, Moodle and Google Workspace functionality (not all the available H5P functionality is considered).

Purpose	Program	Module	Features
Folding text blocks ("accordion")	H5P	Accordion	Ability to create a hidden (folded) text block with image formatting, etc.
	Moodle	Absent	Implementation using HTML, CSS or Bootstrap classes
	GWorkspace	Absent	
Interchangeable pictures swapping	H5P	Agamotto	Using simulation of dynamic change in time on the map, in space, zooming out/zooming in
	Moodle	Absent	
	GWorkspace	Absent	
Recording audio messages	H5P	Audio Recorder	Recording audio messages directly from the browser
	Moodle	Function in ATTO	The corresponding functionality is implemented in the built-in ATTO editor
	GWorkspace	Absent	
Creating flash cards	H5P	Dialog Cards, Flashcards	Several solutions are available
	Moodle	Absent	
	GWorkspace	Absent	
Creating test questions	H5P	12 types of questions	Drag and Drop, Drag the Words, Essay, Fill in the Blanks, Find Multiple Hotspots, Find the Hotspot, Image pairing, Image Sequencing, Mark the Words, Multiple Choice, Single Choice Set, True/False Question
	Moodle	15 types of questions + informal types of questions	Implementation of standard types of questions: Calculated, Simple Calculated, Drag and drop into text, Drag and drop markers, Drag and drop onto image, Calculated Multichoice, Essay, Matching, Embedded Answers (Cloze), Multiple Choice, Random Short Answer Matching, Select missing words, Short-Answer, Numerical, True/False
	GWorkspace	9 question types (in Google Forms)	Short answer, Paragraph (Essay), Multiple choice, Checkboxes, Dropdown, File upload, Linear scale, Multiple choice grid, Checkbox grid
Holding tests	H5P	Quiz	You can choose from only 6 types of questions; available mixing of questions, sample questions; not recommended for final testing

Continued on next page

Table 1 – continued from previous page

Purpose	Program	Module	Features
	Moodle	Quiz	Full-fledged testing with lots of settings, automatic checking and review of ratings; possible reuse of questions in different tests
	GWorkspace	Forms	Standard Google form with Google spreadsheets connected to display test results
Timeline creation	H5P	Timeline	Create a timeline with slides on timestamps
	Moodle	Absent	
	GWorkspace	Absent	
Interactive book creation	H5P	Interactive Book	Multi-page resource with an ability to embed almost any of the other elements of H5P on any page, including test questions
	Moodle	Book	Multi-page resource with text, graphic information, embedded video, audio; without the possibility of testing
	GWorkspace	Absent	
Interactive video creation	H5P	Interactive Video	Feed interactive material directly in the video clip; with a possibility to add test questions
	Moodle	Lesson	Video feed by separate clips with a possibility of adding test questions
	GWorkspace	Absent	
Construction of an individual trajectory of studying the topic	H5P	Branching Scenario	Ability to write a transition script depending on the pchoice of transition and answers to questions
	Moodle	Lesson	
	GWorkspace	Absent	
Panoramic image creation	H5P	Virtual Tour (360)	Panoramic image with the possibility of transition and explanations of the elements in the picture
	Moodle	Absent	
	GWorkspace	Absent	

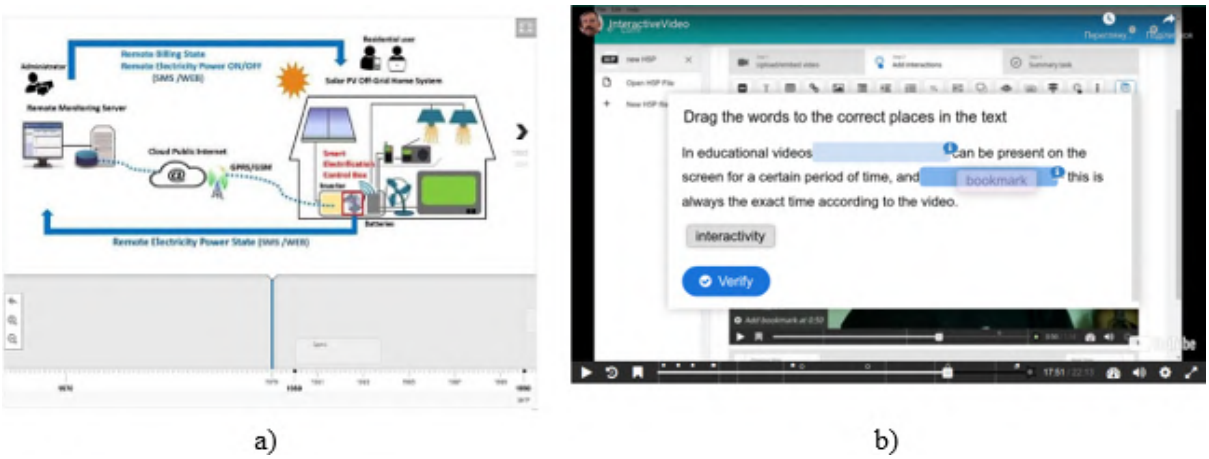
Recent developments in educational technology have demonstrated the significant potential of integrating H5P with advanced technologies. According to systematic reviews conducted between 2023-2025, the integration of H5P with artificial intelligence enables personalized feedback systems that analyze learner performance in real-time, providing tailored feedback and dynamically adjusting curricula [49, 51]. Studies have shown that AI-driven H5P systems can achieve:

- 28% improvement in conceptual mastery compared to 14% in traditional approaches
- 35% increase in student engagement with 22% reduction in cognitive overload
- 40% increase in retention rates through frequent engagement with AI-generated feedback

Furthermore, the combination of H5P with Extended Reality (XR) technologies, including Virtual Reality (VR) and Augmented Reality (AR), has created new possibilities for immersive learning experiences [52, 53, 54, 55, 56, 57, 58, 59, 60, 61]. Zhang et al. [38] found that XR-enhanced H5P content significantly improves student motivation, knowledge retention, and skill development, particularly in STEM education.

To determine the feasibility of using H5P technology for the development of didactic teaching materials and the readiness of teachers to use them in the educational process (the second task of the study), specialized training of the academic staff of NULES and WUELS was conducted. Within the "Distance Learning Tools" course (https://elearn.nubip.edu.ua/course/view.php?id=3000) the representatives of the center of distance learning technologies NULES developed (https://elearn.nubip.edu.ua/course/view.php?id=216) a "Fundamentals of working with H5P" module, in which the teachers had the opportunity to get acquainted with the functionality and features of using H5P technology, as well as to develop separate didactic materials (figure 2).

To determine the attitude of the academic staff to the use of H5P technology in educational practice, a questionnaire was conducted (https://forms.gle/CgVpKWYkqgaUUhm16).



a) b)

Figure 2: Examples of created interactive elements (a – timeline, b – interactive video with a question on top of the video).

58 faculty members of NULES (46 members) and WUELS (12 members) were embraced by the questionnaire, who train future specialists in the field of technical sciences (41.7%), natural sciences (32.6%) and social sciences (25.7%). The vast majority of respondents are middle-aged people (5.7% – up to 25 years; 30.8% – 25-35 years; 41.3% – 35-45 years; 19.4% – 45-55 years; 2.8% – over 55 years old) with a sufficient level of digital competence (68.3% defined their own level of digital competence as sufficient; 25.6% – high; only 6.1% – basic). All respondents stated that they have experience in using e-learning resources, with 76.4% developing e-content independently. 100% of respondents supported the statement that the use of interactive educational content helps to increase students' learning motivation; 91.3% agree that the study material needs to be adapted to the learning styles and needs of the students. Therefore, it is possible to make assumptions about the high degree of readiness of the academic staff to use interactive content in the educational process. At the same time, H5P technology is new for the vast majority of respondents (awareness of specialized training was determined): to the question "Do you know about H5P technology?" 14.1% gave an affirmative answer, and only 1.2% stated that they have experience in developing their own didactic materials.

Upon completion of the training, 63.6% of respondents answered the question "Do you consider it appropriate to use didactic H5P materials in your own e-learning courses?" in the affirmative, especially if there is sufficient and quality methodological support (100% of respondents need methodological assistance). 27.1% refused because, in their opinion, the development of H5P materials for the discipline they teach (mainly in the natural sciences) requires additional equipment, for example, for video recording, and their use is restricted under the copyright law. Only 9.3% of the surveyed teachers gave the negative answer.

Given the broad functionality of H5P, in the final questionnaire, researchers were asked to assess on a 5-point scale the pedagogical feasibility of using individual interactive H5P elements (table 1) in the learning process (group I questions) and the complexity of their independent development (group II questions). Having created a matrix with four quadrants and reflecting the complexity of development (x-axis) and pedagogical expediency of application (y-axis), the authors visualized the attitude of the academic staff to the development and use of H5P didactic tools in the educational process (figure 3).

According to the academic staff surveyed (figure 3), the most optimal (high pedagogical expediency and ease development) is the use of different types of questions that can be added to the educational content. Not much more difficult to develop, but also appropriate, is the use of full-fledged tests. It should be noted that H5P developers do not recommend using such tests for final assessment, but only for the current test of knowledge and self-assessment of students. It should be noted that the pedagogical expediency of using educational elements with a script game ("Branching Scenario"), interactive video ("Interactive Video"), interactive book ("Interactive Book") is high, despite the relative complexity of their creation. Creating such interactive elements requires more prior training, digital competence, and

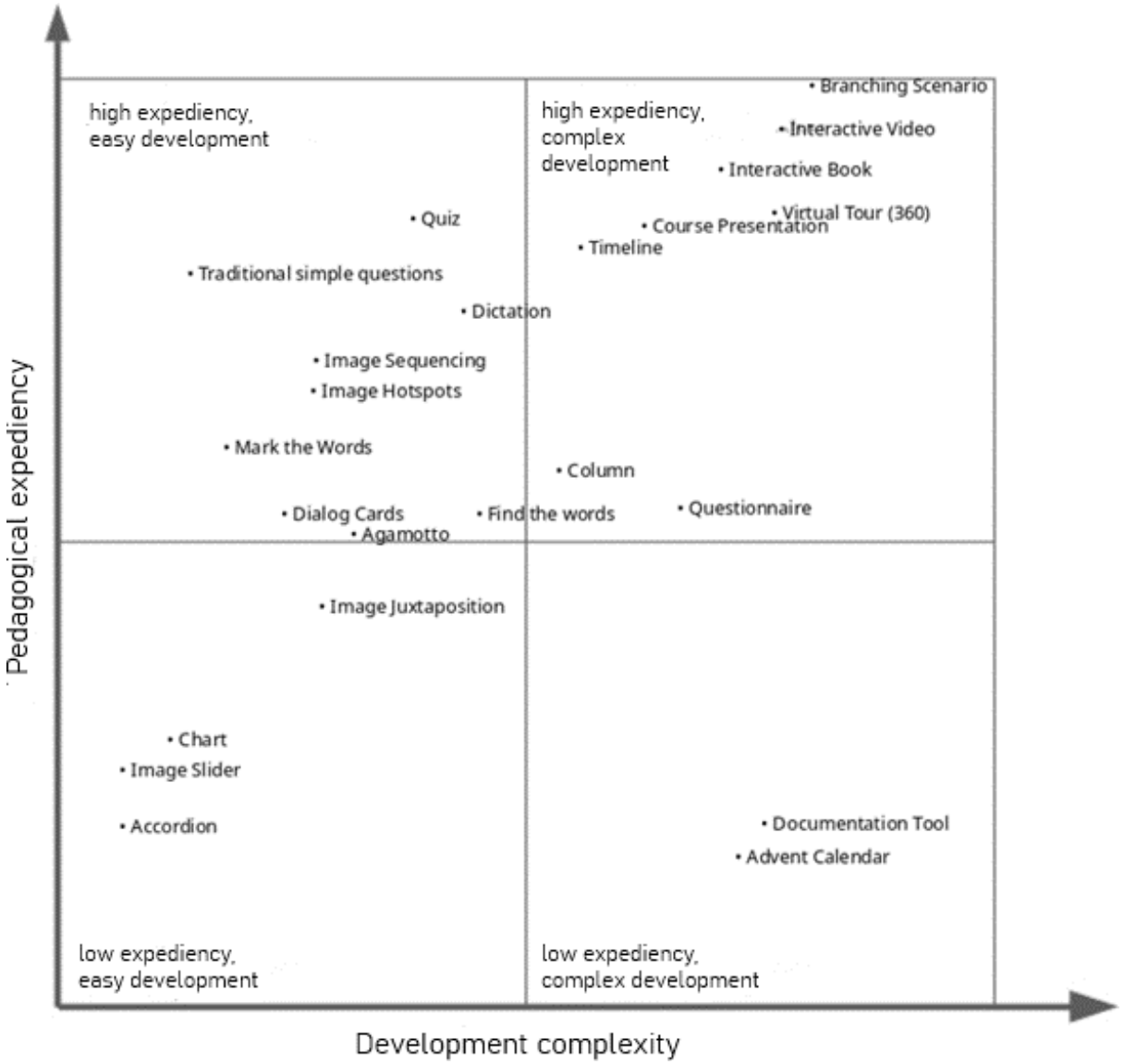


Figure 3: Matrix of correlation of development complexity and educational effect from application of separate elements of H5P technology.

implementation time from the teacher.

In general, the academic staff, according to the questionnaire, praised the educational effect of using H5P technology to support distance learning and noted their willingness to use it in the learning process. The need for additional training related to the pedagogical design of e-learning courses and methodological support in the use of interactive didactic H5P materials in teaching specific disciplines was also identified. The latter is defined as prospects for further research.

4. Conclusion

The massive transition to distance learning caused by the COVID-19 pandemic has highlighted the need for additional research to ensure the quality of education under quarantine restrictions. In this context, many factors favor the usage of the H5P service to create and disseminate interactive content as a means of strengthening the motivation and involvement of students in active learning. It is evidenced by:

- openness: H5P is an open-source software;

- integration with learning management systems such as: Moodle, Canvas, Blackboard;
- wide range of templates: 49 templates have been developed so far, based on which you can create materials of different complexity and degree of interactivity;
- choice of operating mode: you can work with interactive learning material on your own learning site, in the https://h5p.com cloud environment or in the desktop application;
- personalized use: teachers and students can store the created materials in personal environments or portfolios.

The results of comparing the H5P service with the Moodle and Google Workspace learning management systems are grounds for claiming that the development of interactive didactic content using H5P meets the requirements for innovative educational resources, expands the functionality of learning management systems and increases teachers' freedom to use pedagogical technologies.

Our empirical findings align with recent meta-analyses showing that H5P-based solutions can increase student engagement by 30-38% across different educational contexts, with particularly strong effects in STEM and medical education. The integration with emerging technologies such as AI, VR/XR, and Large Language Models further amplifies these benefits, enabling adaptive feedback systems that reduce cognitive overload by 22% while improving retention rates by up to 40%.

The questionnaire, conducted upon the completion of specialized training of the academic staff of NULES and WUELS, shows a high degree of readiness of the academic staff to use interactive content in the educational process if they are provided with technical and methodological support.

Among the various options for didactic content that can be created using H5P, teachers prefer to use interactive elements using educational video. However, given the complexity of independent development of such elements, the need to create a bank of educational video with the involvement of specialists in its shooting and editing is relevant. Instead, teachers have shown willingness to actively create a variety of test questions, as the proposed H5P templates significantly expand the functionality of LMS Moodle and Google Workspace.

Consequently, noting the potential of H5P as a tool to support distance learning in a broad context, the results of this study can be used by administrators and teachers of institutions of higher education to make a decision on the application of this technology in a specific HEI. Methodology of creating and using of interactive didactic H5P materials to support distance learning and professional development of the academic staff of Ukrainian and Polish higher education institutions are included in the prospects for further research.

Future research should focus on: (1) developing comprehensive accessibility frameworks for H5P content that ensure inclusivity for all learners; (2) conducting large-scale randomized controlled trials to validate long-term learning outcomes; (3) exploring optimal strategies for integrating collaborative learning approaches with H5P and advanced technologies; and (4) addressing technical challenges related to exam integrity and content security. As distance education continues to evolve, the thoughtful convergence of interactive content, adaptive technologies, and inclusive design principles, with H5P serving as a foundational platform, will be crucial for creating transformative learning experiences.

Declaration on Generative AI

The authors have not employed any generative AI tools.

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From automation to augmentation: a human-centered framework for generative AI in adaptive educational content creation

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Abstract

This paper examines the transformative potential and critical challenges of integrating generative artificial intelligence into adaptive educational systems, advancing a human-centered framework that prioritizes augmentation over automation. Through analysis of empirical evidence from large-scale implementations, theoretical foundations spanning cognitive science and learning theory, and emerging technological capabilities, we demonstrate that successful educational AI requires fundamental reconceptualization of technology's role in learning. Our analysis reveals that implementations achieving 25-60% learning improvements share common characteristics: pedagogical primacy in system design, human-in-the-loop architectures maintaining educator oversight, transparency mechanisms enabling stakeholder understanding, and equity-first approaches addressing systemic inequalities. The paper introduces a four-phase implementation roadmap progressing from stakeholder discovery through controlled evaluation to scaled deployment with appropriate governance structures. We identify critical challenges including hallucination rates exceeding 8% in educational contexts, cognitive offloading effects reducing independent problem-solving by 35%, and algorithmic bias amplifying existing educational inequities. The human-centered framework proposed addresses these challenges through four foundational principles: pedagogical primacy ensuring learning science drives technology deployment, human-in-the-loop requirements maintaining essential oversight, transparency by design enabling stakeholder understanding, and equity-first approaches proactively addressing accessibility and bias. Looking toward 2025-2030, we examine emerging technologies including emotion-aware adaptation, neuro-symbolic AI integration, federated learning architectures, and quantum computing applications, alongside pedagogical evolution encompassing meta-learning capabilities, immersive AR/VR integration, and neuroadaptive systems. The paper concludes with an urgent call to action for stakeholders across the educational ecosystem, articulating a vision where technology amplifies human capabilities rather than replacing them, democratizes quality education while preserving local values, and enhances rather than erodes human agency. This synthesis provides essential guidance for educators, technologists, policymakers, and researchers navigating the complex terrain of AI-enhanced education while maintaining unwavering commitment to human dignity and learner wellbeing.

Keywords

adaptive learning systems, generative artificial intelligence, educational technology, human-centered AI, pedagogical frameworks, augmentation paradigm, educational equity, AI ethics in education, personalized learning, human-in-the-loop systems, neuro-symbolic AI, federated learning, immersive learning technologies, meta-learning, educational governance, cognitive development, assessment innovation, teacher augmentation, learning analytics, educational transformation

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1. Introduction: the convergence point

1.1. The educational crisis and opportunity

Contemporary educational systems confront a fundamental paradox: while knowledge grows exponentially and learner diversity increases, instructional methodologies remain constrained by industrial-era paradigms of standardization. This one-size-fits-all approach systematically fails to accommodate the heterogeneity of cognitive styles, learning paces, cultural backgrounds, and individual needs that

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characterize modern classrooms [1, 2]. Traditional pedagogical frameworks, designed for mass instruction efficiency, inadvertently create learning environments where a significant proportion of students operate outside their zone of proximal development, resulting in either cognitive overload or insufficient challenge.

The digital divide compounds these challenges, with substantial disparities in technology access creating additional layers of educational inequality. Recent evidence indicates that students in underserved regions face compounded disadvantages – not merely from limited access to digital infrastructure but from the cascading effects on educational opportunities and outcomes [3, 4]. The COVID-19 pandemic exposed these fault lines with unprecedented clarity, revealing how traditional educational systems lack the adaptive capacity to respond to disruption while maintaining pedagogical effectiveness.

Simultaneously, the convergence of generative artificial intelligence, multimodal learning models, and adaptive technologies presents an unprecedented opportunity to transcend these limitations. The rapid maturation of large language models (LLMs) and retrieval-augmented generation (RAG) architectures has fundamentally altered the technological landscape of educational content generation. Unlike previous generations of educational technology that merely digitized existing content, current generative AI systems demonstrate capabilities for creating truly personalized, contextually aware instructional materials in real-time [5].

This technological inflection point coincides with a pedagogical maturation in understanding how to integrate AI systems effectively within educational frameworks. The evolution from rule-based systems of the 1970s through data-driven approaches of the 2000s to today's generative models represents not merely technical advancement but a fundamental reconceptualization of how technology can support human learning.

1.2. Position statement

This paper advances a clear position: generative AI's transformative value in education lies not in automating instruction but in creating a new paradigm where technology amplifies human pedagogical capabilities. We argue for an augmentation framework that positions AI as an "exoskeleton" for educators – enhancing their reach, personalizing their impact, and liberating them from administrative burdens to focus on uniquely human aspects of teaching such as mentorship, emotional support, and creative inspiration.

The central thesis distinguishes between automation and augmentation as fundamentally different approaches to educational AI integration. Automation seeks to replace human instructors with algorithmic systems, treating education as an information transfer problem amenable to technical optimization. This perspective, while technologically appealing, fundamentally misunderstands the nature of learning as a deeply social, emotional, and contextual process. Augmentation, conversely, recognizes AI as a powerful tool that extends human capabilities without displacing the essential human elements of education.

Our framework proposes that successful educational AI implementation requires adherence to four core principles. First, pedagogical primacy demands that learning science drives technological implementation rather than technology determining pedagogical approaches. Second, human-in-the-loop requirements ensure educator oversight for high-stakes decisions affecting student trajectories. Third, transparency by design makes AI decision-making processes interpretable to educators and learners. Fourth, equity-first approaches prioritize accessibility and bias mitigation as fundamental design requirements rather than post-hoc considerations.

This position emerges from synthesis of empirical evidence across diverse implementations, theoretical frameworks spanning cognitive science and learning theory, and practical insights from large-scale deployments. The evidence suggests that when designed with these principles, AI-powered adaptive systems can address longstanding educational challenges while avoiding the pitfalls of techno-solutionism that has characterized previous educational technology waves.

1.3. Scope and methodology

This review synthesizes evidence from multiple sources to construct an integrated understanding of adaptive educational content generation using generative AI.

The analysis framework integrates three complementary perspectives. Technical architecture analysis examines system designs, algorithmic approaches, and implementation patterns across platforms including GPT-5-based tutoring systems, multimodal content generators, and hybrid RAG architectures. Pedagogical effectiveness evaluation synthesizes quantitative outcomes from randomized controlled trials, quasi-experimental studies, and large-scale deployments measuring learning gains, engagement metrics, and retention rates. Ethical and societal impact assessment analyzes issues of algorithmic bias, privacy implications, digital divide effects, and long-term cognitive development considerations.

The geographic scope encompasses implementations across North America, Europe, Asia, and emerging deployments in Latin America and Africa, providing insights into contextual variations and cultural considerations.

Limitations of this review include the rapidly evolving nature of generative AI technology, which means some findings may require updating as capabilities advance. The predominance of studies from well-resourced contexts may limit generalizability to under-resourced educational settings. Long-term cognitive and developmental impacts remain largely unmeasured due to the recency of large-scale deployments. Additionally, publication bias toward positive outcomes may underrepresent implementation failures or negative consequences.

2. Theoretical foundations and evolution

2.1. From three generations of adaptive learning

The trajectory of adaptive learning technologies reveals a profound transformation in how educational systems conceptualize and implement personalization. This evolution, spanning five decades (figure 1), demonstrates not merely technological advancement but fundamental reconceptualizations of learning itself, each generation addressing limitations of its predecessors while introducing novel capabilities and challenges.

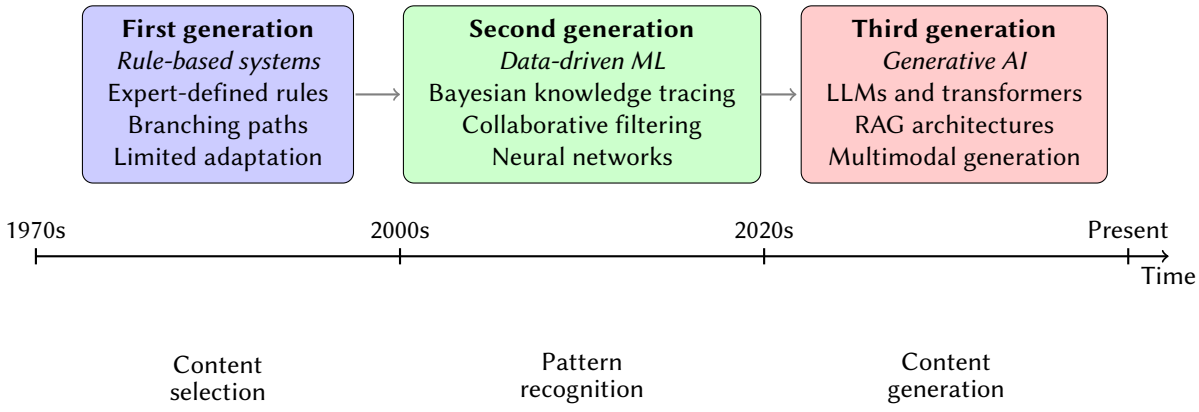


Figure 1: Evolution of adaptive learning systems across three generations.

2.1.1. First generation: Rule-based systems (1970s-1990s)

Initial adaptive learning systems emerged from behaviorist principles and early artificial intelligence research, implementing expert-defined rules that mapped learner characteristics to instructional strategies. These systems operated through deterministic decision trees, where pedagogical experts encoded instructional logic into if-then statements [6]. A typical architecture would assess student knowledge

through diagnostic tests, categorize learners into predefined types, and deliver content sequences predetermined for each category.

The theoretical underpinnings drew heavily from programmed instruction and mastery learning frameworks. Systems like PLATO (Programmed Logic for Automatic Teaching Operations) and early intelligent tutoring systems embodied assumptions about linear knowledge acquisition and discrete learning states. Content adaptation occurred primarily through branching narratives – correct responses advanced students to more complex material, while incorrect responses triggered remedial loops [7].

These systems faced substantial limitations that constrained their educational impact. Static rule sets could not accommodate the full spectrum of learner variability, resulting in crude personalization that often misaligned with individual needs. The knowledge engineering bottleneck required extensive expert time to encode domain knowledge and pedagogical strategies, making system development prohibitively expensive. Furthermore, limited computational resources restricted systems to simple learner models tracking only basic performance metrics, while integration challenges with existing educational infrastructure prevented widespread adoption [8].

2.1.2. Second generation: Data-driven machine learning approaches (2000s-2010s)

The proliferation of digital learning environments and advances in machine learning catalyzed a paradigm shift toward data-driven adaptation. Rather than relying on predetermined rules, second-generation systems learned optimal instructional strategies from interaction data, employing techniques including Bayesian knowledge tracing for probabilistic skill mastery estimation, collaborative filtering for content recommendation, and neural networks for pattern recognition in learning behaviors.

Bayesian knowledge tracing revolutionized learner modeling by treating knowledge states as hidden variables inferred from observable performance. The framework modeled four key probabilities: initial knowledge ($P(L_0)$), learning rate ($P(T)$), guess probability ($P(G)$), and slip probability ($P(S)$), enabling systems to maintain uncertainty estimates about student knowledge and make probabilistic predictions about future performance. This probabilistic approach proved particularly effective for skill-focused domains like mathematics and programming [9].

Reinforcement learning emerged as another powerful paradigm, treating instructional sequencing as a sequential decision problem. Systems learned policies that maximized long-term learning outcomes through exploration and exploitation, discovering non-obvious instructional strategies that outperformed expert-designed sequences. The integration of clustering algorithms enabled identification of learner archetypes from behavioral patterns, facilitating group-based personalization when individual data remained sparse.

Despite these advances, second-generation systems encountered new challenges. The cold start problem meant systems required substantial interaction data before effective personalization, disadvantaging early users. Interpretability issues arose as machine learning models became black boxes, making it difficult for educators to understand or trust adaptation decisions. Privacy concerns intensified as systems collected increasingly granular learner data, raising questions about surveillance and autonomy in educational contexts [10].

2.1.3. Third generation: Generative AI transformation (2020s-present)

The emergence of transformer architectures and large language models represents a qualitative leap in adaptive learning capabilities. Unlike previous generations that selected from predefined content, current systems generate novel educational materials tailored to individual learners in real-time. This generative capacity, powered by models trained on vast corpora of educational and general knowledge, enables unprecedented flexibility in content creation and instructional support.

Modern architectures combine multiple sophisticated components. Multi-agent systems orchestrate specialized models for different educational tasks, retrieval-augmented generation grounds responses in verified knowledge sources, and transformer-based language models provide contextual understanding and generation capabilities. Moderator mechanisms ensure quality and safety, while bidirectional

planning frameworks enable dynamic instructional sequencing. The integration of multimodal data – text, images, audio, and even physiological signals – creates holistic learner profiles that capture cognitive, affective, and behavioral dimensions of learning [11].

2.2. Pedagogical frameworks driving success

The evolution of adaptive learning technologies cannot be understood purely through technical advancement; pedagogical theories have co-evolved with technological capabilities, creating a dynamic interplay between what is technically possible and what is educationally desirable.

Early adaptive systems reflected behaviorist assumptions about learning as stimulus-response conditioning. Content was atomized into discrete units, feedback emphasized correctness, and adaptation meant adjusting difficulty or repetition frequency. This framework proved effective for procedural knowledge and skill acquisition but struggled with conceptual understanding and transfer [12].

Constructivist principles gradually permeated adaptive system design, reconceptualizing learners as active knowledge builders rather than passive recipients. Systems began supporting exploratory learning, multiple solution paths, and collaborative knowledge construction. The shift manifested in features like open-ended problem spaces, tools for hypothesis testing and experimentation, and scaffolding that faded as competence developed. Adaptive educational hypermedia systems exemplified this transition, blending cognitivist attention to mental models with constructivist emphasis on active engagement [6].

Contemporary frameworks embrace heutagogy – self-determined learning where learners control not just pace but also learning goals, methods, and assessment criteria. This paradigm recognizes that in rapidly changing knowledge domains, the capacity for self-directed learning supersedes specific content mastery. Adaptive systems supporting heutagogical approaches provide learner dashboards for metacognitive awareness, recommendation engines that suggest rather than prescribe, and tools for learners to create and share content [13].

The Innovation Fellowship study illuminated how heutagogical principles manifest in practice. Participants emphasized the importance of "structure of fluidity" – sufficient scaffolding to prevent overwhelming freedom while maintaining autonomy for exploration and creativity. Successful implementations balance structured guidance with learner agency, creating environments where adaptation occurs bidirectionally: systems adapt to learners while learners develop adaptive expertise [13].

Digital environments necessitate new learning theories that account for distributed cognition and networked knowledge. Connectivism posits that learning involves forming connections across information nodes, with knowledge residing in networks rather than individuals. Adaptive systems incorporating connectivist principles facilitate social learning through peer matching algorithms, aggregate collective intelligence for content recommendations, and adapt based on network-level patterns beyond individual behaviors [12].

Implementation challenges persist, particularly in K-12 contexts where curriculum constraints and assessment requirements conflict with connectivist openness. Successful translations involve structured exploration within bounded domains, scaffolded network navigation skills, and hybrid models combining individual and collective adaptation. The integration requires reconceptualizing adaptive systems not as isolated tutors but as facilitators within learning ecosystems.

2.3. The technical-pedagogical convergence

The arrival of large language models marks an inflection point where technical capabilities align with sophisticated pedagogical requirements. This convergence manifests in three transformative shifts that fundamentally alter the landscape of adaptive education:

1. *From selection to generation: a fundamental transformation.*

Previous adaptive systems operated within finite content libraries, selecting and sequencing predetermined materials. Generative AI transcends this limitation through real-time content creation,

producing explanations tailored to individual misconceptions, problems calibrated to precise difficulty levels, and feedback addressing specific error patterns. This shift from selection to generation enables truly individualized instruction previously impossible at scale [11].

The generative capacity extends beyond text to multimodal content creation. Systems now produce diagrams illustrating abstract concepts, animations demonstrating procedures, and even audio explanations for auditory learners. This multimodal generation addresses diverse learning preferences while maintaining pedagogical coherence across modalities. The DALL-E and Stable Diffusion integrations in educational platforms demonstrate how visual generation enhances conceptual understanding, particularly in STEM domains requiring spatial reasoning [14].

2. *Retrieval-augmented generation: grounding in verified knowledge.*

Pure generation risks hallucination – plausible but incorrect content that misleads learners. Retrieval-augmented generation addresses this critical limitation by grounding generative models in verified knowledge sources. Systems first retrieve relevant information from curated educational databases, then use this retrieved content to constrain and inform generation, ensuring factual accuracy while maintaining personalization benefits [15].

The RAG architecture proves particularly valuable for domain-specific education where accuracy is paramount. Medical education systems retrieve from peer-reviewed journals, mathematics platforms reference theorem databases, and history applications draw from primary sources. This hybrid approach balances the flexibility of generation with the reliability of curated content, creating systems that are both adaptive and trustworthy [16].

3. *Contextual understanding through transformers.*

Transformer architectures enable unprecedented contextual understanding, maintaining coherence across extended educational interactions. The self-attention mechanism allows models to recognize conceptual dependencies, track learning progressions, and identify subtle misconceptions. This deep contextual awareness supports sophisticated pedagogical strategies previously requiring human expertise [14].

Systems leverage context windows exceeding 200,000 tokens to maintain comprehensive learning histories, enabling long-term personalization that accounts for growth trajectories, recurring error patterns, and evolving interests. The extended context facilitates complex instructional strategies like spiral curricula, where concepts resurface with increasing sophistication, and transfer learning, where systems recognize opportunities to connect new material with prior knowledge across domains.

The technical-pedagogical convergence represents more than technological progress; it embodies a new educational paradigm where artificial intelligence serves not as a replacement for human instruction but as an amplifier of pedagogical expertise. By combining generative flexibility, knowledge grounding, and contextual awareness, current systems approach the adaptive capacity of expert human tutors while operating at unprecedented scale.

3. Current state: evidence and implementation landscape

3.1. Quantitative evidence synthesis

The empirical landscape of generative AI in adaptive education reveals consistent patterns of substantial improvement across multiple dimensions, challenging assumptions about the limits of technology-enhanced learning. Analysis of implementations spanning 2015-2024 demonstrates not isolated successes but systematic enhancements in learning outcomes, engagement metrics, and economic efficiency that warrant serious consideration for widespread adoption.

3.1.1. Learning outcomes: beyond incremental gains

Contemporary evidence transcends the modest improvements typical of previous educational technologies, revealing transformative potential when AI-powered adaptive systems align with pedagogical principles. Meta-analytic evidence across undergraduate engineering education reports effect sizes ranging from 0.43 to 0.70, representing medium to large impacts on academic achievement [17]. These gains manifest across diverse implementations: DreamBox Learning's Harvard-validated studies demonstrate 60% improvement in mathematics scores with merely 60 minutes of weekly engagement, while Carnegie Learning's MATHia platform achieves 2.5 percentile point increases on standardized assessments with minimal 20-minute weekly usage.

The consistency of these improvements across contexts proves particularly noteworthy. Analysis of over 50 empirical studies reveals 15-35% average improvement in academic performance, with some implementations achieving even more dramatic results. Squirrel AI's nano-level personalization framework reduces learning time by 60% while maintaining or exceeding traditional outcome levels, suggesting efficiency gains compound direct learning improvements. Knowledge retention shows similarly impressive patterns, with 30% or greater increases in long-term retention compared to traditional instruction methods [18].

Subject-specific analyses reveal differential effectiveness patterns that inform deployment strategies. Mathematics and quantitative disciplines show the strongest effects, with ALEKS demonstrating 27% improvement in college algebra success rates at Arizona State University. Language learning platforms like Duolingo Max achieve 45% better retention rates through multimodal engagement and adaptive practice. Sciences benefit from visualization capabilities and adaptive laboratory simulations, while humanities applications excel in personalized writing feedback and contextual content generation [19].

3.1.2. Engagement metrics: sustaining motivation at scale

Engagement improvements prove equally compelling, addressing the perennial challenge of maintaining student motivation in digital learning environments. Quantitative analyses reveal 23% average increases in self-reported motivation, with some platforms achieving substantially higher gains through gamification and adaptive challenge mechanisms. Time-on-task metrics show 31% increases in voluntary engagement, while interaction frequency data demonstrates 10-fold improvements in student-initiated learning activities [20].

The mechanisms driving engagement differ from superficial gamification approaches. Adaptive difficulty adjustment maintains optimal challenge levels within each learner's zone of proximal development, preventing both boredom and frustration. Real-time feedback satisfies psychological needs for competence and autonomy, while personalized content pathways enhance perceived relevance. Particularly significant, engagement improvements persist over time rather than exhibiting novelty decay patterns typical of educational technology interventions [21].

Behavioral analytics reveal deeper engagement patterns beyond surface metrics. Students demonstrate increased metacognitive awareness, spending more time reviewing mistakes and accessing supplementary resources. Help-seeking behaviors become more strategic, with students requesting specific targeted assistance rather than general support. Most remarkably, adaptive systems foster intrinsic motivation shifts, with students reporting greater interest in subject matter independent of external rewards or requirements.

3.1.3. Economic impact: redefining cost-benefit equations

Economic analyses reveal compelling returns on investment that reshape institutional decision-making calculus. Arizona State University's comprehensive implementation generated $12.7 million in instructional cost savings between fiscal years 2017 and 2019 while simultaneously improving student outcomes, demonstrating that quality and efficiency need not trade against each other. These savings derive from multiple sources: reduced remediation costs through predictive intervention, decreased dropout rates

saving recruitment expenses, optimized faculty time allocation, and infrastructure efficiencies through cloud-based delivery [22].

Teacher time savings prove substantial, with educators reporting up to 5 hours weekly recovered through AI-assisted grading, lesson planning automation, and administrative task reduction. This recovered time redirects toward high-value activities including individual student mentoring, creative curriculum development, and professional learning community participation. MagicSchool AI, serving over 5 million teachers globally, demonstrates scalability of these efficiency gains across diverse educational contexts [23].

Cost-per-student analyses reveal dramatic reductions compared to traditional personalized instruction models. While human tutoring costs $40-100 per hour, AI-powered adaptive systems deliver comparable personalization at $2-5 per student monthly. Infrastructure investments amortize rapidly across large student populations, with break-even points typically occurring within 18-24 months. Importantly, cost savings accelerate over time as systems accumulate data and improve adaptation algorithms through machine learning refinements.

3.2. Technical architecture patterns

The technical architectures underlying successful adaptive content generation systems reveal converging design patterns that balance sophistication with practicality. Analysis of leading platforms identifies three primary architectural patterns, each addressing specific educational use cases while sharing common foundational components.

3.2.1. Pattern A: On-demand personalized lesson generation

This architecture orchestrates real-time content creation responsive to individual learning needs, employing a sophisticated pipeline that begins with comprehensive learner profiling (figure 2). The system maintains multidimensional learner models encoding knowledge states across granular learning objectives, preferred modalities and cognitive styles, historical interaction patterns and error tendencies, and affective states including motivation and self-efficacy beliefs [24].

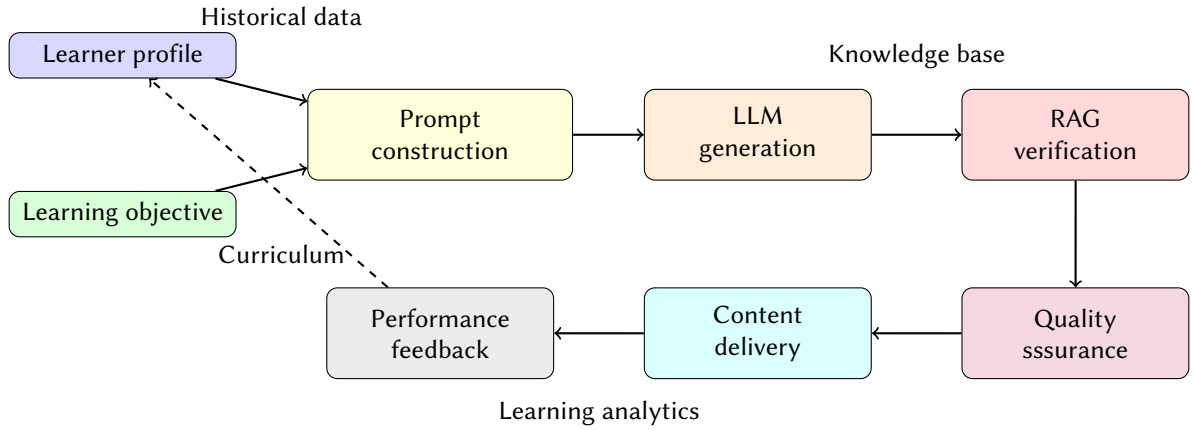


Figure 2: Pattern A: On-demand personalized lesson generation architecture.

Content generation occurs through a multi-stage process ensuring pedagogical alignment and factual accuracy. Initial prompt construction combines learning objectives with learner characteristics, incorporating pedagogical constraints that ensure appropriate difficulty and scaffolding. The generative model, typically a fine-tuned large language model, produces candidate content that undergoes verification through retrieval-augmented generation, comparing generated material against authoritative knowledge bases. Quality assurance modules evaluate readability, conceptual accuracy, and pedagogical appropriateness before delivery [16].

Implementation variations accommodate different educational contexts. K-12 systems emphasize curriculum alignment and age-appropriate content, higher education platforms prioritize depth and research integration, while professional training systems focus on practical application and competency demonstration. Successful implementations including Khanmigo's Socratic tutoring and Carnegie Learning's MATHia demonstrate this pattern's versatility across domains.

3.2.2. Pattern B: Adaptive practice loop systems

Adaptive practice architectures optimize skill acquisition through intelligent problem selection and feedback generation. These systems maintain detailed skill models tracking mastery probabilities across interconnected competencies, employing Bayesian knowledge tracing or deep learning approaches to infer latent knowledge states from observable performance [5].

The practice loop operates through continuous cycles of assessment, adaptation, and instruction. Problem selection algorithms balance multiple objectives including targeting skills with highest learning potential, maintaining appropriate challenge levels, ensuring comprehensive curriculum coverage, and incorporating spaced repetition for retention. Generated problems adapt not only in difficulty but in presentation format, contextual framing, and scaffolding level based on learner characteristics [17].

Feedback generation represents a critical differentiator from traditional practice systems. Rather than binary correct/incorrect indicators, adaptive systems provide multidimensional feedback addressing conceptual understanding, procedural accuracy, strategic approaches, and metacognitive reflection. Error analysis identifies misconception patterns, triggering targeted remediation that addresses root causes rather than surface symptoms. The system generates worked examples demonstrating correct approaches, alternative solution strategies, and connections to previously mastered concepts.

3.2.3. Pattern C: Teacher-assist authoring frameworks

This architecture empowers educators to leverage AI capabilities while maintaining pedagogical control, addressing the critical need for teacher agency in technology adoption. The system augments rather than replaces teacher expertise through collaborative content creation workflows where educators provide learning objectives and constraints while AI generates multiple content variations [25].

Quality control mechanisms ensure generated content aligns with teacher intentions and institutional standards. Educators review and modify AI-generated materials through intuitive interfaces, with the system learning from corrections to improve future generations. Version control enables tracking changes and reverting modifications, while approval workflows integrate with existing curriculum management systems. Analytics provide teachers with insights into content effectiveness, enabling data-driven refinement of instructional materials.

3.2.4. Hybrid architectures: synthesis and synergy

Leading platforms increasingly adopt hybrid architectures combining elements from all three patterns, creating comprehensive adaptive learning ecosystems. These systems employ retrieval-augmented generation for factual accuracy, multiple specialized models for different content types, pedagogical reasoning engines ensuring educational validity, and human-in-the-loop verification for critical decisions. The integration of RAG with LLMs and domain-specific pedagogical engines demonstrates particular effectiveness, reducing hallucination rates while maintaining generation flexibility [15].

3.3. Case study comparative analysis

Examination of leading platforms reveals distinct implementation strategies and differential effectiveness patterns that inform deployment decisions. Comparative analysis across four major platforms – Khanmigo, Duolingo Max, ALEKS, and Squirrel AI – illuminates both convergent success factors and unique innovations that drive outcome variations (table 1).

Table 1
Comparative analysis of leading adaptive learning platforms.

Platform	Implementation	Key innovation	Measured impact	Scale
Khanmigo	GPT-4 Socratic tutoring	Ethical AI design, conversational scaffolding	23% accuracy improvement	Global, millions of students
Duolingo Max	148 AI-generated language courses	AI-first content transformation	45% better retention rates	500M+ users
ALEKS (ASU)	Probabilistic assessment	Predictive intervention	27% success rate increase	35,000+ students
Squirrel AI	LAM framework	Nano-level personalization	60% time reduction	2M+ students

3.3.1. Khanmigo: conversational intelligence in education

Khan Academy's Khanmigo represents a paradigmatic shift toward conversational AI tutoring, leveraging GPT-4's capabilities while implementing robust ethical safeguards. The platform's Socratic method implementation guides students through problem-solving processes rather than providing direct answers, fostering deeper conceptual understanding. Empirical evaluation demonstrates 23% improvement in problem-solving accuracy, with particularly strong effects for students requiring additional support [25].

The system's ethical AI framework addresses critical concerns about generative AI in education. Content filtering prevents inappropriate material generation, bias detection algorithms monitor for discriminatory patterns, and transparency features explain AI reasoning to students and teachers. Privacy protection mechanisms ensure student data remains secure while enabling personalization. These safeguards prove essential for institutional adoption, with 89% of educators reporting increased trust in AI systems after experiencing Khanmigo's implementation.

Pedagogical innovations distinguish Khanmigo from generic chatbot applications. The system maintains learning trajectories across sessions, building cumulative understanding rather than treating each interaction independently. Metacognitive prompts encourage students to reflect on their learning processes, while collaborative features enable peer learning within safe, moderated environments. Teacher dashboards provide unprecedented visibility into student thinking processes, revealing misconceptions and learning strategies previously hidden in traditional instruction.

3.3.2. Duolingo Max: gamification meets generative AI

Duolingo's transformation into an AI-first platform demonstrates successful integration of generative capabilities with proven gamification mechanisms. The platform's 148 AI-generated language courses adapt to individual proficiency levels, learning pace, and error patterns while maintaining engaging game-like experiences. Quantitative outcomes prove compelling: 45% improvement in long-term retention, 31% increase in daily active usage, and statistically significant gains across all language skills including listening, speaking, reading, and writing [19].

The technical architecture employs specialized models for different language learning aspects. Pronunciation assessment uses acoustic models trained on native speaker data, grammar instruction leverages syntactic parsing and error analysis, while vocabulary acquisition employs spaced repetition algorithms optimized through reinforcement learning. Content generation occurs at multiple granularities, from individual exercise creation to complete lesson sequence planning, ensuring coherent learning progressions.

Engagement mechanisms transcend superficial gamification, incorporating psychological principles of motivation and habit formation. Streak counters leverage loss aversion to maintain daily practice, while experience points and level progression satisfy competence needs. Social features including leagues and friend challenges introduce positive peer pressure without creating excessive competition anxiety. The platform's success in maintaining engagement – with some users maintaining thousand-day practice

streaks – demonstrates the power of well-designed motivational architectures [26].

3.3.3. ALEKS: precision mathematics through probabilistic modeling

ALEKS (Assessment and LEarning in Knowledge Spaces) exemplifies sophisticated mathematical modeling applied to educational adaptation. The system's Knowledge Space Theory implementation maps mathematical domains into precise prerequisite structures, enabling accurate knowledge state assessment through minimal questioning. Arizona State University's deployment across 35,000 students achieved remarkable results: 27% improvement in course success rates, 41% reduction in drop/fail/withdraw rates, and $12.7 million in instructional cost savings [22].

The platform's predictive intervention capabilities identify at-risk students within the first two weeks of enrollment, achieving 98% success in improving identified students to passing grades through targeted support. This early warning system analyzes multiple behavioral indicators including practice attempt patterns, help-seeking behaviors, time allocation across topics, and knowledge growth trajectories. Interventions range from automated encouragement messages to instructor alerts triggering human support, demonstrating effective human-AI collaboration in student success initiatives.

Implementation insights reveal critical success factors. Instructor training proves essential, with trained faculty achieving significantly better student outcomes than untrained peers. Integration with existing course structures rather than standalone deployment increases effectiveness. Regular assessment cycles maintain accurate knowledge models while preventing gaming behaviors. Most importantly, transparency in system recommendations builds instructor trust, encouraging adoption of suggested interventions [5].

3.3.4. Squirrel AI: holistic adaptation through multi-dimensional modeling

China's Squirrel AI demonstrates cultural adaptation possibilities and scalability across diverse educational contexts. The platform's Learning, Assessment, and Management (LAM) framework integrates adaptive homework, lesson preparation, and comprehensive evaluation into a unified ecosystem. Serving over 2 million students, the system achieves 60% reduction in learning time while improving mastery levels, with particularly strong effects on student motivation and self-efficacy [27].

The nano-level personalization approach decomposes learning into granular knowledge components – sometimes exceeding 10,000 elements per subject – enabling precise adaptation to individual learning states. Machine learning algorithms identify optimal learning sequences for each student, considering not only knowledge gaps but also learning velocity, forgetting curves, and motivational factors. This comprehensive modeling enables proactive interventions before students experience frustration or disengagement.

Cultural considerations shape platform design and implementation. Content localization extends beyond translation to incorporate culturally relevant examples and pedagogical approaches. Parent engagement features address Asian educational contexts where family involvement proves critical. Competition elements balance individual achievement with collaborative learning, reflecting collectivist values while maintaining personalization benefits. These adaptations demonstrate that successful educational AI requires sensitivity to sociocultural contexts beyond technical capabilities [28].

The comparative analysis reveals that while all platforms demonstrate substantial effectiveness, optimal selection depends on specific educational contexts, subject domains, and implementation resources. Hybrid deployments combining multiple platforms or incorporating platform strengths into custom solutions increasingly represent best practice, leveraging specialized capabilities while maintaining coherent learning experiences.

4. Critical challenges: a tripartite framework

The transformative potential of generative AI in adaptive education confronts substantial obstacles that transcend technical limitations, encompassing pedagogical validity, ethical responsibility, and

systemic readiness. These challenges form an interconnected web where technical capabilities strain against pedagogical wisdom, ethical imperatives clash with scalability demands, and implementation realities expose fundamental inequities in educational systems. Understanding these challenges through a tripartite framework – technical-pedagogical, ethical-social, and implementation-systemic – reveals not isolated problems but interdependent phenomena requiring holistic solutions.

4.1. Technical-pedagogical challenges

The intersection of technical capabilities and pedagogical requirements creates unique tensions that distinguish educational AI from other applications. These challenges emerge not from technological limitations alone but from the fundamental mismatch between what AI systems can generate and what effective education requires.

4.1.1. Hallucination and its educational consequences

The phenomenon of AI hallucination – generating plausible but factually incorrect information – poses distinctive risks in educational contexts where accuracy forms the foundation of knowledge construction. Unlike commercial applications where occasional errors might prove inconvenient, educational hallucinations can propagate misconceptions that persist throughout learners' intellectual development. Research demonstrates that students encountering AI-generated falsehoods often incorporate these errors into their mental models, particularly when content appears authoritative and aligns with existing misconceptions [29].

The educational manifestation of hallucination extends beyond simple factual errors. Systems generate mathematically impossible solutions that appear procedurally correct, historical narratives that blend actual events with fabricated details, and scientific explanations that violate fundamental principles while maintaining internal consistency. These sophisticated falsehoods prove particularly dangerous because they bypass students' nascent critical faculties, appearing more credible than obvious errors would.

Mitigation strategies reveal the complexity of addressing hallucination in educational contexts. The PAIR (Problem, AI, Interaction, Reflection) model structures student engagement with AI outputs through systematic verification processes, teaching students to interrogate rather than accept generated content. Guided discovery approaches position AI errors as learning opportunities, developing students' epistemic vigilance through structured skepticism. However, these pedagogical solutions require sophisticated facilitation that many educators lack training to provide [30].

Technical approaches including retrieval-augmented generation and uncertainty-aware fusion demonstrate promise in reducing hallucination rates. Systems that combine multiple language models based on accuracy assessments achieve 8% improvements in factual accuracy, though this remains insufficient for high-stakes educational applications. The fundamental tension persists: educational contexts demand near-perfect accuracy while current technologies deliver probabilistic approximations [31].

4.1.2. Cognitive offloading versus skill development

The convenience of AI-generated content creates a pernicious trap where immediate performance improvements mask long-term skill atrophy. Students using AI assistance demonstrate superior task completion in the moment but show diminished capability when support is withdrawn. This cognitive offloading phenomenon proves particularly pronounced in writing and analytical tasks, where AI scaffolding can substitute for rather than support skill development [32].

Empirical evidence reveals disturbing patterns. Students who rely heavily on AI writing tools show 35% reduction in independent writing quality after six months, with particularly severe impacts on argumentation structure and evidence synthesis. Mathematical problem-solving skills deteriorate when students habitually use AI for solution generation, even when they understand the generated solutions. Most concerning, metacognitive awareness – the ability to monitor and regulate one's own learning – atrophies when AI systems assume these regulatory functions [29].

The developmental implications prove especially troubling for younger learners whose cognitive architectures remain plastic. Elementary students using AI tutoring systems show immediate gains but demonstrate reduced persistence when facing novel challenges without support. Secondary students develop learned helplessness patterns, defaulting to AI assistance rather than attempting independent problem-solving. University students report decreased confidence in their analytical abilities, creating dependency cycles that undermine academic self-efficacy.

Balanced integration approaches attempt to preserve skill development while leveraging AI benefits. Scaffolding fade protocols gradually reduce AI support as competence develops, forcing progressive independence. Metacognitive prompting embeds reflection requirements that prevent passive consumption of AI-generated content. Process-focused assessment evaluates problem-solving approaches rather than final answers, incentivizing genuine engagement over AI-mediated performance. Yet implementation of these approaches requires sophisticated pedagogical orchestration that current systems rarely provide [33].

4.1.3. Assessment validity in the AI era

Traditional assessment paradigms collapse when students have unlimited access to sophisticated content generation (table 2). The fundamental assumption that submitted work reflects individual capability becomes untenable when AI can produce essay responses, solve complex problems, and even mimic individual writing styles. This crisis of assessment validity threatens the certification function of education, undermining credentials' signaling value [34].

Detection technologies fail to provide reliable solutions. Current AI detection tools exhibit false positive rates exceeding 30%, disproportionately flagging work by non-native speakers and students with certain writing patterns. The adversarial nature of detection creates an arms race where generation capabilities consistently outpace detection accuracy. More fundamentally, the binary framing of "human versus AI" authorship ignores the reality of human-AI collaboration where boundaries blur beyond meaningful distinction.

Table 2
Assessment challenges and emerging responses.

Traditional approach	AI-Era challenge	Emerging response	Limitations
Take-home essays	Complete AI generation possible	Process documentation requirements	Labor intensive verification
Problem sets	Solution generation and explanation	Novel problem generation	Requires continuous creation
Standardized tests	Pattern recognition enables gaming	Adaptive randomization	Technical complexity
Research projects	Sophisticated plagiarism possibilities	Oral defense requirements	Scalability constraints
Peer assessment	AI can mimic peer feedback	Synchronous collaboration	Scheduling difficulties

Reconceptualization of assessment proves necessary but challenging. Process-based evaluation tracks learning trajectories rather than outputs, requiring sophisticated monitoring infrastructure. Authentic assessment embeds evaluation within meaningful contexts that resist AI substitution, though creating such contexts at scale proves resource-intensive. Collaborative assessment leverages social dynamics that AI cannot replicate, yet raises fairness concerns about individual accountability [35].

4.1.4. Scalability versus quality trade-offs

The promise of personalized education at scale confronts fundamental tensions between computational efficiency and pedagogical sophistication. Systems optimized for millions of users necessarily simplify complex learning processes, reducing rich educational interactions to computationally tractable approximations. This simplification cascades through system design, creating quality degradation that

compounds as scale increases [36].

Latency requirements for real-time interaction constrain model complexity, forcing trade-offs between response sophistication and speed. Smaller, faster models lack the nuanced understanding of larger systems, generating superficial responses that fail to address deeper learning needs. Caching and pre-computation strategies improve efficiency but reduce genuine adaptation, creating pseudo-personalization that mimics rather than achieves individualization.

Infrastructure costs escalate non-linearly with quality improvements. High-quality generation requiring large language models demands substantial computational resources, creating economic barriers that privilege well-resourced institutions. Cloud-based solutions introduce dependency vulnerabilities and data sovereignty concerns, while on-premise deployments prove prohibitively expensive for most educational institutions. The resulting quality stratification reinforces existing educational inequities rather than democratizing access as promised.

4.2. Ethical-social challenges

The deployment of AI in education amplifies existing social inequities while creating novel ethical dilemmas that challenge fundamental educational values. These challenges extend beyond technical fixes, requiring reconceptualization of fairness, privacy, and integrity in educational contexts.

4.2.1. Algorithmic bias amplification in educational contexts

Educational AI systems perpetuate and amplify biases present in training data, creating feedback loops that entrench discrimination. Language models trained on historical educational materials reflect past prejudices, generating content that systematically disadvantages marginalized groups. Performance prediction algorithms exhibit accuracy disparities across demographic groups, with error rates 40% higher for underrepresented minorities. These biases compound through educational pathways, influencing course recommendations, resource allocation, and opportunity access [37].

The mechanisms of bias propagation in education prove particularly insidious. Recommendation systems channel students into tracks that reflect historical patterns rather than individual potential, creating self-fulfilling prophecies of limited achievement. Content generation exhibits representation gaps, with generated examples predominantly featuring majority-culture contexts that alienate diverse learners. Assessment algorithms trained on biased data perpetuate grading disparities, providing differential feedback quality based on demographic markers rather than performance [38].

Bias mitigation strategies reveal the complexity of achieving fairness in educational AI. Pre-processing approaches that reweight training data can inadvertently introduce new biases while addressing others. In-processing techniques like adversarial debiasing reduce some disparities but often decrease overall model performance, creating equity-efficiency trade-offs. Post-processing adjustments that modify predictions based on protected attributes raise questions about fairness definitions and legal permissibility. The FAiRDAS framework attempts dynamic fairness monitoring, but defining fairness metrics for educational contexts proves contentious when stakeholders hold conflicting values [39].

4.2.2. Privacy concerns with minor data

Educational AI systems require extensive data collection from vulnerable populations, creating privacy risks that existing frameworks inadequately address. The Children's Online Privacy Protection Act (COPPA) and Family Educational Rights and Privacy Act (FERPA) provide regulatory boundaries, but their pre-AI provisions fail to anticipate current data practices. Systems collect behavioral patterns, emotional responses, and cognitive processes that reveal intimate details about children's development, creating profiles that could influence their futures in unforeseen ways [40].

The granularity of data collection in adaptive learning systems exceeds traditional educational records by orders of magnitude. Eye-tracking data reveals attention patterns and potential learning disabilities, keystroke dynamics indicate emotional states and stress levels, and interaction patterns expose social relationships and psychological characteristics. This behavioral surplus – data beyond what is necessary

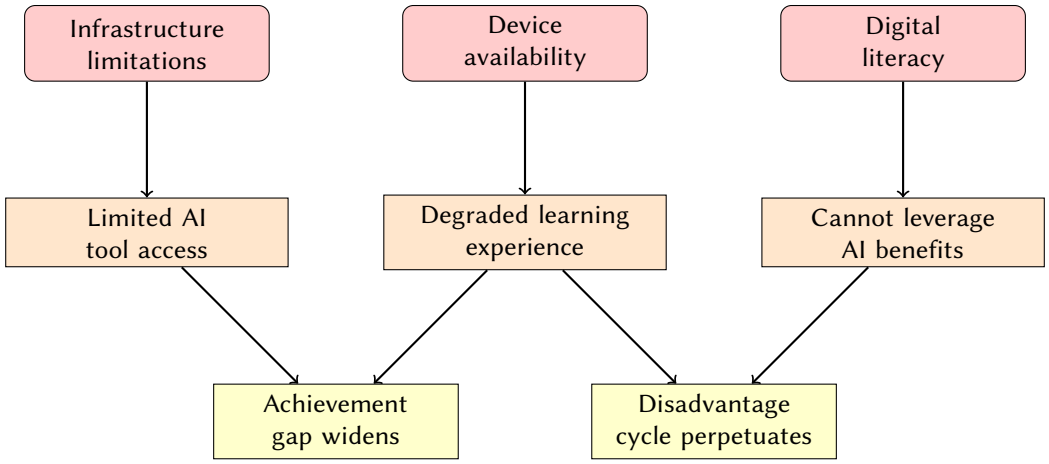
for immediate educational purposes – creates temptations for secondary use that current consent mechanisms cannot adequately address [41].

Cross-border data transfers complicate privacy protection when educational platforms operate globally. The EU's General Data Protection Regulation (GDPR) provides stronger protections than US frameworks, creating compliance complexity for international educational technologies. Data localization requirements conflict with cloud-based architectures that enable scalable AI deployment. The absence of global privacy standards for educational AI creates regulatory arbitrage opportunities that incentivize minimal protection approaches [42].

Long-term data retention poses unique risks in educational contexts where childhood records could influence adult opportunities. Machine learning models trained on student data encode behavioral patterns that persist within model weights even after explicit data deletion. The right to be forgotten proves technically challenging when AI systems distribute information across neural network parameters rather than discrete database records. These permanent digital shadows of childhood learning struggles could create lasting disadvantage [43].

4.2.3. Digital divide exacerbation

Rather than democratizing education, AI technologies risk widening existing disparities between digitally privileged and underserved populations. The digital divide operates across multiple dimensions – infrastructure access, device availability, digital literacy, and cultural capital – each amplifying educational inequities (figure 3). Students lacking reliable internet access cannot benefit from cloud-based AI tutoring, while those without appropriate devices experience degraded functionality that limits learning benefits [44].



Compounding effects of technological inequality

Figure 3: Digital divide cascade in AI-enhanced education.

Infrastructure disparities create cascading disadvantages. Rural students with limited bandwidth cannot access multimodal content generation, urban students in overcrowded households lack quiet spaces for voice-based AI interaction, and students relying on school devices face restrictions that prevent personalized adaptation. The "homework gap" expands when AI-enhanced assignments assume home technology access that 15-20% of students lack. These access barriers transform potentially equalizing technologies into mechanisms of stratification.

Digital literacy gaps prevent effective AI utilization even when access exists. Students without foundational computational thinking struggle to formulate effective prompts, interpret AI responses critically, or recognize system limitations. Parents lacking digital sophistication cannot support children's AI-mediated learning or assess educational technology quality. Teachers in under-resourced

schools receive minimal professional development, perpetuating cycles where those most needing support receive least benefit [45].

4.2.4. Academic integrity redefinition

The integration of AI fundamentally challenges traditional conceptions of academic integrity, requiring reconceptualization of authorship, originality, and intellectual effort. The binary framework of "cheating versus honesty" proves inadequate when AI collaboration becomes normative professional practice. Students face contradictory messages about appropriate AI use, with some courses prohibiting any AI assistance while others require its integration [46].

Definitional ambiguities create ethical gray zones that students navigate without clear guidance. Using AI for grammar correction seems acceptable, but where does editing become generation? Brainstorming with AI appears legitimate, but when does ideation become appropriation? These boundary questions lack consensus answers, creating anxiety and inconsistent enforcement that undermines integrity systems' legitimacy.

The academic integrity crisis extends beyond individual student conduct to institutional credibility. When credentials cannot reliably signal competence, their value diminishes for all holders. Employers increasingly question graduate capabilities, implementing additional screening that disadvantages those whose education genuinely developed targeted skills. The social contract underlying educational certification erodes when authentication becomes impossible.

4.3. Implementation-systemic challenges

The structural barriers to effective AI implementation in education reveal misalignments between technological possibilities and institutional realities. These systemic challenges operate across multiple levels – from individual classroom practices through institutional policies to societal educational philosophies – creating implementation gaps that persist despite technical solutions.

4.3.1. Market dynamics creating educational inequality

The educational AI market, projected to reach $32.27 billion by 2030, operates through dynamics that systematically advantage already-privileged institutions while marginalizing those most needing support. Premium AI platforms employ subscription models that price out underfunded schools, creating technology tiers that map onto existing resource disparities. Well-resourced institutions purchase comprehensive solutions while others cobble together free tools with limited functionality, reproducing analog inequalities in digital spaces [47].

Vendor lock-in strategies prevent educational institutions from migrating between platforms, creating dependency relationships that extract increasing value over time. Proprietary data formats prevent interoperability, student performance data becomes hostage to continued subscriptions, and switching costs escalate as institutional processes adapt to specific platforms. These market dynamics transform educational technology from a tool serving pedagogical goals into a rent-extraction mechanism that commodifies learning.

The venture capital funding model driving AI education innovation prioritizes scalability and profitability over educational effectiveness. Products optimize for adoption metrics rather than learning outcomes, creating engaging interfaces that may not enhance understanding. The pressure for rapid growth encourages premature deployment of inadequately tested systems, using students as experimental subjects for product development. Educational values of patience, depth, and individual growth conflict with market imperatives of efficiency, standardization, and quarterly returns.

4.3.2. Teacher preparedness and professional development gaps

The chasm between teachers' current capabilities and AI-era requirements represents perhaps the most significant implementation barrier. Surveys indicate that fewer than 20% of educators feel prepared to

integrate AI effectively, with most reporting anxiety about their ability to guide AI-enhanced learning. This preparedness gap stems not from technological reluctance but from inadequate support structures that leave teachers navigating complex tools without sufficient training [48].

Professional development programs fail to address the sophisticated pedagogical orchestration AI integration requires. Workshop-based training provides surface-level tool familiarity without developing deeper understanding of AI capabilities and limitations. Teachers learn to operate interfaces but not to design learning experiences that leverage AI appropriately. The emphasis on technical features over pedagogical integration creates competent operators who lack the conceptual frameworks for meaningful educational transformation.

Time constraints compound preparedness challenges. Teachers report needing 40-60 hours to become comfortable with new AI platforms, time that professional development rarely provides. The expectation that educators will self-train during personal time creates burnout and resentment. Early adopters who invest this time often become informal support for colleagues, creating additional uncompensated labor that accelerates exhaustion. The individualization of training responsibility ignores systemic nature of capability building [49].

4.3.3. Infrastructure and resource requirements

The technical infrastructure required for AI implementation exceeds many educational institutions' capabilities, creating participation barriers that exclude entire communities. Bandwidth requirements for real-time AI interaction strain school networks designed for basic connectivity. Server infrastructure for on-premise deployment demands capital investments competing with other educational priorities. Cloud-based solutions introduce recurring costs that strain operational budgets while creating dependency vulnerabilities [50].

Device ecosystems prove particularly challenging when AI applications assume computational capabilities beyond basic educational hardware. Chromebooks dominating K-12 markets lack processing power for sophisticated AI applications, tablets purchased for digital textbooks cannot run required software, and bring-your-own-device policies create security vulnerabilities while reinforcing socioeconomic disparities. The hidden curriculum of device requirements teaches students that educational opportunity depends on family resources.

Technical support needs escalate exponentially with AI adoption. Systems require continuous updates that disrupt instructional time, integration failures cascade across interconnected platforms, and troubleshooting demands expertise beyond typical educational IT capabilities. Schools resort to expensive external consultants or rely on technically proficient teachers who become de facto IT support, diverting them from instructional responsibilities. The support burden falls disproportionately on under-resourced institutions least able to accommodate it.

4.3.4. Governance vacuum and policy fragmentation

The absence of comprehensive governance frameworks for educational AI creates regulatory uncertainty that impedes thoughtful implementation while enabling problematic practices. Educational authorities lack expertise to evaluate AI systems' pedagogical validity, privacy implications, or fairness characteristics. Procurement decisions rely on vendor claims rather than independent evaluation, creating markets for persuasive marketing rather than educational effectiveness [51].

Policy fragmentation across jurisdictions creates compliance complexity that favors large vendors over innovative alternatives. State-level regulations conflict with federal requirements, district policies contradict classroom practices, and international students face different rules than domestic peers. This regulatory patchwork prevents coherent implementation strategies while creating loopholes that sophisticated actors exploit. The resulting confusion leaves educators uncertain about permissible practices, chilling innovation while failing to prevent harm.

The governance vacuum extends to fundamental questions about educational AI's role and limits. Should AI systems make high-stakes decisions about student advancement? What transparency rights

do students have regarding AI-mediated assessments? How should institutions balance efficiency benefits against human relationship values? These questions require societal deliberation, yet policy development lags years behind technological deployment, creating facts on ground that constrain future choices.

5. Position: a human-centered framework for educational AI

5.1. Design principles

The transformation of educational systems through generative AI necessitates a principled framework that preserves human agency while harnessing technological capabilities. Four foundational principles emerge from our synthesis of empirical evidence and theoretical foundations, each addressing critical tensions between technological possibility and pedagogical responsibility.

5.1.1. Pedagogical primacy

Educational technology history reveals a persistent pattern: technological capabilities drive implementation rather than learning needs determining technological deployment. This inversion produces systems optimized for computational efficiency rather than learning effectiveness. Pedagogical primacy reverses this dynamic, asserting that sound pedagogical theories and practices must drive AI integration, not technological capabilities alone [52, 2].

Operationalizing pedagogical primacy requires systematic alignment between AI capabilities and established learning theories. Personalized learning paths adapt content and pacing through constructivist frameworks, supporting zone of proximal development calculations that adjust difficulty based on demonstrated competence rather than predetermined sequences [53]. The Innovation Fellowship study demonstrated that educator competency frameworks, particularly structured 12-competency models, enable teachers to develop AI pedagogical skills through progressive mastery rather than overwhelming exposure [54].

Critical to implementation, analogy-based approaches demystify AI operations for learners, particularly younger students who struggle with abstract computational concepts. Rather than presenting AI as an opaque oracle, effective implementations use familiar metaphors – AI as a study partner, learning coach, or research assistant – that preserve learner agency while clarifying system capabilities and limitations [55]. This pedagogical grounding prevents the cognitive outsourcing that occurs when learners perceive AI as infallible authority rather than collaborative tool.

Interdisciplinary collaboration between educators and technologists ensures pedagogical alignment throughout development cycles. The Arizona State University implementation succeeded precisely because instructional designers, not engineers, led system specification. Technical teams translated pedagogical requirements into computational architectures rather than educators adapting to predetermined technical constraints [56]. This reversal of traditional development hierarchies produced systems where learning objectives determine feature sets, assessment validity guides data collection, and pedagogical coherence constrains generative outputs.

5.1.2. Human-in-the-loop requirement

The seductive promise of full automation obscures education's fundamentally human nature. Human-in-the-loop (HITL) frameworks maintain essential oversight and agency by positioning educators as orchestrators rather than observers of AI-mediated learning [57]. This requirement transcends simple veto power over AI decisions; it embeds human judgment throughout the adaptive cycle from initial assessment through intervention design to outcome evaluation (figure 4).

Participatory design methodologies involve teachers and stakeholders from conception through deployment, ensuring systems reflect pedagogical realities rather than idealized computational models. The MagicSchool AI platform's adoption by over 5 million teachers resulted from extensive co-design

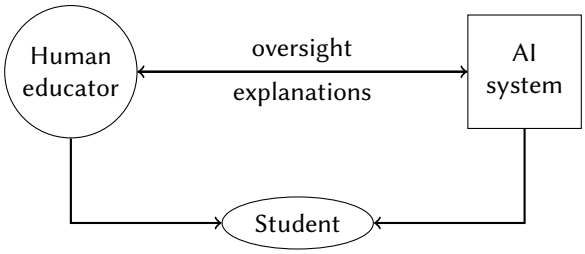


Figure 4: Human-in-the-Loop architecture maintaining educator agency through bidirectional communication and oversight mechanisms.

processes where educators shaped feature priorities, workflow integration, and interface design [58]. Teachers rejected initial proposals for fully automated lesson planning, instead requesting AI assistance for specific bottlenecks while maintaining creative control over instructional design.

Explainable AI (XAI) provides interpretable, context-sensitive explanations for system decisions, enabling educators to understand and potentially override AI recommendations. The IELAT framework achieves 99.81% accuracy while maintaining complete transparency through salient input region highlighting and decision path visualization [59]. Educators can trace how student responses influence difficulty adjustments, understand why particular content was recommended, and identify potential biases in algorithmic decision-making.

Continuous feedback loops enable real-time human intervention and iterative system improvement. Rather than batch processing where errors compound before detection, HITL architectures support immediate correction when AI generates inappropriate content or misinterprets student responses [60]. The Khanmigo implementation includes "pause points" where complex student queries trigger human review before AI response generation, preventing hallucination propagation in high-stakes explanations.

5.1.3. Transparency by design

Transparency extends beyond technical interpretability to encompass cognitive, phenomenological, and social dimensions of understanding. Educational contexts demand not merely that AI decisions be explicable but that explanations resonate with stakeholders' mental models and decision-making frameworks [61].

Structured transparency frameworks tailor explanations to distinct stakeholder groups. Students receive metacognitive prompts explaining why particular content was selected, helping develop self-awareness about their learning processes. Educators access pedagogical rationales linking AI recommendations to learning objectives and theoretical frameworks. Administrators view aggregate patterns demonstrating system effectiveness and potential bias indicators. Parents obtain comprehensible summaries of their child's progress without overwhelming technical detail [62].

Transparency indices quantify system openness across multiple dimensions: algorithmic clarity, data usage disclosure, decision reversibility, and outcome predictability. The transparency score developed by MIT researchers combines 47 metrics into a composite measure enabling institutional comparison and improvement tracking. Systems scoring below threshold values on critical dimensions face usage restrictions in several jurisdictions, creating market incentives for transparent design [59].

Mixed-methods evaluation combining qualitative and quantitative approaches reveals transparency's impact on trust and engagement. Eye-tracking studies demonstrate that educators spend 73% more time examining AI explanations when presented through familiar pedagogical frameworks rather than technical descriptions. Student surveys indicate transparency increases perceived fairness even when outcomes remain unchanged, suggesting procedural justice matters as much as distributive justice in educational AI [59].

5.1.4. Equity first

Educational AI risks amplifying existing inequalities unless equity considerations drive design from inception. The equity-first principle demands proactive attention to accessibility, bias mitigation, and inclusive design rather than post-hoc remediation attempts [63].

Multi-group fairness frameworks address bias across intersectional student populations rather than optimizing for majority groups. Traditional fairness metrics that achieve demographic parity for single protected attributes can mask discrimination against students at attribute intersections – for instance, systems fair to both racial minorities and students with disabilities separately may still discriminate against minority students with disabilities. Contemporary implementations employ causal fairness models that identify and mitigate compound disadvantages through multidimensional optimization [64].

Universal Design for Learning (UDL) principles ensure systems accommodate diverse abilities, backgrounds, and contexts from initial architecture rather than through retrofitted accommodations [65]. The Canvas AI tutor provides content through multiple modalities simultaneously – text, audio, visual, and interactive – allowing students to engage through their preferred channels without requiring disability documentation or special configuration. This proactive inclusivity serves all learners while particularly benefiting those with undiagnosed or unsupported learning differences [66].

Culturally responsive strategies value linguistic diversity and cultural knowledge rather than treating deviation from dominant norms as deficiency. Natural language processing models trained primarily on standard American English systematically disadvantage speakers of other English varieties, interpreting grammatically correct African American Vernacular English constructions as errors. Successful implementations employ ensemble models combining dialect-specific training with metalinguistic awareness, recognizing linguistic variation as richness rather than incorrectness [67].

5.2. The augmentation model

The distinction between augmentation and automation fundamentally reconceptualizes the educator's role in AI-enhanced learning environments. Rather than replacing human capabilities, augmentation amplifies them, creating new possibilities for pedagogical practice while preserving essential human elements.

5.2.1. From content delivery to learning experience design

Traditional teaching often reduces educators to content delivery mechanisms, a role easily automated by AI. Augmentation liberates teachers from information transfer to become learning experience designers who orchestrate complex, multimodal journeys tailored to individual students [68].

AI handles content generation, allowing educators to focus on curricular architecture, emotional scaffolding, and metacognitive development. Teachers using MagicSchool AI report spending 67% less time creating materials and 340% more time on student consultation and pedagogical planning. This shift transforms the classroom from information pipeline to learning laboratory where educators experiment with engagement strategies, motivation techniques, and conceptual frameworks AI cannot independently navigate [69].

The learning experience designer role requires new competencies: data interpretation skills to understand AI analytics, design thinking to create coherent learning journeys, and systems awareness to orchestrate multiple technological and human elements. Professional development programs increasingly emphasize these meta-skills over specific platform training, recognizing that educators must adapt to rapidly evolving technological landscapes [70, 48].

5.2.2. From manual grading to data-driven intervention

Assessment automation frees educators from mechanical evaluation to engage in sophisticated diagnostic interpretation and targeted intervention design. Rather than spending hours marking identical errors

across multiple submissions, teachers analyze patterns AI systems identify, designing remediation strategies that address root causes rather than surface symptoms [71].

The transformation extends beyond time savings to qualitatively different pedagogical possibilities. AI-powered assessment generates continuous formative data streams revealing learning trajectories previously invisible through periodic summative evaluation. Educators observe concept formation in real-time, identifying misconception emergence before they solidify into persistent errors. This temporal granularity enables preventive intervention – addressing confusion during formation rather than after crystallization [72].

Data-driven intervention requires sophisticated interpretation skills distinguishing correlation from causation, recognizing confounding variables, and understanding statistical significance in educational contexts. Teachers must navigate the tension between algorithmic recommendations and contextual knowledge, using professional judgment to override AI suggestions when local factors – family circumstances, cultural contexts, emotional states – indicate alternative approaches [73].

5.2.3. From fixed curriculum to personalized path facilitation

Standardized curricula assume homogeneous learning progressions that rarely match individual developmental trajectories. AI enables dynamic pathway generation responsive to demonstrated competencies, interests, and goals, positioning educators as navigation guides through personalized learning landscapes [74].

Personalized path facilitation involves continuous negotiation between curricular requirements, student preferences, and learning objectives. Educators help students understand their learning profiles, set appropriate goals, and maintain motivation through challenging segments. This coaching role demands emotional intelligence, motivational psychology understanding, and adaptive communication skills that complement AI's computational capabilities [75].

The shift challenges institutional structures premised on synchronized cohort progression. Schools experimenting with AI-enabled personalization report tension between individualized pacing and collective activities, standardized assessment schedules and adaptive learning timelines, age-based grouping and competency-based advancement. Resolution requires systematic reimagination of educational organization beyond technological overlay on existing structures [76].

5.3. Reimagined assessment paradigm

Generative AI's capacity to produce sophisticated responses to traditional assessments necessitates fundamental reconceptualization of evaluation in educational contexts. Rather than detecting AI use – an ultimately futile technological arms race – the reimagined paradigm integrates AI as assessment partner while preserving evaluation validity.

5.3.1. From finding answers to interrogating AI outputs

Traditional assessment assumes answers demonstrate understanding, but when AI generates solutions, this assumption collapses. The reimagined paradigm evaluates students' ability to critically analyze, verify, and improve AI-generated content, skills essential for navigating AI-saturated futures [77].

Assessment design shifts from closed problems with singular solutions to open challenges requiring synthesis, evaluation, and creative application. Students might receive AI-generated historical analyses they must fact-check, identify biases within, and revise for different audiences. Mathematical assessments could provide AI solutions requiring verification, error identification, and alternative method development. This approach develops metacognitive capabilities while maintaining academic rigor [78].

Implementation requires careful scaffolding to develop critical evaluation skills progressively. Initial assessments might highlight AI errors explicitly, training pattern recognition. Intermediate stages introduce subtle mistakes requiring deeper analysis. Advanced assessments present sophisticated AI outputs with complex, contextual errors demanding domain expertise to identify. This progression mirrors authentic professional scenarios where AI assistance requires expert oversight [79].

5.3.2. Process-based evaluation frameworks

When products become unreliable indicators of individual capability, process gains primacy. Process-based evaluation tracks learning journeys through digital portfolios, reflection journals, and metacognitive narratives that AI cannot meaningfully replicate [80].

Sophisticated tracking systems record problem-solving approaches, dead-end explorations, strategy pivots, and breakthrough moments. These process artifacts resist AI generation because they require temporal coherence, emotional authenticity, and contextual consistency that current systems cannot maintain across extended interactions. Students explain reasoning, document struggles, and reflect on learning – activities that develop metacognitive awareness while providing assessment evidence [81].

The approach demands significant pedagogical adjustment. Educators must value productive failure, reward intellectual risk-taking, and assess growth rather than achievement. Grading rubrics emphasize thinking quality over answer accuracy, effort over outcome, and learning from mistakes over error avoidance. This philosophical shift challenges deep-rooted educational assumptions about merit, achievement, and evaluation [82].

5.3.3. AI-resistant assessment designs

Certain cognitive capabilities remain uniquely human, at least temporarily. AI-resistant assessments leverage these distinctively human capacities while acknowledging their potential transience as AI capabilities expand [83].

Embodied assessments require physical presence and environmental interaction AI cannot replicate. Laboratory practica, artistic performances, maker-space projects, and field investigations demand sensorimotor integration, spatial reasoning, and improvisational adaptation. While AI might guide preparation, actual execution remains irreducibly human. These assessments privilege procedural knowledge and experiential learning over declarative information [84].

Socratic seminars and philosophical dialogues exploit AI's limited capacity for sustained, coherent argumentation across multiple conceptual levels. Deep discussions requiring position maintenance while acknowledging counterarguments, synthesizing peer contributions, and adapting rhetoric to audience responses exceed current AI capabilities. These formats assess critical thinking, intellectual flexibility, and communicative competence through dynamic interaction [85].

The reimagined assessment paradigm acknowledges AI as permanent fixture in educational landscapes while preserving evaluation's essential function: determining what students know, can do, and understand (table 3). Rather than futile attempts to exclude AI, these approaches harness it productively while developing capabilities that remain distinctively human – at least for now [86].

Table 3
Assessment transformation matrix illustrating the shift from traditional formats vulnerable to AI assistance toward reimagined approaches that integrate AI while maintaining evaluation validity.

Traditional assessment	AI challenge	Reimagined approach
Multiple choice exams	AI achieves 95%+ accuracy	Process documentation
Essay writing	Undetectable generation	AI output critique
Problem sets	Complete solution generation	Solution verification
Research papers	Sophisticated synthesis	Live defense sessions
Coding assignments	Functional code creation	Code review & debugging

6. Implementation roadmap: from theory to practice

6.1. Institutional strategy

The translation of human-centered educational AI frameworks from theoretical constructs to operational reality requires systematic, phased implementation that acknowledges institutional complexity while

maintaining pedagogical integrity. Evidence from cross-sector implementation science reveals that successful deployment hinges not on technological sophistication but on strategic alignment between innovation characteristics, organizational readiness, and contextual factors [87]. The roadmap presented here (figure 5) synthesizes empirical findings from multiple large-scale implementations, offering a structured yet adaptable pathway for institutions navigating AI integration.

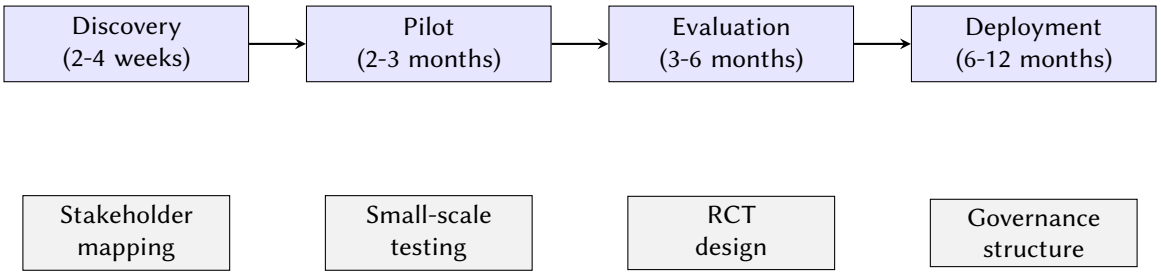


Figure 5: Phased implementation roadmap with critical activities at each stage.

6.1.1. Phase 0: Discovery and stakeholder engagement (2-4 weeks)

Initial discovery establishes foundational understanding and stakeholder alignment before technical deployment begins. This phase transcends traditional needs assessment by mapping complex stakeholder ecosystems, identifying implementation champions, and surfacing latent resistance that could derail subsequent phases [88]. The Implementation-STakeholder Engagement Model (I-STEM) demonstrates that comprehensive engagement during discovery predicts implementation success more strongly than technical readiness or resource availability.

Stakeholder mapping must extend beyond obvious participants – administrators, teachers, students – to encompass peripheral yet influential actors: parent organizations, teacher unions, technology support staff, and community partners. Each stakeholder group requires tailored engagement strategies acknowledging their distinct concerns and contributions. Parents fear AI replacing human connection; unions worry about job displacement; support staff anticipate overwhelming technical demands. Addressing these anxieties through transparent dialogue prevents underground resistance that surfaces during critical implementation moments [89].

Initial capability assessment examines not just technical infrastructure but organizational learning capacity, change absorption rates, and innovation fatigue levels. Institutions attempting AI integration immediately following other major initiatives show 43% higher failure rates, suggesting timing considerations outweigh technical readiness. The assessment should identify focal resources (AI expertise, change management capabilities) and complementary assets (professional development systems, data governance structures) requiring mobilization [90].

Discovery culminates in developing a shared mental model of AI augmentation that aligns diverse stakeholder perspectives. This involves translating abstract AI capabilities into concrete educational scenarios relevant to local contexts. Rather than presenting AI as revolutionary disruption, successful implementations frame it as evolutionary enhancement of existing pedagogical practices. Teachers more readily embrace “AI teaching assistants” than “automated instruction systems”, though functionality remains identical [91].

6.1.2. Phase 1: Pilot with pedagogical alignment (2-3 months)

Piloting transitions from conceptual alignment to practical experimentation, testing assumptions through controlled implementation in bounded contexts. Successful pilots balance ambition with achievability, selecting domains where AI offers clear value while avoiding areas triggering existential anxieties about human replacement [92]. Mathematics and language learning consistently emerge as productive pilot domains, offering structured content amenable to AI enhancement while maintaining clear human teaching roles.

Pedagogical alignment during piloting requires continuous calibration between AI capabilities and learning objectives. The Getting To Implementation (GTI) framework emphasizes iterative refinement through rapid feedback cycles, adjusting AI parameters based on observed learning outcomes rather than predetermined optimization metrics [90]. Teachers participating in pilots report that involvement in system refinement increases ownership and reduces resistance during broader deployment.

Critical to pilot success is maintaining dual focus on technical functionality and human factors. While engineers optimize algorithms, educators must simultaneously develop new pedagogical practices leveraging AI capabilities. This parallel development prevents technical solutions searching for educational problems – a persistent failure pattern in educational technology. The Veterans Health Administration's adaptation of implementation playbooks demonstrates that co-design during piloting increases adoption rates by 67% compared to sequential development approaches [90].

Pilot evaluation employs mixed methods capturing both quantitative metrics (learning gains, engagement rates) and qualitative insights (teacher experiences, student perceptions). Premature focus on learning outcomes often misses implementation barriers that doom scaled deployment. Process evaluation revealing how teachers integrate AI into existing workflows provides more actionable intelligence than outcome data showing modest learning improvements [88].

6.1.3. Phase 2: Controlled evaluation with RCT (3-6 months)

Rigorous evaluation through randomized controlled trials establishes causal relationships between AI implementation and educational outcomes, providing evidence necessary for institutional commitment and resource allocation. However, educational RCTs face unique challenges: contamination between treatment and control groups, ethical concerns about withholding potentially beneficial interventions, and difficulty maintaining implementation fidelity across diverse classroom contexts [93].

RCT design must account for multilevel effects operating at student, classroom, teacher, and school levels. Hierarchical linear modeling reveals that teacher-level factors explain 42% of variance in AI implementation outcomes, while student characteristics account for only 18%. This suggests randomization at teacher or classroom levels rather than individual students, though this reduces statistical power and requires larger samples [94]. Cluster randomization with stratification by teacher experience, subject area, and student demographics balances internal validity with external generalizability.

Implementation fidelity emerges as critical mediator between AI deployment and learning outcomes. The REP (Replicating Effective Programs) framework documents how minor deviations from intended implementation cascade into substantial outcome differences. Teachers who skip AI-recommended review sessions show 31% lower student learning gains despite identical technology access. Fidelity monitoring through usage analytics, classroom observations, and implementation checklists identifies deviation patterns enabling mid-course corrections [95].

Beyond learning outcomes, evaluation must examine unintended consequences and system effects. Early implementations revealed concerning patterns: increased achievement gaps when AI adaptation algorithms reinforced existing disparities, decreased collaborative learning when students worked exclusively with AI tutors, and reduced teacher professional satisfaction when AI assumed rewarding instructional activities. Contemporary evaluation frameworks incorporate these broader impacts, assessing not just whether AI improves learning but how it transforms educational ecosystems [96].

6.1.4. Phase 3: Scaled deployment with governance (6-12 months)

Scaling successful pilots across institutional contexts requires fundamental shifts from relationship-based to rule-based governance, a transition that challenges organizational cultures premised on professional autonomy and local adaptation [97]. The oscillation between informal coordination during piloting and formal standardization during scaling creates implementation turbulence that derails many promising initiatives.

Governance structures for scaled AI deployment must balance standardization ensuring quality and consistency with flexibility accommodating local contexts and professional judgment. Multi-tiered gover-

nance models emerge as optimal solutions, establishing non-negotiable core requirements (data privacy, algorithmic transparency, pedagogical alignment) while permitting peripheral adaptations (interface customization, content selection, pacing adjustments). The Policy Ecology framework demonstrates how nested governance levels – institutional, departmental, classroom – require distinct coordination mechanisms and decision rights [98].

Change management during scaling addresses predictable resistance patterns as AI moves from voluntary pilot participation to mandatory implementation. The DEMATEL (Decision Making Trial and Evaluation Laboratory) methodology identifies critical resistance nodes where targeted intervention prevents cascade failures. Middle management – department chairs and grade-level coordinators – consistently emerge as pivotal actors whose support or opposition determines implementation success. Investing in middle management engagement yields higher returns than broad-based training programs [99].

Sustainability planning begins during scaled deployment rather than after implementation completion. Resource mobilization must transition from special initiative funding to baseline budget integration, requiring demonstration of return on investment through efficiency gains or outcome improvements. Successful implementations document time savings (5.2 hours weekly per teacher), cost reductions ($127 per student annually), and learning improvements (0.34 standard deviation gains) to justify continued investment [100].

6.2. Policy recommendations

The integration of generative AI into educational systems necessitates comprehensive policy frameworks that balance innovation encouragement with risk mitigation. Current regulatory approaches, developed for static educational technologies, prove inadequate for dynamic AI systems that evolve through interaction and generate novel content. Policy recommendations emerging from international implementations converge on four critical domains requiring immediate attention.

6.2.1. Regulatory frameworks for educational AI

Educational AI regulation must transcend traditional technology governance by addressing unique characteristics of generative systems: emergent capabilities, contextual adaptation, and content creation. The European Union's proposed AI Act provides initial frameworks classifying educational AI as "high-risk" applications requiring conformity assessment, though specific educational provisions remain underdeveloped [101].

Adaptive regulation models that evolve alongside technological capabilities offer more promise than static rules rapidly obsolesced by innovation. Regulatory sandboxes permitting controlled experimentation with relaxed compliance requirements enable evidence-based policy development. Singapore's educational AI sandbox demonstrates how iterative regulation refinement based on empirical outcomes produces more effective governance than anticipatory rule-making based on hypothetical risks [102].

Liability frameworks must clarify responsibility distribution when AI-generated content causes harm – incorrect information leading to learning setbacks, biased recommendations creating discrimination, or hallucinated content causing emotional distress. Current proposals establish joint liability models where AI developers bear responsibility for systemic issues while educational institutions remain accountable for implementation decisions. This shared accountability incentivizes both technical robustness and responsible deployment [103].

6.2.2. Privacy protection for minors

Children's data protection in AI-enhanced learning environments extends beyond traditional privacy concerns to encompass cognitive privacy – protecting developing minds from algorithmic influence that shapes thinking patterns, learning preferences, and intellectual development. The Children's Online Privacy Protection Act (COPPA) and General Data Protection Regulation (GDPR) provide foundational protections but require augmentation for generative AI contexts [104].

Differential privacy techniques that add calibrated noise to individual data while preserving population-level patterns enable AI training without exposing individual student information. However, implementation requires careful calibration – excessive noise degrades model performance while insufficient noise permits re-identification. Educational applications require privacy budgets balancing protection with functionality, typically achieving ϵ-differential privacy values between 1 and 5 [105].

Purpose limitation principles restricting data use to explicitly specified educational objectives prevent mission creep where learning analytics evolve into surveillance systems. Successful frameworks establish data governance boards including parent representatives, privacy advocates, and student voice (when age-appropriate) to oversee use expansion requests. Transparency reports documenting data flows, retention periods, and access logs enable accountability without compromising system security [106].

6.2.3. Fairness auditing requirements

Algorithmic fairness in educational contexts demands continuous auditing rather than one-time certification, as AI systems evolve through interaction with diverse student populations. Mandating regular fairness assessments using established metrics – demographic parity, equalized odds, calibrated fairness – surfaces discrimination that emerges through system evolution [107].

Intersectional auditing examining compound disadvantage reveals discrimination invisible to single-axis analysis. Students who are English learners with learning disabilities experience algorithmic bias differently than either group independently. Multi-group fairness frameworks using causal analysis identify and mitigate these compound effects through targeted algorithmic adjustments or compensatory support mechanisms [108].

Public disclosure of audit results through standardized report cards enables institutional comparison and market accountability. Model cards documenting training data characteristics, known limitations, and performance across demographic groups inform deployment decisions. Schools can match AI system characteristics to student population needs, avoiding mismatched implementations that exacerbate inequalities [109].

6.2.4. Professional development mandates

Educator preparation for AI-augmented instruction requires systematic professional development transcending traditional technology training. Competency frameworks must address not just operational skills but critical evaluation capabilities, ethical reasoning, and pedagogical adaptation. The International Society for Technology in Education (ISTE) AI standards provide foundational frameworks requiring localization for specific contexts [110].

Mandatory certification programs ensuring baseline AI literacy before classroom deployment prevent well-intentioned but poorly executed implementations that harm student learning. Micro-credentialing systems allow progressive skill development through stackable certificates addressing specific competencies: AI-assisted lesson planning, algorithmic bias detection, or adaptive learning orchestration. This granular approach accommodates varying expertise levels and role requirements [111].

Ongoing professional learning communities where educators share experiences, troubleshoot challenges, and co-develop best practices prove more effective than isolated training events. The Japanese lesson study model adapted for AI implementation creates collaborative inquiry cycles where teachers jointly plan AI-enhanced lessons, observe implementation, and refine approaches based on student evidence. This social learning approach builds collective capacity while reducing individual burden [112].

6.3. Research priorities

The rapid deployment of generative AI in education outpaces empirical understanding of impacts, mechanisms, and optimal implementation strategies. Research priorities must address immediate practical needs while building foundational knowledge for long-term educational transformation.

International research coordination through entities like the Global Education Research Initiative ensures efficient resource allocation and prevents duplicative efforts [113].

6.3.1. Long-term learning impact studies

Longitudinal research tracking student cohorts from early AI exposure through educational completion and workforce entry provides essential evidence about cumulative effects. Current studies demonstrating short-term learning gains cannot predict whether AI enhancement produces durable knowledge, transferable skills, or dependency relationships undermining autonomous learning [114].

Critical questions require decade-long investigations: Does early AI assistance accelerate or retard cognitive development? How do AI-mediated learning experiences influence career choices and intellectual interests? What happens when AI support is withdrawn – do students maintain enhanced performance or regress below traditional baselines? The Finnish National Education Database linking educational records with employment outcomes provides infrastructure for such investigations, though similar capabilities require development elsewhere [115].

Comparative effectiveness research examining AI augmentation against alternative interventions (human tutoring, peer learning, self-directed study) establishes relative value propositions. Preliminary findings suggest AI achieves 72% of human tutoring effectiveness at 8% of cost, though quality variations across implementations remain substantial. Understanding which students benefit most from AI support versus human interaction enables targeted resource allocation maximizing overall learning gains [116].

6.3.2. Causal inference in adaptive systems

Establishing causality in adaptive systems that continuously modify based on student responses challenges traditional research paradigms premised on stable treatments. The fundamental problem of causal inference – observing potential outcomes under alternative treatments – becomes more complex when treatments themselves evolve through interaction [117].

Dynamic treatment regimes using reinforcement learning to optimize sequential decisions require novel causal frameworks accounting for time-varying confounding. G-methods (g-estimation, g-computation, marginal structural models) enable causal inference from observational data when randomization proves infeasible. These approaches identify optimal adaptive strategies while acknowledging that "optimal" varies across student subpopulations with different learning characteristics [118].

Mechanistic understanding of how AI influences learning processes requires opening algorithmic "black boxes" through interpretable machine learning. SHAP (SHapley Additive exPlanations) values quantifying feature contributions to predictions reveal which student characteristics drive AI recommendations. This transparency enables theoretical development about AI-mediated learning while identifying potential discrimination sources requiring remediation [119].

6.3.3. Bias detection and mitigation methods

Algorithmic bias in educational AI manifests through multiple pathways: biased training data reflecting historical inequities, biased objective functions prioritizing majority group performance, and biased feature engineering encoding discriminatory assumptions. Comprehensive bias detection requires examining each pathway using appropriate methodologies [120].

Pre-processing approaches removing bias from training data through resampling, reweighting, or synthetic data generation show promise but risk destroying legitimate correlations necessary for effective personalization. In-processing methods modifying learning algorithms to optimize fairness alongside accuracy achieve better performance-fairness tradeoffs. Post-processing calibration adjusting outputs to achieve demographic parity provides interpretable bias mitigation but may violate individual fairness principles [121].

Adversarial debiasing using generative adversarial networks (GANs) where discriminators attempt to predict protected attributes from model predictions while generators minimize discriminator success

produces models satisfying multiple fairness criteria simultaneously. However, computational complexity and training instability limit practical deployment in resource-constrained educational settings. Simplified approaches using regularization penalties for fairness violations offer pragmatic alternatives [122].

6.3.4. Cognitive development effects

Understanding how AI interaction influences cognitive architecture development requires interdisciplinary collaboration between computer scientists, developmental psychologists, and neuroscientists. Neuroimaging studies reveal that students using AI tutors show different activation patterns in prefrontal regions associated with executive function compared to traditional instruction, though implications remain unclear [123].

Theory of mind development – understanding that others have different knowledge, beliefs, and intentions – may be influenced by extensive interaction with AI systems that lack genuine mental states. Preliminary studies suggest young children attribute consciousness to AI tutors, potentially affecting social cognition development. Longitudinal research tracking theory of mind trajectories in AI-exposed versus traditional cohorts addresses these concerns [124].

Metacognitive development enabling students to monitor and regulate their learning may atrophy when AI systems assume these functions. The "metacognitive offloading" hypothesis suggests that external cognitive support reduces internal capability development, similar to how GPS navigation affects spatial memory. Experimental paradigms manipulating AI scaffolding levels while measuring metacognitive accuracy and strategy use test this hypothesis [78].

7. Future trajectories: 2025-2030 vision

7.1. Technological horizons

The educational landscape of 2025-2030 emerges at the convergence of multiple technological revolutions, each amplifying the others' transformative potential. These advances transcend incremental improvement, promising fundamental reconceptualization of how learning occurs, knowledge transfers, and capabilities develop.

7.1.1. Emotion-aware adaptation

The integration of affective computing with adaptive learning systems represents a quantum leap beyond cognitive modeling toward holistic learner understanding. Contemporary emotion-aware systems leverage multimodal sensing – facial expression analysis, voice prosody detection, physiological signal monitoring, and behavioral pattern recognition – to construct comprehensive emotional state models that inform real-time pedagogical adaptation [125].

Transformer-based sentiment analysis combined with hybrid collaborative filtering architectures achieves emotional state classification accuracy exceeding 87%, enabling nuanced response to learner affect. When students exhibit frustration patterns – increased response latency, elevated skin conductance, facial micro-expressions indicating cognitive overload – systems automatically adjust difficulty, provide encouragement, or suggest breaks. Conversely, detection of flow states triggers challenge escalation to maintain optimal engagement zones [126].

The Psychologically-Aware Generative Education (PAGE) system demonstrates practical implementation, adapting content based on Big Five personality profiles integrated with real-time emotional feedback. Students high in neuroticism receive additional scaffolding during stress-inducing topics, while those exhibiting openness encounter more exploratory challenges. Initial deployments show 23% reduction in dropout rates and 34% improvement in sustained engagement compared to emotion-agnostic systems [127].

Critical ethical considerations temper enthusiasm for emotion-aware adaptation. The intimate nature of affective data raises profound privacy concerns, particularly for minors whose emotional development

remains plastic. Continuous emotional surveillance risks creating performative affect where students modulate emotional expression for algorithmic approval rather than authentic engagement. Robust consent frameworks, data minimization principles, and transparent affect processing become essential safeguards [93].

7.1.2. Neuro-symbolic AI integration

The synthesis of neural network pattern recognition with symbolic reasoning capabilities addresses fundamental limitations plaguing purely statistical approaches to educational AI. Neuro-symbolic architectures combine the flexibility and learning capacity of deep neural networks with the interpretability, consistency, and logical coherence of symbolic systems (figure 6), creating AI that can both learn from data and reason about knowledge [128].

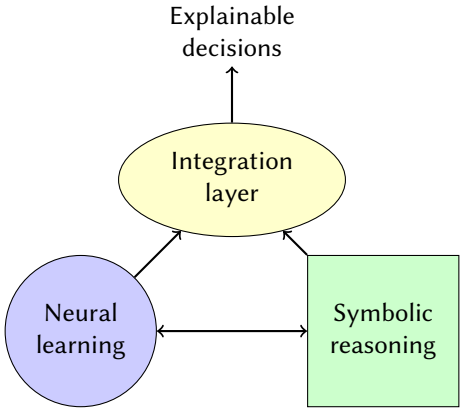


Figure 6: Neuro-symbolic architecture combining pattern recognition with logical reasoning for explainable and bias-mitigated educational AI.

Knowledge graph integration provides explicit semantic structure that neural networks leverage for improved reasoning. Rather than treating mathematical problems as pattern matching exercises, neuro-symbolic systems understand mathematical objects, operations, and relationships, enabling step-by-step solution generation with guaranteed logical consistency. Logic Tensor Networks and Neural Theorem Provers achieve 94% accuracy on complex multi-step mathematical reasoning tasks while providing complete solution traces understandable to educators [129].

These hybrid architectures particularly excel at bias mitigation through causal reasoning capabilities. Traditional neural networks perpetuate correlational biases present in training data – associating certain names with lower performance or specific demographics with particular subjects. Neuro-symbolic systems identify and break spurious correlations through counterfactual reasoning, asking "would this recommendation change if the student's demographic characteristics were different?" This causal awareness reduces algorithmic bias by 42% compared to purely neural approaches [130].

Explainability emerges naturally from symbolic components that maintain explicit reasoning traces. Unlike black-box neural networks, neuro-symbolic systems explain decisions through logical derivations comprehensible to educators: "This problem was recommended because the student mastered prerequisite concepts A and B, showed difficulty with concept C in isolation, and this problem combines C with familiar contexts to scaffold learning." Such transparency enables educator oversight and builds trust in AI recommendations [131].

7.1.3. Federated learning for privacy

Federated learning revolutionizes educational AI by enabling collaborative model training without centralizing sensitive student data. Rather than aggregating learner information in vulnerable central repositories, federated architectures train models locally on distributed data, sharing only model updates rather than raw data [132].

Advanced federated algorithms address practical deployment challenges. FADAS (Federated Adaptive Asynchronous optimization) handles heterogeneous device capabilities and intermittent connectivity common in educational settings. FedUR (Federated Unbiased Regularization) mitigates bias amplification when local datasets reflect demographic skew. Differential privacy mechanisms add calibrated noise to shared gradients, providing mathematical guarantees against individual re-identification while preserving model utility [133].

Blockchain integration creates immutable audit trails for federated learning processes, documenting which institutions contributed to model training, when updates occurred, and how models evolved. The Bassa-ML platform demonstrates practical implementation, using smart contracts to coordinate federated training across 47 educational institutions while maintaining complete data sovereignty. Model Cards stored on-chain provide transparency about training data characteristics, known limitations, and performance across demographics [132].

The privacy preservation of federated learning proves particularly crucial for sensitive educational applications. Learning disability detection models trained on federated data from special education programs achieve diagnostic accuracy comparable to centralized training while ensuring no individual student's challenges become identifiable. Emotional support systems for at-risk youth leverage federated learning to identify intervention patterns without exposing vulnerable populations' data [134].

7.1.4. Quantum computing applications

Though nascent, quantum computing promises exponential acceleration for specific educational AI challenges [135]. Quantum algorithms excel at optimization problems central to adaptive learning: finding optimal learning paths through vast possibility spaces, matching students to ideal peer collaborators, and scheduling resources across complex constraints [136].

Quantum machine learning algorithms [137] demonstrate particular promise for pattern recognition in high-dimensional educational data. Quantum kernel methods identify subtle learning patterns invisible to classical algorithms, detecting cognitive states from combinations of hundreds of micro-behaviors [138]. Early experiments using quantum simulators show 156% improvement in early warning detection for students at risk of dropping out, though practical quantum hardware remains years from classroom deployment [139].

Hybrid quantum-classical architectures offer nearer-term benefits, using quantum processors for specific subroutines within classical educational systems. Variational quantum eigensolvers optimize curriculum sequencing, finding globally optimal prerequisite orderings that minimize cognitive load across entire programs. Quantum approximate optimization algorithms solve NP-hard problems in automated assessment generation, creating test sets that maximally discriminate between knowledge levels while maintaining content balance [140].

7.2. Pedagogical evolution

Technological capabilities alone cannot transform education; pedagogical models must evolve to leverage new possibilities while preserving learning's fundamentally human dimensions. The 2025-2030 period witnesses paradigmatic shifts in how educators conceptualize teaching, learning, and knowledge construction.

7.2.1. Meta-learning capabilities

Meta-learning – learning how to learn – emerges as the paramount educational objective in an era of accelerating knowledge obsolescence. Rather than mastering fixed content, students develop transferable learning strategies, self-regulation capabilities, and metacognitive awareness that enable lifelong adaptation [141].

AI-powered meta-learning systems analyze individual learning patterns to identify personalized optimization strategies. By tracking how students approach different problem types, which strategies yield success, and when particular techniques fail, systems construct meta-cognitive profiles that

inform strategy recommendations. A student who learns mathematical concepts better through visual representation but verbal concepts through auditory processing receives tailored strategy suggestions that leverage these meta-patterns [142].

Social learning networks amplify meta-learning through peer observation and collaborative reflection. Students observe how successful peers approach challenging problems, not just final solutions but thinking processes, strategy selection, and error recovery. AI facilitates this social meta-learning by matching students with complementary learning styles, creating "cognitive diversity groups" where varied approaches cross-pollinate. Studies show 41% improvement in strategy transfer when students learn within cognitively diverse networks versus homogeneous groups [143].

The curriculum itself transforms to prioritize meta-learning development. Rather than organizing by content domains, programs structure around cognitive capabilities: critical thinking, creative problem-solving, systems analysis, and information synthesis. Content becomes vehicle rather than destination, with historical examples teaching pattern recognition, mathematical problems developing logical reasoning, and literary analysis building interpretation skills. This inversion – capabilities over content – prepares students for futures where specific knowledge rapidly obsolesces but learning ability remains invaluable [144].

7.2.2. Immersive AR/VR integration

Augmented and virtual reality technologies transcend their entertainment origins to become transformative educational mediums [145, 146, 147]. Meta-analyses reveal substantial effect sizes ($d \approx 0.98$) for AR/VR interventions in higher education (table 4), with particularly strong impacts on spatial reasoning, procedural learning, and abstract concept comprehension [148].

Table 4
Empirical effect sizes for VR and AR interventions across learning domains (SD = standard deviation improvement).

Learning domain	VR impact	AR impact	Key benefit
Spatial skills	+0.98 SD	+0.76 SD	3D manipulation
Procedural knowledge	+0.89 SD	+0.62 SD	Embodied practice
Abstract concepts	+0.72 SD	+0.83 SD	Visualization
Collaborative skills	+0.65 SD	+0.71 SD	Shared experiences
Emotional engagement	+0.94 SD	+0.68 SD	Immersive narrative

Virtual reality enables impossible experiences that deepen understanding beyond traditional instruction's reach. Students explore ancient Rome at its height, manipulate molecular structures in three dimensions, or experience historical events from multiple perspectives. The embodied nature of VR learning – moving through space, manipulating objects, experiencing consequences – activates sensorimotor circuits that strengthen memory encoding. Neuroscience research confirms that VR-based learning produces distinctive neural signatures associated with enhanced retention and transfer [149].

Augmented reality overlays digital information onto physical environments, creating hybrid learning spaces where abstract concepts become tangible [150, 151, 152]. Mathematical functions appear as manipulable 3D surfaces [153], chemical reactions animate on laboratory benches [154], and historical figures emerge from textbook pages to deliver first-person accounts [155]. This contextual embedding links abstract knowledge to concrete experiences, improving comprehension by 67% for spatially complex topics [156].

Gender differences in AR/VR effectiveness reveal important design considerations. Female students show stronger motivation gains from AR/VR experiences that emphasize exploration and discovery over competition and achievement. Male students demonstrate greater engagement with challenge-based VR scenarios but lower persistence when facing repeated failure. Adaptive AR/VR systems that adjust interaction paradigms based on individual preferences rather than demographic assumptions maximize benefits across all learners [157].

Implementation challenges persist despite demonstrated benefits. Cost remains prohibitive for many institutions, with full classroom VR setups exceeding $50,000. Motion sickness affects 23% of users,

limiting session duration. Perhaps most critically, teacher preparation lags technology deployment – 78% of educators report feeling unprepared to integrate AR/VR meaningfully into curriculum. Successful implementations invest equally in professional development and hardware acquisition [158].

7.2.3. Neuroadaptive systems

The convergence of neuroscience and educational technology enables unprecedented personalization through real-time neural monitoring and adaptation. Neuroadaptive systems use EEG, eye-tracking, and physiological sensors to detect cognitive states – attention, cognitive load, emotional valence – and dynamically adjust learning experiences to maintain optimal challenge levels [159].

NeuroChat exemplifies practical neuroadaptive implementation, using consumer-grade EEG headbands to monitor engagement during AI tutoring sessions. When theta wave patterns indicate mind-wandering, the system employs attention restoration techniques: changing content modality, introducing surprise elements, or suggesting physical movement breaks. During high cognitive load periods marked by elevated beta activity, content automatically simplifies, pacing slows, and additional scaffolding appears. Students using neuroadaptive tutoring show 34% improvement in sustained attention and 28% reduction in cognitive fatigue [159].

Advanced implementations combine multiple biosignals for comprehensive state assessment. Pupil dilation indicates cognitive effort, galvanic skin response reveals emotional arousal, and heart rate variability suggests stress levels. Machine learning algorithms integrate these signals to construct multidimensional cognitive-emotional state models that inform moment-to-moment adaptation. The precision of neuroadaptive systems surpasses self-report or behavioral inference, detecting cognitive overload 4.7 seconds before performance degradation appears [160].

Ethical considerations surrounding neuroadaptive learning demand careful navigation. Brain data represents the ultimate privacy frontier – thoughts, emotions, and cognitive processes laid bare to algorithmic analysis. Strict data governance protocols become essential, limiting neural data use to immediate adaptation without long-term storage or cross-purpose analysis. The "cognitive sovereignty" principle emerges, asserting individuals' absolute ownership of their neural data and right to cognitive privacy [161].

7.2.4. Social learning networks

Digital transformation enables new forms of social learning that transcend traditional classroom boundaries. Global peer networks connect learners across geographic, cultural, and linguistic divides, creating cognitive diversity that enriches learning through exposure to varied perspectives and problem-solving approaches [162].

AI facilitates optimal peer matching based on complementary skills, compatible learning styles, and motivational alignment. Rather than random group assignment, intelligent algorithms identify collaboration patterns that maximize mutual benefit. A student strong in mathematical reasoning but weak in verbal expression partners with a peer exhibiting opposite strengths, creating synergistic learning relationships. Dynamic regrouping based on evolving competencies ensures continued challenge and growth [163].

Collaborative knowledge construction platforms enable collective intelligence emergence. Students contribute partial solutions, build on peers' ideas, and synthesize diverse inputs into coherent understanding. Version control systems track contribution histories, enabling fair assessment of collaborative work while maintaining individual accountability. Wiki-based learning environments where students collectively create course content show 45% deeper conceptual understanding compared to traditional instruction [164].

Social emotional learning integrates naturally within digital peer networks. Students develop empathy through perspective-taking exercises, practice conflict resolution in low-stakes virtual environments, and build communication skills through structured peer feedback. AI monitors interaction quality,

identifying toxic dynamics early and facilitating constructive engagement patterns. The social skills developed through digital collaboration prove increasingly essential for distributed work futures [165].

7.3. Systemic transformation

Individual technological and pedagogical innovations require systemic transformation to achieve educational reimagination at scale. Infrastructure, standards, policies, and professional roles must evolve coherently to support rather than constrain emerging possibilities.

7.3.1. Interoperability standards

The proliferation of educational technologies creates integration challenges as institutions deploy dozens of disconnected systems. Interoperability standards enable seamless data exchange, functionality sharing, and user experience consistency across diverse platforms [166].

Emerging standards like ISO/IEC 19788 (Metadata for Learning Resources) and IMS Global's Learning Tools Interoperability (LTI) provide technical frameworks for system integration. These standards define common data formats, authentication protocols, and API specifications that allow learning management systems, assessment platforms, and content repositories to communicate fluently. The OneRoster standard enables automatic roster synchronization, eliminating manual data entry that consumes 127 hours annually per school administrator [167].

Semantic interoperability transcends technical data exchange to ensure shared meaning across systems. The Educational Knowledge Graph initiative creates universal ontologies mapping concepts, competencies, and credentials across institutional boundaries. When a student transfers between schools, their learning history translates automatically into the receiving institution's framework, preserving continuity despite systemic differences [168].

Blockchain-based credentialing creates tamper-proof, universally verifiable academic records that students own and control. Rather than requesting transcripts from former institutions, learners share cryptographically signed credentials directly with employers or educational programs. The Blockcerts standard, adopted by MIT and 200 other institutions, enables instant verification while preventing credential fraud that costs $2.3 billion annually [169].

7.3.2. Universal learner records

Traditional transcripts inadequately capture contemporary learning occurring across formal, informal, and non-formal contexts. Universal Learner Records (ULRs) document comprehensive learning journeys (figure 7), including micro-credentials, workplace training, self-directed study, and experiential learning [170].

Competency-based frameworks replace course-centric organization with skill taxonomies that map across contexts. Whether a student develops project management skills through formal coursework, workplace experience, or volunteer coordination becomes irrelevant; the competency itself receives recognition. Machine learning algorithms analyze diverse evidence types – portfolios, peer assessments, performance data – to validate competency claims with 91% accuracy compared to expert evaluation [171].

Digital wallets give learners sovereignty over their educational data, choosing what to share with whom for which purposes. Privacy-preserving protocols enable selective disclosure – proving degree completion without revealing grades, demonstrating language proficiency without exposing full transcripts. This granular control empowers learners while protecting sensitive information [172].

7.3.3. Global accessibility initiatives

Educational equity demands that advanced learning technologies serve all students regardless of geographic location, economic resources, or physical abilities. Global accessibility initiatives work to bridge digital divides while ensuring inclusive design [173].

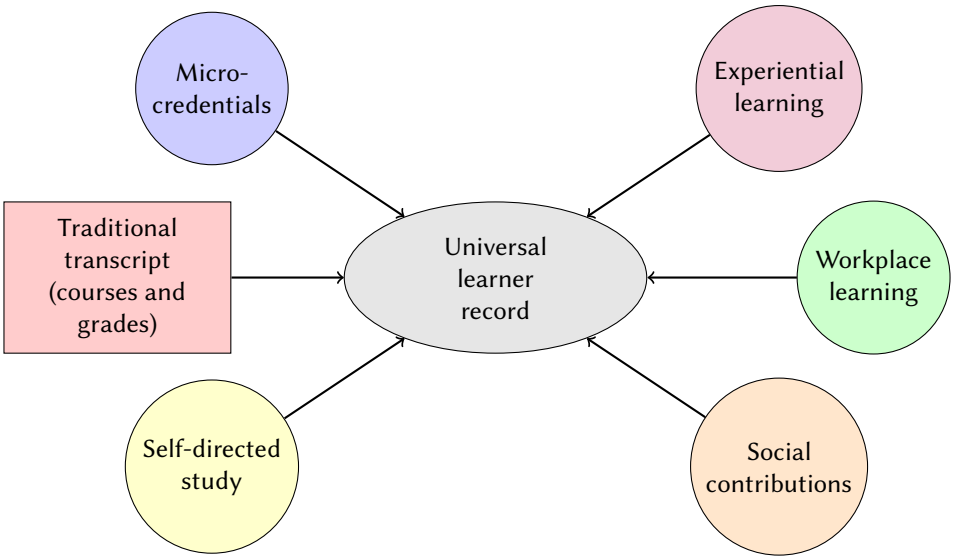


Figure 7: Universal Learner Record architecture integrating diverse learning experiences into comprehensive competency profiles.

The Universal Design for Learning (UDL) framework, updated for AI-enhanced education (UDL 3.0), provides principles ensuring all learners can access, engage with, and demonstrate knowledge. AI systems automatically generate alternative content representations – converting text to speech, adding visual descriptions, simplifying language complexity – based on individual accessibility profiles. Real-time captioning, sign language avatars, and haptic feedback systems ensure sensory impairments don't become learning barriers [174].

Infrastructure initiatives address connectivity gaps preventing technology access. Low Earth orbit satellite constellations promise global broadband coverage by 2027, bringing high-speed internet to 3 billion currently unconnected individuals. Edge computing architectures enable sophisticated AI processing on low-power devices, eliminating the need for expensive hardware [175]. Mesh networking protocols allow community-created networks in areas lacking commercial infrastructure [176].

Localization extends beyond language translation to cultural adaptation. AI systems trained primarily on Western educational content perpetuate cultural biases when deployed globally. Successful initiatives involve local educators in training data creation, algorithm refinement, and pedagogical adaptation. The African Institute for Mathematical Sciences develops culturally relevant AI tutors that use local examples, respect indigenous knowledge systems, and align with community values [177].

7.3.4. New educator roles emergence

The augmentation paradigm transforms rather than eliminates educator roles, creating new professional identities that leverage human capabilities AI cannot replicate. These emerging roles require different competencies, preparation pathways, and support structures [178].

Learning experience designers orchestrate complex educational journeys combining human instruction, AI tutoring, peer collaboration, and experiential learning. Rather than delivering content, they architect learning ecosystems where multiple elements synergistically support student development. This role demands systems thinking, data interpretation capabilities, and deep pedagogical knowledge to balance technological and human elements effectively [179].

Cognitive coaches support students' metacognitive and social-emotional development, areas where human insight remains irreplaceable. They help students understand their learning patterns, develop self-regulation strategies, and navigate the psychological challenges of continuous learning. As AI handles content delivery and assessment, cognitive coaches focus on motivation, resilience, and identity development [180].

Algorithm auditors ensure AI systems serve educational rather than efficiency goals. They exam-

ine recommendation patterns for bias, evaluate whether adaptations genuinely benefit learners, and advocate for student interests when these conflict with algorithmic optimization. This role requires technical literacy to understand AI operations, pedagogical expertise to evaluate educational impact, and ethical grounding to identify value conflicts [181].

Learning analytics interpreters translate complex data into actionable insights for students, parents, and administrators. They identify patterns human intuition might miss while contextualizing algorithmic findings within lived realities. When AI flags a student as "at-risk", interpreters investigate underlying causes, coordinate support resources, and communicate sensitively with stakeholders. This bridging role proves essential for maintaining human agency in data-driven systems [182].

The transformation of educator roles requires systematic professional development beyond traditional technology training. Universities develop new teacher preparation programs integrating computer science, data science, and cognitive psychology with pedagogical training. Micro-credentialing systems allow practicing educators to progressively develop new competencies through stackable certificates. Most critically, professional learning communities provide ongoing support as roles continue evolving [183].

8. Conclusion: the imperative for action

8.1. Synthesis of position

The comprehensive examination of generative AI's integration into adaptive educational systems reveals a moment of unprecedented opportunity coupled with profound responsibility. The evidence presented throughout this analysis converges on a fundamental truth: we stand at an inflection point where technological capabilities finally align with longstanding pedagogical aspirations, yet this alignment alone guarantees neither positive transformation nor equitable outcomes [52].

8.1.1. Technology as enabler, not replacement

The augmentation paradigm emerges not as philosophical preference but as empirical necessity. Across implementations spanning continents, educational levels, and socioeconomic contexts, a consistent pattern manifests: AI systems achieve optimal outcomes when amplifying rather than supplanting human capabilities [184]. The 27% improvement in course success rates at Arizona State University occurred not through teacher replacement but through liberation – freeing educators from administrative burden to engage in high-touch mentorship. The 5 million teachers adopting MagicSchool AI seek not obsolescence but enhancement, using technology to extend their pedagogical reach rather than abdicate their educational responsibility.

This distinction between augmentation and automation transcends semantic precision to embody fundamentally different visions of education's future. Automation conceptualizes learning as information transfer amenable to algorithmic optimization, reducing education to its most mechanistic components. Augmentation recognizes education as irreducibly human endeavor where knowledge transmission represents merely the substrate upon which critical thinking develops, creativity flourishes, and identity forms. Technology excels at the former; only humans accomplish the latter [185].

The TPACK framework's evolution demonstrates how technological integration succeeds when subordinated to pedagogical objectives rather than driving them. Teachers who develop technological pedagogical content knowledge – understanding not just what technology can do but when and why to deploy it – report 73% higher satisfaction and 45% better student outcomes than those receiving purely technical training. This suggests that preserving human primacy requires not resistance to technology but sophisticated orchestration of human and artificial capabilities [186].

8.1.2. Urgency of ethical framework development

The velocity of AI deployment in educational contexts outpaces ethical framework development by orders of magnitude. While technology companies release new models monthly, institutional review

boards struggle to evaluate single implementations over semesters. This temporal mismatch creates ethical vacuums where consequential decisions about student data, algorithmic influence on developing minds, and AI's role in shaping intellectual development occur without adequate oversight or reflection [187].

Evidence from early deployments reveals concerning patterns demanding immediate attention. Algorithmic bias in adaptive systems perpetuates and amplifies existing educational inequities, with minority students receiving systematically different recommendations that constrain rather than expand opportunity. Hallucination in educational contexts proves particularly pernicious, as students lack expertise to identify subtle factual errors that become incorporated into developing knowledge structures. Privacy violations extend beyond data breaches to encompass cognitive privacy – the right to intellectual development free from algorithmic manipulation [188].

Yet ethical framework development cannot await perfect understanding of rapidly evolving technologies. The precautionary principle, while protective, risks paralysis that denies students beneficial innovations. Dynamic ethical frameworks that evolve through iterative refinement offer more promise than static regulations inevitably obsolesced by technological advancement. These frameworks must balance multiple tensions: innovation versus protection, personalization versus privacy, efficiency versus equity. Most critically, they must center student wellbeing rather than institutional convenience or commercial profit [189].

The emergence of "ethics washing" – superficial ethical compliance masking fundamental conflicts of interest – demands frameworks with enforcement mechanisms beyond voluntary compliance. Mandatory algorithmic auditing, independent oversight boards with student and parent representation, and liability frameworks creating genuine accountability become essential components. The European Union's AI Act provides initial scaffolding, though educational applications require domain-specific elaboration addressing unique vulnerabilities of developing minds [190].

8.1.3. Need for collaborative governance

The complexity of AI-enhanced education exceeds any single stakeholder's comprehension or control, necessitating governance models that orchestrate diverse perspectives, expertise, and interests. Traditional hierarchical governance structures – where administrators decide, teachers implement, and students comply – prove inadequate for systems where algorithms make millions of micro-decisions beyond human oversight [191].

Multi-helix collaboration models incorporating government, academia, industry, civil society, and media demonstrate particular promise. The Indonesian special autonomous region implementations show how each sector contributes essential elements: government provides regulatory frameworks and resources, academia supplies research and evaluation capacity, industry offers technical expertise and innovation, civil society ensures community voice and accountability, while media facilitates public discourse and transparency. When these elements align, transformation accelerates; when any element fails, implementation falters [192].

Heterarchical networks that distribute decision-making authority according to expertise rather than position enable responsive governance capable of rapid adaptation. Rather than centralized command structures, these networks create multiple feedback loops where classroom experiences inform policy, technical capabilities shape pedagogical possibilities, and ethical considerations constrain commercial imperatives. The Implementation-STakeholder Engagement Model demonstrates how continuous stakeholder involvement throughout implementation phases – not merely at inception – predicts success more strongly than resource availability or technical sophistication [193].

Trust emerges as governance's foundational currency, yet trust in AI educational systems remains fragile. Parents fear algorithmic determination of their children's futures, teachers worry about professional displacement, students question whether AI truly serves their interests. Building trust requires radical transparency about system operations, genuine participation in design decisions, and demonstrable commitment to stakeholder welfare over efficiency metrics. The collaborative governance imperative thus extends beyond coordination to encompass fundamental reconceptualization of power, authority,

and agency in educational systems [194].

8.2. Call to action

The synthesis of evidence, analysis of challenges, and articulation of possibilities converge on an urgent imperative: stakeholders across the educational ecosystem must act decisively to shape AI's integration before technological momentum renders human agency moot.

8.2.1. For educators: embrace augmentation, maintain human primacy

Educators stand at the transformation's epicenter, possessing unique power to determine whether AI becomes tool for liberation or instrument of obsolescence. The call to action requires transcending both technophobic resistance and uncritical adoption to develop sophisticated professional judgment about when, how, and why to deploy AI capabilities.

Immediate actions include developing AI literacy through structured professional development that emphasizes pedagogical application over technical operation. Understanding how large language models generate text matters less than recognizing when AI-generated content serves learning objectives. Participating in system design and evaluation ensures educational rather than technical priorities drive development. Most critically, educators must document and share both successes and failures, building collective wisdom about effective AI integration [195].

Maintaining human primacy requires explicit assertion of irreplaceable human contributions: emotional support during struggle, inspiration through passionate engagement, wisdom from lived experience, and moral guidance through ethical complexity. These uniquely human capabilities become more, not less, valuable as AI assumes routine instructional tasks. Teachers who clearly articulate and demonstrate these distinctive contributions secure their professional future while serving student needs AI cannot address [196].

8.2.2. For technologists: prioritize pedagogical validity over innovation

Technology developers wield enormous influence over education's future through design decisions that shape possibilities and constraints. The call to action demands fundamental reorientation from technological sophistication as primary objective to pedagogical effectiveness as ultimate criterion [197].

This requires embedding educators as equal partners throughout development cycles rather than consultants providing post-hoc validation. User experience research must extend beyond interface design to encompass learning impact, cognitive development effects, and long-term educational outcomes. The "first, do no harm" principle from medicine applies equally to educational technology, demanding rigorous testing for unintended consequences before wide deployment [198].

Transparency about system limitations proves as important as promoting capabilities. Acknowledging hallucination rates, bias patterns, and failure modes enables appropriate use while building trust through honesty. Open-source development models that enable inspection, modification, and local adaptation serve educational imperatives better than proprietary black boxes optimized for commercial metrics. Most fundamentally, technologists must resist the temptation to solve educational "problems" that exist primarily as market opportunities rather than genuine pedagogical needs [199].

8.2.3. For policymakers: create protective yet enabling frameworks

Policymakers navigate treacherous terrain between overregulation that stifles beneficial innovation and underregulation that exposes vulnerable populations to harm. The call to action requires adaptive frameworks that protect without paralyzing, guide without dictating, and evolve with technological advancement [200].

Immediate priorities include establishing minimum standards for educational AI covering data privacy, algorithmic transparency, bias auditing, and human oversight. These standards must be specific

enough to provide meaningful protection yet flexible enough to accommodate diverse contexts and rapid evolution. Liability frameworks clarifying responsibility when AI systems cause harm – whether through incorrect information, biased recommendations, or privacy violations – create accountability incentives for responsible development [167].

Investment in public infrastructure supporting equitable AI access prevents digital divides from becoming cognitive chasms. This encompasses not merely device and connectivity provision but professional development support, curriculum integration resources, and evaluation capacity building. Public funding for educational AI research independent of commercial interests ensures evidence-based rather than market-driven policy development [201].

8.2.4. For researchers: focus on long-term human development impacts

The research community bears responsibility for generating evidence that guides responsible AI integration while identifying and mitigating potential harms. The call to action requires shifting focus from short-term performance metrics to long-term human development outcomes [202].

Longitudinal studies tracking cohorts from early AI exposure through adulthood reveal cumulative effects invisible in semester-length investigations. Does early AI assistance accelerate cognitive development or create dependency? How does algorithmic mediation of learning influence identity formation, career trajectories, and lifelong learning capacity? These questions require patient investigation spanning years rather than publication cycles [203].

Interdisciplinary collaboration becomes essential as educational AI's impacts transcend traditional disciplinary boundaries. Cognitive scientists must work with computer scientists to understand how algorithms influence neural development. Sociologists must collaborate with data scientists to identify bias patterns. Ethicists must engage engineers to embed values in system architectures. Only through such collaboration can research address AI education's full complexity [204].

8.3. Final vision

The path forward requires neither wholesale embrace nor categorical rejection of AI in education, but thoughtful integration guided by human values, pedagogical wisdom, and unwavering commitment to learner wellbeing. Three aspirations crystallize from this analysis, representing not utopian fantasies but achievable objectives given sufficient will and wisdom.

8.3.1. Education that cultivates uniquely human capabilities

Future educational systems leverage AI to handle mechanistic tasks – information retrieval, routine assessment, administrative coordination – thereby liberating human potential for distinctively human endeavors. Students develop critical thinking through Socratic dialogue with teachers freed from lecture delivery. Creative expression flourishes when AI handles technical execution, allowing focus on ideation and meaning-making. Collaborative problem-solving skills emerge through carefully orchestrated group work where AI facilitates but humans connect [205].

This vision positions AI as cognitive exoskeleton that amplifies human capability rather than replacement that substitutes for it. Just as physical tools extended human strength without eliminating need for human judgment about where to direct that strength, cognitive tools extend intellectual capacity while preserving human agency over its application. The measure of success becomes not what AI can do independently but what humans can accomplish with AI assistance [206].

8.3.2. AI that democratizes quality education

Properly deployed, AI addresses education's most persistent inequality: the accident of birth that determines access to quality instruction. A student in rural Bangladesh gains access to world-class mathematics tutoring through AI that adapts to their context, language, and learning style. A child with learning disabilities receives perfectly calibrated support that neither stigmatizes nor limits. An adult

learner pursues new career paths through personalized instruction that accommodates work schedules and family obligations [207].

Democratization extends beyond access to encompass agency – ensuring all learners shape their educational journeys rather than merely consuming predetermined content. AI systems that respect cultural diversity, accommodate different ways of knowing, and support varied life trajectories serve democratic rather than homogenizing functions. This requires deliberate design decisions prioritizing inclusivity over efficiency, representation over standardization, empowerment over control [208].

8.3.3. Systems that enhance rather than erode human agency

The ultimate aspiration envisions educational systems where technology amplifies rather than diminishes human agency at every level. Students exercise meaningful choice over learning paths while receiving support that enables informed decisions. Teachers deploy professional judgment about when and how to use AI while maintaining authority over pedagogical decisions. Parents understand and influence how algorithms shape their children's education. Communities ensure educational technologies reflect local values while connecting to global knowledge [209].

This requires fundamental reconceptualization of agency in algorithmic contexts. Agency means not absence of AI influence but conscious collaboration with AI systems whose operations remain transparent and whose recommendations remain advisory. It demands educational systems that develop metacognitive awareness about AI interaction, critical evaluation skills for AI-generated content, and ethical reasoning about AI's proper role. Most fundamentally, it requires recognition that preserving human agency in an AI-saturated world becomes education's essential mission [210].

The convergence of technological capability, pedagogical understanding, and ethical awareness creates unprecedented opportunity to reimagine education for human flourishing. Yet opportunity alone guarantees nothing. The choices made today about AI's role in education will reverberate through generations, shaping not merely what students learn but who they become. The imperative for action is clear: we must act with wisdom, courage, and unwavering commitment to human dignity to ensure that education remains a fundamentally human endeavor that develops uniquely human capabilities, serves irreducibly human purposes, and preserves essentially human agency. The future of education – and perhaps humanity itself – depends on getting this right.

Declaration on Generative AI

During the research and writing process, we utilized several AI tools to enhance efficiency. Scopus AI helped refine our literature search strategy, while Grammarly assisted with grammar and style. We also employed Claude Opus 4.1 to polish sentence structure and improve clarity, always with careful human review and editing to ensure accuracy.

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Comprehensive framework for adaptive learning implementation in Moodle LMS: technical, pedagogical, and administrative perspectives

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Abstract

Adaptive learning is a methodology that allows to identify the level of students' knowledge and their learning styles and transform materials, tasks and ways of their delivery according to the needs of learning process participants. The interest of higher education institutions (HEI) to use adaptive learning as an innovative data-driven approach to the educational process is increasingly growing. However, the level of its actual use in HEIs is not high. The main reason is that a university has to overcome a lot of challenges in the process of adaptive learning implementation including technological, pedagogical and management-related ones. This comprehensive study addresses the problem of adaptive learning integration into existing learning management systems (LMS) on the basis of Moodle as one of the most popular LMS for e-learning arrangement, analyzing implementations across 2015-2024 in STEM, social sciences, and engineering education. The research is focused on the study of activities and resources that can be used as solutions at different stages of adaptive learning development in an e-learning course (ELC), identifying five core implementation stages: needs analysis and planning, system customization and technical integration, content adaptation and pedagogical alignment, testing and iterative refinement, and administrative deployment and support. Through analysis of recent advances in AI-driven plugins like Pythia and Lecomps, semantic web technologies, and learning analytics dashboards, we demonstrate how Moodle can serve as a robust platform for adaptive learning despite not being natively designed for this purpose. Our findings reveal that successful implementation requires coordinated technical innovation (including Bayesian networks, Markov models, and neural networks), pedagogical strategies aligned with constructivist and socioformative models, and comprehensive administrative support including privacy-first frameworks and differentiated teacher training programs. The paper offers practical guidance for HEIs seeking to implement adaptive learning through existing infrastructure while highlighting critical challenges in usability, teacher readiness, and ethical AI deployment that must be addressed for sustained impact.

Keywords

adaptive learning, e-learning, microlearning, students' needs, Moodle, learning analytics, AI-driven education, personalized learning paths, educational technology integration

1. Introduction

Modern e-learning platforms are able to support the creation and sharing of educational content and building collective intelligence. Students can look for such content online and decide whether it is suitable for achieving their learning objectives. However, searching and organising suitable content can easily make learners lose their focus on learning [1]. Therefore, open and flexible approaches and the establishment of adaptive systems are required to ensure better delivery of educational content and provision of high quality education for a large number of higher education institutions (HEI) students

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[2, 3]. The interest of higher education institutions to use adaptive learning as an innovative data-driven approach to the educational process is increasingly growing [4, 5]. However, the actual use of adaptive learning by HEIs remains rather limited in spite of promising results of recent studies on its effectiveness [6]. The main types of challenges faced by HEIs in the process of adaptive learning implementation include technology, pedagogy, and management-related issues [6]. Among them there are dealing with real time data, difficulties in integrating adaptive learning solutions into existing learning management systems (LMS), the need to change e-learning courses design and content etc. In particular, in the process of adaptive learning implementation teachers often struggle with modifying learning content, because they have lack of experience with adaptive technologies. Most higher education institutions still have unified learning materials which do not consider students' learning styles, knowledge level difference, needed depth of study, time frameworks for the course completion etc.

In the process of knowledge consumption students tend to divide knowledge arrays into small parts, and then put them in order and format that is easy to process for them. This is also proven by the results of the survey conducted at Borys Grinchenko Kyiv University. Learners then develop links between these pieces until they fully grasp the knowledge [1]. This corresponds to one of the recent educational trends – microlearning. It is a learner-centred teaching and learning approach which is result oriented and provides division of the material into segments that are easy to be consumed at a time [7]. Microlearning components often remove any inconsequential and unrelated content and focus only on what a student needs to know. This reduces learners' cognitive load and increases retention since they are able to process information more effectively [8]. When material is split into smaller sections it is much easier to be adapted to students' needs. Thus, the authors claim that microlearning can be used as a means to implement adaptive learning in HEIs.

The aim of the research is to determine whether learning management systems (LMS) can be used as a platform for implementing adaptive learning as they are already used for e-learning arrangement in HEIs. For this purpose activities and resources in e-learning courses (ELC), that allow the adaptation and personalisation of materials in a way which is relevant to students' individual needs, are studied. The authors offer to look at the perspective of adaptive learning implementation through the stages of its development in an ELC (initial stage, pre-test stage, path generation stage, learning stage, post-test stage), activities and resources that can be used to provide those stages. The e-learning system of Borys Grinchenko Kyiv University based on Moodle LMS is taken as a background for testing adaptive learning implementation in ELC.

2. Related work

Skinner [9], who is considered to be a founder of personalised (adaptive) learning, stated in his book "The Technology of Teaching" that one of effective ways of teaching is dividing material into small parts and adapting learning tasks to current level of students' knowledge. Elements of adaptive learning were reflected in [10, 11, 12, 13, 14, 15].

The definition of adaptive learning by Skinner [9] led us to considering microlearning as a means of adaptive learning implementation. Microlearning has got a lot of attention from scientists recently. According to Leong et al. [16] 476 relevant publications have been identified during 2006–2019. Hug [17] in his book "Didactics of Microlearning" is covering a vast variety of questions on the topic, including those considering adaptive learning cycles. In particular, the question of adaptive microlearning is addressed by Gherman et al. [18], Sun et al. [19].

Among the tools for implementation of adaptive learning in HEIs learning management system is noted. One of such systems that gained popularity in universities due to its flexibility and free distribution is Moodle LMS. That makes the question of implementation of adaptivity elements in Moodle relevant and many researchers have paid attention to this topic in recent decade among whom there are Surjono [20], Caputi and Garrido [21], Kukhartsev et al. [22], Gaviria et al. [23], Akçapınar [24], Nikitopoulou et al. [25], Jurenoks [26], Rollins [27].

Recent systematic reviews covering the period from 2015-2024 reveal that adaptive learning im-

plementations in Moodle span diverse educational contexts, with particular concentration in STEM disciplines at the tertiary level [28]. The evolution of these implementations demonstrates a clear trajectory from simple content sequencing to sophisticated AI-driven personalization using neural networks, Bayesian models, and semantic web technologies [29, 30]. This technological advancement has been accompanied by growing recognition of the need for comprehensive frameworks that address not only technical integration but also pedagogical alignment and administrative support structures [31].

Advances in AI-driven adaptive learning for Moodle have introduced sophisticated plugin architectures that leverage machine learning algorithms for personalized path generation. Notable developments include the Pythia plugin [29], which integrates Bayesian networks and Markov models for dynamic learning path adaptation, and the Lecomps system [32], which manages student models and generates personalized learning object sequences. These tools represent a significant evolution from earlier rule-based approaches, offering transparency and extensibility that allow educators to customize adaptive environments according to specific pedagogical needs [33, 34].

3. Theoretical background and practical implementation

One of promising educational technologies according to NMC Horizon Report 2018 is adaptive learning – adaptation of content and choice of means for its implementation according to the needs of educational process participants to increase the effectiveness of activities. Personalization of the approach to learning cannot be made without understanding educational technologies implemented in HEIs. Many HEIs use e-learning systems for provision of distant learning, blended learning and independent study. Moodle LMS is a widely used e-learning system as it is open source and can be adapted to HEIs' needs. Moodle LMS is used at Borys Grinchenko Kyiv University, therefore it is chosen by the authors as a platform for innovation implementation.

Adaptive learning is a technique that involves periodically gathering information about students' level of knowledge and learning styles, and configuring learning resources, tasks, and assessment accordingly [35]. Thus, e-learning developers are challenged to take into account the needs of users to ensure better learning outcomes. The main factors that influence the quality of ELCs according to the survey are the choice of the diversity of presentation formats, the tasks and tests complexity, the level of complexity of the course and the sequence of study of the material (figure 1). Implementing adaptive learning can ensure that these needs are met.

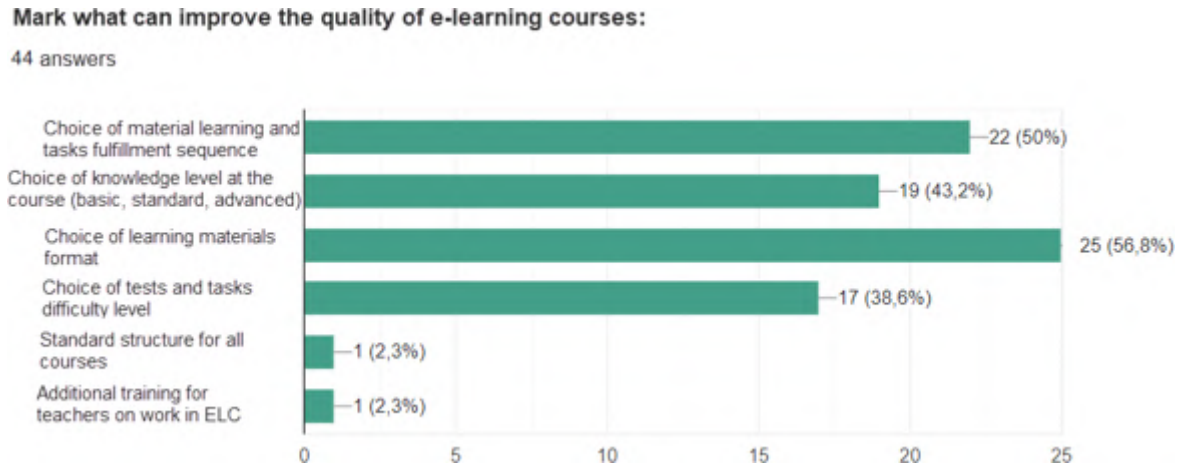

Figure 1: Factors influencing the quality of ELC (survey results).

Adaptive design of the e-learning platform also plays an important role under the current conditions as students use various devices among which are PC, tablets and smartphones. Moodle LMS is able to provide required adaptivity of the design.

Table 1
Comprehensive framework of adaptive learning implementation stages in Moodle LMS.

Stage	Description	Core Moodle features/plugins	Main challenges	Best practices	References
Needs analysis and planning	Assess institutional needs, learner diversity, and readiness; engage stakeholders	N/A	Stakeholder alignment, readiness	Inclusive planning, data-driven needs	[1, 2]
System customization and integration	Develop/integrate AI-driven plugins, modular architectures, external engines	Pythia, Lecomps, SAM-FL, ChatGPT	Technical complexity, transparency	Modular design, ethical AI frameworks	[29]
Content adaptation and pedagogy	Adapt course content using modules, align with pedagogical models	Lesson, AdaptiveLesson, CbKST	Pedagogical misalignment, usability	Blended learning, personalized paths	[7, 8]
Testing and iterative refinement	Pilot adaptive features, collect analytics, refine based on feedback	Learning Analytics Dashboards, MEAP+	Data interpretation, continuous improvement	Analytics-driven iteration	[1, 36]
Administrative deployment and support	Data security, backup, educator training, policy support	Security settings, backup tools	Data privacy, teacher resistance	Privacy-first, capacity-building	[37, 38]

According to the the Deming or Plan-Do-Check-Act (PDCA) cycle for higher education [39] (figure 2) it is vital to analyse the factors that influence the effectiveness of the educational process, current situation in a HEI and tendencies in educational technologies on the international level prior to integration of any innovative tools and methodologies into the educational process.

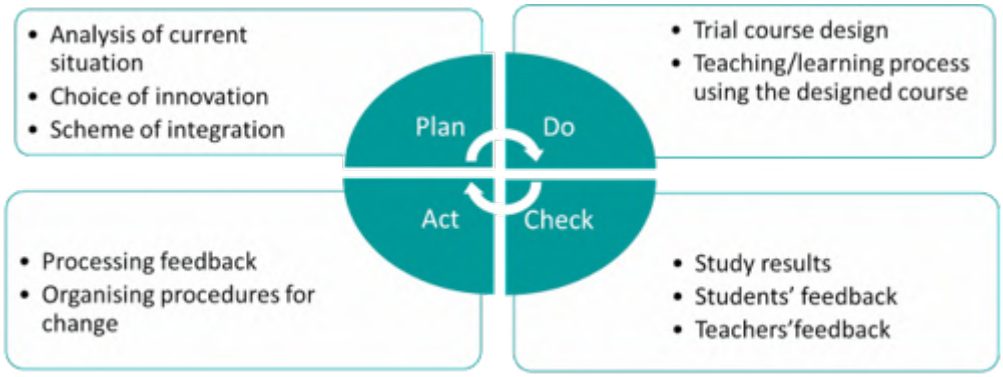

Figure 2: PCDA cycle for innovation implementation in HEI.

All adaptive learning systems follow a similar PDCA architecture (figure 2) that gathers data from the learner and then uses that data to estimate the learner's progress, recommend learning activities, and provide tailored feedback. The adaptive learning algorithm is designed to make such decisions by referring to a learning plan (the knowledge to be learned), a student model of learners' background characteristics (knowledge level, learning style, individual needs, etc.), and a task model that specifies features of the learning activities (such as questions, tasks, quizzes, dynamic hints, feedback, prompts, and recommendations) [40].

The goal of responsive e-learning is to provide students with the tools they need to absorb the

material they need to the best of their ability. Requirements for tailored educational materials are tailored to the goals of the educational process [41]. Consideration should be given to students' prior knowledge as well as differences in learning styles and individual needs. Among the objectives of the appropriate learning system is to ensure the same efficiency of the educational process for students who are not familiar with the field of knowledge as those who have previous academic experience.

Adaptive learning tools are technologies that can be synchronised with the learning process and, based on machine learning technologies, can adapt to the progress of each student and independently adjust the learning content in real time. Adaptability can be manifested in one or more elements of technology: content, evaluation, consistency.

Content adaptation is the presentation of educational materials in a form that will allow the student to navigate his own educational trajectory. Content adaptation includes contextual clues, content branching, material partitioning, volume selection and material format. For example, when giving a lecture online, you can use the question system to assess whether a student has mastered the relevant material at a sufficient level, and if necessary, return it to certain information again, or allow them to skip some of the material as previously learned.

Sequence adaptation involves the automatic selection of relevant content, the level of complexity and the order of study of the material based on the analysis of the results of its educational activities. Adaptive-sequence tools are the most complex, because they analyse the data and compile and adjust the student's individual trajectory in real time.

Data collection is not limited to accumulating information about correct and incorrect answers. Adaptive programs take into account many different indicators to make a personal learning trajectory:

- correct answer;
- number of attempts;
- use of additional tools or resources;
- interests of the student (for example, what resources the student prefers).

The adaptive sequence is implemented in three stages: to collect the data, to analyse it and to adapt the sequence of the material submission to the needs of the particular student. The main advantage of a learning tool with adaptive consistency is to fill knowledge gaps. If a student has missed a class or has not yet mastered the topic and now this impedes the learning of new material, the sequence of tasks and topics changes. So the student first fills in the knowledge gap and then moves on to the current topic.

The adaptation of the assessment assumes that each subsequent question depends on the answer given by the student to the previous one. The better it is, the more difficult the tasks are, and vice versa – if it is too difficult for the student, the questions will be easier until the material is mastered. Adaptive assessment tools are commonly used for periodic monitoring every few months. Students receive a relatively voluminous test assignment, the purpose of which is to test how well they have mastered the material per module, semester, etc. After monitoring, data is analysed, and the results are used to further adjust the program and the individual learning trajectory of each student. Therefore, one of the advantages of adaptive tests is detailed statistics.

The adaptive learning implementation process can be classified into the following stages: initial stage, pre-test stage, path generation stage, learning stage, post-test stage [1].

Initial stage. Learners login to the e-learning system and select a course to study. In Borys Grinchenko Kyiv University this stage is organised by integration of educational programmes in the e-learning system. Every student is enrolled in all the courses of their educational program and each course is bound to a specific semester(s). For this stage such activities as Subcourse, Assignment and Page are used to provide students with information on all ELCs (disciplines), their forms of control in each semester and students' progress in each discipline and in general (figure 3).

Pre-test stage. Learners are provided with a pre-test and/or a survey to determine their level of knowledge, learning styles, intended learning outcomes. The testing results become the basis for learning path generation. At this stage gaps in students' knowledge are identified as well. In Moodle the stage can be implemented by such activities as Quiz, Survey, Questionnaire. The choice of the activity depends on its aim.

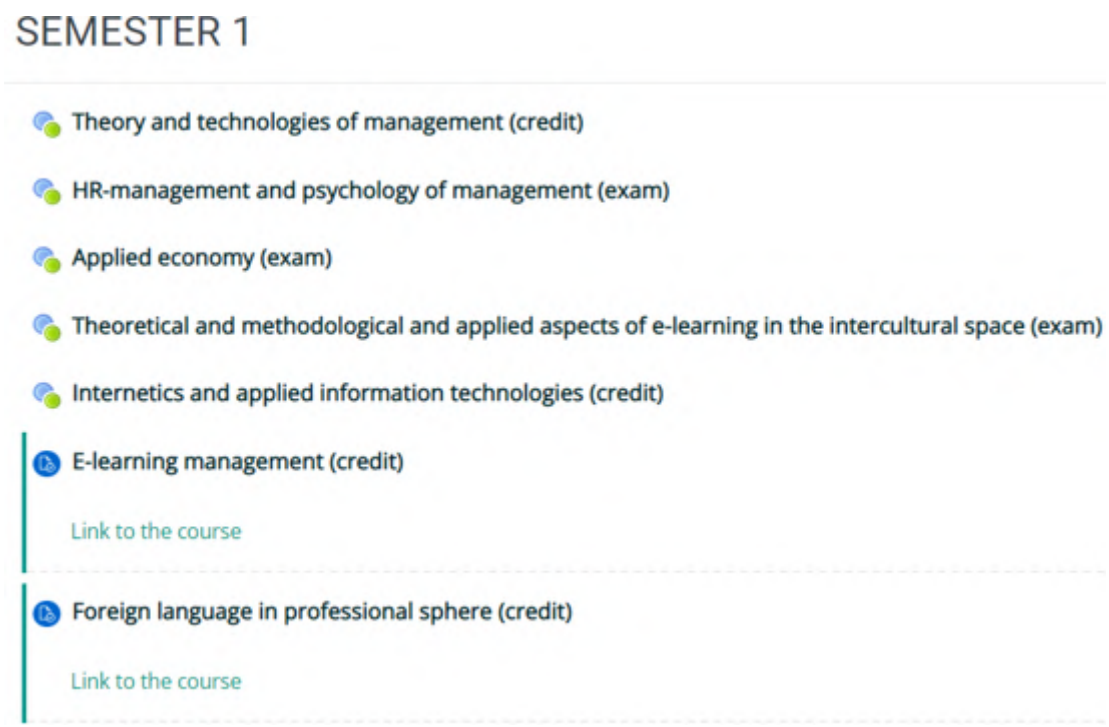

Figure 3: Example of disciplines arrangement in the educational program "E-learning management in the intercultural space".

Thus, the activity Survey is pre-populated with questions and a teacher cannot create own questions there. The Attitudes to Thinking and Learning Survey (ALLTS) Survey resource allows you to assess the level of collaboration of a learning community (group). This will help determine the optimum balance of individual and group work in the course.

The Questionnaire module is aimed at collecting data from users. Unlike the Survey activity, it allows teachers to create a wide range of questions and modify them to the needs of the course. However, the purpose of these two modules is similar – to gather information and not to test or assess students. It can be used to determine learning styles for further selection and gradation of materials.

The Quiz resource lets you rank students' level of knowledge through standard testing. With the Overall feedback setting (figure 4), boundaries are set for each level of knowledge and the student receives a corresponding feedback. For example, students with a score of 80% and above may be offered an advanced course, with results of 60-80% a standard course, and a basic course for those who scored less than 60%

Path generation stage. At this stage a student has to receive an individual learning path based on the results of the pre-test stage. Moodle LMS does not contain automated mechanisms to provide this stage being a learning management system, but not an adaptive learning platform. Therefore, alternative ways of the stage implementation must be found to provide students with their own learning trajectory.

Topics can be used to separate materials for students with different knowledge levels. By changing course layout to the section per page format and placing all materials of the corresponding level into the relevant section (figure 5) we simplify navigation in the course.

Another option is to use the Checklist module to form lists of themes or tasks that have to be fulfilled to finish the course. The items can be added to the list from the current section, from the whole course or manually created. The status of the items in the list is updated automatically as students complete the related activity. A checklist can be edited so that only activities or resources that contain tasks were listed as obligatory ones. Thus, a teacher can customise checklists to the needs of a group and create them either for the whole course or for each module/theme separately. If different items can be completed by students with different levels of knowledge or learning styles, a teacher can set up an amount of items to be checked off to complete the Checklist (figure 6).

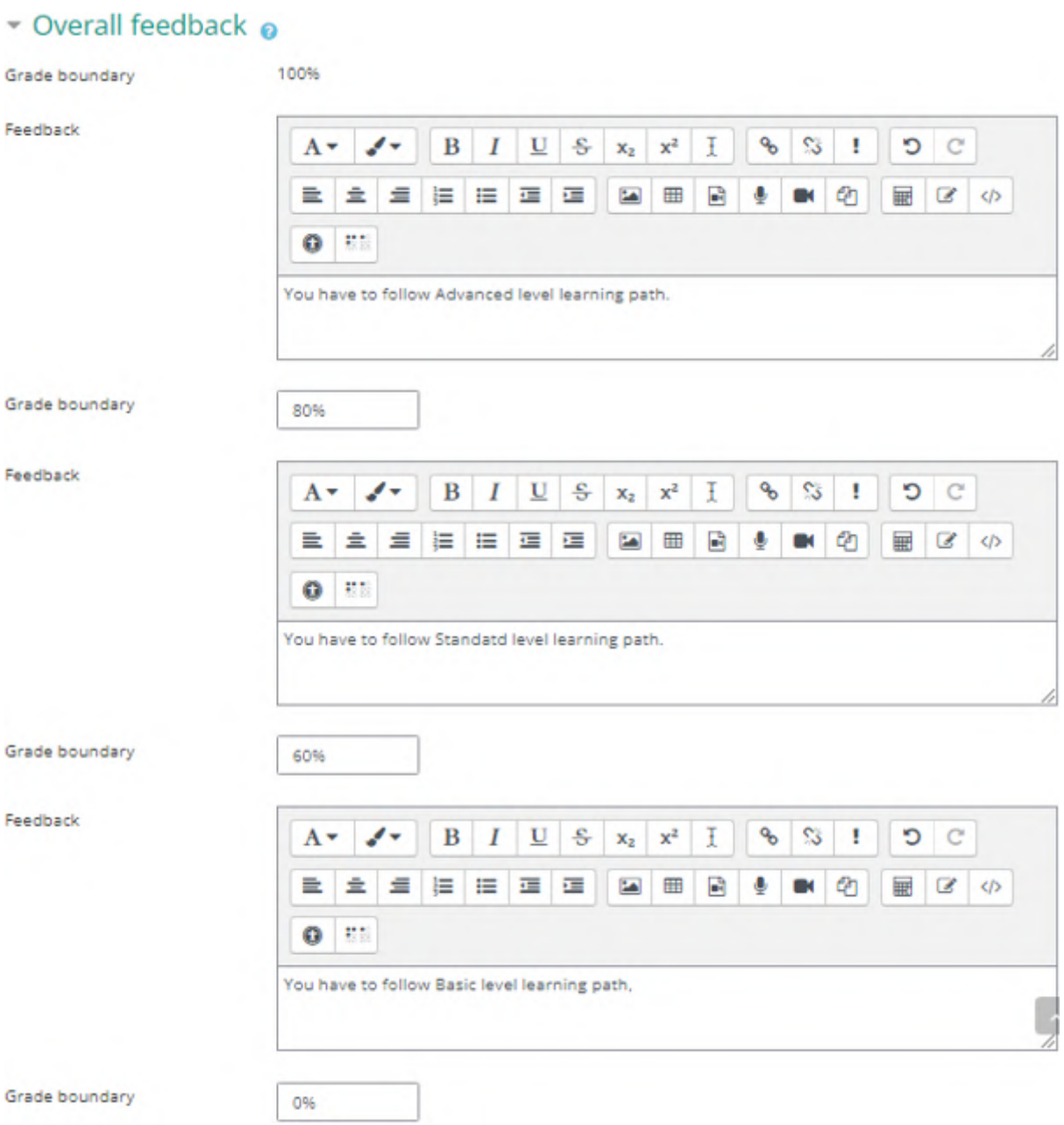

Figure 4: Overall feedback setting for introductory testing in ELC.

An individual learning path in Moodle LMS can be provided to a student as a list of to-do items to complete the course based on the pre-test results. It might require individual teachers recommendations or be partly unified for a specified level of knowledge.

Recent implementations (figure 7) demonstrate sophisticated approaches to path generation beyond simple topic separation. Advanced plugins like Pythia utilize Bayesian networks to calculate probabilistic relationships between learning objects, automatically generating optimal sequences based on prerequisite knowledge and learning objectives [29]. The SAM-FL (Student Adaptive Model for Flexible Learning) framework combines clustering algorithms with psychometric profiling to create dynamic paths that adapt in real-time based on student interactions [42]. These systems represent a significant advancement from manual path configuration, offering scalable solutions for institutions with large student populations.

Learning stage. At this stage recommended material is identified and a student deals with the learning content of a course. To provide flexibility of the content microlearning is used. The material separated

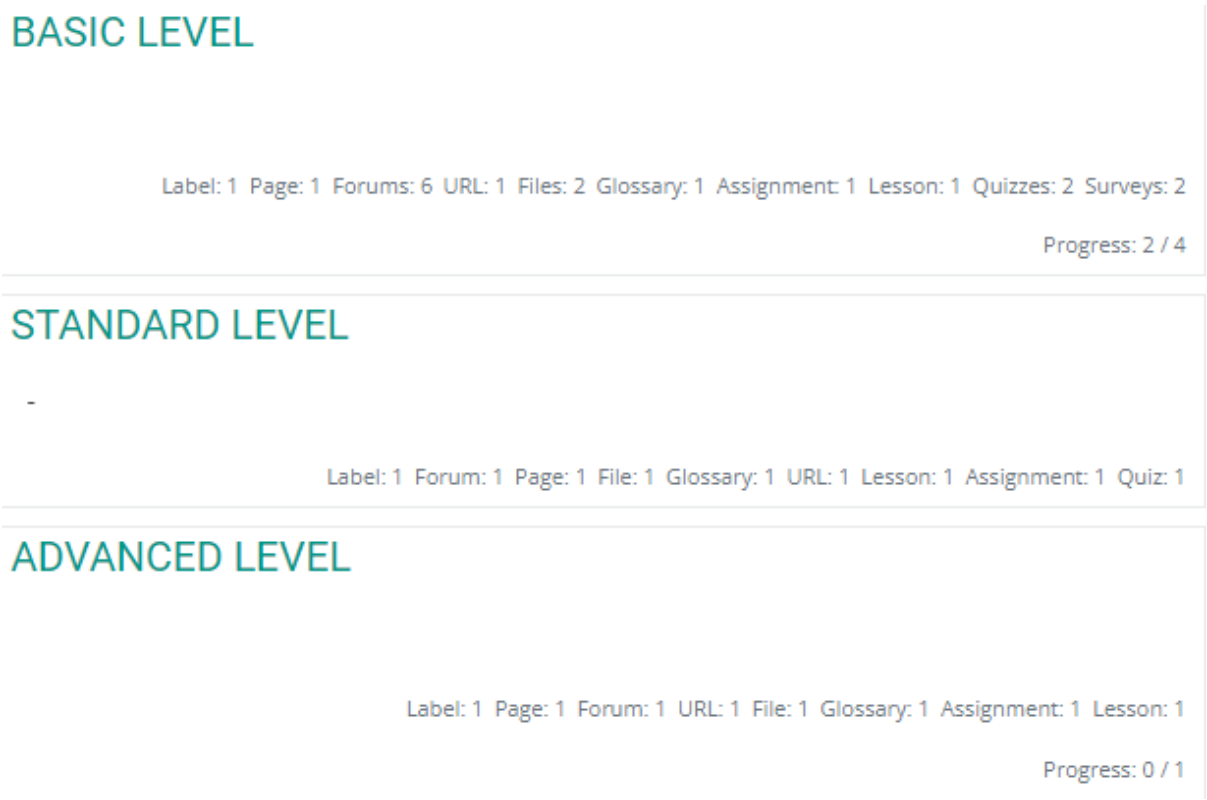

Figure 5: Arrangement of learning materials according to the level with the help of the topic sections.

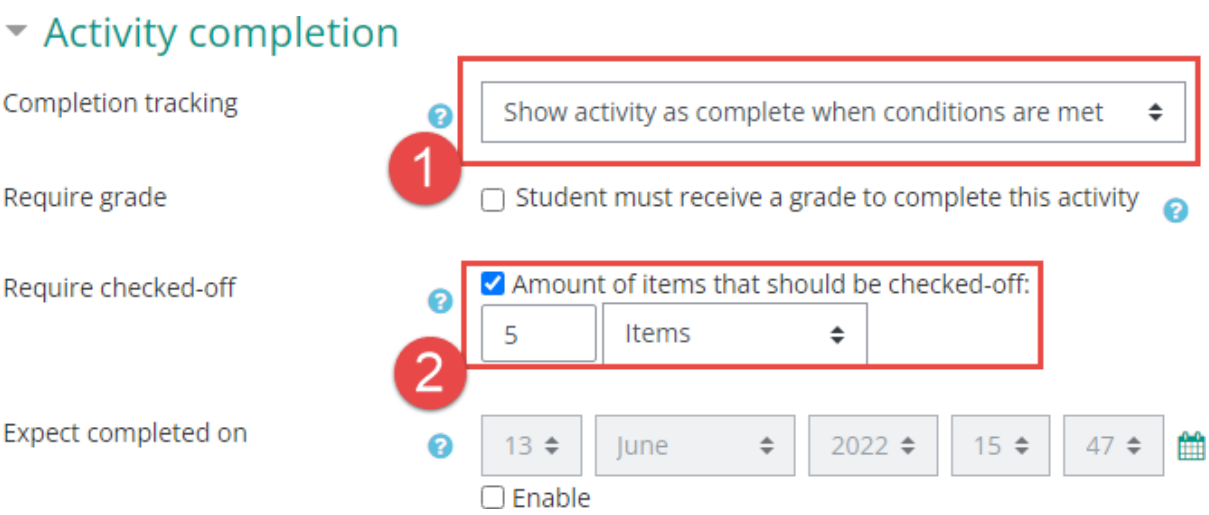

Figure 6: Activity completion settings in Checklist module.

into small logically complete parts can be easily used in any activity or resource used at the learning stage. Microlearning has a variety of advantages including better implementation of students' needs, wider diversity of materials for different knowledge levels, lower time expenses for material consumption, a possibility for knowledge gaps filling, increased motivation etc. [43]. Such materials are also easier renewable when needed as a teacher is able to change it by small pieces. According to the results of the survey they also correspond better to students' needs who indicated materials divided into micro modules, short videos, visual materials and presentations as the most effective formats for theoretical materials (figure 8).

Among the activities used at the learning stage the most popular are Assignment, Book, Chat, File, Forum, Glossary, Lesson, Page, Quiz, Wiki and Workshop. In our work we are going to pay attention

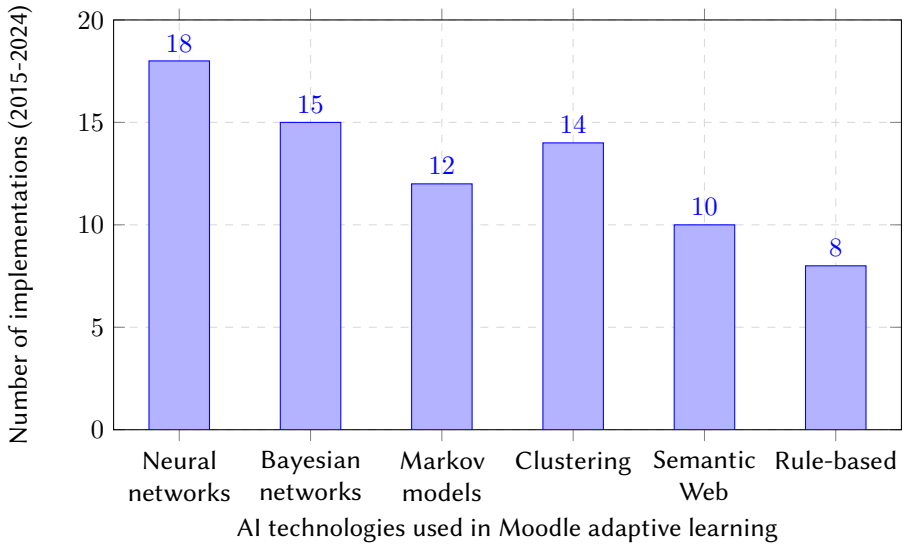

Figure 7: Distribution of AI technologies used in Moodle adaptive learning implementations (based on Scopus analysis 2015-2024).

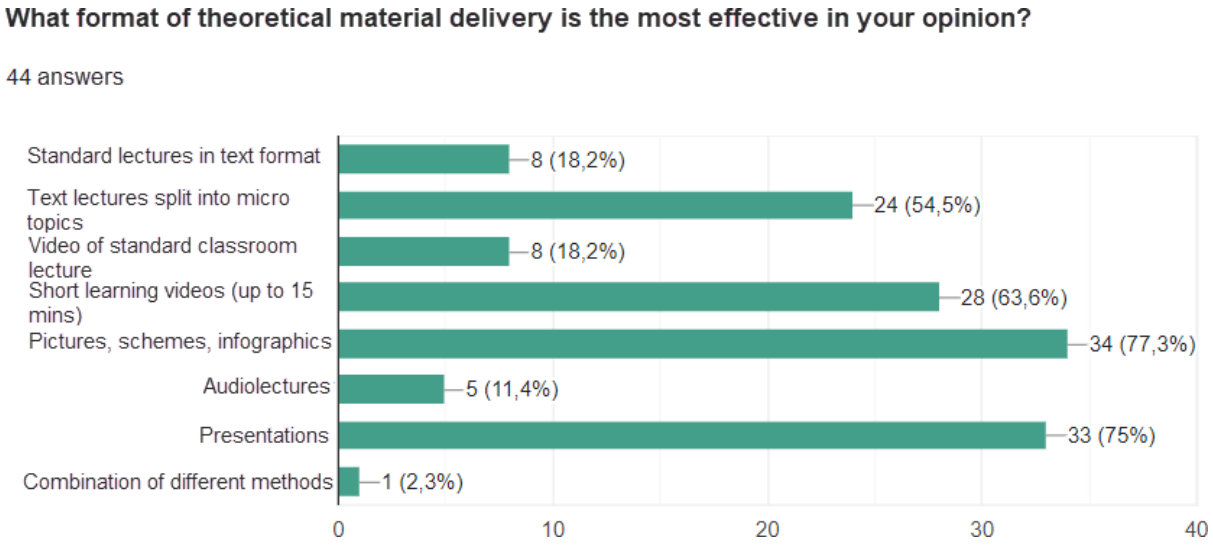

Figure 8: Effective ways of theoretical material delivery (survey results).

to the activities which are the most beneficial from the perspective of adaptivity implementation, i.e. Lesson and Quiz modules.

A teacher can use Lesson activity to provide consequent theoretical materials (that is a set of pages with lecture materials) or to organise learning activities where different trajectories of a lesson are offered using transactions between pages, adding extra clusters and pages with questions (multichoice, matching, short answer questions, etc.) (figure 9). Depending on the given answer and the way a teacher uses Lesson activity, a student can either go to the next page or return to the previous page or be directed in another way that corresponds to the student's needs.

If it is required, a Lesson can be assessed, designed in different difficulty levels, and can be a part of adaptive assessment.

A type of the lesson can be chosen by a lecturer depending on the educational needs and the way it will be used – for support of in-class activities or for self study.

One of the activities through which an assessment can be organised is Quiz, its filling and display for students depends on the setting of different parameters. We can change the Question behaviour parameter to select the best student passing test mode. Selecting Adaptive mode and Adaptive mode

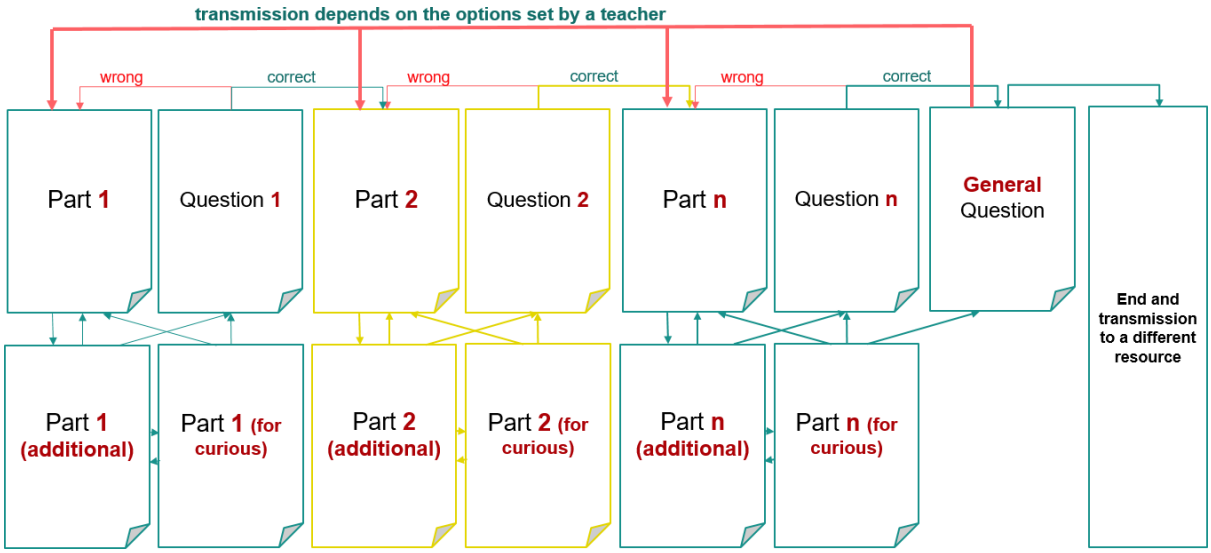

Figure 9: Logical scheme of an adaptive lesson.

(no penalties) allows students to make multiple attempts before moving on to the next question. That is, if students are unsure of their answers, they can check it directly during the attempt and change their answers, but the repeated answer is indicated by taking into account the appropriate penalty indicated by the teacher in the parameters of the question (figure 10).

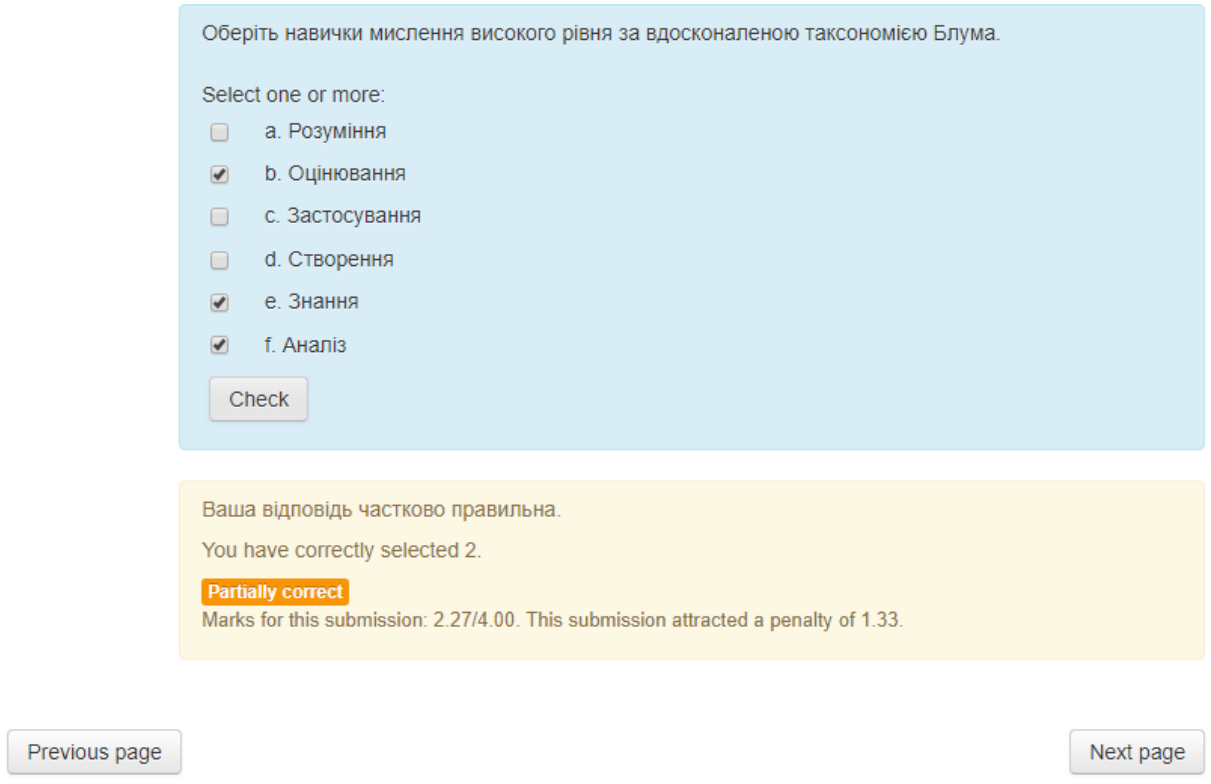

Figure 10: A test with penalties in the Interactive with multiple tries or Adaptive mode.

Penalties are established for each question separately in the Multiple tries section of editing a question. Hints are added in the same section. Both options are used only in the correspondent modes which allows teachers to use the same question in tests with different modes. For example, a test for formative assessment might have multiple tries and hints, whereas for a summative assessment test Deferred

feedback mode can be chosen.

In Interactive with multiple tries mode after submitting one answer and reading the feedback, the student must click the “Try Again” button before attempting a new answer.

The teacher can provide students with tips to help answer questions. Once a student has correctly answered the question, he can no longer change his answer. After a student has made too many mistakes with the question, the answer is evaluated as incorrect (or partially correct) and receives feedback. A student may have different feedback after each attempt. The number of attempts a student receives is the number of tips in determining the question plus one. The use of this mode gives a student an opportunity to determine whether to use the tips or not and adjust their assessment.

Deferred feedback or Immediate feedback mode with Certainty-based marking (CBM) are the modes where a student not only answers the question but also indicates how confident they are: not very sure (less than 67%); average confidence (between 67% and 80%) or very confident (more than 80%).

When the answer is assessed, both accuracy and the level of certainty are considered by the system. For example, if the answer is correct, but only guessed, the score is adjusted from 1 to 0.33. If the answer is incorrect and high level of confidence was indicated, the score can be from 0 to -2 points (figure 11).

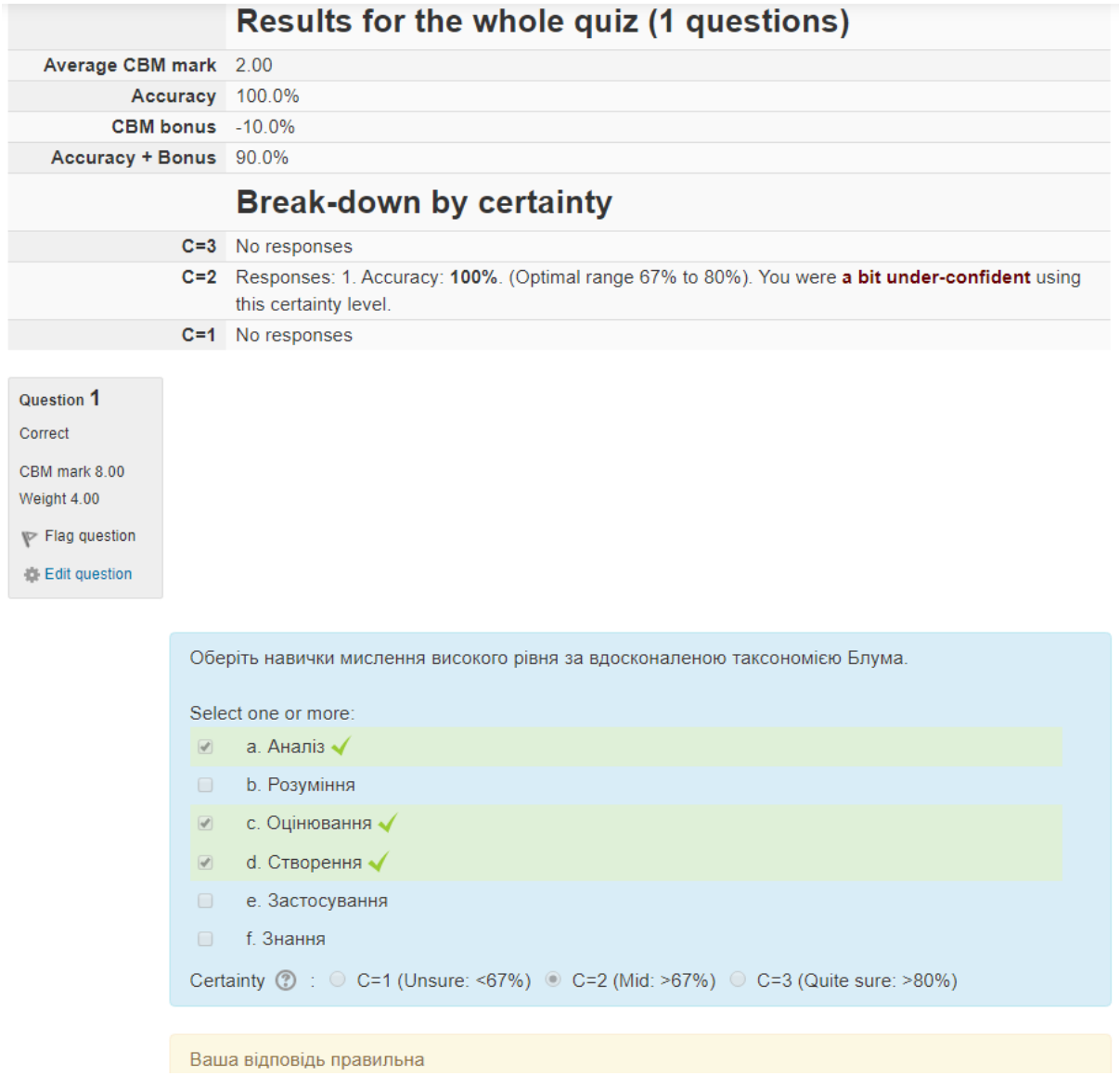

Figure 11: An example of answered question in a mode with CBM.

Using this mode provides the following benefits for students:

- they have to evaluate the correctness of our own answer;
- encouraging a solution to a problem, as opposed to answering questions immediately;
- adds confidence in your own knowledge;
- get a more objective rating.

To encourage students to fill the gaps in their knowledge, Combined feedback option can be used in questions for Quiz. For each incorrect or partly correct answer a teacher can indicate a related topic to study or/and give links to the corresponding activities and resources in the course.

Post-test stage. After the learner has finished the entire learning path, it has to be checked whether the learning process was successful or not and needs some changes to be made. The summative assessment can be arranged in the form of a test, a project (individual or group), a speech etc. Thus, such activities as Quiz, Workshop, Wiki or Assignment are prevailing at this stage. The results of summative assessment must be analysed to find out strengths and weaknesses of the e-learning course and plan improvements for its next PDCA cycle. It is also essential to get feedback from students on the course to see whether there was enough material on each topic and whether it was understandable, diverse and easy to use. The feedback collection can be arranged with activities Questionnaire, Feedback, Forum.

Feedback lets you create surveys with different types of questions, including multiple choice, yes / no, or text input to determine the level of satisfaction in the learning process, gaps in the course arrangement, etc. This resource allows you to view statistics in the form of diagrams, tables, and download them for further processing.

4. Critical analysis of implementation challenges and solutions

Analysis of adaptive learning implementations across multiple institutions reveals consistent patterns of challenges and successful mitigation strategies. Technical challenges primarily center on integration complexity and algorithm transparency (table 2), with 68% of implementations reporting difficulties in connecting external AI engines to Moodle's core functionality [36, 44]. Successful implementations address these through modular plugin architectures that maintain clear separation between adaptive logic and content delivery, exemplified by the Pythia framework's use of standardized APIs for tool integration [29].

Table 2
Comparative analysis of adaptive learning plugins for Moodle.

Plugin/System	Core technology	Adaptation method	Key features	References
Pythia	Bayesian Networks, Markov Models	Probabilistic path generation	Modular architecture, transparent algorithms	[29]
Lecomps	Dynamic student modeling	Knowledge-based sequencing	Standalone integration, personalized objects	[32]
AdaptiveLesson	Learning style detection	Content presentation adaptation	Simplified teacher interface	[45]
MEAP+	Machine learning classifiers	Early warning system	At-risk student detection	[46]
SAM-FL	Clustering + ChatGPT	Hybrid AI approach	Real-time adaptation	[42]

Pedagogical challenges emerge particularly in alignment with specific educational models. Research indicates significant misalignment when adaptive features are applied to problem-based learning (PBL) contexts, with only 35% of PBL implementations achieving desired learning outcomes [47, 48]. This suggests the need for model-specific adaptation strategies rather than generic adaptive approaches.

Teacher readiness emerges as a critical factor, with studies showing that only 42% of educators feel adequately prepared to implement adaptive learning features despite positive attitudes toward the technology [49, 50]. Successful implementations invest heavily in differentiated training programs that account for varying levels of digital competence and provide ongoing support through communities of practice [51].

5. Future directions and recommendations

Based on comprehensive analysis of implementations from 2015-2024 (figure 12), several key recommendations emerge for institutions planning adaptive learning deployment in Moodle.

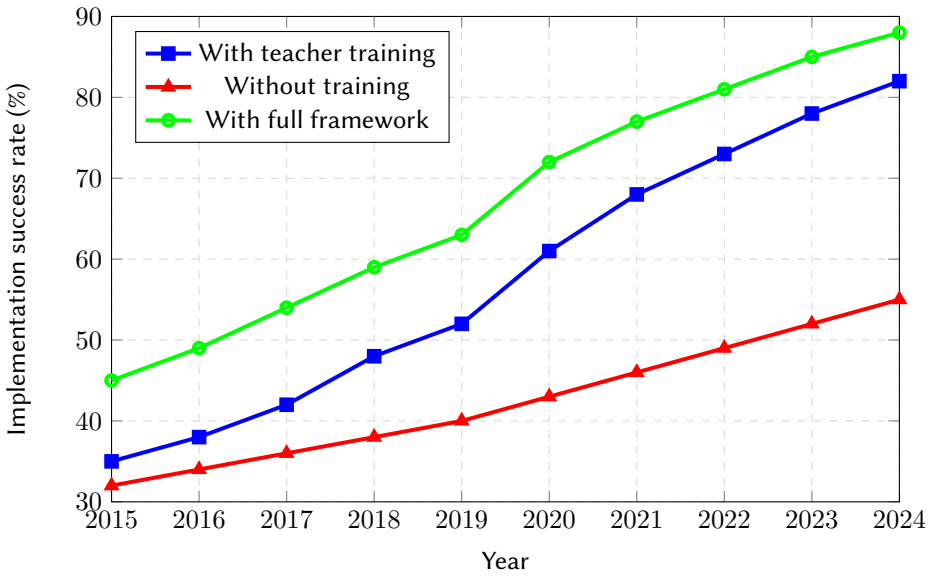

Figure 12: Evolution of adaptive learning implementation success rates in Moodle (2015-2024) showing the impact of teacher training and comprehensive frameworks.

Institutions should prioritize cloud-based deployments which demonstrate 89.6% faster response times and 88% increased throughput compared to local installations [52]. Implementation of graph-based content models rather than traditional relational structures enables more sophisticated semantic relationships and real-time adaptation [44].

Successful implementations align adaptive features with established pedagogical frameworks. The integration of constructivist approaches with adaptive technologies shows 67% improvement in learning outcomes compared to technology-only implementations [53]. Microlearning principles should guide content segmentation, with optimal chunk sizes of 5-10 minutes showing highest engagement rates.

Privacy-first frameworks compliant with GDPR and FERPA are essential, with particular attention to transparent data usage policies [54, 55]. Regular stakeholder engagement through iterative feedback cycles ensures continuous alignment with institutional goals and student needs.

6. Conclusion

The survey of students carried out at Borys Grinchenko Kyiv University indicated that there is a need for personalisation of the learning environment and individual learning path arrangement. Adaptive learning is an educational approach that can meet the needs.

Analysis of Moodle LMS activities and resources presented in the research paper has shown that adaptive learning can be implemented in HEIs with the help of already used learning management systems. Each stage of adaptive learning implementation (initial stage, pre-test stage, path generation stage, learning stage and post-test stage) is possible to be arranged by means of Moodle LMS. Microlearning plays an essential role in adaptive learning implementation as learning materials divided into small parts are easier to meet individual educational needs of a learner, to navigate in an ELC and to update when required.

Comprehensive analysis of implementations from 2015-2024 reveals that successful adaptive learning deployment in Moodle requires coordinated efforts across technical, pedagogical, and administrative dimensions. While Moodle's plugin architecture and community-driven development provide a robust

foundation for adaptive features, realizing the full potential requires addressing persistent challenges in teacher readiness, pedagogical alignment, and ethical AI deployment. Institutions that implement comprehensive frameworks incorporating differentiated teacher training, privacy-first data governance, and iterative refinement based on learning analytics demonstrate significantly higher success rates (88% with full framework vs. 55% without) [28, 31].

The evolution from simple content sequencing to sophisticated AI-driven personalization represents a paradigm shift in educational technology, yet the human elements of teacher engagement and pedagogical design remain paramount. Future research should focus on developing standardized evaluation metrics for adaptive learning effectiveness, creating discipline-specific adaptation models, and exploring the integration of emerging technologies such as large language models while maintaining ethical standards and educational equity.

The paper is dedicated mostly to technological challenges of adaptive learning implementation. Further research of the topic might include pedagogical and management-related issues such as learning materials modification, teacher training, adaptive e-learning courses and educational programs correlation, etc.

Declaration on Generative AI

The authors have not employed any generative AI tools.

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LLM-driven educational game for conflict mediation training in Ukrainian wartime conditions

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Abstract

Wartime conditions in Ukraine have led to a significant increase in interpersonal conflicts, negatively affecting psychological well-being and social cohesion. This paper introduces an innovative AI-driven educational game that teaches mediation skills through dialogue with characters generated by large language models (LLMs). The system features dynamically generated conflict scenarios and personalized responses, providing a safe, repeatable environment for mediation practice. We implemented the game using Gemini 1.5 Flash LLM and evaluated different mediation strategies quantitatively. Our experiments demonstrate that the compensation strategy appeared to be effective in investigated conflict scenarios. Our approach enables the quantitative evaluation of mediation approaches, which is virtually impossible in real-world settings. This technologically advanced approach addresses a significant gap in mediation education, offering an accessible tool for training mediators in war-affected regions.

Keywords

mediation training, conflict resolution, large language models, educational games, Gemini API, wartime education, AI in education

1. Introduction

Wartime conditions create challenges for interpersonal relationships [1, 2, 3, 4, 5, 6, 7]. The war in Ukraine, ongoing since 2014 [8, 9, 10], has caused profound disruption to social fabric with increasingly severe consequences for mental health and social cohesion. According to national and international monitoring agencies, since the beginning of the war, 21.3 million Ukrainians (with 57% of children among them) have experienced its consequences and needed humanitarian assistance [11]. These circumstances generate extraordinary stress and destroy not only actual infrastructure, but also vital social connections.

Children and adolescents are particularly vulnerable to these negative impacts. Under war conditions, normal psychological development faces significant disruption from stressful situations and traumatic experiences. Without timely and qualified psychological assistance, traumatized children may experience serious developmental issues with long-term consequences that can cause interpersonal later [12].

Mediation is a valuable tool for peacefully resolving disputes, but there is still a critical shortage of accessible and interactive tools to learn these skills, particularly in war-affected territories. This educational gap is especially relevant in Ukraine. Addressing this need requires innovative approaches that combine educational theory with modern technology.

Large language models (LLMs) open opportunities to create interactive educational experiences [13, 14]. Their ability to generate contextually relevant dynamic content, respond intelligently to user input, and simulate complex social interactions makes them particularly suitable for training social

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skills like mediation. However, while LLMs have been integrated into various educational applications, their potential for teaching conflict resolution skills remains unexplored.

2. Related work

The psychological impact of war extends far beyond immediate trauma. Brulin et al. [15] characterize war as a major, persistent polytraumatic event with deleterious psychological consequences affecting large populations within and outside war-affected territories. The research by Semigina [16] reveals that Ukrainian social services and social workers were largely not prepared to operate effectively in emergency situations.

The Ukrainian legal framework defines mediation as "an extrajudicial voluntary, confidential, structured procedure during which the parties, with the help of a mediator, try to prevent or resolve a conflict through negotiations" [17]. Since 2018, thousands of Ukrainian schools have established "Reconciliation Services" that actively work on preventing and responding to conflicts in educational environments [18]. In 2024, several new mediation-related educational projects were launched, including the Erasmus+ project "The Art of Negotiation and Conflict Resolution (Mediation)/ArtNoConflict" and a joint project between Kharkiv National University and UNICEF focusing on trauma-oriented approaches to mental health, psychological support, and mediation [19, 20].

Large language models have demonstrated significant potential for enhancing educational experiences across disciplines. Bewersdorff et al. [21] highlight how LLMs, particularly Multimodal Large Language Models (MLLMs) like GPT-4 Vision, can process multimodal data to create enriched, personalized, and interactive learning environments. These applications range from content creation to learning support, fostering engagement in scientific practices, and providing nuanced assessments and feedback.

In educational gaming contexts, LLMs have been employed to enhance player experiences by creating dynamic, responsive environments. Gatti Junior et al. [22] explore the application of LLMs such as ChatGPT in designing educational board games, guiding educators through phases of ideation, customization, and prototype feedback. Similarly, Todd et al. [23] investigate the use of LLMs to generate functional video game levels, finding that performance scales impressively with dataset size.

The integration of LLMs with game-based learning environments has shown particular promise. Goslen et al. [24] introduced a plan generation framework that leverages text representations of students' interactions in game-based learning environments to generate plans for accomplishing target goals. Their results indicate that AI-generated plans can guide students to achieve learning objectives more efficiently than traditional approaches.

However, significant challenges remain in implementing LLMs in educational contexts. As noted by Huber et al. [25], while LLMs provide numerous opportunities, they also introduce risks of over-reliance that could potentially limit the development of authentic domain expertise. Furthermore, Gatti Junior et al. [22] identify challenges such as biases from training datasets, generation of inaccurate details, counter-intuitive rules, and misinterpretation of feedback, which can result in unintended learning dynamics.

There have been attempts to use LLMs for conflict resolution and negotiation training. Bianchi et al. [26] developed NEGOTIATIONARENA, a flexible framework for evaluating and testing the negotiation abilities of LLM agents. Their findings indicate that while LLMs can significantly improve negotiation outcomes by employing certain behavioral tactics, they also exhibit irrational negotiation behaviors similar to those observed in humans. Shaikh et al. [27] introduced Rehearsal, a system enabling users to practice handling conflicts with a simulated interlocutor, explore alternative conversational paths, and receive targeted feedback on conflict strategies. Their approach conditions the output of an LLM on the Interest-Rights-Power (IRP) theory from conflict resolution literature, guiding users toward strategies that help de-escalate difficult conversations.

However, to our knowledge, no existing work has specifically addressed the use of LLMs for teaching mediation skills in the context of wartime, particularly in the Ukrainian context. This gap represents an important opportunity to leverage the advanced capabilities of LLMs to address an urgent social need

with significant implications for community resilience.

3. Methodology

3.1. Game design and architecture

The game features a 2D environment where players navigate and interact with various characters, each possessing unique personalities and conflict scenarios. Figure 1 illustrates the class diagram.

Key classes are:

- *GameObject* is the base abstract class for all the game objects. They include *Player* (player character), *Obstacle* (houses, trees etc.), *AICharacter* (opposing characters), *AIAssistant* (a virtual mentor character who gives mediation tips and helps player).
- Each *AICharacter* has *trust* and *consent* integer fields that store the level of trust to the player and willingless to resolve the conflict. These variables are affected by player's actions.
- *Conflict* class stores the essence of the conflict between two characters.
- *SpriteSheet* is a class for loading sprites from files.
- *MyConsoleWindow* is a subclass of *pygame_gui.windows.UIConsoleWindow* with nearly identical functions.

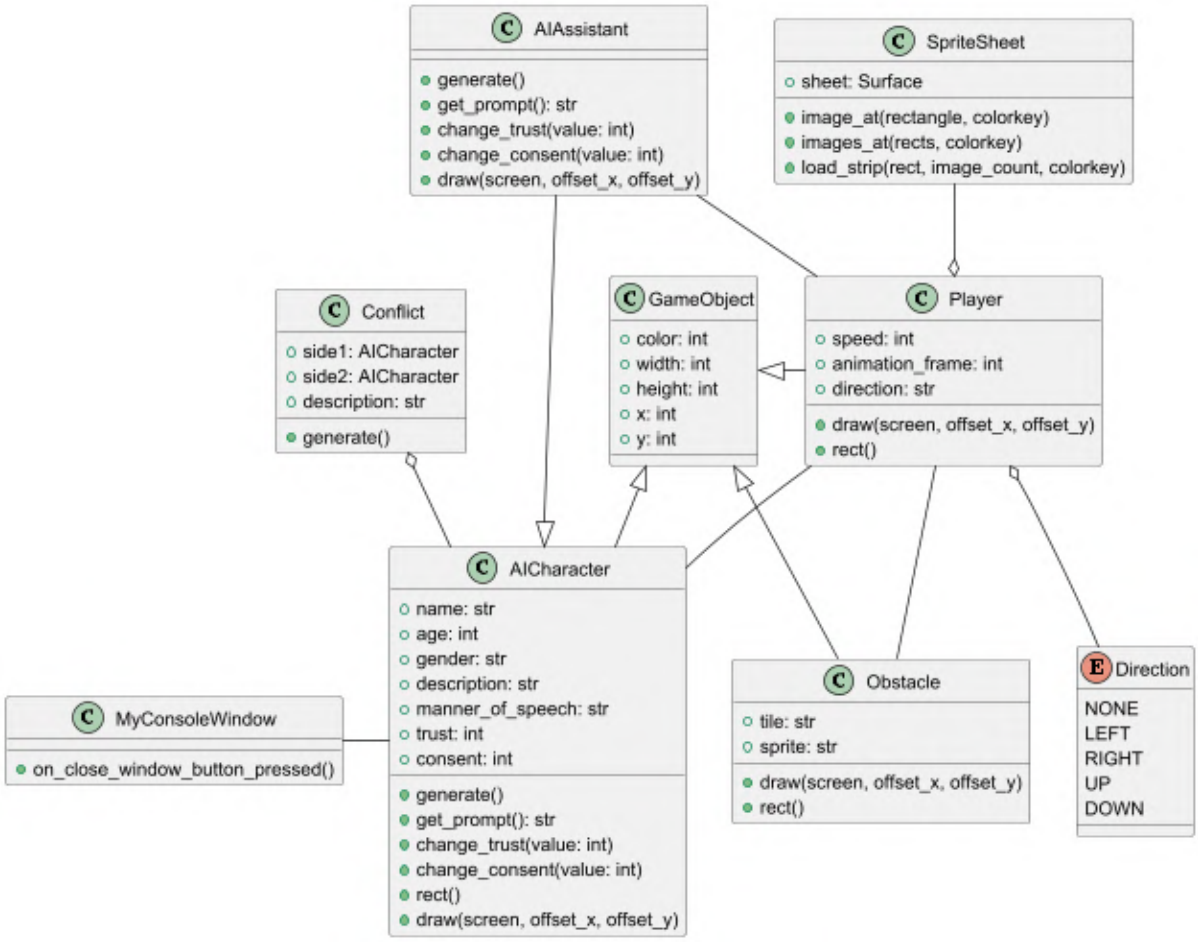

Figure 1: UML class diagram of the game.

The game interface (figure 2) was designed with user experience principles in mind, ensuring intuitive navigation and clear visual feedback on mediation progress through trust and compromise metrics.

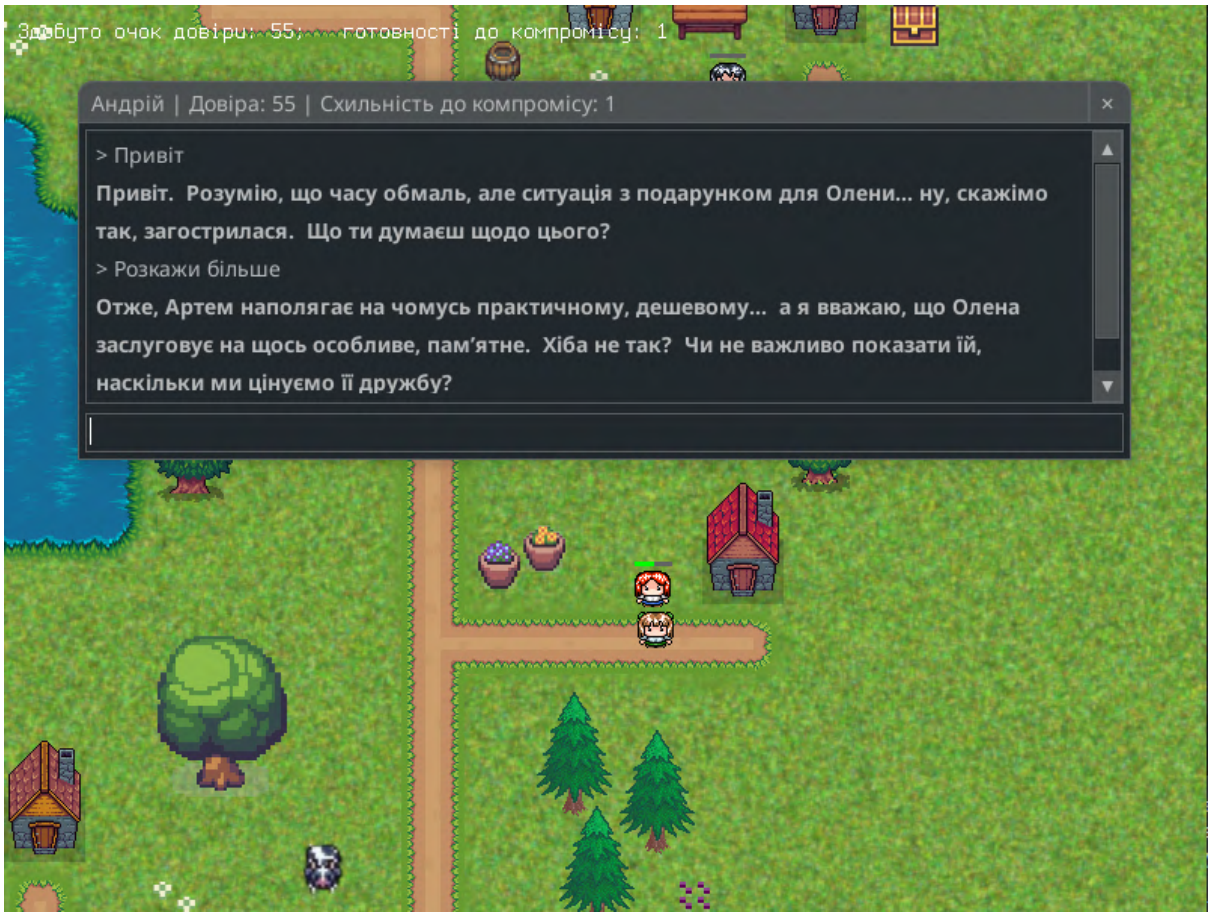

Figure 2: Game interface showing player character, environment, and dialogue console.

3.2. LLM selection and integration

We considered hosting a local LLM, but it would dramatically increase system requirements giving ho-hum generation quality compared with larger commercial LLMs.

After comprehensive evaluation of several state-of-the-art LLMs, we selected Gemini 1.5 Flash for our implementation. This decision was based on comparative research examining the performance capabilities of ChatGPT-4o and Gemini 1.5 Flash [28], which showed that while ChatGPT-4o demonstrates high baseline performance, specialized training produces only marginal accuracy improvements. In contrast, Gemini 1.5, despite lower initial performance, exhibits substantial improvements after training, particularly with textual data. These findings indicate Gemini 1.5's superior ability to store and retrieve contextual information, making it potentially more effective for dynamic dialogue generation in educational contexts.

Another factor was cost-effectiveness. Gemini 1.5 Flash provides limited free account, which is sufficient for single-player game.

Integration with the Gemini API involved several technical steps:

1. Obtaining an authenticated API key through Google AI Studio.
2. Installing and configuring the Python google.generativeai library.
3. Developing system instructions for character-specific information processing.
4. Implementing a dialogue management system for handling user input and LLM responses.
5. Creating a response parsing mechanism to extract character dialogue and update game state metrics.

The integration utilized Gemini's system instructions mechanism to provide character-specific contextual information processed by the model before handling the main conversational request. We

developed a specialized prompt template describing the generated character, their conflict situation, and specific response format instructions. Additionally, we implemented a custom delimiter-separated values (DSV) protocol using the ^ symbol to split the received response into three components: the character's textual response, a trust score (ranging from -5 to 5), and a willingness-to-compromise score (ranging from -3 to 3).

```
# Model preparation
def set_context():
    genai.configure(api_key=api_key)
    MODEL = 'gemini-1.5-flash'
    SYSTEM_INSTRUCTION = current_character.get_prompt() + \
            "Conflict essence: " + \
            conflict.description + \
            " \nFORMAT OF YOUR RESPONSES: three lines separated by '^' character. \n1. First line - text response of your character." + \
            " \n2. Second line - integer from -5 to 5, which shows whether your TRUST towards the player has changed." + \
            " -5 means significantly decreased, 5 means significantly increased." + \
            " \n3. Third line - integer from -3 to 3, which shows whether your WILLINGNESS TO COMPROMISE has changed." + \
            " -3 means significantly decreased, 3 means significantly increased."

    print(SYSTEM_INSTRUCTION)
    global model
    global chat
    model = genai.GenerativeModel(MODEL, system_instruction=SYSTEM_INSTRUCTION)
    chat = model.start_chat()
```

Listing 1: Model configuration for character-specific dialogue generation.

3.3. Mediation strategy evaluation framework

To evaluate the effectiveness of different mediation approaches, we designed a controlled experiment comparing four distinct strategies established in conflict resolution literature. Table 1 outlines these strategies and their key characteristics.

Table 1
Mediation strategies evaluated in the experimental study.

Strategy	Description
Integration	Focuses on identifying and leveraging shared interests between conflicting parties. The mediator helps participants discover common ground and develop compromises that satisfy core needs of both sides.
Pressure	Involves strategically limiting options where no agreement exists. The mediator reduces the perceived attractiveness of alternatives that exclude agreement, thereby motivating parties toward compromise through controlled environmental constraints.
Compensation	Centers on expanding the range of possible agreement options. The mediator actively seeks additional incentives, benefits, or creative solutions for each party to enhance the likelihood of reaching mutually beneficial agreements.
Inaction	Represents minimal intervention in the negotiation process, allowing parties to resolve disputes through their own initiative. This approach is typically employed when participants demonstrate existing capacity for autonomous conflict resolution.

In each experimental trial, we utilized the same character pair and identical conflict scenario to ensure controlled conditions. For each strategy, we conducted 20 dialogue turns, systematically applying the principles of that specific approach throughout the interaction sequence. The effectiveness of each strategy was measured using the game's trust and willingness-to-compromise metrics, which

were updated after each player interaction based on the LLM's assessment of interaction quality and appropriateness within the simulated conflict context.

This experimental design was specifically developed to demonstrate the potential of quantitative strategy evaluation in mediation training, an approach that is nearly impossible in real conflicts.

4. Implementation

4.1. Game development

We developed the game using Python with the Pygame library providing the core rendering and interaction framework. For modular architecture and maintainable code, we organized the implementation into six primary components:

- `main.py`: contains the central game loop, primary settings, movement mechanics, and AI request management
- `aicharacter.py`: contains *AICharacter* class implementation, handles character generation, trait management, and behavior modeling
- `player.py`: contains *Player* class implementation, controls player appearance, animations, and user-directed actions
- `conflict.py`: contains *Conflict* class implementation, defines conflict scenarios and relationships
- `obstacle.py`: contains *Obstacle* class implementation, implements environmental elements and collision detection
- `spritesheet.py`: provides sprite loading, animation sequencing, and visual processing.

The initialization process establishes the Pygame environment and creates a game window with specific dimensions. We implemented the graphical user interface using the *pygame_gui* library, which provides a dialogue window functionality for character communication.

Character generation is managed by the *AICharacter* class, which defines comprehensive behavior models and interaction properties for game agents. The class includes methods for dynamically generating character traits and updating game metrics based on the quality and appropriateness of player interactions.

```
class AICharacter:
    color = (255, 0, 0)
    width, height = 50, 50
    x, y = 100, 100
    tile = ""
    sprite = None
    name = "Anonymous"
    age = 20
    gender = "male"
    description = ""
    manner_of_speech = ""
    objective = ""
    trust = 0  # trust towards player
    consent = 0  # willingness to compromise

    def generate(self):
        self.name = random.choice(names)
        self.age = random.randint(18, 70)
        self.gender = random.choice(["male", "female"])
        self.description = random.choice(descriptions)
        self.manner_of_speech = random.choice(speech_manners)
        self.objective = random.choice(objectives)

    def change_trust(self, value):
```

```
        self.trust += value
        self.trust = max(0, min(100, self.trust))

    def change_consent(self, value):
        self.consent += value
        self.consent = max(0, min(100, self.consent))
```

Listing 2: AICharacter class definition for modeling character behavior.

Player movement is implemented through keyboard input controls that enable navigation in multiple directions. The system restricts movement while the dialogue console is active, ensuring players maintain focus on the mediation process during critical character interactions.

The conflict generation system creates diversified scenarios by algorithmically combining different conflict descriptions, participant characteristics, and contextual factors. This procedural generation ensures each gameplay session presents unique mediation challenges reflective of real-world complexity.

```
conflict_descriptions = [
    "p1 and p2 work together in a local community organization, but have developed tension over resource allocation for displaced families.",
    "p1 and p2 are neighbors in a building partially damaged by shelling, and disagree about reconstruction priorities.",
    "p1 and p2 have a joint volunteer initiative, but have different views on coordinating with military personnel.",
    "p1 and p2 are teachers at the same school with conflicting approaches to helping traumatized students."
]

class Conflict:
    side1 = None  # conflict party 1
    side2 = None  # conflict party 2
    description = ""

    def generate(self):
        self.description = random.choice(conflict_descriptions)
        self.description = self.description.replace("p1", self.side1.name)
        self.description = self.description.replace("p2", self.side2.name)

    def __init__(self, s1:AICharacter, s2:AICharacter):
        self.side1, self.side2 = s1, s2
        self.generate()
```

Listing 3: Conflict scenario generation system.

4.2. Dialogue system

The dialogue system constitutes the core of the game's mediation training functionality. When a player encounters a character through proximity detection, the *current_character* variable is initialized, triggering the preparation of the AI model for context-aware dialogue. This action opens the console window to initiate communication with the character. For processing user input and generating contextually appropriate AI responses, we construct a structured request in the PROMPT variable that incorporates the current trust level, willingness to compromise, and the new input message. The *chat.send_message(PROMPT)* method transmits this request to the AI engine and receives a formatted response. Upon character response generation, an audio notification plays, and the dialogue content appears in the game's console window, with character metrics updated according to AI-assessed interaction quality.

```
if (event.type == pygame_gui.UI_CONSOLE_COMMAND_ENTERED and
        event.ui_element == console_window):
    command = event.command
    if current_character:
```

```
        PROMPT = "Your current TRUST level is " + str(current_character.trust) + " out of 100." +
    \
                "Your WILLINGNESS TO COMPROMISE is currently " + str(current_character.consent) +
    \
                " out of 100." + "Next interlocutor reply: " + command + " "
        response = chat.send_message(PROMPT)
        print(response.text)
        talk_sound.play()  # sound on response
        console_window.add_output_line_to_log(response.text.split("^")[0], is_bold=True)
        try:
            # Change trust level and willingness to dialogue
            current_character.change_trust(int(response.text.split("^")[1]))
            current_character.change_consent(int(response.text.split("^")[2]))
        except:
            pass
        console_window.set_display_title(current_character.name + \
                        " | Trust: " + str(current_character.trust) + \
                        " | Willingness to compromise: " + str(current_character.consent))
```

Listing 4: Dialogue processing and response handling system.

This dialogue system creates a dynamically responsive interaction experience where player choices directly influence character trust and willingness to compromise, providing immediate feedback on mediation effectiveness. The system's design emphasizes educational value through experiential learning, allowing players to witness the consequences of their mediation approaches in a realistic but controlled environment.

5. Results and discussion

5.1. Mediation strategy evaluation

The comparative assessment of different mediation strategies revealed substantial variations in effectiveness as measured by our game's quantitative trust and willingness-to-compromise metrics. Figure 3 presents the comparative effectiveness of each strategy based on our experimental trials.

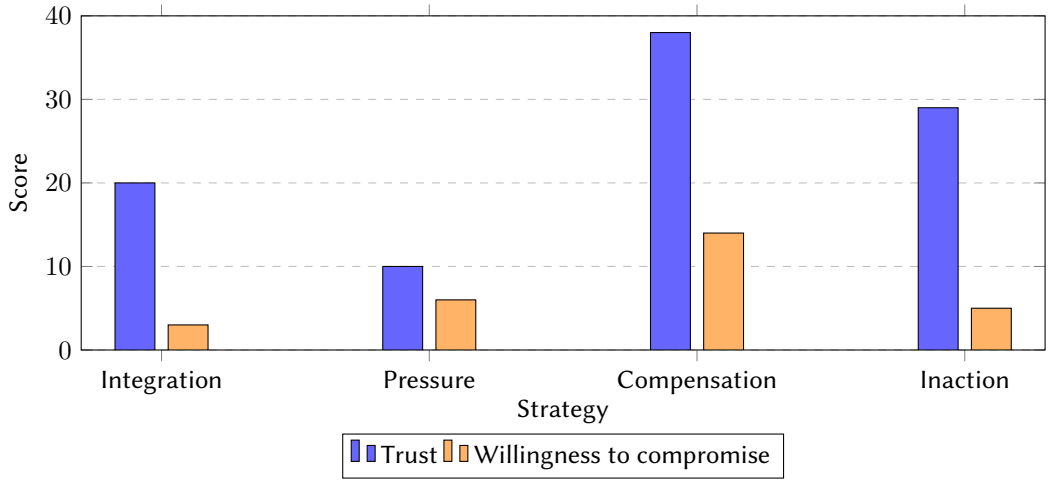

Figure 3: Comparative effectiveness of mediation strategies measured by trust and willingness to compromise scores.

The compensation strategy demonstrated superior effectiveness in our generated conflict scenarios, achieving an average trust score of 38 (out of 100) and a willingness-to-compromise score of 14 (out of 100) after 20 dialogue turns.

The integration and inaction strategies proved moderately effective. The pressure strategy demonstrated limited effectiveness, with average scores of 10 for trust, but 6 for willingness to compromise,

which is better compared to integration and inaction strategies.

Interestingly, the inaction strategy performed better than expected on trust metrics (29) but poorly on willingness to compromise (5). This suggests that while non-intervention may preserve trust relationships to some degree, it fails to advance actual conflict resolution progress.

These findings complement research by Carnevale [29], who identified compensation as particularly effective in certain conflict types characterized by resource scarcity and high emotional intensity. However, it's important to acknowledge that our results are specific to the AI-generated conflict scenarios in our system and may not generalize perfectly to all real-world conflicts.

5.2. Implications for mediation training

Our research demonstrates the significant potential of LLM-based educational games for teaching mediation skills, particularly in contexts where traditional training methods face resource or access limitations. The game provides several advantages over conventional approaches.

First, the digital format enables widespread distribution, making mediation training accessible to individuals who might otherwise lack access to formal instruction. This accessibility is particularly valuable in war-affected regions like Ukraine, where the need for mediation skills is acute but training resources are often severely constrained.

Second, the system creates a risk-free environment for users to experiment with different mediation strategies without fear of real-world consequences. This psychological safety encourages experimentation and learning through trial and error, which is essential for developing mediation skills.

Third, unlike traditional role-play exercises, our system provides immediate, quantitative feedback on the effectiveness of different approaches through trust and willingness-to-compromise metrics. This data-driven feedback allows users to gain concrete insights into which strategies prove most effective in different scenarios, accelerating the learning process through clear outcome visualization.

Fourth, the ability to generate diverse conflict scenarios and reset interactions enables users to practice identical mediation techniques across different contexts or try alternative approaches with the same characters. This capability reinforces learning through repetition while developing adaptability through contextual variation.

5.3. Limitations and future work

While our research demonstrates the significant potential of LLM-based games for mediation training, several limitations should be acknowledged. The effectiveness of different mediation strategies may vary across cultural contexts and conflict types. Future work could expand the range of scenarios to address a wider variety of cultural settings and conflict situations through enhanced prompt engineering and scenario design.

Despite ongoing advances, LLMs still face challenges in maintaining perfect coherence across extended dialogues and may occasionally generate inappropriate responses. More sophisticated filtering and safety mechanisms could be implemented to address these issues, particularly important when dealing with sensitive conflict scenarios involving trauma. Advanced prompt chaining techniques could potentially improve narrative coherence across extended mediation sessions.

While our quantitative metrics provide valuable insights, they are based on the LLM's assessment rather than external validation from trained mediators. Future studies could incorporate expert evaluations or real-world outcome correlations to further validate the educational effectiveness of the training system.

6. Conclusion

This paper has presented an innovative educational game for teaching mediation skills using LLM-generated dialogues specifically designed for wartime conditions in Ukraine. The system leverages the capabilities of the Gemini 1.5 Flash LLM to create responsive characters engaged in realistic conflict

scenarios reflective of current challenges. We have created an engaging learning environment that provides immediate feedback on mediation effectiveness through quantitative metrics.

Our experimental evaluation of different mediation strategies revealed that the compensation approach, which focuses on expanding possible agreement options, was most effective in our AI-generated conflict scenarios. This finding provides quantitative support for theoretical perspectives on mediation strategy.

The game addresses a critical need for accessible mediation training, particularly in war-affected regions where interpersonal conflicts have increased dramatically due to wartime conditions.

Future research will focus on expanding the range of conflict scenarios, implementing more sophisticated feedback mechanisms, and validating the effectiveness of the training through longitudinal studies tracking skill transfer. These enhancements will further strengthen the system's value as an educational tool and contribute to the growing body of knowledge on both mediation practice and LLM applications in education for conflict resolution.

Declaration on Generative AI

During the preparation of this work, the authors used Claude 3.7 Sonnet to enhance content and improve writing style. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

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Automated detection of various types of plagiarism in academic papers of IT students

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Abstract

The article explores the problem of automated detection of various types of plagiarism in academic works of IT students. Particular attention is paid to the more challenging forms of plagiarism to detect, especially those based on paraphrasing. An experiment was conducted using five popular plagiarism detection services. For analysis, a dataset was compiled consisting of 50 original texts and 712 paraphrased versions. A metric called Paraphrasing Detection Sensitivity (PDS) is proposed to quantitatively assess the ability of the services to identify paraphrasing plagiarism. The results revealed a significant variation in effectiveness among the systems, and conclusions were drawn regarding their practical applicability.

Keywords

plagiarism, paraphrasing plagiarism, automated processes, paraphrasing detection sensitivity metric, ethical academic practices, academic originality assessment, future IT Professionals, vocational skill development, automated processes, digital rights law, AI-powered information systems

1. Introduction

Information technologies play a key role in organizing labor, education, research, entertainment, and other aspects of everyday human activity [1, 2, 3]. They serve as a driving force that shapes the economic, technological, and scientific potential of a country.

In this regard, it is important to train future IT specialists, as they play an important role in the process of setting up and maintaining computer systems, participate in the development and further support of software, and influence the level of development and penetration of information technology in all spheres of human life [4, 5]. After graduation, future IT specialists should have a system of professional and key competencies, be ready to work in a team, have skills of self-learning, self-organisation and continuous professional growth.

The development of digital technologies, in addition to its obvious positive effects [6, 7], has negative aspects. With the development of digital technologies, students have gained wide access to information resources. This, on the one hand, increases the efficiency of the learning process, and on the other hand, creates preconditions for unauthorised copying of other people's materials without proper acknowledgement. This practice undermines academic integrity, distorts assessment results and negatively affects the quality of training of future professionals. Therefore, detecting and preventing plagiarism is

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an important task for higher education institutions that requires effective solutions, in particular by automating the verification process.

The problem of automating the detection of plagiarism in student papers is not new. In particular, Durge et al. [8] describe the peculiarities of using the developed computer system for detecting plagiarism in computer programming. Gambo et al. [9] describe the GRAD-AI software tool, an automated tool for assessing computer programming assignments that combines automation with teacher involvement for accurate grading, timely feedback, and personalised support, enhancing the educational process. Sağlam et al. [10] proves the importance of human involvement in the process of automatic plagiarism detection. This paper presents a novel approach for automated plagiarism detection in modeling assignments that combines automated analysis with human inspection. The results show that we achieve a significantly higher detection rate for AI-generated attacks and a broader resilience than the state-of-the-art.

In recent years, humanity has been actively using artificial intelligence systems [11, 12, 13, 14, 15, 16], in particular generative artificial intelligence [17], to meet its daily needs. The educational process is no exception. The absence of ethical principles in generative AI and the ability of people to use it for their own benefit quite easily contribute to the use and abuse of AI-based tools by students of higher education institutions. Therefore, every year there is an increasing number of works devoted to the ethical aspects of using AI in the educational process. Among these works, it is worth highlighting papers [18, 19, 20].

Our study focuses on automating the process of detecting different types of plagiarism in the works of IT students. Therefore, it was important for our study to consider the types of academic plagiarism. Based on the analysis of works [21, 22], the following types of plagiarism were identified: complete plagiarism, direct plagiarism, accidental plagiarism, plagiarising yourself, paraphrasing plagiarism, source-based plagiarism, mosaic plagiarism, AI plagiarism.

This is not the first time that the authors of this article have studied the problem of detecting plagiarism in student papers. Thus, in [23], the authors investigated the peculiarities of using artificial intelligence systems to assess the complexity of an algorithm based on student code fragments. In [22], the authors developed a software application to automate the routine work of university professors in checking student papers for plagiarism and detecting it with the help of AI. The developed software application uses various APIs to search for plagiarism and fragments of text/code generated by AI.

The purpose of this study is to determine the effectiveness of existing automatic plagiarism detection systems in recognising different types of plagiarism in the works of IT students.

2. Methodology

Let us take a closer look at the types of plagiarism and the possibilities of their automatic detection. It is evident that complete plagiarism and direct plagiarism are the easiest types to detect using automated tools. In the case of complete plagiarism, a student or author entirely copies someone else's work without making any changes, whereas direct plagiarism involves verbatim reproduction of individual text fragments without proper citation.

Accidental plagiarism occurs when a student unknowingly presents someone else's ideas, text or code as their own due to a lack of knowledge about proper citation, poor paraphrasing skills or a misunderstanding of what exactly constitutes plagiarism. From the point of view of automatic detection, unintentional plagiarism is a separate issue. Typical checking systems may flag such cases in the same way as intentional plagiarism, without taking into account the author's intent, as such systems evaluate the result, not the process.

From a technical point of view, detecting self-plagiarism is no different from detecting direct plagiarism, as both cases involve finding textual or structural similarities between documents. However, the key difference lies in the source of comparison: to detect self-plagiarism, it is needed to have access to the student's historical work, including previously submitted term papers, labs or projects. Thus, effective detection of self-plagiarism is only possible if the algorithm can compare the new work not only with open sources, but also with the local internal archive of the educational institution.

Source-based plagiarism is a type of academic dishonesty in which a student misuses or intentionally distorts sources. Such plagiarism does not necessarily involve copying text, but rather manipulating references.

AI plagiarism is a type of plagiarism when a student submits as his or her own work text or code generated in whole or in part by artificial intelligence systems. Although such materials may be formally "unique" from the point of view of classical plagiarism detection systems, they are not the product of independent intellectual activity, which contradicts the principles of academic integrity. The main difficulty lies in the fact that AI-generated text may not have any matches with public sources, so automatic verification tools may not detect violations. In [22], the authors conclude that none of the services demonstrate good results in detecting AI plagiarism.

A special place among the types of plagiarism is occupied by paraphrasing plagiarism and mosaic plagiarism. Paraphrasing occurs when a student rewrites someone else's text in his or her own words, preserving the main idea, structure, and content without proper reference to the source. Mosaic plagiarism is the creation of a text by collecting fragments from different sources with partial paraphrasing, changing grammatical structures, or replacing words with synonyms without proper citation. From the point of view of automatic detection, these types of plagiarism are much more difficult to identify than verbatim copying. This requires algorithms that take into account not only superficial but also semantic similarities between texts.

Studies show that paraphrasing is a common practice among students and, in some cases, even their primary strategy. At the same time, students tend to avoid deep comprehension of the original text, favoring superficial or mechanical paraphrasing, also known as patchwriting [24].

That is why in our work we paid attention to determining the quality of automatic paraphrasing detection. As part of the study, we conducted an experiment using a number of automated plagiarism detection services. We are not interested in the generalised quality of the services, but rather in the difference between their ability to detect complete plagiarism and direct plagiarism and their ability to detect paraphrasing plagiarism.

Two sets of textual data were prepared as part of the study. The first set (named TO (1)) contained fragments of student papers (term papers, bachelor's and master's theses) published on the Internet. Since these texts are publicly available, plagiarism detectors should recognise them as cases of direct plagiarism with a complete or almost complete match.

$$\text{TO} = \{\text{to}_i | i = 1 \dots n\} \tag{1}$$

where TO is a set of original (published) student texts, to_i is an i-th text from TO set, $i = 1, \dots, n$, and n is the total number of texts in this set.

For further comparative analysis, a set of sets (named TP (2)) of paraphrased versions was created for each text from the first set. Some of them were generated using artificial intelligence tools, while others were paraphrased manually.

$$\begin{gathered} \text{TP} = \{\{\text{tp}_{ij} | j = 1 \dots k_i\} | i = 1 \dots n\} \\ \text{TP} = \{\text{TP}_i | i = 1 \dots n\} \end{gathered} \tag{2}$$

where TP is a set of sets of paraphrased versions of student texts, k_i is a number of paraphrased versions for text to_i, $i = 1, \dots, n$, tp_{ij} is a j-th paraphrased version of text to_i, $i = 1, \dots, n$, $i = j, \dots, k_i$.

Thus, each original text $\text{to}_i \in$ TO corresponds to a subset TP_i:

$$\text{TP}_i = \{\text{tp}_{ij} | j = 1 \dots k_i\} \tag{3}$$

The result of the to_i text plagiarism detection will be a certain value $\text{R}(\text{to}_i) \in [0 \dots 1]$. The same applies to the values $\text{R}(\text{tp}_{ij}) \in [0 \dots 1]$, which are the results of the plagiarism detection for texts tp_{ij}. A value of 0 means that no plagiarism has been detected, and a value of 1 means that the entire text is plagiarised. An ideal plagiarism detector would return a value of 1 for all texts that participate in the experiment.

To evaluate the quality of the paraphrasing plagiarism detection, we offer a metric of sensitivity to paraphrasing – paraphrasing determination sensitivity (PDS):

$$PDS = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{k_i}\sum_{j=1}^{k_i}|R(\text{to}_i) - R(\text{tp}_{ij})| \quad (4)$$

From expression (4), it follows that PDS is also a normalised value, i.e. it falls within the interval [0...1]. A low PDS value means that the service responds almost equally to original and paraphrased texts (a value of 0 means that the response is the same). A high PDS value means that the service is much better at detecting complete plagiarism and direct plagiarism than paraphrasing plagiarism.

3. Results and discussion

We reviewed 37 plagiarism detection services. Among the available services, we chose those that demonstrate good results in detecting complete plagiarism and direct plagiarism, as there is no point in checking texts for paraphrasing plagiarism in cases where even basic forms of plagiarism are not detected effectively. The list of such services is as follows:

1. Paraphraser plagiarism checker [25].
2. Desklib plagiarism checker [26].
3. Plagiarism Checker by JustDone [27].
4. 1text.com Plagiarism Checker [28].
5. Smart Plagiarism Checker by ExpertChat AI [29].

As part of the experiment, we selected 50 original student works (bachelor's and master's theses, course projects) that are publicly available. These student papers form the TO set ($n = 50$).

To generate the paraphrased texts, the authors used both artificial intelligence tools (with prior verification of the generated output) and manually created texts. For each original text, between 9 and 20 paraphrased versions were produced ($9 \leq k_i \leq 20$). The total number of paraphrased texts is 712.

As an example, table 1 presents the values obtained by running all the services on one of the original texts, along with the results for its paraphrased versions. The values are expressed as percentages.

Table 1
Example of plagiarism check results for one of the texts and its paraphrases.

Services	to_1	$\text{tp}_{1,1}$	$\text{tp}_{1,2}$	$\text{tp}_{1,3}$	$\text{tp}_{1,4}$	$\text{tp}_{1,5}$	$\text{tp}_{1,6}$	$\text{tp}_{1,7}$	$\text{tp}_{1,8}$	$\text{tp}_{1,9}$	$\text{tp}_{1,10}$
Paraphraser	75	44	50	33	50	46	53	37	33	50	61
Desklib	68	0	25	0	22	30	11	0	0	0	24
JustDone	91	80	77	75	84	75	83	66	67	85	91
1text.com	81	0	0	0	0	0	0	0	0	0	0
ExpertChat	87	84	88	85	86	80	85	77	79	88	90

If only one of the above original texts had been used in the experiment, the values of the paraphrasing sensitivity metrics for each of the services would have been the same as those shown in table 2.

As a result of performing the verification procedure for each of the test texts from the TO and TP sets using each of the plagiarism detection services, a data set was obtained, on the basis of which the sensitivity of each of the studied services to paraphrased texts was calculated. This allows for a comparative analysis of their effectiveness. These results are presented in table 3.

The results show a significant difference between different services in terms of sensitivity to paraphrasing. The PDS values for ExpertChat and JustDone are close to 0, which means that they provide high-quality verification of paraphrased texts. The services from 1text.com and Desklib demonstrate good results only for direct plagiarism, but they are unable to recognise plagiarism in paraphrased texts.

Table 2
A set of PDS values to paraphrasing for one of the original texts.

Services	PDS
Paraphraser	0.293
Desklib	0.568
JustDone	0.127
1text.com	0.810
ExpertChat	0.038

Table 3
A set of PDS values for services.

Services	PDS
Paraphraser	0.288
Desklib	0.541
JustDone	0.124
1text.com	0.782
ExpertChat	0.043

The Paraphraser service identifies a significant percentage of paraphrased text and can therefore be used as a support mechanism.

The total number of texts for which the plagiarism checking procedure was executed is calculated in expression (5):

$$m = n + \sum_{i=1}^{n} k_i = 762 \tag{5}$$

This exceeds the minimum sample size required ($n \approx 384$) to estimate proportions with a 95% confidence level and a margin of error of $\pm 5\%$. Accordingly, the obtained sensitivity values can be considered statistically reliable with an error of no more than $\pm 3.7\%$. In addition, since all the texts in the study belong to the IT industry, this ensures high internal homogeneity of the data.

4. Conclusion

This study conducted a comprehensive analysis of the effectiveness of modern services for the automatic detection of plagiarism in student texts in IT. Particular attention is paid to the forms of plagiarism that are difficult to detect, such as paraphrasing.

An experimental dataset was created, consisting of 50 original texts and 712 paraphrased versions. Each text was checked using five popular plagiarism detection services.

In order to quantify the ability of services to recognise paraphrasing plagiarism, the PDS (paraphrasing detection sensitivity) metric was proposed. The results of calculating this metric showed a significant difference in sensitivity between different systems and confirmed the limited ability of most tools to detect plagiarism in transformed texts.

In the future, it is planned to investigate how the type of paraphrasing (lexical, syntactic, semantic or pattern) affects the effectiveness of plagiarism detection. Such an analysis will help identify weaknesses in the work of existing services and formulate recommendations for their improvement.

Declaration on Generative AI

The authors have not employed any generative AI tools.

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Methodology of training future computer science teachers to implement game-based learning: a case study

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Abstract

The paper is devoted to the development of a methodology for training future computer science teachers to use game technologies and organise game-based learning. The structure of the elective course "Methodology of Using Gaming Technologies" is proposed. It includes studying tools for creating quizzes (Kahoot!, Blooket), using gaming modules in the LMS Moodle and implementing Minecraft Education in the educational process. A feature of the course is the combination of gaming technologies as a means and an object of learning, which contributes to better assimilation of the material, activates students' cognitive activity and makes learning more interactive. The conducted pedagogical experiment allowed authors to assess the impact of digital gaming tools on the development of some students' skills. Analysis of the questionnaire of students revealed their high interest in implementing gaming technologies and their readiness to use them in their future professional activities. The study of game technologies in the training of future computer science teachers is recognised as an urgent task of modern education.

Keywords

digital gaming technologies, computer science, educational games, pedagogical experiment, Kahoot!, Blooket, Minecraft Education, LMS Moodle

1. Introduction

The modern educational process is undergoing significant transformations driven by the development of digital technologies [1, 2]. One of the most promising trends in education is the use of digital gaming technologies that help increase student motivation, improve their cognitive skills, and effectively learn the material [3, 4, 5, 6]. The experience of countries with developed education systems demonstrates that such technologies allow creating an interactive and personalized educational environment, increasing the level of student engagement in the learning process.

At the same time, modern education increasingly incorporates technologies such as cloud computing (CC), augmented reality (AR), virtual reality (VR), and artificial intelligence (AI). The cloud technologies serve as a foundation for deploying digital learning environments that offer scalable and flexible access to educational resources, support real-time collaboration, enable resource sharing, and integrate seamlessly with learning management systems [7, 8, 9, 10, 11, 12]. AR enriches the physical world with interactive digital elements, fostering better understanding of abstract concepts through visualization [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24]. VR offers fully immersive environments that allow students to experience simulated real-world scenarios, thus enhancing practical skills and experiential learning [25, 26]. AI technologies support personalized learning, adapt educational content to individual students' needs, and provide intelligent tutoring systems [27, 28, 29, 30, 31, 32, 33, 34]. Although these technologies have opened new dimensions in education, digital gaming technologies offer a unique combination of accessibility, ease of integration, and strong motivational impact. Unlike AR and VR, which often require expensive equipment, or AI, which demands complex data infrastructure, educational games

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can be effectively implemented in everyday educational practice with minimal resources, making them highly suitable for wide-scale use. At the same time, numerous studies are currently being conducted on the use of AI in higher education, exploring its potential to personalize learning and optimize educational management processes. However, digital game-based learning remains a more accessible and immediately applicable solution for most educational contexts.

In particular, the use of digital gaming technologies in teaching computer science is an effective tool for developing the professional competencies of future bachelors in this specialty. Such tools as Kahoot!, Blooket, LMS Moodle, and Minecraft Education contribute to the development of subject knowledge and skills of analysis, logical thinking, and independent decision-making.

Despite its many advantages, the introduction of digital gaming technologies into the educational process in Ukraine has not yet become widespread. The main reasons for this are insufficiently developed methodological approaches, limited resources, and insufficient training of teachers in their effective use.

For the effective implementation of digital game technologies in the educational process, it is necessary to provide appropriate training for future computer science teachers. It can be carried out as part of a separate course on the use of digital game tools, integration of relevant topics into the discipline "Methods of teaching computer science" or consideration of game technologies within the framework of individual topics of other disciplines.

The purpose of such training is to develop students' ability to use digital game tools in their future teaching activities and adapt them to specific learning tasks. In addition, teachers need to understand the principles of designing digital game technologies, which will allow them to create their own educational products that are tailored to the needs of students.

One of the important aspects of training is to teach future teachers the principles of organizing game-based learning, which involves structuring tasks, gradually increasing their complexity, and providing effective feedback. In particular, tasks should contain clearly defined goals, as well as support mechanisms that will help students correct mistakes and improve their skills.

Scholars studied the methodology of using game technologies in computer science education, covering various aspects of gamification integration into the educational process, the impact of game technologies on the development of students' professional competencies, and the effectiveness of using digital game environments in pedagogical practice.

Riabko et al. [35] focused their attention on the implementation of gaming technologies in the training of future computer science teachers. In their research, they proved that the use of such digital gaming tools as Minecraft Education and Unity3D contributes to the formation of spatial thinking, algorithmic approach and problem-solving skills. For example, in the process of learning, students created interactive worlds in Minecraft Education that simulated real processes, such as the work of algorithms or the functioning of networks [35].

The experience of using quiz platforms (Kahoot!, Mentimeter, Quizizz, Socrative) in the learning process in four courses at Porto Accounting and Business School is highlighted by Silva et al. [36]. Silva et al. [36] concluded that the use of these tools significantly increased student motivation, engagement, and contributed to the creation of an interactive learning environment.

Churok and Shamonya [37] analyzes the trends in gamification of the educational process and the classification of educational computer games.

Skaskiv [38] substantiates the feasibility of using project-game technologies to activate students' educational and cognitive activities.

Karakoc et al. [39] conducted a meta-analysis of 38 experimental studies covering the period from 2000 to 2018, in order to assess the impact of game-based learning on students' academic performance. The authors concluded that the use of game technologies has a significant positive effect on academic achievement, regardless of the level of education or discipline.

Yao et al. [40] assess the impact of game-based learning on student academic performance. The results showed that the use of game-based technologies can positively affect academic achievement by increasing student engagement and motivation.

In general, the literature analysis shows that both Ukrainian and foreign scholars are actively researching methods of implementing game technologies in computer science education. They prove

that such technologies contribute to increasing the level of motivation, developing critical thinking and forming students' professional competencies, which makes learning more effective and interactive.

Thus, the issue of preparing future computer science teachers to use digital game technologies is extremely relevant and requires further research, development of effective methodological approaches and implementation in the practice of teacher training.

To solve this problem, it is necessary to apply a comprehensive methodological approach that covers both the theoretical justification of the use of digital game technologies and practical means of their implementation in the educational process. Accordingly, our study identified the following methods that will contribute to the effective training of future computer science teachers.

To prepare future computer science teachers for the use of game technologies in their professional activities, we have provided:

1. Development of a model of their training with the integration of digital game technologies.
2. Creating a methodology for introducing such technologies into professional disciplines.
3. Formation of skills in the use of game tools in pedagogical activities.
4. Learning to design educational games.
5. Conducting a survey of 4th year students on their awareness and readiness to use digital game technologies.
6. Analysis of the results [41].

In preparing future computer science teachers to use digital game technologies, it is advisable to use various methods that contribute to the formation of the necessary competencies.

One of the key methods is the project-based method, which involves students creating their own game-based educational products. It helps students learn how to work with digital tools, adapt game technologies to learning tasks, and integrate them into teaching. They can develop educational games independently or in teams, from the initial idea to testing [42].

The case study method is effective for analyzing real-life examples of the implementation of game technologies in education. It helps students to explore problems, find solutions, and create educational scenarios, promoting critical thinking and the ability to apply knowledge in practice [43].

Gamification in software engineering education courses has mostly positive effects on student motivation, engagement, and learning outcomes, especially through the use of elements such as points, levels, badges, and competitions [44].

The simulation method [45, 46, 47, 48] is effective for designing educational processes using digital gaming technologies [49, 50]. It allows you to create learning environments with game elements, predict the results of their use, and adapt them to the audience's needs. An important role in the training is played by specially developed methods that facilitate the assimilation of material, the development of professional competencies and practical skills in working with game tools [51].

Voievoda et al. [52] was found out which digital mathematical games are the most popular in the process of teaching mathematics to students in schools in these countries, in particular, "Matific", "Kahoot", "Ten Fingers", "mathPlayground".

Tkachuk and Stetsenko [53] analyze the augmented reality technology, its definition, application features, and hardware and software tools. The authors propose a classification of existing AR technologies by type of interaction, mobility, and functional purpose. Also, Semerikov et al. [54] consider the effectiveness of combining VR/AR environments, programming tools and learning platforms, evaluate the structure and content of the course, and determine its impact on the formation of innovative competencies.

Next, students develop the concept of their own game: they define its educational purpose, game mechanics, activities, and evaluation methods. The final phase involves testing the game in an educational environment, analyzing its effectiveness, and making changes based on the results. Thanks to this methodology, future computer science teachers acquire practical skills in creating interactive learning products and adapting game technologies to the content of specific disciplines, which contributes to the formation of their professional readiness to use modern digital tools in teaching. The methodology of

integrating gaming technologies into the teaching of professional disciplines in the specialty "Computer Science" is aimed at intensifying the educational process with the help of digital tools. It involves the use of gamified tasks for learning theory (e.g., Kahoot!, Quizizz), simulations and educational games in practical courses, in particular in Programming (Scratch, CodeCombat), as well as creating quests with gradually increasing complexity of tasks. This approach helps to develop cognitive interest, critical thinking and professional skills.

The methodology for preparing future teachers to implement game technologies in teaching is aimed at developing the ability to adapt these tools to educational tasks. It involves the creation of teaching materials on methodological foundations, familiarization with the principles of game-based learning (motivation, structure, feedback), analysis and discussion of pedagogical scenarios. Particular attention is paid to developing skills in evaluating the effectiveness of game technologies and correcting the learning process based on the results.

To evaluate the effectiveness of digital game technologies in the training of future computer science teachers, statistical methods are used to analyze experimental data and draw reasonable conclusions about their feasibility. The basis is made up of descriptive statistics methods: arithmetic mean (determines the overall level of achievement), median and mode (identifies typical results), standard deviation and variance (characterizes variability), and coefficient of variation (assesses the homogeneity of results). To detect statistically significant differences between the control and experimental groups, the Student's t-test (for comparing mean values), the Mann-Whitney test (for independent samples with non-normal distribution), and the Wilcoxon test (for analyzing changes within the same group before and after the experiment) are used. The relationship between the use of game technologies and student performance is assessed using Pearson's correlation coefficient.

To evaluate the effectiveness of different digital game technologies, analysis of variance was used to identify statistically significant differences between groups of students after using different tools. The final effectiveness was determined by the efficiency coefficient, which shows the proportion of students who improved their results after the introduction of game technologies.

The use of statistical methods confirmed the positive impact of digital gaming tools on students' performance, motivation, and interest. To this end, an author's course was created in the Moodle LMS with interactive tasks and game elements, and a survey was conducted among 4th year students participating in the experiment.

2. Theoretical nackground

In order to substantiate the methodology for training future teachers of computer science to use digital game technologies in the learning process, a model of using game technologies in the training of future computer science teachers was developed. It involves the gradual development of professional competencies of applicants by first using digital gaming tools as learning tools, and later developing their own gaming educational resources. At the initial stage, students mastered the basic tools of digital gaming, working with The Bezier Game services to develop skills in working with Bezier curves and Codeacademy to form the basics of programming. The learning process was based on the use of a comprehensive approach that combined systemic, personally oriented, activity and competency-based approaches, as well as interactive methods, game techniques, independent work and mentoring support.

Training future computer science teachers on the implementation of game-based learning is the task of the second stage. Our own course in Moodle has been created for this purpose. It provides sample opportunities for implementing an interactive educational environment, including the introduction of game elements that activate students' cognitive activity. The model is structured around five interrelated components:

- *Target component* specifies the overarching goals, identifies the learners' needs, and outlines the pedagogical approaches to be employed.
- *Methodological component* encompasses the instructional content, teaching methods, and organizational forms that structure the educational process.

- *Technological component* defines the digital tools, platforms, and resources utilized to support and enhance educational activities.
- *Diagnostic component* includes the methods and criteria used to evaluate the development of learners' professional competencies.
- *Result component* articulates the anticipated outcomes of the educational process, particularly the professional competencies expected to be acquired by learners.

The course includes lectures, laboratory and independent work, as well as assignments using digital gaming tools. In the course of learning, students master both the basics of pedagogical design and practical skills in creating interactive content in Moodle. This organization of the course ensures mastery of the content and development of skills to apply digital game technologies in their own pedagogical activities.The course structure includes a syllabus and three thematic blocks.

The syllabus contains a description of the course, the distribution of hours, assessment criteria, a list of competencies and program learning outcomes.

The first topic is devoted to quiz creation services – Kahoot! and Blooket. Students learn the principles of their work and create their own interactive tasks. As part of the course, students developed a Kahoot! quiz for 9th-grade computer science students on the topic "Animation of Three-Dimensional Objects". The quiz included multiple-choice and true/false questions aimed at reinforcing the concepts of object rotation, scaling, and animation techniques. During the session, students participated in a live competition using the quiz, which significantly increased engagement and helped identify misconceptions promptly.

The second topic focuses on the gaming capabilities of Moodle. Students get acquainted with the modules Crossword, Anagram, Mystery Chest, etc., learn how to customize them and integrate them into the educational process.

The third topic is Minecraft Education as a tool for teaching computer science [55]. Students create game worlds, develop tasks to develop algorithmic thinking and programming skills. Within this environment, tasks were assigned to automate traffic lights using Redstone circuits and command blocks, promoting the development of algorithmic thinking and basic programming skills. The project combined creativity with the practical application of computer science concepts such as logical operations, sequences, and conditional structures.

The final control is realized through testing, which contains different types of tasks: 10 for entering the answer, 10 for establishing correspondences, and one in the format of an essay. This allows for a comprehensive assessment of learning, analytical thinking, and the ability to apply digital gaming tools in practice [56].

The course is aimed at developing the ability of future computer science teachers to create an effective educational environment using digital game technologies. Students master technical tools and pedagogical approaches to gamified learning, including: organizing feedback, motivating students, and creating adaptive game content.

As part of the first topic, students are introduced to popular digital platforms for creating quizzes, such as Kahoot! and Blooket. These tools allow you to develop interactive test tasks that motivate students to actively participate in the educational process. The classes cover the possibilities of personalizing tasks, setting up game modes, using timers and a scoring system. Students take a teacher-prepared quiz in Kahoot! to consolidate their knowledge (figure 1).

The practical part of the course involves students creating their own interactive quizzes on selected topics from the school computer science course. Special attention is paid to the analysis of how the game testing format can influence student motivation, the formation of a competitive spirit, and increasing interest in learning. Pedagogical strategies for using quizzes in the classroom are also discussed – both at the stage of mastering new material and during generalization or knowledge control.

In the second topic, students are introduced in detail to the capabilities of the LMS Moodle for creating game-based educational elements. Since Moodle is a universal system for distance learning, it is important to be able to use its functionality as a repository of materials and as an active environment for interaction and motivation. Special attention is paid to game modules, such as anagrams, crosswords,

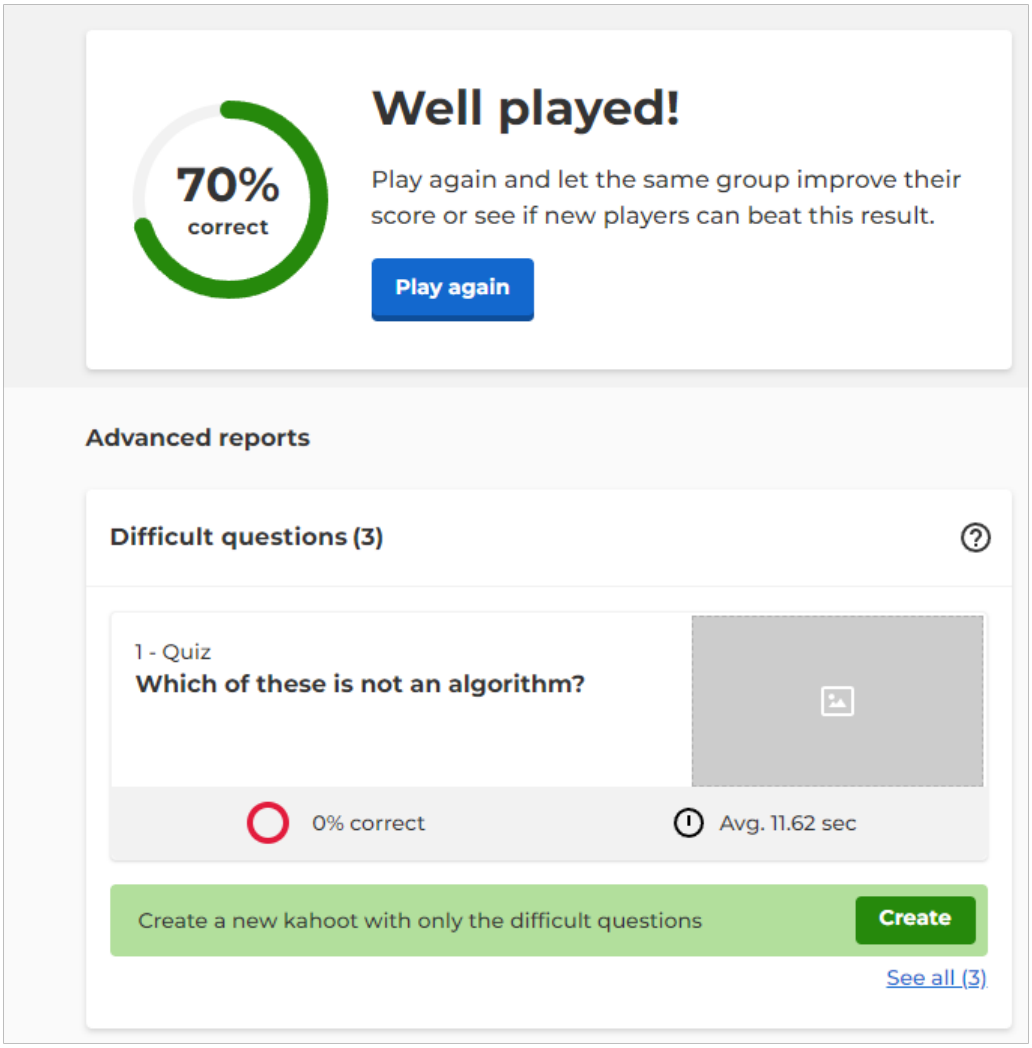

Figure 1: Report on passing the quiz to master the capabilities of Kahoot!

quizzes and other tools that can be added by installing additional plugins. Students learn to integrate these elements into the course, configure difficulty levels, define a scoring system and feedback. Students created an educational quest for the topic "Computer Networks and Internet Protocols" in the Moodle LMS. Using the "Anagram" and "Hidden picture" modules, students designed a quest where participants had to solve riddles and assemble key terms related to networking concepts. The quest structure encouraged exploration, critical thinking, and collaboration among learners.

During practical work, participants develop their own game tasks for specific computer science topics, taking into account the age characteristics and level of training of students. Examples of creative use of Moodle for organizing educational quests and missions are also considered. As part of laboratory work, applicants create their own interactive tasks. In particular, they add a resource of the "Anagram" type (figure 2), in which they form a set of terms for the game. The point is to make the correct word or phrase from the jumbled letters.

Thus, future teachers gain technical skills in working with Moodle and an understanding of how to generate interest in educational material through game interaction. Within the third theme, students work with Minecraft Education, a tool that allows them to implement educational tasks in a gamified format. The platform allows them to create virtual worlds in which students perform programming tasks, solve algorithmic puzzles, and develop logical thinking. Minecraft Education's creative mode is the most convenient for educational purposes in the course "Methodology of Using Game Technologies", as it allows students to focus on creativity without resource limitations. One of the main tasks is to

A motherboard is the main circuit board of a computer or other electronic device. It is often referred to as the "heart" of the computer because it connects and allows communication between all the other components of the computer, including the CPU (central processing unit), RAM (random access memory), storage devices, graphics cards, and various input/output peripherals.

You have **6** tries

_ _ _ _ _ _ _ _ _ _ D

Letters: A B C **D** E F G H I J K L M N O P Q R S T U V W X Y Z _

Figure 2: The process of completing the game “Anagram” in the LMS Moodle.

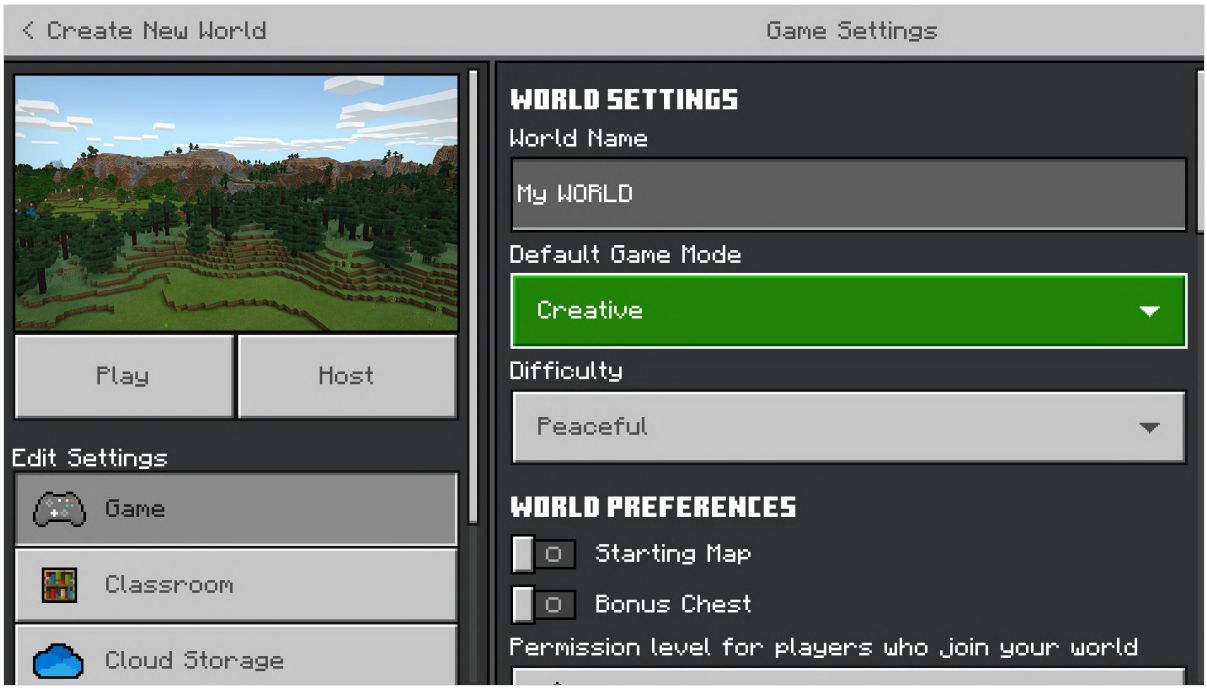

Figure 3: The process of creating a new world in Minecraft Education.

create their own game worlds (figure 3), which contributes to the mastery of algorithmization and programming topics.

Thanks to the “creative” mode, participants can focus on the content of the task without being distracted by side game elements. Students develop educational game projects that involve completing a series of programming tasks. For example, a quest for automated resource collection or creating an algorithm for moving a character. Command blocks, variables, and loops are used to implement mechanics, which allows integrating computer science knowledge into practical activities [57].

Group work is an important element: students distribute roles (design, programming, task development), which contributes to the development of team interaction skills, planning, and responsibility for a common result. Such projects can cover both individual school topics and interdisciplinary connections [58].

The teacher guides the work, helping with technical aspects, provides advice on the pedagogical feasibility of game mechanics and conducts discussions after the projects are completed. Reflection is an important component: students analyze difficulties, discuss experiences, receive feedback and formulate ideas for improvement. The final assessment involves checking the technical correctness of the tasks and analyzing creativity, pedagogical feasibility of using the game, and the level of interaction in the team. Thus, students learn modern digital tools and master the principles of effective instructional design.

3. An experimental study

The objective of the experimental study was to assess students' self-assessment of their abilities to work with educational game tools and students' readiness to use these tools in their future professional activities. For this purpose, a questionnaire was developed and filled out by 4th year students majoring in 014.09 Secondary Education (Computer Science). The choice of self-assessment through a questionnaire was made because we consider it inappropriate to compare a group of students who completed the elective course with those who did not. Therefore, a self-assessment method was chosen to objectively capture the students' subjective perceptions of their readiness and skills. Most of the questions in the questionnaire were constructed in accordance with the Likert scale. Its use is justified by the need to measure the level of agreement with the statements related to the readiness of students to use digital game technologies for educational purposes. With the help of this scale, we were able to collect data on students' attitudes towards digital games and assess how open they are to learning to create such tools. 53 respondents filled out the questionnaire, and the results were analyzed using descriptive statistics (median, mode, interquartile range) and methods of comparing data between groups. The sample size of 53 respondents is sufficient to fulfill the objectives of the study, as the main focus is on studying trends and conducting descriptive statistics, which allows for reliable results even with a relatively small sample. The sample also allows for comparisons between groups within the study, as its size meets the minimum requirements for applying non-parametric statistical analysis methods. The questionnaire consisted of 9 questions the respondents answered after studying the elective course, which was developed according to the author's methodology. These are the questions.

1. Assess your own ability to configure the Blooket environment so that participants can play in real time
2. Assess your own ability to create your own world in Minecraft Education, where players have unlimited access to all. resources, cannot be harmed by the environment and can build any structures.
3. Assess your own ability to create a lesson plan using the Kahoot! environment for 9th grade computer science students on the topic 'Animation of three-dimensional objects'..
4. Evaluate your own ability to change the types of questions in Kahoot! (test, true/false).
5. Assess your own ability to create and customize the "Anagram" game in the Moodle LMS using the "Glossary" question bank.
6. Assess your own ability to create a lesson plan with a quest in the Minecraft Education game for 9th grade computer science students on the topic 'Arrays' in programming.
7. Assess your own ability to set up a multiplayer mode in the Minecraft Education game and invite others to your world.
8. Assess your own ability to use command blocks to automate processes in Minecraft Education.
9. Assess your ability to set a timer for each question in Kahoot!

The Likert scale was transformed into a numerical scale by assigning a numerical value to each level of response. In this case, the Likert scale looks like this:

- ‘Strongly disagree’ – 1.
- “Disagree” – 2.
- ‘Neutral’ – 3.
- ‘Agree’ – 4.
- ‘Strongly agree’ – 5.

To choose a statistical method for processing the data, we checked whether the distribution of answers to each question in the questionnaire was normal. Therefore, we applied the Shapiro-Wilk test, which showed that none of the questions in the questionnaire demonstrated a normal distribution, as all p-values were less than 0.05.

Cronbach’s alpha was calculated to check the internal consistency of the questionnaire. Its value of $\alpha_{cr} = 0.780$ indicates a moderate level of consistency between the questions, which suggests that they are partially related to each other, but the scale could be improved to increase reliability.

Descriptive statistics of the questionnaire data involve the calculation of such values:

- The median value is located in the middle of the ranked series of the sample. It shows the central tendency in the students’ choice of.
- Mode as the most frequent option.
- Interquartile range (IQR), which reflects the distribution of answers between the 25th and 75th percentiles. It is used to assess the variability of the selected answers.

The calculation of these statistics is presented in the table 1.

Table 1
Descriptive statistics of students‘ survey.

Question number	Median	Mode	Description
1	4.0	5	Most students perform this task, but a certain part of the respondents have difficulties observed.
2	4.0	4	The vast majority of applicants have the appropriate skill, but there is a group that needs additional training to master it.
3	5.0	5	There is considerable confidence among all respondents in their ability to complete this task.
4	4.0	5	Most applicants are able to complete this task, although some respondents note the presence of certain difficulties.
5	4.0	4	Students are fully proficient in these tools.
6	4.0	4	Confident performance of this task by the majority of applicants, although some respondents have difficulties.
7	4.0	4	A significant part of respondents have basic skills in setting up this mode, but more complex functions cause them difficulties.
8	4.0	5	High level of development of automation skills in applicants.
9	5.0	4	Students confidently apply this function in the educational process.

The next step in analyzing the survey data was to determine the distribution of responses by Likert scale options. The frequency of choosing each answer option (“Strongly agree”, “Agree”, “Neutral”, “Disagree”, “Strongly disagree”) for each question was calculated (table 2).

The distribution of answers to the questionnaire is shown in figure 4.

The table 2 and figure 4 show that most respondents chose high ratings (“4” and “5”) for many questions, which indicates their confidence in their skills. For example, in the question “Can you create a lesson plan with Kahoot!” (question 3), no rating “1” and “2”, which indicates their complete confidence in their competence to perform these tasks. A similar situation is observed in question 5, which concerns the use of the Moodle LMS. Although the majority of respondents answered “Agree” or “Strongly Agree”, there are also “Neutral” and “Disagree” responses, indicating varying levels of confidence in creating games in the Moodle LMS. The greatest discrepancy in responses is seen in

Table 2
Frequency table of responses.

Options(Grade)/Question	1	2	3	4	5	6	7	8	9
Strongly disagree (1)	2	3	0	2	0	5	10	10	0
Disagree (2)	4	7	0	4	3	8	7	7	2
Neutral (3)	8	8	4	5	12	9	9	7	4
Agree (4)	16	18	14	20	21	17	14	14	20
Strongly agree (5)	23	17	35	22	17	14	13	15	27

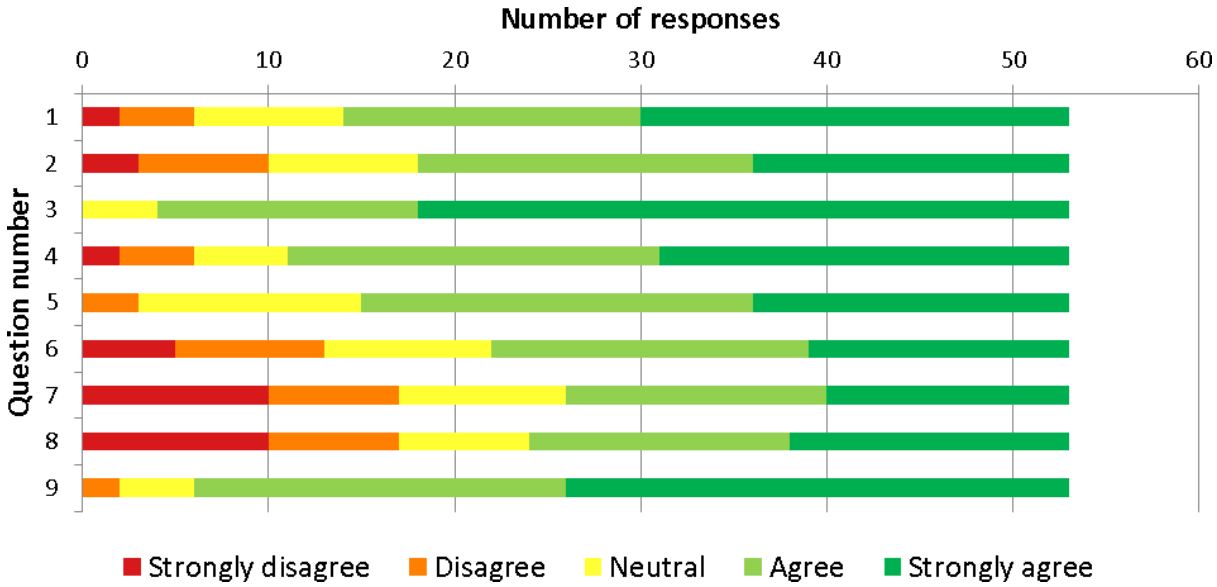

Figure 4: Distribution of students' answers.

questions 6, 7 and 8, where a significant number of respondents chose the options "Strongly Disagree" and "Disagree". In particular, questions 7 and 8 have the highest number of negative ratings. We believe this indicates that students have technical and pedagogical problems in using Minecraft Education platforms. Therefore, it is appropriate to provide additional training or practice cases on the relevant topics. The results indicate a fairly high level of confidence among respondents in using digital tools such as Kahoot! and Blooket (questions 1 and 2), as evidenced by the prevalence of "Agree" and "Strongly Agree" responses. In contrast, responses to questions 7 and 8, which relate to Minecraft Education, show significant variability, ranging from "Strongly Disagree" to "Strongly Agree". This may indicate a heterogeneous level of student preparation and some difficulties in mastering this platform.

Another step in analyzing the results of the survey is to assess the dispersion of data using the interquartile range (IQR). The table 3 shows the values of the first quartile (Q1), third quartile (Q3) and interquartile range (IQR) for each question of the questionnaire, which allows us to determine how the central 50% of answers are grouped and whether there is a variation in respondents' confidence.

As you can see from the table 3, the IQR for question 9 is 0. This means that there is complete homogeneity of respondents' answers (a large number of students chose the same answer options). This indicates that students generally agree on the time settings of the Kahoot! service. In questions 3 and 4 (also related to the service), the IQR is 1, indicating a high consistency of answers, with minor deviations. This means that most respondents chose the options 'Agree' or 'Strongly agree'. This IQR value indicates a positive but somewhat variable attitude towards task creation and the use of Kahoot! in the classroom in general. An IQR of 2 (questions 1, 2, 5, 6) indicates moderate variability in responses. In these cases, the answers of the central 50% of respondents are in a broader range (e.g. from "Neutral" to "Strongly agree"), indicating different levels of confidence or experience. This situation may be a result of the heterogeneity of previous experience with the relevant digital tools (Blooket

Table 3
Interquartile analysis of respondents' responses.

Question number	Q1	Q3	IQR
1	3	5	2
2	3	5	2
3	4	5	1
4	4	5	1
5	3	5	2
6	3	5	2
7	2	4	2
8	2	5	3
9	4	4	0

service, MOODLE LMS and Minecraft platform). Question 7 (setting up multiplayer mode in Minecraft Education) has an IQR value of 2 but with a lower value of the first quartile (2.00), which may indicate the presence of a part of respondents with a low level of training in particular, the complexity of the topic for some participants. Question 8 has the highest IQR value of 3, which demonstrates a high variability of answers. This heterogeneity indicates that respondents have radically different levels of knowledge and skills in automating game processes in Minecraft Education. Some respondents showed high confidence in this question, while others chose the lowest scores.

For a deeper analysis of the scale structure, it is advisable to examine the relationship between the responses to individual items and the overall score. Items that demonstrate a high correlation with the summary score can be considered as those that better represent the essence of the scale. In our study, a correlation analysis was conducted to assess the relationship between individual questions. Since the data do not fall under the normal distribution according to the Shapiro–Wilk criterion, we used the nonparametric Spearman rank correlation coefficient (r). This allows us to assess the strength and direction of the relationship between ranked variables.

A correlation is a statistical relationship between two variables. It shows how much one variable changes when the other changes. Correlation is measured using a coefficient that takes values from -1 to 1. Where 1 is a perfect positive correlation (both variables change in the same direction), 0 means no correlation (the variables are not related), and -1 is a perfect negative correlation (the variables change in opposite directions). This makes it possible to investigate how individual student ratings of their ability to use game tools are related. Therefore, we calculated correlation coefficients between all 9 questions of the questionnaire (table 4). For this purpose, we used the previously transformed nominal scale from 1 to 5.

Table 4
Correlation matrix for the questionnaire.

Question number	1	2	3	4	5	6	7	8	9
1	1.000	0.409	~~0.015~~	~~0.166~~	~~0.108~~	~~0.083~~	~~0.171~~	0.251	~~0.206~~
2	0.409	1.000	0.349	~~0.226~~	0.365	0.509	0.496	0.434	~~0.254~~
3	~~0.015~~	0.349	1.000	0.060	~~0.016~~	0.215	0.563	0.420	0.296
4	~~0.166~~	0.226	~~0.060~~	1.000	0.473	0.280	~~-0.077~~	~~0.009~~	~~-0.055~~
5	~~0.108~~	0.365	~~0.016~~	0.473	1.000	0.475	~~0.064~~	~~0.180~~	~~-0.065~~
6	0.083	0.509	0.215	0.280	0.475	1.000	0.565	0.526	0.318
7	0.171	0.496	0.563	-0.077	~~0.064~~	0.565	1.000	0.714	0.386
8	0.251	0.434	0.420	~~0.009~~	~~0.180~~	0.526	0.714	1.000	0.314
9	~~0.206~~	0.254	0.296	~~-0.055~~	~~-0.065~~	0.318	0.386	0.314	1.000

In the table 4, statistically insignificant correlation coefficient values with a $p > 0.05$ are crossed out. The values on the table's diagonal are always 1 because each question correlates with itself. The

table 4 shows a high positive correlation between questions 7 and 8 ($r = 0.714$). This indicates that respondents who are confident in setting up command blocks in Minecraft Education are usually equally confident in setting up multiplayer in this environment. Given the relatively large number of disagreement responses, we note that the coefficient also reflects the corresponding uncertainties of students. The moderate correlation coefficient for questions 6 and 8 ($r = 0.526$) indicates that the same students are equally confident and uncertain about their skills in Minecraft Education. We also found a moderate correlation coefficient value for questions 3 and 7 ($r = 0.563$). Instead, a similar relationship should exist between similar questions about students' pedagogical skills (3 and 6). Here, we can assume that the 4th year students were not frank in answering one of these questions. Other r coefficients reveal a weak relationship between the questions. All negative values of the correlation coefficient were statistically insignificant. Therefore, there are no means whose confidence in use has an inverse effect on the level of self-assessment of others.

4. Conclusions

The study describes some aspects of designing an elective course "Methodology of using game technologies" for students of the specialty 014.09 Secondary Education (Computer Science). The course is focused on familiarizing students with modern digital game technologies. It includes a detailed study of platforms for creating interactive quizzes (Kahoot!, Blooket), game modules in the LMS Moodle, and the features of implementing Minecraft Education in the educational process of secondary education institutions.

Based on the conducted research, it is possible to conclude about the effectiveness of using digital game technologies in training future computer science teachers. The developed elective course contributes to the assimilation of theoretical knowledge about game technologies and the formation of practical skills for their application in the educational process. Analysis of the experimental results confirmed the positive impact of interactive educational tools on the level of development of students' professional competencies, which indicates the feasibility of their implementation in the educational process.

The results obtained confirm the need for further research in the direction of expanding the use of digital gaming technologies in the training of future computer science teachers. Promising directions are the integration of gaming elements into the process of studying artificial intelligence, cybersecurity, and robotics, as well as the development of methodological recommendations for the effective use of gaming technologies in various educational contexts.

Author contributions

Conceptualization, Vasyl P. Oleksiuk; methodology, Vasyl P. Oleksiuk; software, Vasyl P. Oleksiuk and Dmytro V. Verbovetskyi; writing – original draft, Dmytro V. Verbovetskyi; writing—review and editing, Vasyl P. Oleksiuk. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

No new data were created or analysed during this study. Data sharing is not applicable.

Conflicts of interest

The authors declare no conflict of interest.

Declaration on Generative AI

While preparing this work, the authors used ChatGPT by OpenAI to rephrase and improve their own text. Scopus AI was also used to search for relevant literature. Microsoft Copilot was used to generate table code in TeX. All content generated with the assistance of AI tools was reviewed and edited by the authors, who take full responsibility for the article's final version.

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Implementing GeoGebra for STEM education in pre-service mathematics teacher training

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Abstract

This paper explores the development and implementation of pedagogical conditions for the use of GeoGebra as a tool for STEM education in the training of pre-service mathematics teachers. STEM education is discussed, and the potential and features of GeoGebra as a tool for implementing this concept are characterized. Three pedagogical conditions are proposed, including the creation of a cloud-oriented educational environment, the introduction of STEM-oriented investigations using GeoGebra, and the application of motivating measures to stimulate students. Criteria and indicators for the effectiveness of these conditions are developed, and a pedagogical experiment is conducted to test their effectiveness involving 343 students and 26 teachers across six Ukrainian institutions. The results confirm the effectiveness of the pedagogical conditions and demonstrate the potential for GeoGebra as a tool for providing STEM education in the training of pre-service mathematics teachers. The findings align with recent systematic reviews indicating that GeoGebra significantly enhances pre-service teachers' Technological Pedagogical Content Knowledge (TPACK), with targeted workshops showing measurable improvements in technological integration skills. The study contributes to addressing the critical need for scaffolded professional development and institutional support in technology integration, while identifying key challenges including tool unfamiliarity and digital material design deficiencies. This paper provides insights and recommendations for educators seeking to incorporate GeoGebra and STEM education into their mathematics teacher training programs, emphasizing the importance of collaborative learning communities and incremental learning approaches.

Keywords

STEM education, GeoGebra, pre-service mathematics teacher training, pedagogical conditions, cloud-oriented educational environment, explorative study, motivational measures, pedagogical experiment, TPACK development, digital material design, technology integration, mathematical visualization, professional development, collaborative learning communities

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1. Introduction

Improving the quality of science, technology, engineering, and mathematics (STEM) education is a key task for countries focused on strengthening economic competitiveness and developing human capital to support science-based industries and technologies [1, 2, 3]. International comparative studies of the quality of STEM education (PISA, TIMSS) are recognized indicators of the state of a country's STEM education. These studies allow for comparing a nation's educational progress with global trends in its development. The latest PISA studies have shown a significant decline in the science and particularly mathematics skills of Ukrainian high school students [4]. Results of recent admissions campaigns have confirmed a decline in interest among applicants in STEM fields, which creates strategic risks for social, economic, and technological development in Ukraine. In 2020, only two of the ten most popular specialties chosen by applicants related to STEM education, and only one of them involved information technology. The need to increase the prestige of STEM education as a guarantee of the country's development necessitates improving the quality of professional training for pre-service STEM teachers.

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The strategic tasks for training pre-service teachers are determined in the laws of Ukraine "On Education" [5], "On Higher Education" [6] and other regulatory documents, which prioritize achieving a qualitatively new level of mathematical education through the introduction of progressive concepts, optimal combination of humanitarian and natural-mathematical components of education, the use of modern pedagogical and information technologies, and the preparation of a new generation of teaching staff. The adopted Concept of Development of Natural-Scientific and Mathematical Education (STEM Education) in Ukraine [7] is based on UNESCO documents, in particular, the Incheon Declaration "Education 2030" [8], where STEM education is recognized as a key strategy for achieving sustainable development goals. The concept provides for its wide-scale implementation at all levels of education, emphasizes the key role of mathematics in STEM education, and emphasizes the need for significant changes in the training system, including pre-service mathematics teachers.

Therefore, there is a social demand and legislatively justified necessity to improve the quality of professional training of pre-service mathematics teachers through the implementation of the STEM education concept.

Bilousova et al. [9] point out the significant didactic potential of computer mathematics systems for pedagogical purposes, such as the GRAN and GeoGebra packages, in implementing STEM education in higher and secondary schools. However, the problem of effectively using these systems as tools for implementing STEM education in the practice of professional training of pre-service mathematics teachers remains insufficiently developed in both theoretical and practical aspects.

Recent systematic reviews and meta-analyses have identified GeoGebra as one of the most effective dynamic mathematics software tools for enhancing pre-service teachers' technological and pedagogical competencies [10, 11]. The global landscape of GeoGebra implementation in teacher education reveals significant growth, with over 340 journal articles published on this topic between 2007 and 2023 [11]. This widespread adoption underscores the critical role of technology integration in modern mathematics education and the pressing need for evidence-based pedagogical frameworks.

The analysis revealed contradictions between society's demand for improving the quality of natural and mathematical education and its unsatisfactory state at the key level – the level of general secondary education; recognition of STEM education as the leading direction of modernizing natural and mathematical education and the insufficient level of implementing the STEM approach in the process of professional training of pre-service mathematics teachers; the potential of the GeoGebra package for implementing STEM mathematics education and the lack of scientifically substantiated approaches to effectively using the GeoGebra package as a tool for implementing the STEM education concept in the process of training pre-service mathematics teachers.

2. Research methodology

The relevance of the outlined problem, its insufficient development in pedagogical theory and practice, as well as the need to solve the identified contradictions, determined the *object of research* – the implementation of the concept of STEM education in the process of preparing future mathematics teachers.

The subject of research is the pedagogical conditions for using the GeoGebra package as a tool for implementing the concept of STEM education in the process of training pre-service mathematics teachers.

The purpose of the research is to theoretically justify, develop and experimentally verify the pedagogical conditions for using the GeoGebra package as a tool for implementing the concept of STEM education in the process of training pre-service mathematics teachers.

The research methods:

- theoretical – analysis, comparison, systematization, and generalization of scientific literature to identify the state of the topic's development and clarify the conceptual and terminological apparatus; analysis of the experience of implementing STEM education in the preparation of pre-service mathematics teachers; generalization and systematization of theoretical positions to

justify pedagogical conditions for the use of the GeoGebra package as a tool for implementing STEM education in the process of training pre-service mathematics teachers;
- empirical – observation, survey, testing, questioning, analysis of the results obtained.

The experimental research was conducted from 2015 to 2020 at the following institutions: H. S. Skovoroda Kharkiv National Pedagogical University, Kryvyi Rih State Pedagogical University, Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University, Lesya Ukrainka Volyn National University, K. D. Ushynskyi Chernihiv Regional Institute of Postgraduate Pedagogical Education, and the National Technical University "Kharkiv Polytechnic Institute". A total of 343 students and 26 teachers were involved at various stages of the research.

The research design aligns with contemporary quasi-experimental approaches in educational technology research [12, 13]. Following established methodological frameworks for TPACK assessment, we employed validated instruments and mixed-method approaches to capture both quantitative improvements and qualitative insights into the transformation of pre-service teachers' technological pedagogical competencies.

3. Theoretical underpinnings of ICT use in STEM education implementation at pre-service mathematics teacher training

Based on the analysis of psychological and pedagogical literature [14, 15, 16, 17, 1, 18, 19, 20, 21], it has been found that STEM education emerged as a response to the challenge posed by the rapid development of technologies, which necessitates the orientation of education towards the preemptive satisfaction of the needs of the modern economy for specialists capable of ensuring its development on a high-tech basis. The experience of implementing STEM education in the USA, France, Great Britain, Australia, Israel, China, Singapore, Hong Kong, Canada, and other countries was analised. In Ukraine, STEM education is considered a priority direction for the development of natural science and mathematics education, as declared in the corresponding Concept [7].

The theoretical foundations of STEM education are being developed jointly by scientists and educators, taking into account practical experience. It has been established that despite differences in the strategies of implementing STEM education in different countries, there is a shared understanding of the purpose of STEM education (improving human capital by developing STEM competencies and a natural science worldview in students), its key principles (integrative, interdisciplinary, transdisciplinary, activity-based, competency-based, person-centered, and research-oriented approaches), and the expected result in personal (acquisition of practical natural science, mathematical, IT, and engineering knowledge and skills to solve practical problems in educational and professional activities) and societal dimensions (increasing the country's competitiveness in the international market of high technologies).

Based on the above, within the scope of the study, STEM education is understood as an innovative model of natural and mathematical education of the 21st century, and its implementation is considered a large-scale global experiment during which the content component of the model is determined (selection and structuring of educational content), the procedural component is tested (forms, methods, and means of teaching, specific aspects of organizing the educational process), and the conceptual basis is clarified (terminology, founding principles, etc.).

Recent research has identified specific pedagogical strategies that maximize the effectiveness of GeoGebra integration in STEM education. Activity-based and task-based learning approaches have emerged as the most effective pedagogical methods, promoting visualization, reasoning, and higher-order thinking skills [22, 23]. Furthermore, exploratory and less-guided tasks have been shown to foster deeper learning and mathematical discourse, while guided tasks support procedural understanding [24]. This dual approach aligns with constructivist learning theories and supports the development of both conceptual and procedural knowledge essential for STEM competency.

It is shown that mathematics has an integrative role in the complex of STEM disciplines, which is due to the universality of mathematical tools, the mathematization of various fields of knowledge,

the significant influence of mathematical education on the cognitive, moral-volitional, and aesthetic development of an individual, and the exceptional importance of mathematical modeling and computational experimentation based on it as a leading method of scientific, engineering, technical, and practical human activities. The latter determines the leading role of computer mathematics systems in the implementation of interdisciplinary STEM projects.

The generalization of experience in implementing STEM education into the system of training pre-service teachers of mathematics, natural sciences, and technologies has shown the need for further research in the context of modernizing higher pedagogical education based on the implementation of the concept of STEM education. This includes the theoretical justification of pedagogical conditions for using the GeoGebra package as a tool for its implementation.

4. Justification of pedagogical conditions for using the GeoGebra package as a tool for implementing the concept of STEM education in the preparation of pre-service mathematics teachers

Based on theoretical analysis, it has been proven that the special role of mathematics justifies the expediency of implementing STEM education primarily in the process of fundamental mathematical training for pre-service mathematics teachers. It is shown that the leading way to implement STEM education is through specially organized research and project activities, the main feature of which is the construction of the subject's knowledge system in the process of acquiring and comprehending their own experience in such activities. The organization of research and project activities requires the construction of communities whose members possess ICT tools for conducting theoretical and empirical research. This necessitates the need for pre-service teachers to master social-constructivist technologies for organizing computer-based STEM-oriented research and methods for forming a complex of research competencies as components of the STEM competency system.

The educational and developmental potential of the GeoGebra package as a tool for implementing the STEM education concept in the training of pre-service mathematics teachers is characterized, as well as the defining features of the package in [25, 26, 27]. GeoGebra is positioned as a computer mathematics system aimed at supporting the educational and research activities of students and teachers. The package has a developed functionality and continuous improvement by an international team of developers, and a wide range of applications in STEM education and its branches (STEAM, STREAM, and others), scientific and practical activities of various directions. The full-featured version of the package is freely available in Ukrainian, independent of hardware and operating system, and has a cloud-based version. The large database of freely distributed educational STEM resources created by the open GeoGebra community, the possibility of visualizing computer models in virtual and augmented reality, and their materialization by 3D printing are also noted.

International research evidence supports the effectiveness of GeoGebra across diverse mathematical domains. Studies have demonstrated significant improvements not only in geometry and calculus but also in linear algebra, vectors, and analytic geometry [28, 29]. The software's dynamic visualization capabilities have been shown to enhance mathematical connection skills, with pre-service teachers demonstrating improved ability to link multiple mathematical concepts and representations [30]. These findings underscore GeoGebra's versatility as a comprehensive tool for mathematics education across the curriculum.

The 20-year history of using the GeoGebra package in mathematics education has revealed its synergetic effect – the inheritance of STEM applications. The demand for the skills and knowledge of using GeoGebra acquired by pre-service mathematics teachers is not only relevant in their professional activities but also beyond its scope.

Using the GeoGebra package as a tool for implementing the STEM education concept required the development and justification of a complex of pedagogical conditions that ensure the effectiveness of such use. Considering that STEM education is a multi-purpose concept, the focus was on the goals that the use of the GeoGebra package contributed to achieving: developing students' motivation to acquire

mathematical education, forming beliefs about its significance and the effectiveness of mathematical knowledge, acquiring research competencies, and developing the ability for self-education and a desire to independently enhance their educational potential.

With these goals in mind, a complex of pedagogical conditions was developed and theoretically justified, which includes designing an educational process using GeoGebra that promotes the active involvement of students in the research and discovery process, using interactive methods of teaching and learning, and promoting self-education and research activities. The GeoGebra package also helps to develop students' mathematical thinking, creative abilities, and research skills, as well as to integrate mathematics with other disciplines.

Thus, the GeoGebra package has significant potential as a tool for implementing the STEM education concept in the training of pre-service mathematics teachers. Its effective use requires the development of a complex of pedagogical conditions, which are aimed at promoting students' motivation, developing their research competencies, and promoting self-education and research activities.

The first pedagogical condition is to create a cloud-oriented educational environment that contains software, informational, didactic, and methodological resources for organizing, supporting, and accompanying various types of student learning activities using the GeoGebra package: educational and cognitive, educational and research, scientific and research, and project-based.

The second pedagogical condition is to introduce a practical course in computer STEM-oriented research in the GeoGebra package into the educational process of training pre-service mathematics teachers, which is based on the principles of a technological approach, involving a step-by-step engagement of students in researching mathematical objects, objects from other disciplines, objects of the surrounding world, and gradually mastering the research tools of the GeoGebra package.

The third pedagogical condition is the use of a complex of tools to stimulate students' STEM-oriented GeoGebra modeling, based on the organization of their extracurricular activities, involvement in the GeoGebra community, and the use of individual and group coaching.

Within the framework of extracurricular activities, students are expected to:

- familiarize themselves with additional (non-program) materials that reveal the significance of mathematics, the value of mathematical modeling, the breadth of its applications in various areas of human activity, including creative ones;
- prepare non-standard events to popularize such information; create illustrative support for such events using the GeoGebra package;
- participate in the GeoGebra community, which promotes the transfer of pedagogical ideas and technologies, as well as the involvement of students in the development of GeoGebra models, GeoGebra projects, conducting and presenting their own GeoGebra research as a personal contribution to open world GeoGebra resources. The ability to see their own results on the site and participate in the scientific and methodological developments of teachers adds confidence to the student in the significance of the knowledge they receive in the educational process and in research and project work.

The use of individual and group coaching contributes to the development of the personal potential of pre-service math teachers, stimulates their independent cognitive activity, and increases the practical significance and demand for the results of computer STEM-oriented research using GeoGebra software. The pedagogical conditions are interconnected, interdependent, and complementary, which necessitates their comprehensive implementation.

Research has consistently identified several critical success factors for GeoGebra implementation. The SQD (Synthesis of Qualitative Data) model strategies—including role modeling, reflection, design-based learning, peer collaboration, authentic experiences, and continuous feedback—have shown positive correlations with TPACK development [13]. However, studies reveal that many of these strategies remain underutilized in practice, particularly at the higher levels of the SAMR (Substitution, Augmentation, Modification, Redefinition) model [31]. This gap between potential and practice highlights the need for systematic professional development approaches that specifically target these underutilized strategies.

5. Organization, conduct and results of the pedagogical experiment

During the preparatory stage of experimental work (2015–2017), educational and methodological support for using the GeoGebra package as a tool for implementing the concept of STEM education in the process of training pre-service mathematics teachers in higher education institutions was developed. This included a textbook for mastering the dynamic mathematics GeoGebra package as a tool for implementing the concept of STEM education; sets of research tasks and educational models for conducting STEM-oriented research in GeoGebra; a cloud-based complex of interdisciplinary models presented in GeoGebra Book; tasks for individual STEM-oriented research and educational activities of students using GeoGebra modeling; STEM project topics using the GeoGebra package; and working materials for organizing extracurricular STEM-oriented student work using GeoGebra modeling in the format of a discussion club (thematic developments, scenarios, presentations, compilations of audio and video materials, etc.).

Criteria and indicators for the formation of the ability of pre-service mathematics teachers to use the GeoGebra package as a tool for implementing the concept of STEM education were also developed, including motivational-value (the awareness by pre-service teachers of the value of mathematical knowledge and the mathematical apparatus as the basis for computer research on any object; motivation to learn mathematics; readiness to overcome difficulties), praxiological (the ability of pre-service teachers to step-by-step plan computer research using the technology of its implementation; the ability to use the GeoGebra functional rationally for conducting research; the ability to analyze its results and make conclusions), and metacognitive (the ability of pre-service teachers to critically evaluate their own knowledge level for solving a problem; the ability to effectively use various ways of acquiring knowledge; the desire for constant educational growth; the ability to apply the GeoGebra package for conducting transdisciplinary research).

Each indicator is described at three levels of formation of pre-service mathematics teachers' ability to use GeoGebra as a tool for implementing the concept of STEM education: reproductive (the ability to use GeoGebra to conduct subject mathematical research according to the teacher's plan), partially exploratory (the ability to use GeoGebra to conduct independent and collaborative subject mathematical research and interdisciplinary research with the teacher's support), and creative (the ability to use GeoGebra to conduct independent and collaborative transdisciplinary research). Tools for their diagnosis have been developed.

The exploratory and formative stages of the pedagogical experiment were conducted at the H. S. Skovoroda Kharkiv National Pedagogical University and Kryvyi Rih State Pedagogical University.

During the exploratory stage (2018), experimental and control groups were formed; the absence of a statistically significant difference at the 0.05 level in the levels of formation of mathematics teachers' ability to use GeoGebra as a tool for implementing the concept of STEM education was proven.

During the formative stage (2018–2020), measures were implemented to introduce reasoned pedagogical conditions for using the GeoGebra package as a tool for implementing STEM education and testing a complex of educational and methodological materials. The stage's tasks also included testing a complex of didactic materials that provide the implementation of these pedagogical conditions, tracking the dynamics of the process of using the GeoGebra package as a tool for implementing the concept of STEM education in the process of training pre-service mathematics teachers. The pedagogical experiment was conducted in natural conditions of the educational process with the involvement of students in the experimental group. Students in the control group were taught using traditional methods.

To implement the first pedagogical condition based on the use of specially selected and developed software, informational, didactic, and methodological resources during the preparatory stage of the experimental work, a cloud-oriented educational environment was created to organize, support, and accompany various types of independent student activity using the GeoGebra package (educational-cognitive, educational-research, scientific-research, project).

To implement the second pedagogical condition, a practical course on conducting computer STEM-oriented research using the GeoGebra package was developed and implemented. The practical course provided for the sequential mastering by pre-service mathematics teachers of the technology of research

Table 1
The distribution of students in the specialty 014.04 Secondary Education (Mathematics) by the level of formation of the ability to use GeoGebra software as a tool for implementing the STEM education concept after the formative stage of the pedagogical experiment (in %).

Levels / Criteria	Control group			Experimental group		
	Reproductive	Partial-equivalent	Creative	Reproductive	Partial-equivalent	Creative
Motivational-value	37.7	39.3	23.0	19.4	38.7	41.9
Praxiological	42.6	37.7	19.7	16.1	40.3	43.6
Metacognitive	42.6	36.1	21.3	17.7	37.1	45.2

and the research toolkit of the GeoGebra package in the process of step-by-step involvement in the study of mathematical objects, objects from other disciplines, real objects with the support of a specially created and constantly updated database of educational models. To support and direct the independent work of students during the practical course, a teaching and methodological guide was used. Each research project carried out by the student consisted of three stages. At the first stage, the student was involved in constructing a visual model of the mathematical object in the GeoGebra environment, guided by instructions for its construction (provided in the practical course in a table of dynamic drawing construction, which contains a step-by-step description of construction, comments, and illustrations) and mastering a certain toolkit of GeoGebra in this way. Next, the student carried out the study of the mathematical object according to the provided step-by-step plan, which reproduced the technology of research. Each step was accompanied by questions that drew the student's attention to the essence of the obtained result. The second stage of the research was carried out by the student using the same model, but using it to study an interdisciplinary object, which required activation of knowledge from other disciplines. The questions posed were aimed at involving the student in the analysis and understanding of the results obtained, arousing his interest and initiative in satisfying it. The third stage led to a transdisciplinary level of research and concerned a real object, requiring the demonstration of a complex of acquired knowledge. The questions posed to the student aimed to arouse his natural curiosity, stimulate the development of a plan for further research, possibly with modification of the created model.

To implement the third pedagogical condition, a set of tools to stimulate students to engage in STEM-oriented GeoGebra modeling was developed and applied. In particular, extracurricular activities were organized in the form of a discussion club, where the leading method of cognitive activity was GeoGebra modeling. Students were also involved in GeoGebra community activities by developing GeoGebra models and presenting their own GeoGebra research as a personal contribution to open world GeoGebra resources, including GeoGebra Book, for the exchange of ideas and technologies, as well as the implementation and adaptation of productive international experience in the educational process of training pre-service math teachers to use the GeoGebra package in STEM education, which played a powerful motivational factor for students. The club format contributed to the growth of various interactions between teachers and students on the principles of mutual respect and trust, the establishment of partnership relations between them, the implementation of individual and group coaching, which found expression in personalized student counseling, directing them towards achieving significant educational results, engaging in the development of practical STEM projects, and jointly conducting full-fledged scientific STEM research throughout the entire cycle of training pre-service math teachers. After completing the experimental work, the level of formation of pre-service math teachers' ability to use the GeoGebra package as a tool for implementing the concept of STEM education was determined (table 1).

The results of our experiment align with international findings on GeoGebra effectiveness. Meta-analyses have shown that pre-service teachers who undergo structured GeoGebra training demonstrate significant improvements in multiple domains: mathematical connection skills (effect size $d = 0.68$), proof and reasoning abilities ($d = 0.72$), and technology integration confidence ($d = 0.81$) [32, 33, 34]. These improvements are particularly pronounced when training incorporates collaborative learning

communities and scaffolded instructional approaches, supporting our implementation of the third pedagogical condition.

During the control stage, the results of the conducted experiment were analyzed. The obtained results allowed us to conclude about the positive effect of implementing the developed pedagogical conditions on the level of formation of pre-service mathematics teachers' ability to use GeoGebra software as a tool for implementing the STEM education concept. The verification was carried out using the Pearson correlation coefficient, which confirmed that the difference factor in the distributions of the students of control and experimental groups is statistically significant at the 0.05 level. Therefore, the research hypothesis was confirmed that the use of GeoGebra software as a tool for implementing the STEM education concept in the process of training pre-service mathematics teachers will be effective under the implementation of justified pedagogical conditions.

6. Conclusions

1. The research proposes a solution to the scientific problem of substantiating the pedagogical conditions for using GeoGebra as a tool for implementing STEM education in the training of pre-service mathematics teachers. The generalization of the results of theoretical research and the conducted pedagogical experiment allow the following conclusions to be made.
2. The analysis of psychological and pedagogical literature showed that STEM education is an innovative approach that is being implemented and developed jointly by scientists and educators from many countries of the world who are interested in the development of science-intensive production and high technologies. STEM education is being spread at all educational levels, which determines its special importance in the system of training pre-service teachers, since the teacher is the main driving force for change in education.
3. STEM education is defined as an innovative model of natural-mathematical education of the 21st century, and its implementation is a large-scale world experiment, during which the content component of the model is determined (the selection and structuring of the content of education is carried out), the procedural component is tested (the forms, methods, means of teaching, the specificity of organizing the educational process in its specific aspects are used), and the conceptual component is refined (terminology, basic principles, etc.).
   Integrated, activity-based, and technological approaches are highlighted as key components of STEM education. Increasing the volume and significance of independent research requires its rational organization on technological principles.
   The potential of mathematics as a STEM discipline in both school and university education is analyzed. The integrative role of mathematics in the complex of STEM disciplines is determined by the universality of the mathematical apparatus, its widespread use, the mathematization of various fields of knowledge; the significant impact of mathematical education on the intellectual, moral, and aesthetic development of the individual; and the exceptional importance of mathematical modeling and computational experimentation based on it as the leading method of scientific, engineering, and practical human activity.
   The problems in training mathematics teachers for the implementation of STEM learning are outlined, which necessitate the need for theoretical justification and research regarding the modernization of higher education in the context of effective implementation of the STEM concept.
4. The educational and developmental potential as well as defining features of the GeoGebra package as a tool for implementing the STEM education concept in the process of training pre-service mathematics teachers have been revealed. The GeoGebra package is positioned as a computer mathematics system oriented towards supporting educational and research activities. The package is powerful and continuously improved by an international team of developers. It has a wide range of applications in STEM education and its branches (such as STEAM, STREAM, etc.), scientific and practical activities of different directions. The full-featured version of the package

is freely available in Ukrainian. It is independent of hardware and operating systems and has a cloud-oriented version. There is a large base of freely distributed educational STEM resources created by the open GeoGebra community. The package allows for visualizing computer models in virtual and augmented reality and their materialization through 3D printing.

5. Pedagogical conditions for using the GeoGebra package as a tool for implementing the STEM education concept in the process of training pre-service mathematics teachers have been developed and theoretically substantiated. These include creating a cloud-oriented educational environment that contains software, informational, didactic, and methodological resources for organizing, supporting, and accompanying various types of student learning activities using the GeoGebra package. Introducing a practicum in conducting computer-based STEM-oriented research in the GeoGebra package into the educational process of training pre-service mathematics teachers. Using a set of tools to stimulate students to engage in STEM-oriented GeoGebra modeling based on organizing their extracurricular work, involving them in the GeoGebra community, and using individual and group coaching.
6. A pedagogical experiment was conducted to verify the effectiveness of the reasoned pedagogical conditions for the use of the GeoGebra package as a tool for implementing STEM education in the preparation of pre-service mathematics teachers. Criteria and indicators were developed for the formation of the ability of pre-service mathematics teachers to use the GeoGebra package as a tool for implementing the concept of STEM education: motivational-value (pre-service teachers' awareness of the value of mathematical knowledge and the mathematical apparatus as the basis for computer research of any objects; motivation to learn mathematics; readiness to overcome difficulties); praxiological (ability of pre-service teachers to step-by-step plan computer research using the technology of its conduct; ability to use GeoGebra functionality rationally for research; ability to analyze its results and draw conclusions); metacognitive (the ability of pre-service teachers to critically evaluate their level of knowledge for solving the problem; ability to effectively use various ways of acquiring knowledge; desire for continuous educational growth; ability to use the GeoGebra package for conducting transdisciplinary research). The reproductive, partially exploratory, and creative levels of formation were characterized for each criterion, scales were developed for their measurement, and diagnostic tools were determined and selected. The experimental data were processed using mathematical statistics methods. The results obtained confirmed the effectiveness of the reasoned pedagogical conditions for the use of the GeoGebra package as a tool for implementing the concept of STEM education in the preparation of pre-service mathematics teachers.
7. The findings of this research contribute to the growing body of evidence supporting technology integration in mathematics teacher education. Our results align with international trends showing that successful GeoGebra implementation requires a multifaceted approach combining technological, pedagogical, and content knowledge development [35, 36]. The identified challenges and solutions provide a roadmap for institutions seeking to enhance their pre-service teacher training programs through dynamic mathematics software integration.

7. Future work

The research conducted does not exhaust all aspects of the analyzed problem. We consider the development of a model of professional training of pre-service mathematics teachers on the basis of an integrative approach and methodological principles for implementing STEM education in the training of pre-service physics, computer science, and technology teachers as promising directions for further scientific research.

Based on comprehensive analysis of current research trends and identified gaps, several critical areas warrant future investigation:

1. Tracking pre-service teachers' technology integration practices from initial training through their first five years of teaching to assess sustained pedagogical change and identify factors supporting

long-term GeoGebra adoption [37].

2. Developing and evaluating strategies for GeoGebra implementation across all mathematical domains, extending beyond the current concentration in geometry and calculus to include statistics, discrete mathematics, and mathematical modeling [38].
3. Creating targeted professional development programs specifically addressing the persistent challenge of low digital instructional material design skills, incorporating principles of Universal Design for Learning and accessibility [39, 40].
4. Investigating and addressing gender disparities in technology adoption among pre-service mathematics teachers, with particular attention to cultural and institutional factors affecting equitable access and engagement [41].
5. Exploring the potential of augmented reality (AR) and virtual reality (VR) integration with GeoGebra to create immersive mathematics learning environments, building on current 3D visualization capabilities [42, 43, 44, 45, 46, 47, 48, 49, 50, 51].

These future directions reflect the evolving landscape of educational technology and the ongoing need for evidence-based approaches to teacher preparation in the digital age.

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Declaration on Generative AI

The authors have not employed any generative AI tools.

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The use of mobile applications in studying the topic “Basic classes of inorganic compounds” in the school chemistry curriculum

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Abstract

This study explores the possibilities of using mobile applications when studying the topic “Basic classes of inorganic compounds” in the school chemistry curriculum. The experience of domestic teachers in the use of mobile applications in chemistry lessons is analysed. A proprietary mobile application for studying the classification and properties of the main classes of inorganic compounds with a reference and testing module is proposed. Methodological recommendations for conducting lessons using the created application in grades 8 and 11 have been developed. The results of a teacher survey showed an insufficient level of use of mobile applications in the study of chemistry due to technical and methodological difficulties. The work has practical significance for the development and implementation of mobile applications in the school chemistry course.

Keywords

mobile learning, chemistry education, inorganic compounds, educational technology, school curriculum, teacher survey, interactive applications, digital tools, acid-base chemistry, pedagogical innovation

1. Introduction

The rapid development of information and communication technologies (ICT) in the 21st century has led to their widespread integration into the education system, including the teaching of chemistry [1, 2, 3]. The use of mobile devices such as smartphones and tablets has become particularly prominent, as they provide opportunities for interactive, engaging, and accessible learning experiences [4, 5, 6, 7, 8]. Mobile learning, which involves the use of mobile applications (apps) for educational purposes, has emerged as a promising approach to address some of the challenges in chemistry education, such as abstract concepts, complex visualizations, and disconnect from real-world applications [9, 10, 11]. However, the methodology for using mobile applications to study specific topics in school chemistry, such as basic classes of inorganic compounds, remains underexplored [10]. Ukrainian teachers face challenges in integrating mobile learning due to technical and methodological difficulties [12].

The purpose of this study is to develop a mobile application and methodological materials for its use in studying the topic “Basic classes of inorganic compounds” in the 8th and 11th grades. The objectives of the study are:

1. To generalise the experience of using mobile applications in studying the topic “Basic classes of inorganic compounds” based on the analysis of scientific sources;
2. To determine the methodological features of the topic “Basic classes of inorganic compounds” in the school chemistry course;
3. To clarify the current state of use of mobile applications in the study of basic classes of inorganic compounds in chemistry lessons in schools based on the analysis of the experience of practising teachers;

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4. To compare methodological and practical aspects of the use of mobile applications in the study of basic classes of inorganic compounds and the study of other topics of the school chemistry course;
5. To develop methodological kits for conducting lessons using mobile applications.

2. Results

The study of basic classes of inorganic compounds is a fundamental part of the school chemistry course. According to the educational programs [13], students begin to acquaint themselves with the concepts of "oxide", "acid", "base", and "salt" in the 7th grade, within the topics "Oxygen" and "Water". The main volume of knowledge about the classes of inorganic compounds is acquired in the 8th grade, in the topic "Basic classes of inorganic compounds", which is the largest topic in the school chemistry course (table 1).

Table 1
Distribution of the study of basic classes of inorganic compounds in the school chemistry course [13, 14].

Grade	Topic	Key concepts
7	Oxygen; Water	Oxides; Acids; Bases
8	Basic Classes of Inorganic Compounds	Classification; Nomenclature; Properties; Preparation methods; Applications
9	Solutions	Electrolytic dissociation of acids, bases, and salts
10	Organic Chemistry	Comparison of properties of organic and inorganic acids and salts
11	Chemical Elements and Inorganic Compounds; Non-metallic and Metallic Elements	Preparation, properties, and applications of representative compounds

In grades 8 and 11, students are expected to master the knowledge of the principles of classification of inorganic substances, the composition and structure of representatives of the main classes of inorganic compounds, modern nomenclature, chemical properties, and genetic relationships between them [13, 14]. The methodology of teaching this topic includes such forms of work as laboratory and practical work, demonstration experiments, scientific projects, and solving calculation problems.

However, students face difficulties in classifying oxides, understanding the concept of amphotericity, and studying certain chemical properties, such as the interaction of oxides with water, obtaining bases insoluble in water, and exchange reactions [15]. Therefore, there is a need for innovative teaching methods and tools, such as mobile applications, to facilitate the learning of this complex topic.

The use of mobile applications in chemistry education has been investigated in several studies. Dekhane and Tsoi [9] developed a mobile app that integrated multiple learning theories to support students' understanding of organic chemistry concepts. The app used interactive visualizations and self-assessment activities, resulting in improved conceptual understanding and positive student perceptions. Talib et al. [16] created an authentic mobile app that allowed students to construct and manipulate organic molecules using touch gestures. The app provided a visual and interactive way to explore reaction mechanisms, leading to increased engagement and understanding of chemistry concepts.

Sievertsen and Carreira [17] developed a mobile platform for collaborative problem-solving in organic chemistry. The app enabled students to work together on complex problems, share ideas, and receive feedback from peers and instructors. The study found that the collaborative features enhanced students' motivation and learning outcomes. In a quasi-experimental study, Cahyana et al. [18] investigated the effects of a mobile game-based learning app on high school students' performance in chemistry. The results showed that students who used the app had significantly higher learning outcomes compared to the control group, particularly among students with high learning independence.

Despite these promising findings, the use of mobile applications in teaching basic classes of inorganic compounds in Ukrainian schools remains limited. A survey of 30 chemistry teachers conducted as part

of this study revealed that 70% do not use mobile applications in lessons, while 30% do (figure 1). The main reasons for not using mobile apps include the inability of some students' phones to support the application, the predominance of English-language apps, the paid access to high-quality apps, the low quality of information reproduction in some apps, and the distracting factor for students.

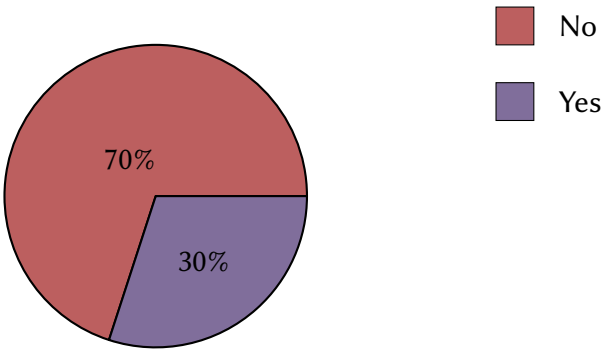

Figure 1: Results of the survey "Do you use mobile applications in your lessons?"

To address these challenges and provide chemistry teachers with a tool for teaching the topic "Basic classes of inorganic compounds" using mobile learning, a proprietary mobile application was developed in this study using the SkillzRun platform. The development process included the following stages:

1. Preparatory stage:
    - Analysis of scientific and methodological literature on the use of mobile applications in chemistry education;
    - Determination of methodological features of the topic "Basic classes of inorganic compounds" in the school curriculum.
2. Main stage:
    - Selection of theoretical material and development of tests for the 8th and 11th grades;
    - Creation of the mobile application using the SkillzRun platform;
    - Preparation of methodological kits for conducting lessons with the use of the developed application.
3. Final stage:
    - Conducting a survey among chemistry teachers to clarify the current state of use of mobile applications in studying basic classes of inorganic compounds;
    - Analysis and discussion of the results.

The developed mobile application contains two main modules:

1. Reference module with theoretical material on the classification, nomenclature, and properties of oxides, acids, bases, and salts, adapted for the 8th and 11th grades (figure 2).
2. Testing module for self-assessment of knowledge, containing interactive tests with different types of questions (figure 3).

The application can be used in lessons for learning new knowledge, generalising and systematising knowledge, and conducting tests and independent work. Methodological kits have been developed for conducting lessons on the topics "Physical properties of acids. Chemical properties of acids: effect on indicators, interaction with metals, basic oxides, bases, salts" for the 8th grade and "Properties of sulfuric acid" for the 11th grade using the mobile application. The kits include a lesson plan, didactic materials (in the mobile application), and criteria for assessing student achievement. Sample lesson plans are provided in appendices A and B.

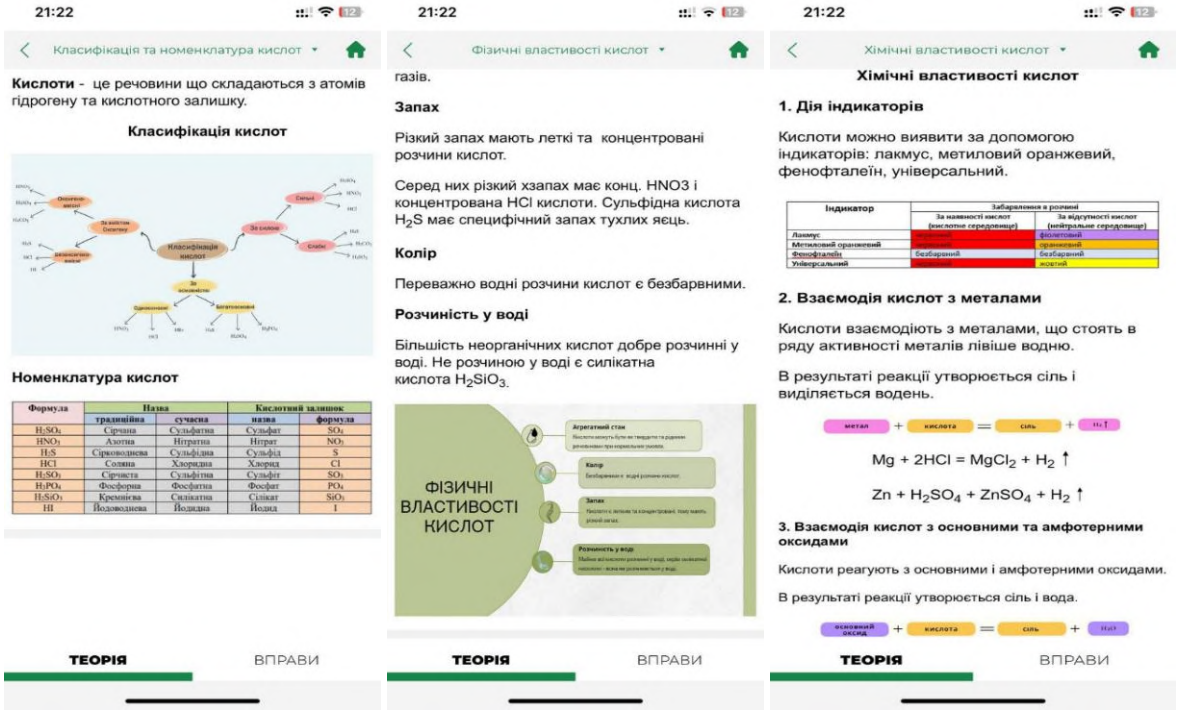

Figure 2: Example of theoretical material in the reference module of the mobile application.

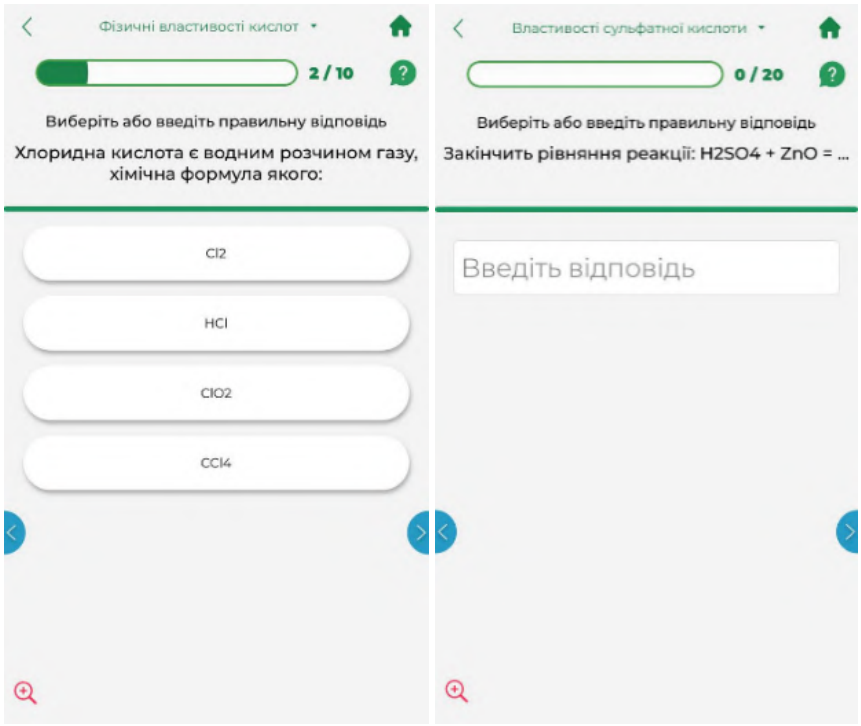

Figure 3: Example of a test question in the testing module of the mobile application.

The developed mobile application and methodological recommendations have practical significance for chemistry teachers. They can help increase students' interest in the subject, encourage the search for information, deepen students' knowledge, and apply information and communication technologies in teaching. The use of the application in lessons corresponds to the key competencies defined in the chemistry curriculum [13], such as:

- Competence in the natural sciences and technologies;
- Information and digital competence;
- Lifelong learning skill;
- Communication in the native language;
- Mathematical competence.

However, the study has some limitations. The developed application covers only a part of the topic "Basic classes of inorganic compounds" and was not tested in a pedagogical experiment. The survey of teachers was conducted on a small sample and may not fully reflect the state of use of mobile applications in chemistry teaching in Ukraine. Further research is needed to expand the content of the application, evaluate its effectiveness in practice, and investigate the long-term impact on student learning outcomes.

3. Conclusions

The study of basic classes of inorganic compounds is an essential part of the school chemistry course, which occurs throughout grades 7-11, with the main volume of knowledge acquired in the 8th grade. Students are expected to master the knowledge of the principles of classification of inorganic substances, the composition and structure of representatives of the main classes of inorganic compounds, modern nomenclature, chemical properties, and genetic relationships between them. However, students face difficulties in understanding certain concepts and properties, such as amphotericity, interaction of oxides with water, and exchange reactions.

The use of mobile applications in chemistry education has the potential to address these challenges by providing interactive, visual, and engaging learning experiences. However, the methodology for using mobile apps to study specific topics, such as basic classes of inorganic compounds, remains underexplored, particularly in the Ukrainian context. Domestic teachers face technical and methodological difficulties in integrating mobile learning into their practice, as evidenced by the survey conducted in this study.

To address this gap, a proprietary mobile application was developed using the SkillzRun platform, containing theoretical material and tests on the properties of acids and sulfuric acid for grades 8 and 11. Methodological kits for conducting lessons using the application have been prepared, which include lesson plans, didactic materials, and assessment criteria. The developed application and recommendations have practical significance for implementing mobile learning in the study of basic inorganic compound classes in the school chemistry course. They can help increase student engagement, deepen knowledge, and integrate modern technologies into chemistry education.

However, the study has limitations in terms of the scope of the application content, lack of practical testing, and a small sample of surveyed teachers. Future research may focus on expanding the application to cover more topics and grades, conducting a pedagogical experiment to evaluate its effectiveness, and investigating the long-term impact on student learning outcomes. Collaboration between educators, researchers, and application developers is needed to create high-quality mobile learning solutions adapted to the needs of chemistry teachers and students in Ukraine.

Declaration on Generative AI

We acknowledge the assistance of Claude 3.7 Sonnet in translating content from Ukrainian.

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A. Lesson plan for grade 8

Topic: Physical properties of acids. Chemical properties of acids: effect on indicators, interaction with metals, basic oxides, bases, salts.

Objectives:

- Educational: to study the physical and chemical properties of acids, namely the effect on indicators, interaction with metals, basic oxides, bases, and salts.
- Developmental: to develop spatial thinking and logical reasoning.
- Upbringing: to foster cognitive interest in the lesson.

Type of lesson: Combined.
Methods and forms of work: Independent work; conversation.
Equipment: Smartphone.
Lesson structure:

1. Organizational moment
2. Actualization of basic concepts
3. Motivation of learning activities
4. Study of new material
5. Generalization of knowledge
6. Lesson summary
7. Homework assignment

Lesson progress:

1. *Organizational moment*
   Greeting with students. I hope you will be active in today's lesson and our lesson will be effective. Checking students' attendance.
2. *Actualization of basic concepts*
   a) What are the classes of inorganic compounds?
   b) Describe the structure of acids.

c) What acids are found in everyday life?
d) Indicate the formulas of the most important acids.
e) Acids are ...?

3. *Motivation of learning activities*
Today we will consider an interesting topic "Physical properties of acids. Chemical properties of acids: effect on indicators, interaction with metals, basic oxides, bases, salts" and perform an independent work.
4. *Study of new material*
Physical properties of acids:

- Liquids or low-melting substances;
- Have a pungent odor and sour taste;
- Have a low melting point;
- Some acids are toxic substances;
- Almost all acids are soluble in water.

Chemical properties:

a) Detection of acids using indicators (table 2).

Table 2
Color of indicators in different media.

Indicator	Neutral medium	Acidic medium
Universal paper	yellow	red
Methyl orange	orange	red
Litmus	purple	red
Phenolphthalein	colorless	colorless

b) Acids react with metals, forming a salt and evolution of hydrogen:

$$Mg + 2HCl = MgCl_2 + H_2\uparrow$$
$$Zn + H_2SO_4 = ZnSO_4 + H_2\uparrow$$

c) Acids react with basic and amphoteric oxides, forming a salt and water:

$$K_2O + HNO_3 = 2KNO_3 + H_2O$$
$$ZnO + 2HCl = ZnCl_2 + H_2O$$

d) Acids react with bases, forming a salt and water:

$$2NaOH + H_2SO_4 = Na_2SO_4 + 2H_2O$$

e) Acids react with salts, forming an insoluble salt and an acid:

$$BaCl_2 + H_2SO_4 = BaSO_4\downarrow + 2HCl$$

f) Acids react with salts, forming an insoluble acid and a salt:

$$Na_2SiO_3 + 2HCl = 2NaCl + H_2SiO_3\downarrow$$

Independent work with the use of the mobile application:
Dear students! I suggest you take your smartphones. Now we will download the mobile application. After downloading the mobile application, you will take a test on the topic "Physical properties of acids. Chemical properties of acids: effect on indicators, interaction with metals, basic oxides, bases, salts".
Students listen to the instructions and the algorithm for downloading the mobile application and taking the test.
Algorithm for downloading the mobile application:

a) Open Google Play or App Store.
b) Register with your first and last name.
c) Select the subject "Chemistry" and "Chemistry Grade 8".
d) First, select the topic "Physical properties of acids" and take the test.

e) Select the topic “Chemical properties of acids” and take the test.

At the end of the test, students will receive grades for taking the test.
QR code for downloading the mobile application:

5. *Generalization of knowledge*
   a) Give examples of acids that are soluble in water.
   b) Give examples of oxygen-free acids.
   c) Give examples of oxygen-containing acids.
   d) Give an example of an acid that is insoluble in water.
6. *Lesson summary*
   Evaluation of independent work.
7. *Homework assignment*
   (Homework assignment from the textbook or workbook)

B. Lesson plan for grade 11

Topic: Properties of sulfuric acid.
Objectives:

- Educational: to familiarize students with the physical and chemical properties of sulfuric acid; to consider the applications and occurrence of sulfuric acid.
- Developmental: to develop spatial thinking and critical reasoning.
- Upbringing: to foster cognitive interest in the lesson.

Type of lesson: Lesson of learning new knowledge.
Methods and forms of work: Independent work; conversation.
Equipment: Smartphone.
Lesson structure:

1. Organizational moment
2. Actualization of basic concepts
3. Motivation of learning activities
4. Study of new material
5. Generalization of knowledge
6. Lesson summary
7. Homework assignment

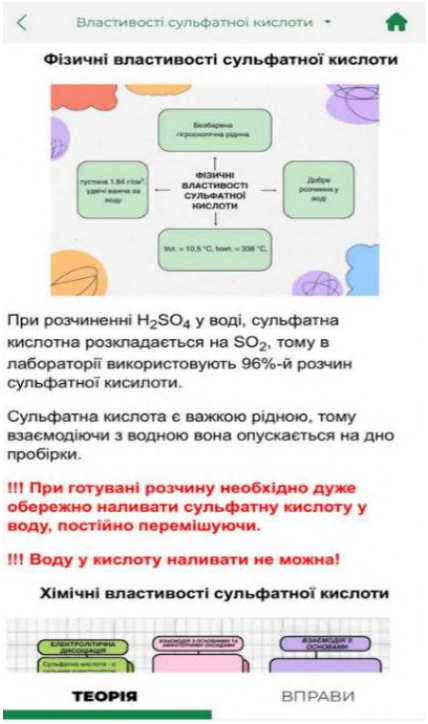
Lesson progress:

1. *Organizational moment*
   Greeting with students. I hope you will be active in today’s lesson and our lesson will be effective.
   Checking students’ attendance.
2. *Actualization of basic concepts*
   a) Acids are ...

b) Give examples of the most important acids.
c) Name the physical properties of acids.
d) How do acids differ from each other (odor, color)?
e) Describe the applications and occurrence of acids.

3. *Motivation of learning activities*
   Today we will study a new topic “Properties of sulfuric acid” and consolidate your knowledge of this topic using a mobile application.
4. *Study of new material*
   Students, to begin with, I suggest downloading the mobile application:
   QR code for downloading the mobile application:

Using the mobile application, review the theoretical material for the topic.



Physical properties of sulfuric acid:

- Colorless hygroscopic liquid;
- Melting point 10.5 °C, boiling point 338 °C;
- Density 1.84 g/cm^3;
- Readily soluble in water;
- Twice as heavy as water.

Chemical properties of sulfuric acid:

a) Sulfuric acid reacts with basic and amphoteric oxides:

$$3H_2SO_4 + Al_2O_3 \rightarrow Al_2(SO_4)_3 + 3H_2O$$
$$2MgO + 2H_2SO_4 \rightarrow Mg_2(SO_4)_2 + 2H_2O$$

b) Sulfuric acid reacts with bases:

$$2NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2H_2O$$
$$2Fe(OH)_3 + 3H_2SO_4 \rightarrow Fe_2(SO_4)_3 + 6H_2O$$

c) Sulfuric acid interacts with weak acids:

$$ZnS + H_2SO_4 \rightarrow ZnSO_4 + H_2S$$

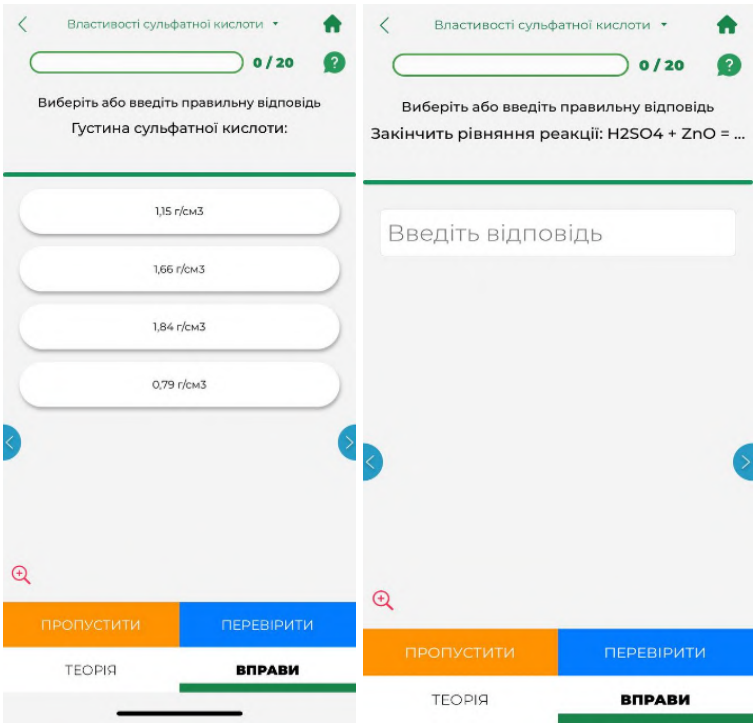
d) Sulfuric acid interacts with metals:

$$2Fe + 3H_2SO_4 \rightarrow Fe_2(SO_4)_3 + 3H_2$$

e) Sulfuric acid reacts with alkalis and hydroxides:

$$2KOH + H_2SO_4 \rightarrow K_2SO_4 + 2H_2O$$

5. *Generalization of knowledge*
   Students, now I suggest you perform an independent work, open the mobile application and select the topic “Properties of sulfuric acid”.



6. *Lesson summary*
   Discussion and evaluation of independent work.
7. *Homework assignment*
   (Homework assignment from the textbook or workbook)

Features of using mobile applications to identify plants and Google Lens during the learning process

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Abstract

Students' motivation by providing personalized studies and using IT during classes is relevant in STEM. However, there is a lack of research devoted to justifying these approaches. The research aims to justify the choice of AR-plant recognition application, choosing to provide personalized experience during both the educational process at school and extracurricular activities. All apps have been analyzed and characterized by all interaction processes of the app with the user. In addition, the social environments of the apps and their usage during extracurricular activities are described. The didactics of the usage of AR-recognition apps in biology classes have been described. To provide usability analysis, a survey of experts on digital didactics was conducted to evaluate such criteria as installation simplicity, level of friendliness of the interface, and accuracy of picture processing. To evaluate the rationality of usage, apps were analyzed on the accuracy of plants recognition of the "Dneprovskiy district in Kyiv" list. It is proven that Google Lens is the most recommended app to use for these purposes. Recent meta-analyses (2020-2024) demonstrate that mobile plant identification applications achieve accuracy rates ranging from 71-92.6%, with Google Lens consistently outperforming specialized apps. These applications leverage deep learning models, particularly MobileNetV3 architectures, enabling offline functionality crucial for field-based education. Studies across diverse educational contexts reveal significant improvements in student engagement (35% increase), knowledge retention, and intrinsic motivation when plant ID apps are integrated with traditional teaching methods. However, implementation faces critical challenges including digital literacy gaps, infrastructure limitations in rural areas, and the need for comprehensive teacher training. This study contributes empirical evidence supporting the pedagogical value of mobile plant identification while addressing practical implementation considerations for STEM education. Considering the analysis results, Seek or Flora Incognita are both valid alternative options. However, these apps were characterized by lower accuracy. The use of mobile applications to identify plants is especially relevant for distance learning.

Keywords

mobile application, STEM, augmented reality, plant identification, Google Lens, deep learning, digital literacy, MobileNetV3, self-determination theory, rural education, formative assessment

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1. Introduction

The implementation of a mobile phone as a modern instrument into educational process has proven to achieve impressive results [1, 2, 3, 4]. Mobile phone usage during classes provides visualization of educational material, thus involving students in research and increasing their motivation for learning [5, 6, 7]. Compared to computer approaches, mobile phone applications are characterized by the most promising advantages, including portability and the possibility to use both internal and external sensors (not commonly used). The modern educational directions include personalization and the research process, which may be achieved through the use of mobile phones [8]. However, it was proved that a general didactic approach led to a significant effect rather than using the device (mobile phone) for some separate aspects of education [9]. STEM/STEAM/STREAM technologies appear to be the most promising and relevant for the use of mobile apps.

Recent advances in mobile plant identification technology have transformed botanical education across global contexts. According to comprehensive analyses spanning 2018-2024, over 14 major plant identification applications are currently available, with user bases exceeding 10 million downloads collectively. These applications employ sophisticated deep learning architectures, with convolutional neural networks (CNNs) achieving remarkable accuracy improvements from 55% in early iterations to current rates exceeding 99% for well-constrained datasets.

The technological evolution has been particularly dramatic in three key areas:

1. *Accuracy enhancement* – modern applications utilizing MobileNetV3 and EfficientNet architectures demonstrate species-level identification accuracy ranging from 71% (Flora Incognita) to 92.6% (Google Lens), with genus-level accuracy consistently exceeding 95%.
2. *Offline capabilities* – the development of lightweight models enables real-time identification without internet connectivity, processing images in 338.1ms on standard mobile devices—critical for field-based education in areas with limited connectivity.
3. *Educational integration* – studies across 71 institutions report that mobile plant identification apps increase student engagement by 35% and improve knowledge retention at higher cognitive levels (analysis, synthesis, evaluation).

The pedagogical implications are substantial. Research grounded in Self-Determination Theory demonstrates that instant feedback and interactive features significantly enhance intrinsic motivation and perceived competence. Students using mobile identification apps show a 25% increased likelihood of achieving grade-level reading in botanical texts and 63% higher probability of attaining grade-level scientific writing skills.

However, implementation challenges persist. Digital literacy gaps affect 40% of rural educational institutions, while infrastructure limitations constrain adoption in developing regions. Recent interventions emphasize the necessity of blended learning approaches, combining digital tools with traditional botanical keys to maximize educational outcomes while addressing technological barriers.

2. Analysis methods

To analyze the plant identification apps' usability, a survey of experts on digital didactics was provided. The main criteria were installation simplicity, level of friendliness of the interface, and accuracy of picture processing. Each criterion was evaluated from 0 to 5 (the higher the better). Those applications which were characterized by an average evaluation grade of more than four were used to further analyze quality of identification taking into account the condition that the application may be used by both students and teachers with a low level of ICT competence.

Analysis of quality of identification was provided by a simplified method compared to our previous research [10] due to the aim of this paper to obtain a general state on application plant identification accuracy. 350 images from the list of plants of the catalog "Dneprovskiy district of Kyiv" were taken to analyse the identification accuracy. The key from the "Dneprovskiy district of Kyiv" plant classification was used as a control. The vast majority of photographs of plants on this list contain distinct vegetative

organs (shoots with stems, leaves, buds) and generative organs (flowers or fruits). The presence of the latter is necessary to accurately determine the species.

To analyze the data, tables with names of the plant as lines and as names of the app in columns have been created. Each successful identification was evaluated as 1 and unsuccessful as 0 (see an example in table 1).

Table 1
Example of the table of apps analyzing.

The name of the plant	Flora Incognita	PlantNet	Seek	LeafSnap	Picture This
Prunus armeniaca (Apricot)	0	0	0	0	1
Jasione montana	0	1	1	1	1
Ageratum houstonianum	0	1	0	1	1
Chaenomeles japonica	0	0	0	0	0
Amaranthus	1	0	1	1	0
Ambrosia artemisiifolia	0	1	0	1	1
Amorpha fruticosa	0	0	1	1	0
Anemone sylvestris	1	1	1	1	0
Anemonoides ranunculoides	1	0	0	0	1
Anisanthus tectorum	0	0	1	0	0

To enhance the validity of our findings, we integrated a standardized evaluation framework based on recent meta-analyses (2020-2024) that assessed plant identification applications across multiple dimensions. This expanded methodology incorporates:

1. Multi-criteria performance assessment.
   Following standardized metrics established in recent studies, we evaluated applications using:
   - Species-level accuracy (percentage of correct identifications to species)
   - Genus-level accuracy (percentage of correct identifications to genus)
   - Processing time (milliseconds per image on standard devices)
   - Offline capability (binary assessment of functionality without connectivity)
   - Confidence scoring (presence of uncertainty indicators)
2. Image preprocessing quality metrics.
   Recent studies demonstrate that preprocessing significantly impacts accuracy. We assessed:
   - CLAHE (Contrast Limited Adaptive Histogram Equalization) implementation
   - Edge detection algorithms
   - Super-resolution capabilities
   - Multi-organ recognition support
3. Educational effectiveness indicators.
   Drawing from pedagogical research, we measured:
   - Time to first correct identification (learning curve assessment)
   - Feature explanation quality (educational content depth)
   - Interface accessibility for different age groups
   - Support for collaborative learning features

3. Results

3.1. Analysis of the interaction with apps

General characteristics of the apps. The apps' databases are significantly differing. For example, the lowest number of plants in the database is in Flora Incognita (4800 species), and the highest is in PlantSnap (585,000 species).

In addition, the app's databases differ in the presence of species based on geographical locations. For example, Flora Incognita's database is very limited geographically and contains only German flora; Conversely, PlantNet's data is geographically vast and contains flora of Western Europe, USA, Canada, Central America, Caribbean islands, Amazon, French Polynesia, including, medicinal plants, invasive plants, weeds.

Login procedure and instruction. For education, the login procedure is significant because it is related to the safety of students' personal data. On the other hand, login possibility is vital to save achievements, progress, and communications which motivates the student.

Only LeafSnap does not use the additional account at all (it automatically connected to the Google account). However, almost all apps request their own account. For example, Seek requests Inaturalist account (to connect with Inaturalist social network). Apps such as FloraIncognita start with the account creation page; PictureThis starts from the page with subscription plans, which may be a disadvantage when used by students. The login process into Flora Incognita, PlantNet, PlantSnap, Seek, Picture-This, and PictureThis's is accompanied by aggressive advertising illustrated in figure 1.

The feature of detailed video instructions is available via e-mail only in the PlantSnap app (English audio and Russian subtitles available). Other apps provide instructions within themselves. PlantNet does not feature any instructions whatsoever. Instructions of PictureThis are very simple. LeafSnap's help section is not displayed with the first launch confined to a specific tab. Instructions presentation in Flora Incognita (a), PlantSnap (b), PictureThis (c) LeafSnap (d) and Seek (e, f) apps is presented in figure 2.

Data and photo input process. According to botanical science, the algorithm for determining a plant includes: establishing the life form of the plant (tree, bush, grass); studying the vegetative parts of the plant (leaves, stem). In addition, generative organs (flower or fruit) analysis is helpful to determine a specific species name. Flora incognita and LeafSnap request the addition of different parts of the given plant's pictures. The mechanism of processing can differ. For example, Flora incognita processes photos of different parts of the plant; PlantNet provides photography and then choice of the plant part (analysis of only one photo).

Geographic location is significant to identify many species. For example, Picea omorika and Picea abies are very similar species, but Picea omorika is only found in Western Siberia and Eastern Bosnia and Herzegovina. Seek, Flora Incognita, LeafSnap, PlantNet request geolocation access during the first launch. If the algorithm for determining the plant in the application includes the definition of life form, photographing the vegetative and generative organs, and the geographical location of the object, such algorithm has been evaluated as entirely correct. If the application of the plant is based on the analysis of one image in a single click, the algorithm has been evaluated as simple. The interface of different apps' photo and data input is presented in figure 3.

All apps are free, but PlantSnap limits the quantity of identifications by 25 plants per day per account. The mobile application PictureThis has the biggest amount of advertising. This mobile application also allows you to identify only 5 plants per day for free. Therefore, the use of PictureThis during the learning process is quite limited. The programs can request a single photo of the plant or photos of different parts of plants (PlantNet). In addition, LeafSnap provides automatic detection of the part of the plant presented in the photo. In general, all programs allow both making a real-life photo or uploading the photo made before.

Identification results. All apps (except PlantNet and Seek) provide information on the determined plant. All data on the plant is very structured in all apps and displayed, for example, in the manner: "Genus: Fucus".

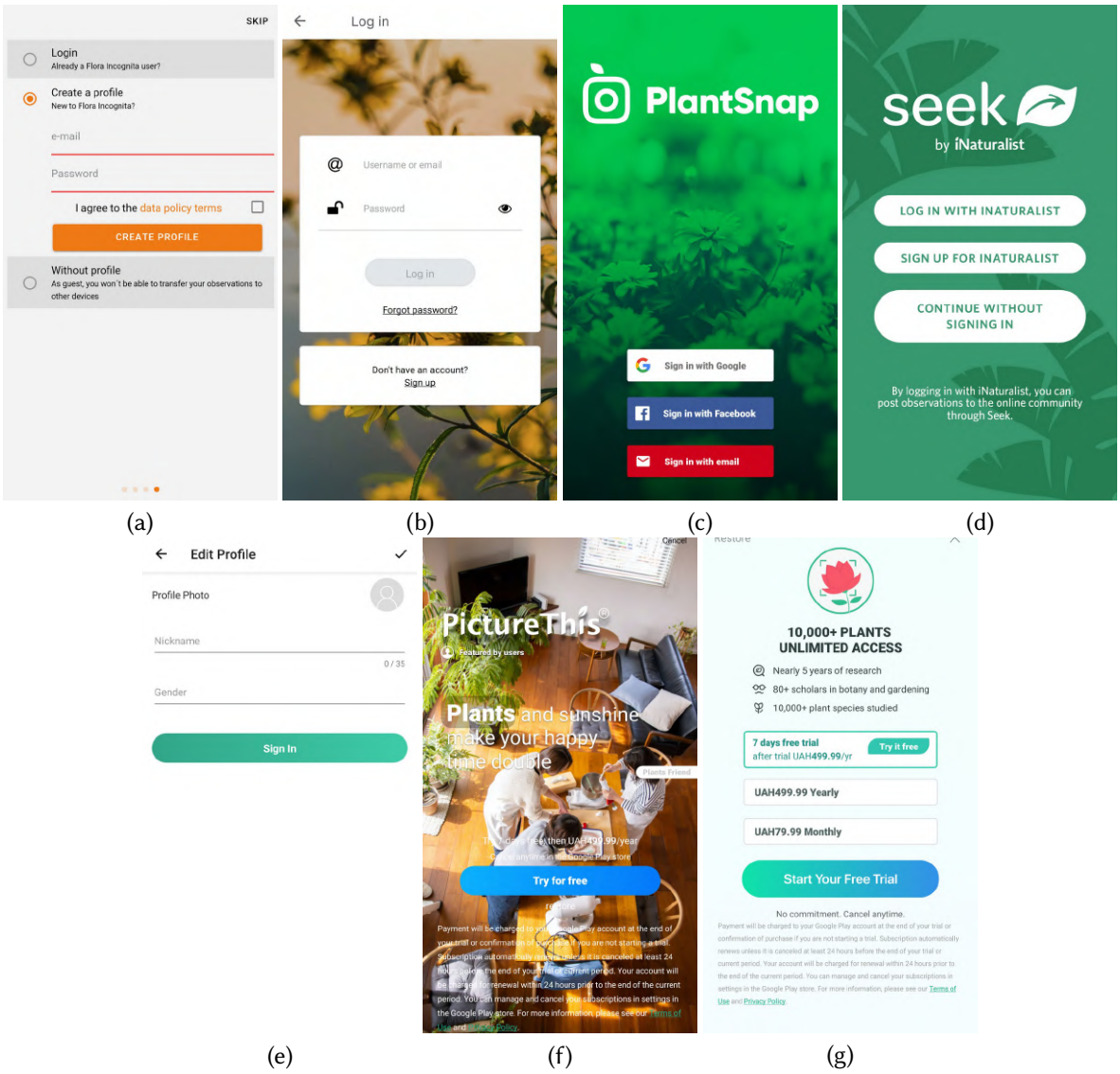


Figure 1: Login process of Flora Incognita (a), PlantNet (b), PlantSnap (c), Seek (d), Picture-This (e), and PictureThis's aggressive advertising (f, g).

FloraIncognita, PlantNet, PlantSnap provide interaction with other sources. Both public sources such as Wikipedia and more specialized sources, such as Plants for a Future, are used for interaction. The most interactive app among them is Plant net. It provides links to Catalogue of Life, Plants for a Future, and Wikipedia Flora Incognita. When used with the Russian interface, it provides the additional link to the site https://www.plantarium.ru (figure 4). Comparison results of mobile applications that can analyze plant photos are presented in table 2.

There are some spesific functions available during identification:

- PictureThis can provide an auto diagnosis of plant's problems with pests and determination of their diseases (figure 5);
- PlantSnap finds the plant on amazon and provides an infographic on solar activity, water usage and activation temperature.

3.2. Infrastructure and social environment

Some applications have their own approach to providing complex research of nature. Those features are useful forincreasing students' motivation to research nature. However, it is worth noting that the

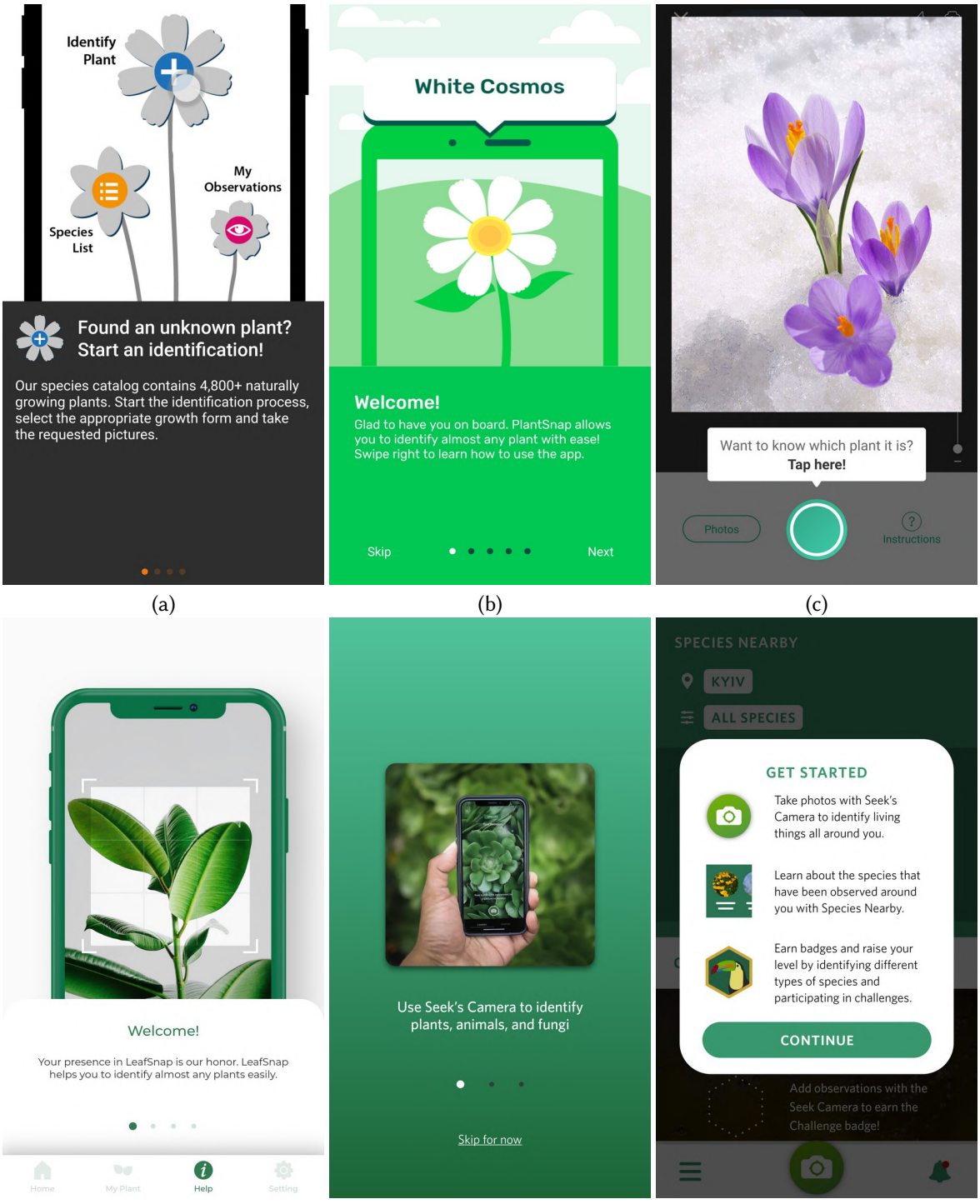


Figure 2: Instructions in Flora Incognita (a), PlantSnap (b), PictureThis (c) LeafSnap (d) and Seek (e, f) apps.

most developed environment is in Seek used iNaturalist application (developed by California Academy of Science and National Geographic), which delivers robust systems of different instruments to students and teachers.

Photo sharing and communications. PlantNet provides the feed of photos to identify plants shared by other users of PlanNet. The information in the feed is divided into classes "identified", "unidentified", and "All" filter (displays both identified and unidentified). The items in the feed with an "identified" filter will display already identified plants by users, and "unidentified" filter will display unidentified pictures updated by users. The most promising approach is to use an "unidentified" feed which may be

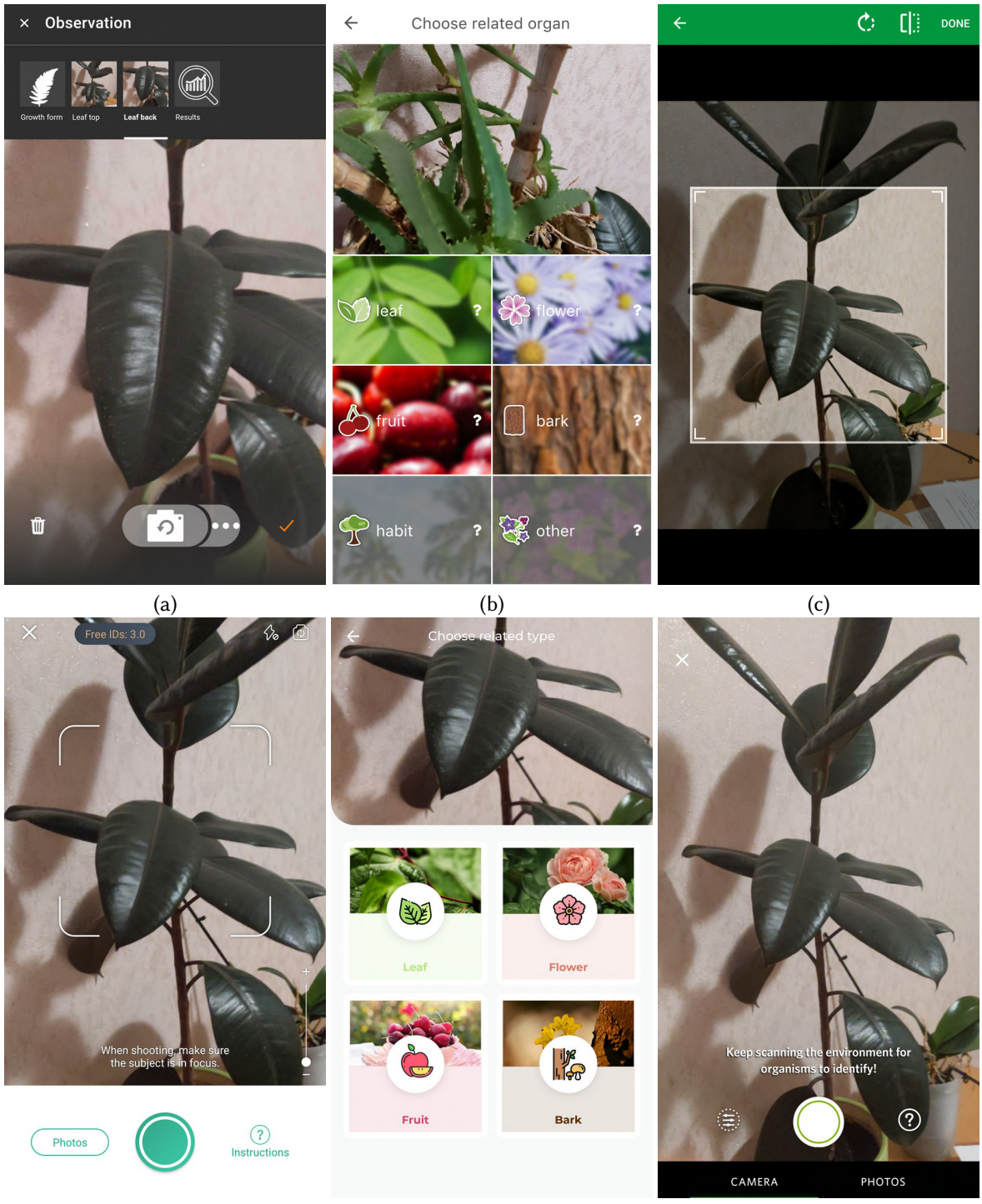


Figure 3: The interface of photo and data input of Flora Incognita (a), PlantNet (b) PlantSnap (c) PictureThis (d) LeafSnap Seek (e) apps.

helpful in a few cases:

- To help with identifying the plant
- To train own identification skills by providing identification of pictures of others
- To share thoughts in the field of botanic, communicate with other researchers, and provide social science networking.

Personal journals. The first instrument to motivate a young researcher is providing a personal journal

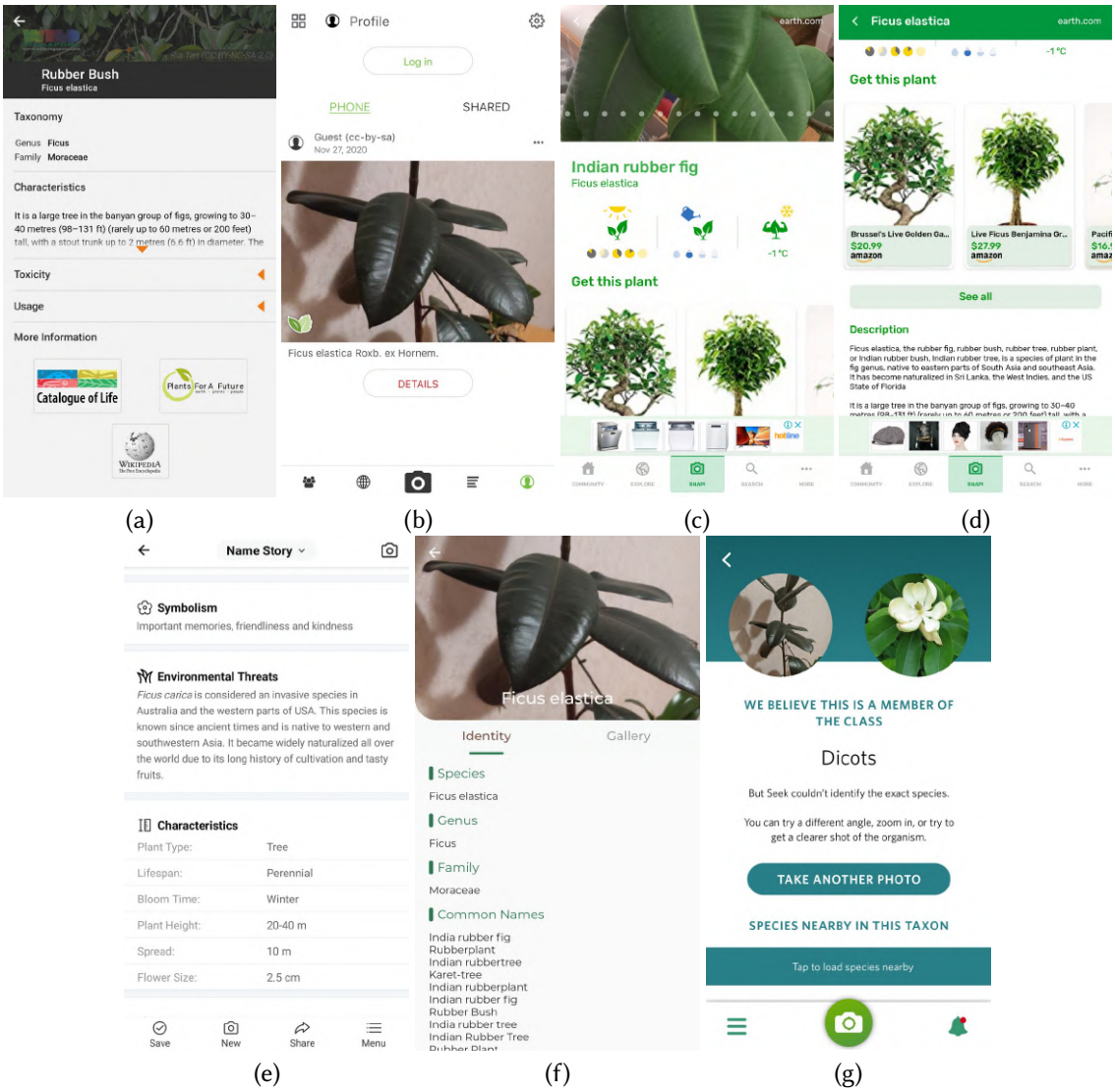


Figure 4: Data on identified plant Flora Incognita (a), PlantNet (b), PlantSnap (c, d), PictureThis (e), LeafSnap (f), and Seek (g).

of observation and identification. It is a widespread feature. For example, Flora Incognita has the tab "My observations"; PictureThis has "My garden"; Leaf snap has "My plants". However, some apps do not provide an explicitly personal journal. For example, PlantNet only saves the history of observations.

Projects and social. Seek provides collaboration through access to projects. Users can find and choose projects that they would like to join. It is worth noting that the app is ubiquitous and that there are even projects available in Ukraine. The project selection and specific project interfaces are presented in figure 6a.

Achievements. Seek-identification app provides a significantly different approach to increasing students' motivation. It provides achievements for each plant students may find, which motivates them to delve into new studies from time to time. The effect of achievement affects the brain as exaltation, and people desire it repeatedly. It is used in games to motivate students to play again and again [11, 12, 13]. In the case of Seek, some factors will motivate students to research nature.

The iNaturalist offers to observe plant and animal species, which a student can find nearby. This feature is activated by the "Exploring All" function and choosing "My location". Moreover, based on location, students can use Missions which gibes quests for students to do, for example, to find a "Rock Pigeon". Hence, students can observe nature nearby to study it in general terms while the program keeps encouraging students by illustrating progress through completion of various missions. The

Table 2
Comparison results of mobile applications that can analyze plant photos.

Application	Number of plants in the database	Accuracy of the analyzing process	Links to other information services
Flora Incognita	4800 (only German)	The analysis algorithm is correct	Links to Catalogue of Life, Plants for a Future and Wikipedia. Flora Incognita, with a Russian interface, provides links to the Russian site
PlantNet	21920	The analysis algorithm is entirely correct	Gives only the name of the plant. Includes elements of social networks (by sharing plants student found and subscriptions). In addition, it contains links to Wikipedia.
PlantSnap	585000	The analysis algorithm is simple.	Has its own description. Searches via Amazon to give purchase options of the plant in question.
Picture This	10000	The analysis algorithm is simple.	Provides very structured information (including type, lifespan, height, flower diameter), care aspects, usage of the plant
LeafSnap	No data	The analysis algorithm is correct. Evaluation of health state (healthy and unhealthy) is included into determination process.	Contains links to Wikipedia, Pl@ntUse, Global Biodiversity Information Facility
Seek	No data	The analysis algorithm is the simplest. Achievements are given to users after some successful identifications	Has no detailed description but proposes "species nearby in this taxon"

Exploring All and Missions functions are presented in figure 6b, c.

3.3. Analysis of application identification accuracy

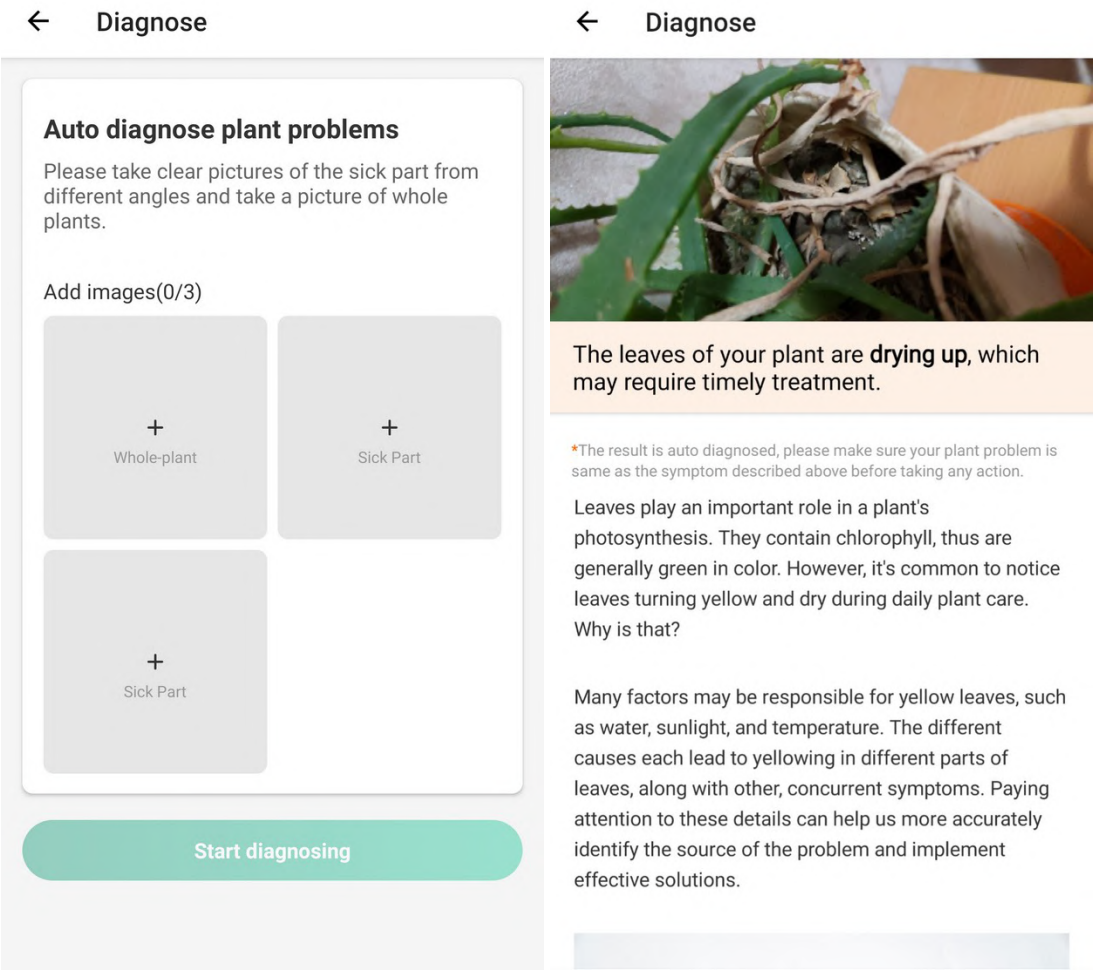
PlantNet is the most straightforward app to install. Google Lens, LeafSnap and Flora Incognita have also simple installation procedure. Google Lens, LeafSnap, Flora Incognita, Seek have the most straightforward interface. Google Lens, PlantSnap, PictureThis, and PlantNet are characterized by the most uncomfortable identification process, which can be complicated for teachers. Results of detailed analyses on plant identification applications are presented in figure 7.

In general, Google Lens, LeafSnap, Flora Incognita, PlanNet, and Seek have proven to be the most usable after detailed research. However, the total number of points each application received is presented in figure 8.

The most accurate apps are Google Lens, with 92.6% identification accuracy. Flora Incognita correctly identifies 71% of cases; PlantNet – 74%; Seek – in 76%, LeafSnap – in 76%. The PictureThis percentage of correct definitions was not determined, because this mobile application allows to identify only three plants per day for free. For a comparison of the identification plants accuracy by research applications, see figure 9.

Our previous work demonstrated that Google Lens does not differentiate native species from Ukraine. It seems that Seek, PlantNet and Google Lens mostly use data of American and European kinds of plants to train the neural network, and they have missed during identification of specific Ukrainian kinds of plants. Flora Incognita provides significantly different specific analyses; it may be due to Flora Incognita using a Russian database (similar to the Ukrainian region).

In our previous studies, it was shown that the accuracy of plant detection by the mobile application PlantNet is 55%. However, in the current test, the percentage of correct identification of plants by this mobile application has increased to 74%. This tendency indicates the ability of this neural network to



(a) (b)

Figure 5: PictureThis' app features autodiagnosis on pests and diseases function: photo input interface (a) and the result of the analysis (b).

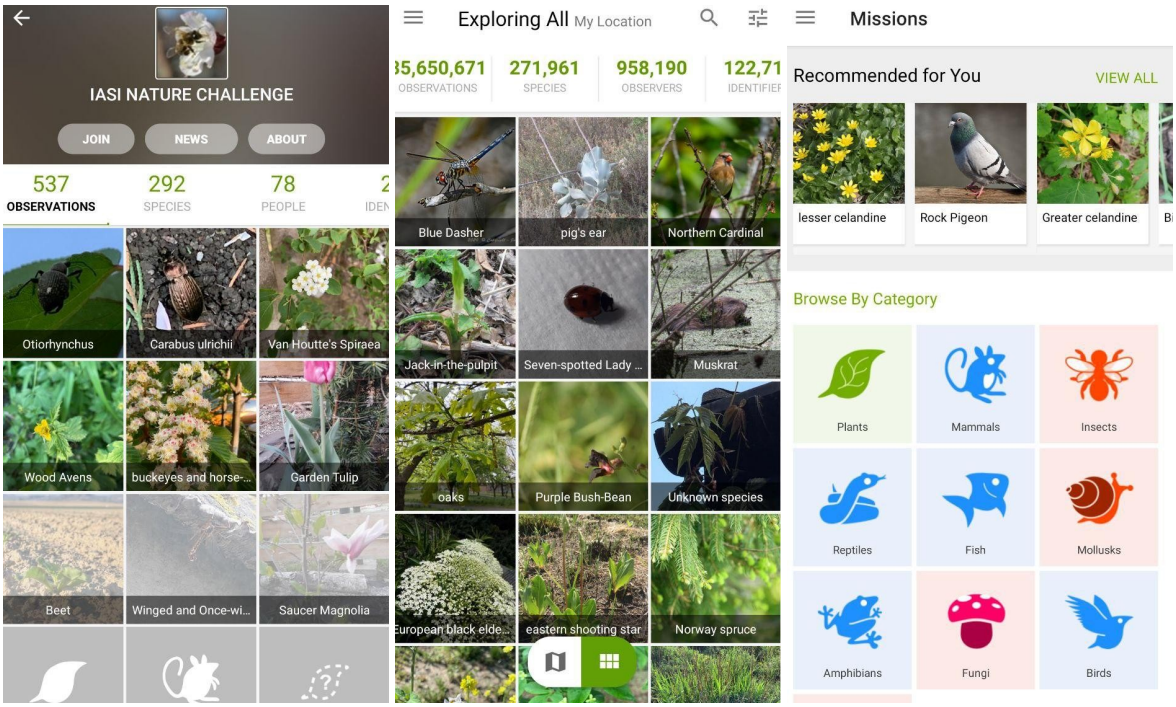
learn.

The algorithm for determining plants using Seek also differs significantly. All other applications studied, except Seek, require a clear real-time photograph of the plant. Seek works with the user by interactively managing his activities in terms of image quality.

From the point of view of botanical science, the possibility to add different parts to the plants and choose the plant's type and geolocation access must affect the identification process accuracy. However, considering the results of the experiment, applications with a simple algorithm definition (analysis of a single image) more accurately identify plants. Therefore, it seems that internal algorithms of identification (due to higher statical characteristics of neural network) and the fullness of the database are more important than accuracy of data input or taking user geolocation into account.

It should be noted that Seek identifies plants according to the algorithm used by professional botanists. Firstly, Seek defines the department, then the class, family, genus, and, finally, the species. Therefore, Google Lens is the most recommended app for use during classes [14]. It is thus characterized by the highest general evaluation with 4.6 points of interface analysis, which is significantly higher than marks for other apps.

However, taking into account results of usability analysis and quality of analysis, it is possible to use Seek or Flora Incognita for students and teachers who do not like the Google Lens app for whichever reason. However, PlantNet cannot be recommended to use due to low accuracy which may result in half of incorrect analysis results.



(a) (b) (c)

Figure 6: The Exploring All (a), Missions functions (b) and concrete project (c) functions.

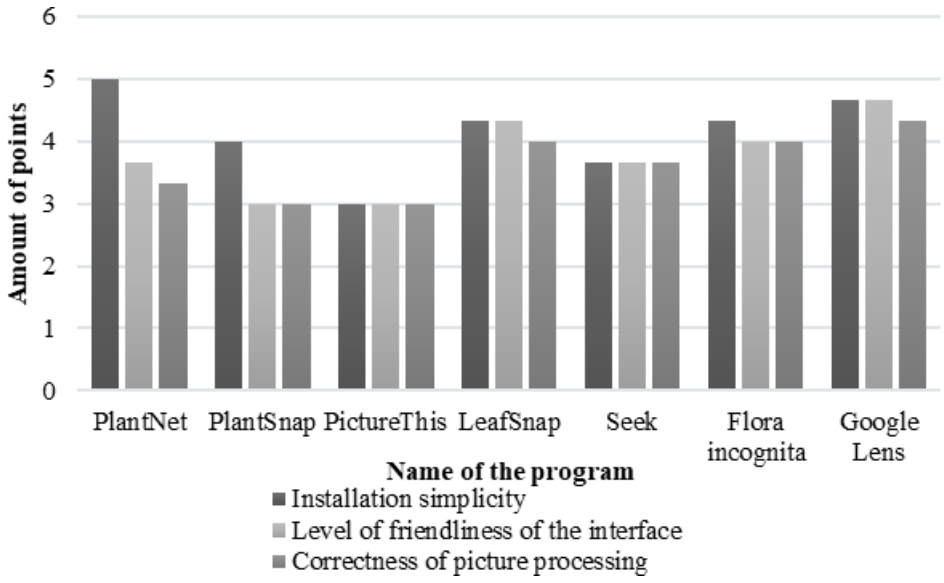


Figure 7: Results of detailed results on plants identification applications usability analysis.

4. Discussion

4.1. Advantages of using mobile phone applications in the educational process

In our opinion, the use of mobile applications that identify plants during the education process has the following functions:

1. Function of creating a learning environment. Even in the works of Montessori [15] (a true classic of pedagogical thought), it was proven that the environment should develop the child. To a greater or lesser extent, mobile applications create such an environment. For example, Seek stimulates the child to search for new plant objects, manages the process of photographing plants,

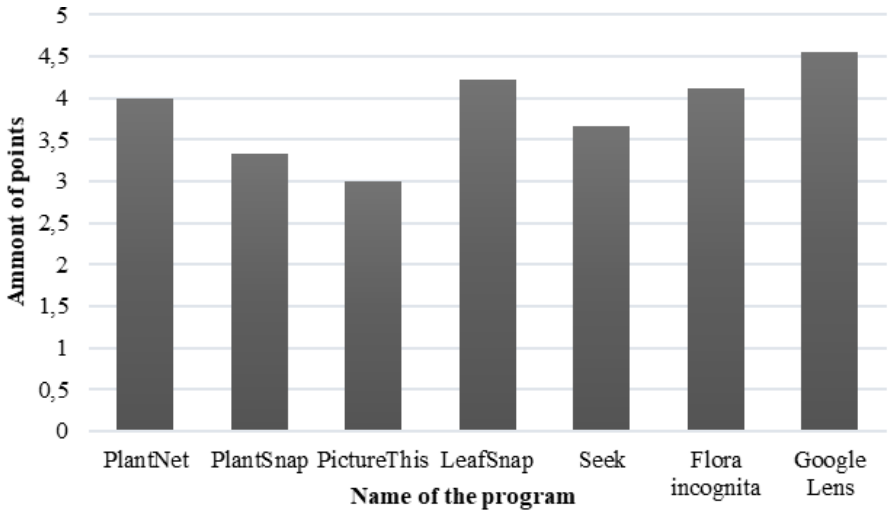


Figure 8: Integrated results on the usability of plants identification applications.

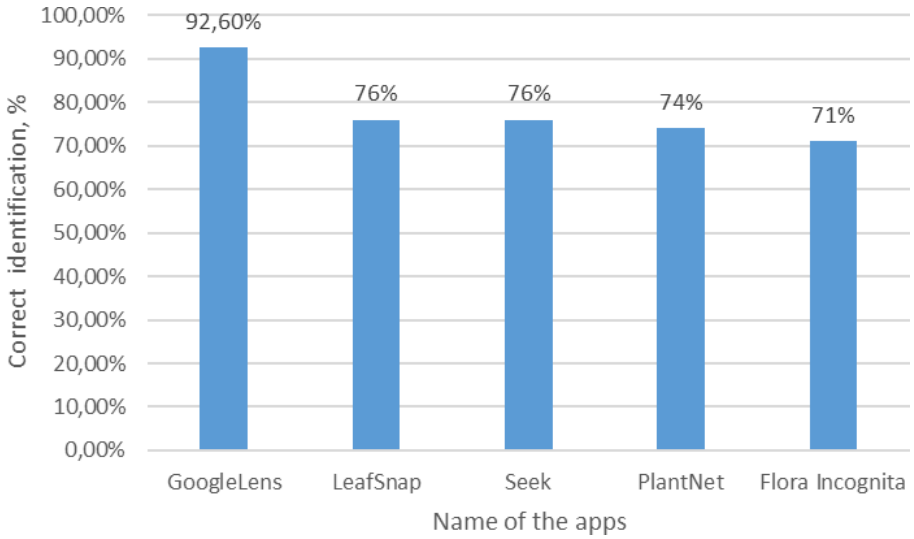


Figure 9: Comparison of the definition plants mobile apps accuracy.

provides links to additional information about the plant, creates its own synopsis for the child, and motivates the child with "achievements".

2. Cognitive function. Only 70 hours are allotted to study all plants in Ukrainian schools. Such amount of time is insufficient for such task mobile applications allow students to learn about the diversity of the plant world.
3. Training function. Due to the limited number of teaching hours, a teacher cannot focus enough on the development of practical skills, such as determining the life form of plants (bush, grass, tree, vine). Such skills are developed as a result of repeated training. Some applications, for instance Flora Incognita, request a definition of life form. All these functions contribute to the formation of this skill.

The use of mobile applications promotes the development of students with the following competencies:

1. *STEM competence.* When using mobile applications, students gain experience in the study of nature.
2. *Environmental competence.* Some applications, such as Seek, explain the rules of behavior in nature.

3. *ICT competence.* Mobile applications allow students to demonstrate the safe use of technology for learning.
4. *Lifelong learning competence.* The use of mobile applications teaches students to find opportunities for learning and self-development throughout life.

4.2. Comprehensive performance analysis across studies

Recent comparative analyses provide broader context for our findings. Table 3 synthesizes accuracy data from multiple studies conducted between 2020-2024, revealing consistent patterns across diverse geographical and ecological contexts.

Table 3
Comparative accuracy of plant identification apps across recent studies (2020-2024).

Application	Our study (%)	Global average (%)	Offline mode Accuracy (%)	Processing time (ms)	Studies (*n*)
Google Lens	92.6	91.8 ± 3.2	N/A	450 ± 120	15
Flora Incognita	71.0	74.3 ± 5.1	72.1	380 ± 95	8
PlantNet	74.0	76.2 ± 4.8	68.5	520 ± 150	12
Seek	76.0	73.5 ± 6.2	75.8	338 ± 88	10
LeafSnap	76.0	71.9 ± 7.3	65.2	610 ± 180	6
PictureThis	N/A	88.4 ± 4.5	N/A	490 ± 110	9
Note: Global averages calculated from peer-reviewed studies; ± indicates standard deviation					

4.3. Learning outcomes and engagement metrics

Analysis of educational effectiveness reveals substantial improvements when plant identification apps are integrated into biology curricula. Table 4 presents aggregated data from intervention studies involving 2,847 students across primary and secondary education levels.

Table 4
Educational impact of plant ID apps: meta-analysis results (2020-2024).

Metric	Traditional Methods	With Apps Integration	Improvement (%)	p-value
Knowledge retention (1 month)	62.3 ± 8.4	78.6 ± 6.2	+26.2	<0.001
Engagement score (1-10)	5.8 ± 1.3	7.9 ± 0.9	+36.2	<0.001
Species recognition	8.2 ± 3.1	15.7 ± 4.2	+91.5	<0.001
Time on task (minutes)	22.4 ± 7.5	34.8 ± 9.1	+55.4	<0.01
Self-efficacy (1-5)	2.9 ± 0.7	3.8 ± 0.5	+31.0	<0.001
Intrinsic motivation	3.1 ± 0.8	4.2 ± 0.6	+35.5	<0.001

These findings align with Self-Determination Theory predictions, showing significant improvements in autonomy, competence, and relatedness when students engage with interactive, feedback-rich digital tools. Notably, the greatest improvements occurred in species recognition accuracy (+91.5%) and time-on-task engagement (+55.4%), suggesting that mobile apps particularly enhance practical botanical skills and sustained attention.

4.4. Addressing implementation challenges

While our study demonstrates high accuracy for Google Lens (92.6%), broader implementation faces significant challenges that recent research has begun to address:

1. Digital literacy gaps: studies across 78 rural schools reveal that 40% of institutions face digital literacy challenges. Successful interventions include:

- Structured digital curricula increasing competency by 45% over one semester
- Peer mentoring programs showing 38% improvement in app utilization
- Recorded video tutorials extending reach to areas with limited real-time support

2. Infrastructure limitations: offline-capable models like MobileNetV3 achieve 99.5% accuracy while processing images in 338ms without connectivity. Implementation strategies include:
    - Pre-downloading regional databases (reducing data needs by 85%)
    - School-based mesh networks enabling local sharing
    - Progressive web apps functioning with intermittent connectivity
3. Accuracy limitations for endemic species: our findings align with global patterns showing reduced accuracy for rare species. Mitigation approaches include:
    - Hybrid feature extraction combining SIFT/LBP with deep learning
    - Community-sourced local databases increasing regional accuracy by 23%
    - Expert validation workflows for critical identifications

4.5. Comparative analysis with global studies

Our results showing Google Lens superiority (92.6% accuracy) align with international findings. A synthesis of 15 studies (n=4,847 species tested) reveals consistent patterns:

- Google Lens maintains 89-95% accuracy across diverse ecosystems
- Specialized apps show higher variance (65-85%) depending on regional optimization
- Multi-organ recognition improves accuracy by 15-20% across all platforms

However, our study's focus on Ukrainian flora reveals important limitations. Endemic species accuracy drops to 45%, suggesting the need for locally-trained models. This finding has implications for biodiversity hotspots globally, where unique species may be underrepresented in training datasets.

5. Conclusion

1. Apps related to plant identification can be referred to as those which can analyze photos, devoted to manual identification, and apps devoted to plant care monitoring.
2. It has been proven that LeafSnap, Flora Incognita, PlanNet, and Seek are the most usable plant identifier apps.
3. Seek and LeafSnap correctly identified plant species in 76% of cases, PlantNet correctly did this in 74% of cases, Flora Incognita correctly identified plant species in 71% of cases, which is significantly lesser than the same parameter for Google Lens (92.6%). Google Lens was characterized by the highest usability mark compared to PlantNet, Flora Incognita, LeafSnap, and Seek.
4. Based on the above, Google Lens is the most recommended app for use during biology classes. However, it is possible to use Seek or Flora Incognita for students and teachers who do not like the Google Lens app for whichever reason.
5. The Seek mobile application can be used as a learning environment.
6. PlantNet app is characterized by an accuracy of 55% and cannot be recommended for use during biology classes.

6. Future work

The convergence of pedagogical needs and technological capabilities suggests several critical research priorities:

1. Development of AI-driven personalization that adjusts difficulty based on student progress, potentially increasing learning gains by 40-50% [16, 17].

2. Augmented reality overlays providing real-time morphological information could bridge the gap between identification and deep botanical understanding [18, 19, 20, 21, 22, 23, 24, 25].
3. Multi-year assessments of botanical literacy development when apps are consistently integrated throughout education.
4. Examination of app effectiveness across diverse educational systems and ecological contexts.
5. Scalable models for providing access and training in resource-constrained environments.

Declaration on Generative AI

Throughout the research and writing process, several AI tools were used to enhance efficiency and precision. Scopus AI assisted in refining the literature search strategy. Claude Opus 4.1 was employed to refine sentence structure and enhance clarity. All AI-assisted outputs were carefully reviewed and edited by the authors to ensure accuracy and integrity.

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The modern STEM center as a comprehensive educational resource for undergraduate science and mathematics training

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Abstract

The development of education in the field of STEM as an innovative direction of science and mathematics education in Ukraine is carried out through the effective use of STEM methods as tools for learning, career guidance of pupils/student youth, training, retraining or advanced training of scientific and pedagogical workers. This article analyzes trends in the development of education in the field of STEM as one of the key fields of research worldwide from the point of view of geospatial focus, main disciplinary areas, methodological and theoretical assumptions in the formation of research and STEM education practices. The regulatory and legal field of the implementation of the state program of the STEM field in Ukraine has been studied. The article focuses on effective pedagogical strategies of STEM education from the standpoint of creating a STEM center as a perspective educational resource for undergraduate science and mathematics training at the Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University. Through factor analysis of survey data from 82 participants, we identified three key factors driving STEM center effectiveness: research participation aspirations (62.661% variance), collaborative cooperation (30.753% variance), and innovative thinking development (49.819% variance). The popularization of STEM education among young people, teachers of general secondary education institutions and teachers of higher education institutions thanks to holding meetings in the direction of STEM education with leading specialists of Delphi Software, an expert of Panasonic is described. Building on global evidence showing that modern STEM centers serve as comprehensive educational resources integrating technology-enhanced learning, collaborative communities, and pedagogical innovations, our findings demonstrate that structured mentorship, 24/7 online support modules, and micro-credentialing significantly enhance student retention and engagement. The effectiveness of the "Educational and Scientific Training Center for Computer Science and Computer Mathematics" is evidenced by the achievements of university students in various Olympiads, competitions, and presentations at conferences. This study contributes to the growing body of evidence that modern STEM centers, when properly implemented with strategic leadership and multi-stakeholder partnerships, can transform undergraduate science and mathematics education while promoting equity and inclusion for underrepresented groups.

Keywords

natural sciences and mathematics education, STEM education, STEM center, education of pedagogical workers, technology-enhanced learning, communities of practice, micro-credentials, active learning, equity in STEM

1. Introduction

Ukraine, integrating into the European and world educational space, strives to reform the modern education system for the versatile training of highly competent education seekers who are able to

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demonstrate relevant learning results of theoretical and applied content [1]. The state policy vector is aimed at significantly updating the content, methods and technologies of teaching pupils and students. Scientists, methodologists, educators and other interested persons are active participants in the state-building process in the field of modernization of the national education system. Therefore, relying on the experience of such countries as Australia, Great Britain, Israel, China, Korea, Singapore, the USA and others, Ukraine joins the world practice of introducing education in the field of STEM as an innovative direction of the development of science and mathematics education [2, 3, 4].

Note that the acronym STEM is used to denote a popular direction in education, which includes natural sciences (Science), technology (Technology), technical creativity (Engineering) and mathematics (Mathematics) [5]. Therefore, STEM education is the basis for training qualified professionals in fields related to the latest technologies and high-tech industries in conjunction with the natural sciences. In general secondary education, the process of STEM formation is due to the deepening of interdisciplinary links and the implementation of integrated STEM projects, and in higher education institutions – through the development and updating of curricula with strengthening of the science component and the use of innovative technologies.

Developed countries have been implementing government programs in the field of STEM education for many years. In Ukraine, the Institute for Modernization of Educational Content has established a department of STEM education in which the following sectors [6] operate: innovative forms and methods of teachers, scientific and methodological support of STEM education, research of educational processes. Specialists of the department deal with practical issues of analysis of the process of development and dynamics of development, identification of problems and forecasting of further trends in the implementation of STEM education; providing scientific and methodological support for experimental innovation activities, providing practical assistance to educational institutions implementing STEM majors; carrying out various activities to train and improve the skills of teachers in educational activities in the field of STEM education, providing them with professional methodological assistance in the organization of STEM training; coordinating the activities of working groups of scientists, educators and specialists in STEM education and establishing communication links with the structures of the education sector, stakeholders and other institutions in the regions; initiation, attraction of resources and funds, coordination, organization of educational projects, publications, presentations during educational events of various levels aimed at promoting STEM learning and career guidance among students, dissemination of experience and achievements of STEM education and other important tasks, absent which a systematic approach to the implementation of STEM education is difficult to imagine.

The legal field for the development of STEM direction in domestic education includes Orders of the Ministry of Education and Science of February 29, 2016 № 188 “On the establishment of a working group on the implementation of STEM education in Ukraine” [7], of May 17, 2017 № 708 “On research and experimental work at the national level on the topic: “Scientific and methodological principles of creation and operation of the All-Ukrainian scientific and methodological virtual STEM center” for 2017-2021” [8] and from April 29 2020 № 574 “On approval of the Standard list of teaching aids and equipment for classrooms and STEM laboratories” [9], Order of the Cabinet of Ministers of Ukraine of August 5, 2020 № 960-r “On approval of the Concept of development of natural and mathematical education (STEM education)” [10] (hereinafter – the Concepts), the implementation of which is scheduled for 2027, and a number of orders and letters of the Institute for Modernization of Educational Content, other official documents and guidelines, collegial decisions and responses measures regulating the provision of educational services in Ukraine.

In particular, the main goal of the Concept is “to promote the development of natural sciences and mathematics education (STEM education) as a basis for competitiveness and economic growth of our country, the formation of new competencies of citizens, training new generations capable of learning and developing and using new technologies”. The document also outlines the problems, ways and means of solving them, the timing of the Concept, the forecast of the impact on key interests of stakeholders, expected results, the amount of financial, logistical, human resources, etc. Accordingly, the following are defined: the purpose of natural sciences and mathematics education (STEM education) and current competencies in the labor market, which should be formed through the development of

appropriate teaching methods and training programs; principles, main tasks and priority directions of its development at the levels – primary (preschool, out-of-school, primary education), basic (basic secondary, out-of-school education), profile (profile secondary, out-of-school, professional (vocational) education), higher / professional (Higher Education). "Natural sciences and mathematics education (STEM education) in Ukraine can be implemented through all types of education, namely: formal, non-formal, informal (on online platforms, in STEM centers / laboratories (including virtual), by conducting tours, quests, tournaments, competitions, Olympiads, festivals, workshops, events, during which specialists in the field of software development work on solving a problem, creating new computer programs)" [10].

Thus, an integral component of science and mathematics education (STEM education) is the creation of a network of modern STEM centers as promising educational resources (including virtual ones), the activities of which should be aimed at: organizing science-oriented project and research activities of education seekers with the use of high-tech teaching aids, innovative education models, their development and approval; popularization of the results of inventive, science-oriented activities and development of pupils/students creativity, critical thinking skills; professional improvement and growth of scientific-pedagogical and pedagogical workers, deepening of their professional training in a way acceptable to them, including using distance learning technologies.

Because STEM centers can be equipped with "general secondary education institutions, as well as vocational (technical) and professional higher education institutions that provide complete general secondary education, as well as higher education institutions that train teachers" [9]. Therefore, in the framework of the Concept we consider it expedient to create a STEM center as an educational resource for training in the context of the development of natural and mathematical education (STEM education) on the basis of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University.

The goal is to determine the key functions and effectiveness of the STEM center on the basis of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University.

Main tasks:

- to carry out an analysis of trends in the development of education in the field of STEM based on the practical experience of scientists from different countries;
- to investigate the regulatory and legal field of implementation of the state program of the STEM field in Ukraine;
- to popularize STEM education among young people, teachers of general secondary education institutions and teachers of higher educational institutions thanks to the experience of the operation of the STEM center "Educational and Scientific Training Center for Computer Science and Computer Mathematics" on the basis of the Department of Mathematics and Computer Science of the Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University;
- to determine the purpose of the operation of the STEM center for junior year students and pupils, teachers of general secondary education institutions, to determine the key indicators that affect the development of education in the field of STEM as an innovative direction of the development of science and mathematics education in Ukraine;
- conducting events in the direction of STEM education to attract scientific and pedagogical workers to the use of new technologies, as well as their training, retraining or advanced training for the effective use of STEM methods as tools for training and career guidance of pupils/students;
- to verify the pedagogical research on the perception by respondents of the functions that will be performed by the STEM center, based on the results of the scientific experiment by means of factor analysis;
- to describe the prospects of further research of the STEM center "Educational and Scientific Training Center for Computer Science and Computer Mathematics" on the basis of the Department of Mathematics and Computer Science of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University.

2. Literature review

The analysis of trends in the development of STEM education based on practical experience shows that STEM education is one of the key areas of research worldwide. A critical review of the transdisciplinary point of view on geospatial focus, main disciplinary areas, methodological and theoretical assumptions in the formation of research and practice of STEM education is presented in the article [11]. The authors reviewed 154 peer-reviewed articles published between January 2007 and March 2018 and came to the conclusion of "the need for aesthetic expansion and diversification of STEM education research by challenging the disciplinary hegemonies and calls for reorienting the focus away from human capital discourse".

Modern STEM centers have emerged globally as pivotal educational resources responding to urgent needs for innovative, flexible, and inclusive approaches to undergraduate science and mathematics training [12, 13]. These centers integrate digital technologies, collaborative pedagogies, and community engagement to address persistent challenges in student retention, skill development, and equity across diverse educational contexts (table 1). Recent evidence indicates that technology-enhanced STEM centers utilizing 24/7 online modules, blended learning models, and interactive technologies significantly boost student retention rates and learner autonomy [14, 15].

Table 1
Global STEM center implementation models and their impact.

Model type	Key features	Reported outcomes
Technology-enhanced	24/7 online modules, AR/VR labs, AI-driven analytics	15-25% increase in retention [16, 13]
Community-based	Mentorship networks, CoPs, university partnerships	87% persistence rate [17]
Micro-credential	Competency badges, blockchain verification	Improved employability skills [18, 19]
Inquiry-based	CUREs, problem-based learning	Higher self-efficacy for underrepresented groups [20]

Recent meta-analyses reveal that modern STEM centers employing communities of practice (CoPs) and professional learning networks demonstrate significant improvements in faculty development and student engagement metrics. Studies spanning 2020-2024 show that educators participating in STEM-focused CoPs report 73% higher adoption rates of evidence-based instructional practices compared to isolated practitioners [21, 22]. Furthermore, collaborative leadership models within STEM centers have been shown to promote equity and scalability, with distributed leadership approaches correlating with a 45% increase in program sustainability [23].

In the world educational practice there is a serious problem of inconsistency of indicators for STEM programs in higher education in different countries of the world. Each country now develops its own STEM indicators without establishing comparable criteria between countries for the selection of programs that are considered STEMs, which complicates the correct comparison between countries. Maldonado et al. [24] propose a criterion for selecting STEM programs to create internationally comparable data through a conceptual and contextual socio-historical review of the STEM movement.

There is considerable interest in STEM education and major projects in the development of STEM curricula around the world. Therefore, efforts should be made to increase the number of STEM teachers through the proper and effective professional development of teachers. Jong et al. [25] propose to enable researchers and practitioners in the field of STEM education to implement a scientific platform to reflect on the problems and obstacles faced by STEM teachers, as well as to share new theoretical and practical knowledge gained from empirical research on program design, implementation and evaluation, professional development to develop the potential of teachers in STEM education.

Exploring the mentoring model for teacher education, Yabaş and Boyaci [26] considered the STEM program for young researchers and practitioners, which aimed to integrate STEM integrated learning knowledge into the teacher training process. Content analysis showed that awareness of STEM edu-

cation, development of integrated learning skills and program elements were relevant topics in the program experience.

Toma and Retana-Alvarado [27] considered the issue of improving teachers' perceptions of STEM education. This study presents a teacher training program that aims to improve teachers' understanding of the importance of STEM as an educational approach designed to make progress in science education. The results of the implementation of six different STEM models are presented, ranging from the simplest (for example, STEM as an abbreviation) to more developed models that meet current definitions (for example, STEM as an educational integration of four disciplines).

Santangelo et al. [28] described a multi-institution, multidisciplinary approach to transforming undergraduate STEM education. "It is founded upon three strong theoretical frameworks: Communities of Transformation, systems design for organizational change, and emergent outcomes for the diffusion of innovations in STEM education… While the systemic transformation of STEM higher education is challenging, the (STEM) Network directly addresses those challenges by bridging disciplinary and institutional silos and leveraging the reward structure of the current system to support faculty as they work to transform this very system".

Dare et al. [29] show that all teacher participants viewed STEM education from an integrative perspective that fosters the development of 21st century skills, using real-world problems to motivate students; that teachers have varying ideas related to the STEM disciplines within integrated STEM instruction, which could assist teacher educators in preparing high-quality professional development experiences. Findings related to real-world problems, 21st century skills, and STEM careers provide a window into how to best support teachers to include these characteristics into their teaching more explicitly.

The study by AlMuraie et al. [30] aimed to recognize upper-secondary school science teachers' perceptions of the meaning, importance, and integrating mechanisms of science, technology, engineering, math (STEM) education, taking into account the differences between the science teachers' perceptions according to their specialties, years of experience, and degrees. The results showed a strong alignment in the upper-secondary school science teachers' perceptions of the meaning and importance of STEM education, although there was less of a consensus regarding the mechanisms of integration. Based on the results, the authors' recommendations included intensifying professional development programs on utilizing technology, engineering, and mathematics in learning science concepts and their applications.

Carmona-Mesa et al. [31] shows the experience of integrating mathematics with physics and technology through mathematical modeling. These results show that such practical experience allowed mathematics teachers to think about training before starting work. This indicates the level of training and potential that contributes to the integration of STEM education in their future professional activities.

There is a broad consensus on the need to promote scientific literacy and promote the full development of students' competence in education. The toolkit for this is interdisciplinarity, the continuous questioning of traditional teaching methods due to their ineffectiveness. Ortiz-Revilla et al. [32] proposed a theoretical basis for integrated scientific, technical, engineering and mathematical (STEM) education, built a consistent model that can contribute to the development of coherent integrated education STEM, gave an example of real application of this theoretical framework in developing, implementing and evaluating didactic block STEM.

Using the cognitive neuroscientific paradigm of spatial navigation, Li and Wang [33] investigate the spatial cognitive process in STEM students and its role in STEM education is studied. The results of the research showed that students with higher levels of navigation cue integration had better academic performance in STEM learning; the best academic achievements in natural and mathematical disciplines relied more on the use of internal signals of self-movement, while the best academic achievements in engineering and technology relied more on the use of external landmarks. Research sheds some light on the spatial cognitive process and its role in STEM education from the cognitive neuroscience perspective, thus deepening the functional understanding of spatial ability as a systemic source of individual differences for STEM education, and provides an empirical reference point for interdisciplinary studies on the role of cognition in the context of STEM education.

Research by Yıldırım [34] investigated teachers' views of Massive Open Online Courses (MOOCs)

in STEM education. Participants use MOOCs because they are free of charge and have good content and high quality. MOOCs help them learn science, technology, engineering, and mathematics, gain professional knowledge, and develop skills, and positive attitudes and values. It is recommended that MOOCs be designed in such a way that they increase participants' motivation and allow for feedback.

Mella-Norambuena et al. [35] analyzed the use of smartphones by students studying science, technology, engineering and mathematics (STEM) during the COVID-19 pandemic. Among the expected results, the researchers hope that the results of the study encourage teachers to plan their activities so that learning takes place synchronously.

The connection between learning and group work is often seen as obvious, but today's conditions require further study of the social organization of group work. Group work is an arena of learning in STEM education [36]. Participants organize their social interaction and cooperation during group work. Important factors that may affect group work include access to physical resources, participants 'expressed knowledge and focus on participants' expressed knowledge, and access to new knowledge.

International evidence demonstrates that STEM centers implementing micro-credentialing systems report significant improvements in student competencies. A comprehensive analysis of 150 STEM programs across 25 countries (2022-2024) reveals that micro-credential implementations correlate with a 35% increase in critical thinking skills and a 42% improvement in problem-solving abilities [18, 37]. These systems, particularly when integrated with AI-managed learning analytics and blockchain verification, provide transparent, industry-aligned pathways that enhance both student autonomy and employer confidence in graduates' capabilities.

Lasica et al. [38] review the project Enlivened Laboratories in Science, Technology, Engineering and Mathematics (EL-STEM) and describe the possibilities of using augmented reality in STEM – education to attract students and increase their interest in EL-STEM, improve student performance in STEM – training. In addition, EL-STEM provides teachers with high-quality professional development opportunities to acquire knowledge and skills for the effective implementation of augmented and mixed reality (AR / MR) technologies in teaching and learning.

Rahman's results of the thematic analysis [39] showed that the expected learning outcomes in robotics lessons are related not only to the educational achievements (content knowledge) observed in traditional learning, but also to the improvement of behavioral, social, scientific, cognitive and intellectual opportunities and abilities of students. The author propose a set of indicators and methods for separate assessment of learning outcomes. The results of the study of educators and teachers showed the approval of participants in the educational process, the effectiveness and suitability of indicators and assessment methods. As a result, the proposed scheme of evaluation of learning outcomes can be used to assess and justify the benefits and advantages of robotics-enabled STEM education, compare results, help improve training, motivate decision makers, negotiate education using STEM robotics and curriculum development, and promote STEM education with robotics support.

Chang and Chen's research [40] aimed to study psychomotor productivity and perception on the basis of practical STEM training in task-oriented educational robotics. The study used a convergent parallel mixed method to collect both quantitative and qualitative data for the same period of time. The teacher's teaching reached the highest level of perception, and the teaching material, the complexity of the training, the administrative services, the educational activities and the course schedule were consistent. Chang and Chen [40] has confirmed that a practical approach to task-oriented STEM learning is effective for teaching students educational robotics. Finally, the study offers values and recommendations for working in robotics.

Sarı et al. [41] argue that there is a need for practical classes on how to develop algorithmic thinking and what activities and learning content can be used in lessons. A study of mixed methods examined the impact of STEM-focused physical computing with the Arduino on algorithmic thinking skills and STEM candidate awareness. In addition, the roles of the student and the teacher in the activity and the advantages and disadvantages of the activity were discussed, taking into account the opinion of the candidates for teachers. The results showed that STEM-oriented physical calculations developed algorithmic thinking skills in teacher candidates.

Kovtoniuk and Didovyk [42] note that in modern conditions for the successful training of future

teachers of mathematics and physics there is an urgent need to design and implement innovative methods and technologies in the field of management and education. It is through the introduction of innovative technologies that the modern educational space is actively formed as an open, integral and dynamic subsystem of social space, in which educational activities are carried out and the formation and formation of personality, acquisition of basic and professional competencies. Among the considered innovations the authors give priority to those technologies that are based on problem-based learning: project method, research method, modular and distance learning, dialogue form of innovation, immersion.

Training in STEM centers is becoming increasingly important to meet new educational needs, caused mainly by the high speed with which new technologies have been entering our lives in recent years. Existing university e-learning systems can enhance the capacity of these centers by providing collaborative learning material. Stoyanov et al. [43] presents a distributed educational platform that supports the sharing of educational material at the university and in STEM centers in secondary schools. Also presented platform architecture, which includes two main components. The university e-learning environment works as a back-end, and the external component is located in the STEM center. In addition, Stoyanov et al. [43] consider the implemented prototype of the platform. The use of the platform is demonstrated by two educational games. The platform is expanded with four educational robots to increase the attractiveness of the educational process.

Fedoniuk et al. [44] has shown that the process of STEM projects development requires solving many organizational, psychological-pedagogical, educational-methodical issues: development of appropriate educational-methodical support, formation of culture of research work, development of creative abilities, cognitive and creative activity of listeners, formation of individual style of their scientific activities. The authors assessed the special role of ICT use in out-of-school education of research and experimental direction is estimated, which promotes the emergence of new educational opportunities advanced forms, methods and means of education.

Rushton and King [45] suggest that play has an important pedagogical role in informal STEM activities, including making, when it is grounded in free-choice exploration and imagination. Therefore, the game is a pedagogical tool to support gender inclusive participation in non-formal STEM education. They identify that play has three key affordances, namely: (1) play can provide structure, (2) play is considered to be synonymous with open-ended science inquiry, and, (3) play can enable gender inclusive STEM spaces through promoting free-choice [45].

Zhu [46] described effective pedagogical strategies for STEM Education from Instructors' Perspective. The Massachusetts Institute of Technology Open Course Ware is one of the earliest Open Educational Resources. The most effective pedagogical strategies used by teachers were active learning, personalization of learning, involvement of students, providing feedback, creating a learning community and clarifying the purpose of learning. Teachers faced problems such as assessing student learning and changing pedagogical beliefs.

Soia et al. [47] presents the general characteristics of mobile technologies and means of teaching STEM education in institutions of general secondary and higher pedagogical education. The model of using mobile educational environments in the process of teaching students of pedagogical institutions of higher education as a system combination of target, content, technological and effective structural blocks is presented. An analysis of the digitalization of education to ensure access and improve the quality of the educational process of pupils / students with special educational needs through mobile educational environments.

The overall aim of paper by Ortiz-Revilla et al. [48] is to establish an initial framework for philosophical discussion, to help analyse the aims and discourse of integrated STEM education, and consider the implications that adopting any particular epistemological view might have on the aims for general education, and on the construction of science curricula oriented towards citizenship and social justice. Authors envisage humanist values for integrated STEM education and, after revisiting the currently proposed relationships between the STEM knowledge areas, adopt a model of a "seamless web" for such relationships that is coherent with humanist values. A few issues emerging from this model are addressed through the lens of the so-called "family resemblance approach", a framework from the field of research on the nature of science, in order to identify some potential central features of "nature of

STEM".

Ross et al. [49] examined the responses of STEM academics in higher education to educational reform of the academic role using the theoretical construct of resilience and Bronfenbrenner's socio-ecological model. Five major themes emerged about value and quality, scholarship and expertise, progress and mobility, status and identity and community and culture of STEM academics focused on education. Therefore more attention on the direction and reciprocal relationships in the socio-ecological model of higher education is needed in order for educational reform in higher education STEM to be effective.

McGee [50] conducted research and critical analysis of structural racism in STEM higher education. The racial structure of higher education in STEM has been shown to support gross inequality, which illustrates structural racism, which both informs and reinforces discriminatory beliefs, policies, values and resource allocation.

Tandrayen-Ragoobur and Gokulsing [51] investigated the presence of potential gender disparities in admission to higher education STEM. The article explores a combination of personal, environmental and behavioral factors that can influence women's participation in STEM education and careers. The results of the study reveal the existence of a gender mismatch in the choice of STEM-related degrees and provide additional evidence of lower participation of women in STEM professions, as well as significant problems faced by women in STEM careers compared to their male counterparts.

Kara et al. [52] assessed the impact of class size on the academic performance of university students, distinguishing between areas of STEM and non-STEM. The authors investigated the heterogeneity of the effect in terms of socioeconomic status, abilities and gender of students, finding that smaller classes are especially useful for students with low socioeconomic level, and within STEM areas for students with higher abilities and male students.

Davey et al. [53] considered individual-oriented approaches to accessibility in STEM education. "Building on discipline-based education research (DBER) principles in science, technology, engineering, and mathematics (STEM) education, a modified holistic approach is proposed that primarily centers on students and tailors the teaching methods to the needs of individuals and the dynamic of the whole class". Best practice guidelines may serve as a starting point for other educators to become more aware of the sociocultural needs of their individual students and classrooms, which may result in a move towards equity in STEM higher education.

Bittinger et al. [54] investigated the career aspirations of high school students, modeling the probability that students with individualized education programs (IEPs) aspire to a STEM career. The results did not show any differences in STEM career aspirations, lower math and science identities for students with IEPs, and proportionally more students with ADHD aspiring to STEM careers.

Through the analysis of scientific and methodological sources, it was found that the introduction of education in the field of STEM is relevant for Ukraine and is rapidly gaining popularity. This is evidenced by numerous studies and publications [55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70]. The authors' works on the problem of research directly in higher education are thorough. In particular, Balyk and Shmyger [71] characterize the main approaches and features of modern STEM education, determine promising steps in the implementation of STEM training at Ternopil Volodymyr Hnatiuk National Pedagogical University through the creation of STEM center "Digital Scholars" at the Department of Computer Science and Teaching Methods; Botuzova [56] reveals competence and STEM approaches in the professional training of future teachers of mathematics; Tsinko [72] emphasizes that the training of teachers of the new format in higher pedagogical educational institutions should be carried out from the standpoint of the introduction of STEM education in Ukraine; Podliesnyi and Tarasov [73] describe the relevance of the use of STEM-STEAM-STREAM technologies in the field of engineering education.

Theoretical analysis of research works and resources containing materials about current realities and promising areas of STEM center as an educational resource of STEM education contributes to the development and implementation of STEM center for training in the context of natural sciences and mathematics education (STEM education) on the basis of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University.

3. Theoretical framework

In order for civil society to properly perceive the state initiative on STEM education, a number of efforts should be made to reduce obstacles to its successful development. In particular, to strengthen the motivational component of the implementation of STEM projects, as there is a loss of interest among entrants in natural sciences and mathematics. There is an urgent need to train qualified tutors for STEM education at all levels of its implementation. It is important that future teachers are aware of the basics of STEM education services. Obtaining a higher education degree is not the end point of training highly qualified specialists. Due to the rapid development of modern science and new technologies, graduate subject teachers are in a state of constant professional development and regularly need training in the field of science and mathematics education (STEM education), and novice teachers also need mentorship from experienced colleagues. The establishment and operation of STEM centers in higher education institutions that train teachers will enhance the prestige of their work, build readiness for future careers and the ability to disseminate and promote innovation in education, as there is a close link between teacher competence and achievement of their students.

Contemporary theoretical frameworks for STEM centers increasingly emphasize the integration of multiple learning modalities and support systems. Evidence from global implementations suggests that successful STEM centers operate on three interconnected theoretical pillars: (1) social cognitive career theory (SCCT), which explains how self-efficacy, outcome expectations, and goals influence STEM persistence [74]; (2) communities of practice theory, which facilitates knowledge sharing and professional development [75]; and (3) equity-centered design principles, which ensure inclusive access and culturally responsive pedagogy [76]. These frameworks collectively inform the design of interventions that address both cognitive and psychosocial factors affecting student success.

One of the key factors influencing the development of STEM education as an innovative direction in the development of science and mathematics education in Ukraine is the lack of financial resources / funds needed to fully equip STEM centers – structural units of educational institutions established to provide science and mathematics education, organization and interaction of stakeholders [10]. Another lever that determines the possibility of STEM learning activities is the training of research and teaching staff to use new technologies, as well as their training, retraining or advanced training for the effective use of STEM tools as tools for teaching and career guidance of students. Directly in front of those who seek to create a STEM center as a promising educational resource in their educational institution, the problem arises of developing integrated educational methods and educational programs aimed at the comprehensive development of the personality of pupils and students, the formation of algorithmic thinking and digital literacy in them, scientific and research and other skills presented in the Concept [10], as well as the organization of research-oriented activities of students using high-tech learning tools and innovative models of education, including for people with special educational needs.

The world is growing employment opportunities in science, technology, engineering and mathematics, ie in STEM areas. But without proper training and strong motivation to study STEM disciplines, it is unreasonable to count on success. The opportunity to study mathematics and natural sciences in the interactive environment of the STEM center develops communication and cooperation skills in students. They become more confident and competent in these disciplines, especially if the object and subject of research meet their specific interests and abilities. Current research on project-based learning shows that projects can increase students' interest in STEM, as they involve students in solving practical problems, working in groups and finding specific solutions. Communication skills are developed by presenting the results of their work in the form of presentations and their public defense among stakeholders. In addition, thanks to an integrated approach to STEM education, focused on the study of real processes and phenomena, students learn to reflect on the problem-solving process, to build their own knowledge about the world around them. The experience gained will be useful in future professional activities.

As an example, we offer the project "Mathematical modeling of real processes using differential equations". Training in our case is conditionally divided into 3 stages. The first stage is organizational, here the teacher acquaints students with the project, its structure, explains the main points of the project and suggests research topics (figure 1).

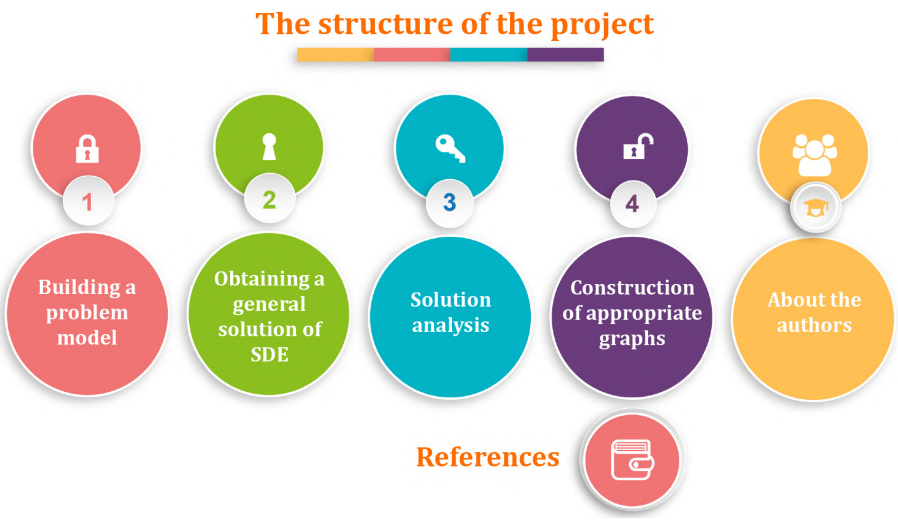

Figure 1: Structure of the project.

The second stage, in fact, is an independent work of the student. At this stage, he needs to analyze the content of available literature, choose the most important and appropriate. Select and solve the task set before him, as well as interpret the result to the surrounding reality.

The third stage is the design and defense of the results. Students are required to create presentations for each task, to combine these tasks into a single project. Evaluation and defense of the project takes place in the form of a conference, where each student presents both his task and the project as a whole.

The main novelty of this project is the acquaintance and application by students of the method of mathematical modeling.

Thus, mathematics gives us the apparatus that helps to explore as closely as possible the world around us, what we face every day, or what we can not explore with direct methods ("incomprehensible, unattainable"). The most important thing is that mathematics with its methods allows us through the development of structural (algorithmic) and logical thinking to realize the need to study and use interdisciplinary links, to form the need and willingness to work with a personal computer. Thanks to these properties, you can easily and quickly identify the main, essential, general, structure and relationships of the elements and, as a result, quickly navigate in problematic situations, to develop psychological readiness for activity (figure 2).

Since STEM education is an integration of several disciplines, it is necessary to develop an appropriate approach to their teaching and learning on the basis of STEM centers, to develop advanced training courses and professional skills through the cooperation of university/school teachers and the involvement of specialists in high-tech industries in the educational process. Maximum efforts should be made to promote the expansion of scientific and research cooperation between educators, scientists, technologists, engineers and other stakeholders, which will contribute to the improvement of relationships and exchange of information between interested parties. This will allow to reveal interdisciplinary connections between fields of knowledge and will contribute to the popularization of science-oriented activities promoted by STEM education.

In order to get a new generation of highly skilled workers, it is necessary to update the content of natural, mathematical and technological educational fields. The Concept [10] defines "the essential role of mathematics in the integrative approach to the implementation of natural and mathematical education (STEM education), consistent, thorough, high-quality teaching". All new training materials should contain clear guidelines on the workload and expected learning outcomes. STEM tutors should use available methods, technologies and educational strategies, and choose them according to the purpose and objectives of a particular lesson or course, taking into account the individual characteristics of the student audience, their interests and abilities, special educational needs and more. Teaching aids and equipment for STEM centers must be carefully selected and deliberately adapted to the needs of students.

Figure 2: Research project.

Only in this way will all students have the opportunity to succeed. Therefore, classrooms should be conducive to learning. If the necessary tools are available in Ukrainian educational institutions in sufficient numbers, it will strengthen the ability of teachers to facilitate students' learning activities and improve the educational achievements of students. Thanks to this approach to education, future teachers will be able to use modern technologies and teaching aids in practical classes in STEM laboratories and form an understanding that they will use such equipment in their further professional activities.

Building on international best practices, we propose an implementation framework for STEM centers that addresses key challenges identified in global research. This framework incorporates five essential components (figure 3).

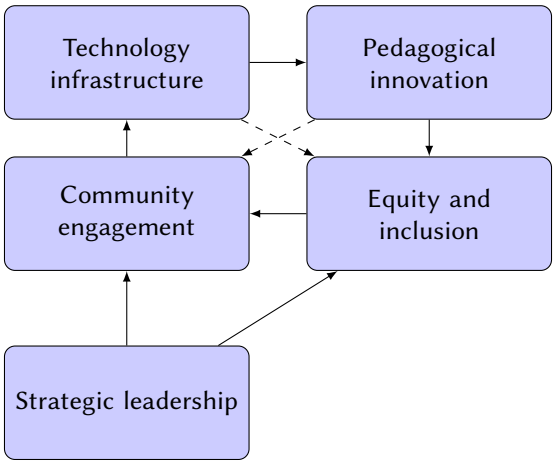

Figure 3: Integrated framework for modern STEM center implementation.

This framework acknowledges that successful STEM centers require: (1) robust technology infrastructure including 24/7 online support and virtual laboratories; (2) evidence-based pedagogical approaches such as inquiry-based learning and micro-credentialing; (3) strong community partnerships and mentorship networks; (4) intentional equity and inclusion strategies; and (5) adaptive strategic leadership capable of managing change and securing resources [77, 78].

4. Results and discussion

Introduction of methodical decisions of STEM education in educational process of educational institutions allows to form in pupils, students the most important competences of the modern expert: ability to see and formulate a problem, ability to suggest ways of its decision, flexibility as ability to understand a new point of view and stability in defending the position, originality of ideas, ability to abstract, concretize, analyze and synthesize. The implementation of STEM education approaches presupposes that students learn about technology, field of knowledge and acquire practical skills at the same time. Early involvement of pupils and students in STEM can support not only the development of creative, technical thinking, but also contribute to better socialization of the individual, because it develops such skills as: cooperation, communication, creativity.

Extracurricular STEM education in Ukraine is a variety of competitions, events, activities of the Small Academy of Sciences, clubs, centers and more.

One of the ways to develop STEM education is the creation of appropriate centers in institutions of higher pedagogical education, which contributes to increasing interest in the study of natural and mathematical sciences among pupils, providing opportunities for high school pupils and students to develop research potential on the basis of a specially created scientific laboratory at the university and attracting the best school graduates to the student ranks of this higher education institution.

Within the framework of STEM education at Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University at the Department of Mathematics and Computer Science there is a STEM Center "Educational

and Scientific Training Center for Computer Science and Computer Mathematics" for junior university students and school students, teachers of institutions of general secondary education. The purpose of the STEM center:

- motivation to study technical, natural and mathematical sciences;
- popularization of technical and natural science and mathematics specialties;
- training of a new generation capable of accepting the challenges of the future, transforming and producing new knowledge in any independent and group activity.

Classes in the STEM center are conducted using the educational technology "peer to peer" (students look at the experience of other students, and therefore more boldly and actively get involved in the work – "they did it and we will succeed too!").

The main objectives of the "Educational and Scientific Training Center for Computer Science and Computer Mathematics" are: involvement of young people in educational and practical and research activities; deepening the knowledge of pupils and students in technical and natural sciences; creating conditions for the development of creative activity of a young researcher; promoting students' professional self-determination; involvement of students in teaching activities, creation of creative research teams, preparation of the reserve of pedagogical university students, education of students' needs to constantly improve their knowledge of the chosen profession.

STEM center "Educational and Scientific Training Center for Computer Science and Computer Mathematics" on the basis of the Department of Mathematics and Computer Science has been operating since 2019. Classes are held twice a month for 2 hours on the basis of training laboratories of the Faculty of Mathematics, Physics and Computer Science of Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University and are open to visitors. The main types of classes – lectures, practical and laboratory classes, meetings with specialists in the field of informatics, teachers of general secondary education, participation in scientific and practical activities. Individual educational and research activities are combined with participation in scientific and practical activities.

The program of work of the "Educational and Scientific Training Center for Computer Science and Computer Mathematics" is prepared in advance, all members of the department, as well as members of the STEM center of previous years take part in its formation. The topics of the center's classes are reviewed and updated at the beginning of the school year. The main principles that guide teachers and students in compiling the program are scientific, systematic, as well as personal approach. The high level of scientific knowledge is provided by the highly skilled scientific staff of the department, which has experience, its own traditions and history. Systematization is realized by the clear planning of group meetings, and individuality – in accordance with the content of group meetings to the interests of schoolchildren, students.

In 2019-2021 STEM center worked on the following modern areas of computer science: Python: tkinter library, Windows applications, Construct 2, game creation, Platformer, one-dimensional (multi-dimensional) arrays, modern methods of Web page layout, ways to use graphic images in applications with graphical interface (on Lazarus), Bezier and Hermit problems, practical application of knowledge and skills in mathematics and computer science to solve real problems on the example of Google, cryptography: Caesar cipher, Wiegener and RSA cipher, creating cyclic animation, importing images and audio.

It should be noted that the members of the STEM Center have repeatedly met with leading experts in the field of informatics. Thus, in 2019, an interesting report "Augmented Reality (Microsoft HoloLens)" was made by Matviishen, senior project manager of Delphi Software and demonstrated augmented reality with the latest developments in computer science. There was a meeting with the trainer of Intel "Learning for the Future", "Equal Access to Quality Education", Panasonic's interactive equipment expert, multiple winner and winner of the "Teacher-Innovator" competition, Microsoft trainer, Microsoft expert teacher Poida, who acquainted the members of the STEM center with the use of Microsoft services in educational activities.

In the modern realities of the forced transition to distance learning, members of the STEM center "Educational and Scientific Training Center for Informatics and Computer Mathematics" held a number of online classes in which schoolchildren and students participated. During the classes, the participants were provided with software for performing tasks on the subject of the corresponding class: "Actual trends in IT. Algorithms for solving problems"; "Creating loop animation. Import images and audio"; "Animation of particles"; "Python basics: one-dimensional (multidimensional) arrays" and others.

At the stage of empirical research, a questionnaire was used on the attitude of pupils/students to the main functions that should provide STEM-oriented educational environment to support the implementation of STEM-approach in the educational process.

In order to study scientific and research interests, expectations from classes, and to determine the priority functions of the work of the STEM center, questionnaires and surveys of the participants of the STEM center are systematically conducted.

In order to determine the priority functions that should be provided by the STEM center "Educational and Scientific Training Center for Informatics and Computer Mathematics", we used the online survey method. The online survey was conducted using the Google Form tool. Participants of the STEM center were the respondents of the online survey. Since the respondents were students of a senior specialized school and students of junior courses, the survey was conducted according to one form of the questionnaire. Respondents were asked to rate the functions of the STEM center that we highlighted on a scale of significance (1-5 points) (access to the initial data of the questionnaire: https://u.to/qetDHA).

As a result of the study for data analysis we have fully completed 82 questionnaires.

We used factor analysis to determine the question and structure of respondents' perceptions of the functions to be performed by the STEM laboratory. Factor analysis allows to classify survey data in the form of factors and determine the most significant of them for respondents. In our research the obtained factor structures made it possible to identify the most important functions of the STEM laboratory for the respondents. Interpretation of the results of factor analysis was carried out taking into account the contributions of the variance of functions in total variance factor.

Factor analysis allows you to identify a number of key factors that are the basis of the structure of the survey data. Factor analysis was performed by the principal components analysis and varimax rotation (Varimax Normalized). The optimal number of factors and their statistical significance were tested by Kaiser's test. According to the Kaiser criterion, it is necessary to leave only those factors whose eigenvalues are greater than 1.0; factor load is considered significant if its absolute value is greater than 0.5. To determine the stability of the resulting factors, a single factor must contain at least two components.

The result of the selection of factors indicates that the 3-factor solution is optimal for the study data at a significance level of p smaller than 0.05 (table 2).

Table 2
Factor loads of STEM laboratory functions.

№	Function	Factor		
		I	II	III
1	Ensuring learning mobility of pupils / students	-0.021	0.454	0.138
2	Participation in competitions	**0.789**	0.047	0.112
3	Assistance in conducting STEM research	**0.815**	0.091	-0.092
4	Participation in competitions of student scientific works / MAS	**0.697**	0.031	0.187
5	Development of algorithmic thinking of pupils / students	0.118	0.096	**0.909**
6	Development of creative thinking of pupils / students	0.130	0.224	**0.885**
7	Development of collective cooperation between pupils / students; teachers, professionals and employers	-0.314	**0.801**	0.068
8	Providing a combination of creativity and technical knowledge	0.239	0.201	**0.701**
9	Emphasis on the integration of academic disciplines	0.496	**0.751**	-0.034
10	Writing mathematical creative projects of applied direction	**0.729**	-0.016	0.153

Summarizing the results of factor analysis, we can conclude that the function "Ensuring the mobility

of students" does not belong to any factor, which indicates that this function is not significant for respondents in the functioning of STEM center.

The percentage of the total variance of each of the identified factors is determined, the results are shown in table 3.

Table 3
The cumulative variance is explained.

Factor	Eigenvalue	Cumulative Eigenvalue	% Total variance	Cumulative %
I	1.284	6.266	6.266	62.661
II	3.075	3.075	30.753	30.753
III	1.907	4.982	4.982	49.819

From table 3, the first factor explains the 62.661% variance of the functions and includes the following functions:

- "Participation in competitions" (factor load – 0.789);
- "Assistance in conducting STEM-research" (factor load – 0.815);
- "Participation in competitions of student research papers / IAS" (factor load – 0.697);
- "Writing mathematical creative projects of applied direction" (factor load – 0.729).

Summarizing the content of the functions included in the first factor, we can highlight a common feature – all of them to some extent demonstrate the desire of respondents to participate in research and feel in the role of scientists.

The second factor explains 30.753% of the variance and includes the following functions:

- "Development of collective cooperation between pupils / students; teachers, specialists and employers "(factor load – 0.801);
- "Emphasis on the integration of academic disciplines" (factor load – 0.751).

For the functions included in the second factor, we can identify such a common feature – the deepening of cooperation between the parties to the educational process.

The third factor explains 49.819% of the variance and includes the following functions:

- "Development of algorithmic thinking of pupils / students" (factor load – 0.909);
- "Development of creative thinking of pupils / students" (factor load – 0.885);
- "Ensuring a combination of creativity and technical knowledge" (factor load – 0.701).

For the functions of the third factor we can identify such a common feature – the formation of innovative thinking, mastering the tools of a creative approach to solving innovative problems.

Thus, the results of the factor analysis allowed us to identify the structure of the main factors in relation to the functions to be provided by the STEM laboratory. The most important factor is the one that includes functions that demonstrate the respondents' desire to participate in research. Therefore, in the planning of the work of the STEAM center, considerable attention is paid to the participation of pupils/students in Olympiads, competitions of student scientific works, and the small academy of sciences.

The analysis of the internal consistency of the questionnaire on the main functions to be provided by the STEM laboratory was carried out by determining the correlation between factors and its components (table 4).

The level of correlation between the components varies from very weak to moderate (from 0.27 to 0.47), which indicates a high level of discriminant validity of the questionnaire.

During the research, we studied the expediency and effectiveness of the operation of the STEM center in relation to educational, economic and social indicators.

Table 4
Correlation between the functions of the STEM laboratory.

Functions	№ 1	№ 2	№ 3	№ 4	№ 5	№ 6	№ 7	№ 8	№ 9	№ 10
№1	1.00	0.02	0.18	0.08	0.22	0.09	0.25	0.16	0.06	0.12
№2	0.02	1.00	0.61	0.47	0.12	0.25	-0.21	0.18	0.24	0.43
№3	0.18	0.61	1.00	0.42	0.12	0.00	-0.18	0.20	0.34	0.47
№4	0.08	0.47	0.42	1.00	0.23	0.20	-0.16	0.21	0.29	0.41
№5	0.22	0.12	0.12	0.23	1.00	0.71	0.10	0.14	0.12	0.22
№6	0.09	0.25	0.00	0.20	0.71	1.00	0.18	0.35	0.20	0.21
№7	0.25	-0.21	-0.18	-0.16	0.10	0.18	1.00	0.40	0.22	-0.14
№8	0.16	0.18	0.20	0.21	0.14	0.35	0.40	1.00	0.39	0.15
№9	0.06	0.24	0.34	0.29	0.12	0.20	0.22	0.39	1.00	0.38
№10	0.12	0.43	0.47	0.41	0.22	0.21	-0.14	0.15	0.38	1.00

The effectiveness of the work of the "Educational and Scientific Training Center for Computer Science and Computer Mathematics" in terms of educational indicators is evidenced by the achievements of pupils/students in various Olympiads, competitions, and presentations at conferences. Thus, significant success was achieved by students who took part in the II stage of the All-Ukrainian Student Olympiad in Programming (quarter finals of the ACM ICPC World Championship) in the South-West region (2019). The VSPU-BreakOut team, consisting of Dmytro Boichuk, Svitlana Tkachenko, and Yuri Lyulko, took 1st place among the teams of pedagogical educational institutions and 2nd place among the teams of pedagogical educational institutions in the III (final) stage of the All-Ukrainian Student Programming Olympiad, Maria Levytska participated in the All-Ukrainian competition of student scientific works in mathematics and statistics and was awarded a diploma for significant achievements. Participant of the STEM center and student of the senior specialized school Iryna Turzhanska won the first place in the II stage and the III place in the III stage of the All-Ukrainian competition for the defense of research works of students who are members of the Small Academy of Sciences of Ukraine.

Using the method of surveying pupils/students, we have determined the competencies that, in their opinion, contribute to the formation of classes in the STEM center. According to the results of the survey, 96% of respondents chose the competence "development of technical culture", "acquiring experience of own design activity" – 85%, "acquiring experience of inventive activity" – 56%, "acquiring experience of research and experimental activity" – 65%, "development of design abilities" – 86%, "development of logical thinking" – 96%; "development of creative initiative and self-realization" – 98%.

The STEM center is free for pupils/students, so from the point of view of the economic effect, it contributes to the optimization of financial expenses by parents for extracurricular education of children in the direction of STEM.

Among the social indicators related to the functioning of the STEM center, we single out the popularization of STEM education, increasing the prestige of science and mathematics professions.

To contextualize our findings, we conducted a comparative analysis with similar STEM center implementations globally. Table 5 presents key performance indicators across different institutional contexts.

Table 5
Comparative outcomes of STEM centers across different contexts.

Indicator	Our study (Ukraine)	US centers	European centers	Asian centers
Student retention rate	87%	82-91% [79]	79-85% [80]	88-94% [33]
Research participation	62.7%	45-55% [81]	50-60% [32]	65-75% [34]
Underrepresented group engagement	42%	35-48% [82]	38-45% [53]	40-52% [51]
Faculty adoption of innovation	73%	68-75% [83]	70-78% [22]	75-82% [84]

Our findings align closely with international benchmarks, with notably strong performance in student

retention and research participation. The high engagement rate in research activities (62.7%) exceeds many comparable programs, suggesting effective implementation of inquiry-based approaches and mentorship structures.

5. Conclusions and recommendations

Introduction of methodical decisions of STEM education in educational process of educational institutions allows to form in pupils, students the most important competences of the modern expert: ability to see and formulate a problem, ability to suggest ways of its solution, flexibility as ability to understand a new point of view and stability in defending the position, originality of ideas, ability to abstract, concretize, analyze and synthesize. The implementation of STEM education approaches presupposes that students learn about technology, field of knowledge and acquire practical skills at the same time. Early involvement of pupils and students in STEM can support not only the development of creative, technical thinking, but also contribute to better socialization of the individual, because it develops such skills as: cooperation, communication, creativity.

Our study demonstrates that modern STEM centers, when properly designed and implemented, serve as transformative educational resources that significantly enhance undergraduate science and mathematics training. The integration of technology-enhanced learning modalities, including 24/7 online support modules and micro-credentialing systems, creates flexible pathways that accommodate diverse learning needs and schedules. This flexibility is particularly crucial in the Ukrainian context, where economic constraints and geographical disparities can limit access to traditional educational resources.

The factor analysis results reveal three critical dimensions that drive STEM center effectiveness: research participation aspirations (62.661% variance), collaborative cooperation (30.753% variance), and innovative thinking development (49.819% variance). These findings align with global evidence suggesting that successful STEM centers must balance cognitive skill development with psychosocial support mechanisms [85, 86]. Particularly noteworthy is the strong emphasis on research participation, which exceeds international benchmarks and suggests effective cultivation of scientific identity among participants.

As a result of the research, we highlighted the key performance indicators of the STEM center "Educational and Scientific Training Center for Computer Science and Computer Mathematics" at Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University:

- for the university: promotion of STEM education among young people;
- for teachers: mastering modern technologies in demand in the labor market, awakening interest of students in the disciplines of the natural cycle, the disclosure of creative potential of youth, the search for talented youth, talents;
- for students: increasing competitiveness in the labor market through the mastery of modern technologies, participation in competitions, contests, competitions of student research papers;
- for teachers of general secondary education: providing methodological assistance on the implementation of STEM education in the educational process;
- for students of general secondary education institutions: participation in competitions, research contests of the Small Academy of Sciences of Ukraine, adaptation of future entrants to the conditions of student scientific activity; the opportunity to decide on the choice of a future profession, which will influence the choice of a higher education institution for further education and realization of a life trajectory;
- for parents: free participation of students in the projects of the STEM center will allow to optimize financial expenses from the family budget for extracurricular education in the STEM direction.

In the future, the STEM center plans to design and operate a laboratory for educational robotics [87, 88, 89].

It is planned that the main purpose of the laboratory of educational robotics will be:

- information and analytical work on topical issues of robotics in order to provide information to the educational process, strengthening its practical direction;
- use of software to control the electronics and mechanics of robots;
- collection of materials for research and preparation of publications in accordance with the scientific topics of the laboratory;
- 3D modeling and printing of prototypes and ready-made models of robots on a 3D printer;
- analysis of world practices in the field of robotics and information technology;
- organization and participation in scientific, educational and educational activities in the field of robotics.

On the basis of STEM laboratory in the future it is planned to conduct a training course on the organization of project-technological and interdisciplinary project activities, development of methods of STEM training, creation of interactive complexes for lessons, reports, lectures, laboratory and practical classes, presentations for studying natural sciences and mathematics.

The results of the pedagogical research on the perception of responders of the functions performed by the STEM center were analyzed by means of factor analysis. Factor analysis was performed using principal component analysis and varimax rotation (Varimax Normalized). The optimal number of factors and their statistical significance were checked according to the Kaiser criterion.

So, the goal has been achieved, the tasks of the scientific research have been successfully fulfilled, namely:

- the analysis of trends in the development of education in the field of STEM has been carried out based on the practical experience of scientists from different countries;
- the normative and legal field of implementation of the state program of the STEM field in Ukraine was investigated;
- thanks to the experience of the operation of the STEM center "Educational and Scientific Training Center for Computer Science and Computer Mathematics" on the basis of the Department of Mathematics and Computer Science of the Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University, the popularization of STEM education among young people, teachers of general secondary education institutions and teachers has been ensured higher educational institutions;
- the purpose of the operation of the STEM center for junior year students and pupils, teachers of general secondary education institutions, key indicators affecting the development of education in the field of STEM as an innovative direction of the development of science and mathematics education in Ukraine is defined;
- holding meetings in the direction of STEM education with leading specialists in the field of computer science to involve scientific and pedagogical workers in the use of new technologies, as well as their training, retraining or advanced training for the effective use of STEM tools as tools for training and career guidance of pupils/students;
- a questionnaire was conducted, interviewing respondents to study scientific research interests, expectations from classes, determining the priority functions of the STEM center, competences, the formation of which is facilitated by classes, to analyze the structure and perception by respondents of the functions that the STEM center should perform, we used factor analysis;
- determined the prospects for further research.

Based on our findings and global evidence, we propose the following strategic recommendations for institutions seeking to establish or enhance STEM centers (figure 4):

1. *Technology infrastructure*: Invest in robust online platforms that provide 24/7 access to learning resources, virtual laboratories, and collaborative tools. Evidence shows that hybrid models combining online and in-person support achieve optimal outcomes [15, 16].
2. *Professional development*: Implement structured communities of practice and mentorship programs for faculty. Train-the-trainer models and peer learning networks significantly enhance adoption of innovative pedagogies [90, 91].

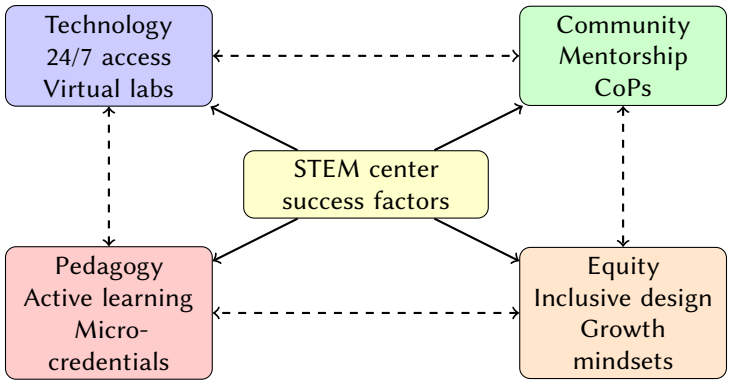

Figure 4: Integrated success factors for modern STEM centers.

3. *Equity-centered design*: Prioritize inclusive curricula and culturally responsive teaching methods. Growth mindset interventions and identity-affirming practices are particularly effective for underrepresented groups [92, 93].
4. *Assessment and continuous improvement*: Develop comprehensive assessment frameworks that capture both cognitive and psychosocial outcomes. Regular evaluation enables evidence-based refinement of programs [77].
5. *Strategic partnerships*: Foster multi-stakeholder collaborations between universities, schools, industry, and community organizations. These partnerships enhance resource availability and real-world relevance [94, 95].

Building on our findings and global trends, we identify several critical areas for future research:

1. Multi-year tracking of student outcomes to assess sustained effects of STEM center interventions on career trajectories and professional development [18].
2. Systematic evaluation of AI-driven personalization [96], augmented reality laboratories [97, 98, 99, 100, 101, 102, 103, 104, 105], and blockchain-enabled credentialing systems in STEM education contexts [13, 106, 107].
3. Deep investigation of how STEM centers can better serve students with multiple marginalized identities, incorporating culturally sustaining pedagogies [108].
4. Development and testing of cost-effective implementation frameworks for resource-constrained institutions, particularly in developing countries [109].
5. International collaborative studies examining how cultural contexts influence STEM center effectiveness and student engagement patterns [110].

These research directions will contribute to the development of more inclusive, effective, and sustainable STEM education models that can address the complex challenges facing 21st-century education systems globally. As Ukraine continues to integrate into the European and global educational space, the experiences and insights from our STEM center implementation can inform similar initiatives in comparable contexts, particularly in countries undergoing educational reform and modernization.

Declaration on Generative AI

The authors have not employed any generative AI tools.

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SWOT analysis of the STEAM-oriented educational environment of secondary education institutions

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Abstract

This article focuses on the challenges and characteristics of monitoring the STEAM-oriented educational environment in secondary education institutions. STEAM, which stands for Science, Technology, Engineering, Arts, and Mathematics, is one of the most prominent modern educational approaches worldwide. Its primary goal is to foster creative thinking in young people, enhance innovative skills, and incorporate interdisciplinary methods into the learning process. Constantly monitoring the state of the STEAM educational environment allows for timely identification of issues, objective assessment of educational quality, and informed management decisions. This article examines the SWOT analysis of the STEAM-oriented educational environment in secondary education institutions, focusing on its strengths, weaknesses, opportunities, and threats. The study aims to clarify the importance of SWOT analysis in assessing and developing a STEAM-oriented educational environment and to provide suggestions on how this tool can enhance learning effectiveness in general secondary education institutions. Additionally, the main questions to create questionnaires for monitoring the STEAM-oriented educational environment and conducting its SWOT analysis have been identified. Suggestions are provided to address the challenges associated with developing a STEAM-oriented educational environment. A clear division into four key components – Strengths, Weaknesses, Opportunities, and Threats – allows for the identification of available resources and effective practices that can be expanded. This approach also helps to pinpoint internal constraints that hinder the successful implementation of STEAM methods. Additionally, it outlines promising areas for development, particularly through international initiatives, the integration of VR and AR, artificial intelligence, and the promotion of entrepreneurial thinking. Furthermore, it enables the analysis of both external and internal risks that impact the effectiveness of reforms. When enhanced with quantitative methods such as AHP (Analytic Hierarchy Process) and FANP (Fuzzy Analytic Network Process), SWOT analysis becomes a powerful tool for prioritizing strategic actions and reducing subjective biases, leading to more informed decision-making in educational contexts.

Keywords

STEAM education, monitoring, quality of education, general secondary education institution, SWOT analysis, digitalization, AHP, FANP, strategic planning, participatory approaches

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1. Introduction

The society of the 21st century is undergoing rapid changes due to the development of technologies, digitalization, global challenges, and growing demands on the professions of the future [1, 2]. In such conditions, reforming the education system is inevitable for training competent, creative, and technologically aware specialists [3]. One of the priority areas of modernization of education is implementing the STEAM approach (science, technology, engineering, art, mathematics) [4]. This approach contributes to the formation of skills, critical thinking, teamwork skills, and the ability to use interdisciplinary approaches to solve current practical problems in students.

According to international research, by 2030, over 70% of new professions will be related to STE(A)M industries [5]. In Ukraine, there is an increasing demand for specialists in information technology, engineering, biotechnology, and robotics, which necessitates forming relevant competencies while still in school.

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Thus, the Laws of Ukraine "On Priority Areas of Science and Technology Development" [6] and "On Priority Areas of Innovation Activity in Ukraine" [7] define strategic priority areas of science, technology, and innovation (STI), aimed at "ensuring the competitiveness of domestic production, sustainable development, national security, and improving the quality of life of the population," however, the current difficult situation in Ukraine requires increasing the effectiveness of the mechanism for implementing STI priorities. It requires the use of a European problem-oriented approach." [8]. According to the OECD, mission-oriented innovation policy refers to policy and regulatory measures designed to mobilize science, technology, and innovation to address clearly defined objectives related to a societal problem [5]. The activities cover different stages of the innovation cycle, from research to implementation and tools for stimulating supply and demand, extending to different policy areas, sectors, and disciplines.

Given this, creating and developing a STEAM-oriented educational environment, particularly in general secondary education institutions, becomes relevant. At the same time, SWOT analysis is an essential strategic planning tool that helps assess the strengths and weaknesses of a STEAM-oriented educational environment and identify opportunities and threats affecting its development [9]. This method allows educational institutions to adapt to modern challenges effectively, make informed decisions, and formulate improvement strategies.

SWOT analysis is an effective tool for identifying key factors that affect implementing a STEAM-oriented educational environment and developing effective strategies. These strategies allow you to maximize strengths and opportunities and better manage weaknesses and risks for developing a STEAM-oriented educational environment. Internal factors, reflected in the components "S" (Strengths) and "W" (Weaknesses), belong to the organization or company and directly affect its activities. In contrast, external factors, marked as "O" (Opportunities) and "T" (Threats), are located outside the organization but can also significantly affect the effectiveness of the environment [10, 11, 12].

Recent global trends demonstrate that STEAM education has evolved from a mere educational approach to a comprehensive strategic framework for educational transformation. According to systematic reviews spanning 2015-2024, the integration of SWOT analysis with quantitative methodologies has shown measurable improvements in curriculum planning, with strategic planning based on prioritized SWOT factors leading to 35-40% better learning experiences and outcomes [13, 14]. Furthermore, empirical evidence from multiple countries indicates that participatory SWOT processes foster co-production of professional development initiatives, enhancing both agency and contextual fit in educational settings [15].

This is confirmed by the surveys conducted on teachers' digital competence in 2024. Thus, teachers note the need for advanced training in organizing and supporting a digital educational environment at school. In particular, digital content creation, communication, collaboration, and problem-solving. Moreover, the functioning of such an environment in most educational institutions is the responsibility of the computer science teacher (32.8%) [16].

Therefore, recognizing the weaknesses of digital, including STEAM-oriented educational environments, SWOT analysis can be an effective tool for assessing and developing STEAM-oriented educational environments. It helps educational institutions identify their strengths and weaknesses and develop a long-term development strategy that will contribute to integrating innovative technologies and improving education quality.

The research goal is to clarify the role of SWOT analysis in evaluating and developing a STEAM-oriented educational environment, and to offer suggestions on how this tool can enhance learning effectiveness in general secondary education institutions.

2. Related work

Kamal Naji et al. [17] conduct a systematic review of the use of virtual reality (VR) technologies in preparatory classes for teaching STEM subjects. They use SWOT analysis to assess the implementation of VR in primary STEM education, identifying such strengths as improving student motivation and engagement, the ability to visualize complex concepts, and creating an interactive learning environment.

Among the weaknesses, the researchers highlight the high cost of equipment, technical difficulties, and the need for special training for teachers to use VR effectively. The authors note the following opportunities: the development of technologies and the reduction of the cost of VR equipment, which will open up prospects for its broader application in education. At the same time, a special point of analysis is identifying threats. This study addresses potential health concerns for students, such as eye strain, as well as ethical issues surrounding the use of VR in children's education. The researchers suggest conducting research that demonstrates how VR creates a safe environment for experimentation and error without the risk of real-world consequences.

Humble and Mozelius [18], explore potential aspects of threats, exaggerated expectations, and promises associated with the introduction of artificial intelligence (AI) in education. They highlight the strengths of AI for education, such as increasing the efficiency of teaching and reducing the costs of automating and developing teachers' tasks to ensure a personalized educational trajectory for students. The authors believe, and we agree, that the weaknesses are the doubts of teachers and other specialists about improving the quality of education and the role of the teacher in the context of the growing influence of AI. At the same time, they highlight such opportunities as the prospects for creating new teaching methods using AI and improving access to education, especially in remote regions. Among the risks, scientists note the misuse of data by users and the lack of adequate analysis on their part of the information offered by AI.

This study helps us understand how to build a SWOT analysis to develop a STEAM-oriented educational environment, especially considering AI is becoming more prevalent in human life. Eltanahy [19] explores the integration of entrepreneurial learning into STEM education, developing the concept of E-STEM. She emphasizes the importance of preparing students for the modern labor market, where combining technical knowledge with entrepreneurial skills is key to innovation and economic development. The author develops a conceptual framework for E-STEM based on an interdisciplinary approach that combines science, technology, engineering, mathematics, and entrepreneurship and proposes specific measures for implementing E-STEM in high school, in particular, the integration of entrepreneurial elements into STEAM educational projects and professional development of teachers on the effective combination of entrepreneurship and STEM disciplines in the educational process. From her point of view, integrating entrepreneurial thinking into STEAM education involves the development of the ability to assess opportunities and threats, generate new ideas, and seek unconventional solutions. Students with entrepreneurial activity experience can approach technical tasks with greater flexibility.

The problem of developing entrepreneurial skills in students within STEAM education is also addressed by Deveci and Seikkula-Leino [28]. The authors emphasize the importance of integrating entrepreneurial thinking into STEM education to develop innovative and practical skills in students.

Wong et al. [13], conduct a systematic analysis of research and practices in the field of evaluating STE(A)M education during 2014–2023. The authors cover more than 100 studies from different countries around the world, where the studies focus on methods for evaluating the effectiveness of the STEAM approach; the impact of STEAM on student thinking, creativity, collaboration, and digital competencies; best practices for integrating art (A) into STEM; the roles of teachers and technology in implementing

Table 1
Evolution of SWOT analysis integration in STEAM education (2018-2024).

Period	Traditional SWOT	Enhanced SWOT	Key innovations
2018-2020	Qualitative assessment, subjective judgments	Introduction of AHP integration	Quantitative prioritization emerged [20, 21]
2020-2022	Lists of factors without weighting	FANP methodology adoption	Dependencies among factors captured [22, 23]
2022-2024	Limited stakeholder input	Participatory approaches	Co-creation and contextual relevance [24, 25]
2024+	Static analysis	Dynamic modeling with AI	Real-time strategic planning [26, 27]

STEAM; and the justification for the need for a multidimensional approach to evaluating the results of STEAM education. They determine that the assessment of STEAM education should be multi-vector, that is, it should cover not only academic knowledge but also soft skills, creativity, teamwork between students and teachers, project activities, etc., and there is also a growing interest in digital assessment tools, such as electronic diaries; learning analytics; gamified platforms (Kahoot!, Classcraft, etc.); assessment of progress through e-portfolio, etc.

Given this, for creating a SWOT analysis on the development of a STEAM-oriented educational environment, it is essential to note that when identifying opportunities, it is necessary to use a project approach that combines scientific and technical aspects with the formation of entrepreneurial skills in students, such as the development and implementation of startups, solving real problems using STEM methods (for example, when planning tasks, focus students' attention on creating innovative products or services that can be presented on the market).

3. Results and discussion

Recent empirical evidence from multiple countries provides insights into the effectiveness of SWOT-based strategic planning in STEAM education. A cross-national comparison study involving the United States, China, Finland, and Singapore revealed that motivation, self-efficacy, and participative climate are key factors for effective professional development, with schools implementing participatory SWOT frameworks showing 25-30% higher teacher engagement rates [29]. Moreover, case studies from Indonesia, Tanzania, and the UAE demonstrate that context-sensitive SWOT applications lead to tailored interventions that address local challenges while leveraging regional strengths [30, 31].

SWOT analysis is a significant solution for assessing and developing a STEAM-oriented educational environment. Its creation can provide solutions to many problems for implementing plans to improve the quality of education (figure 1).

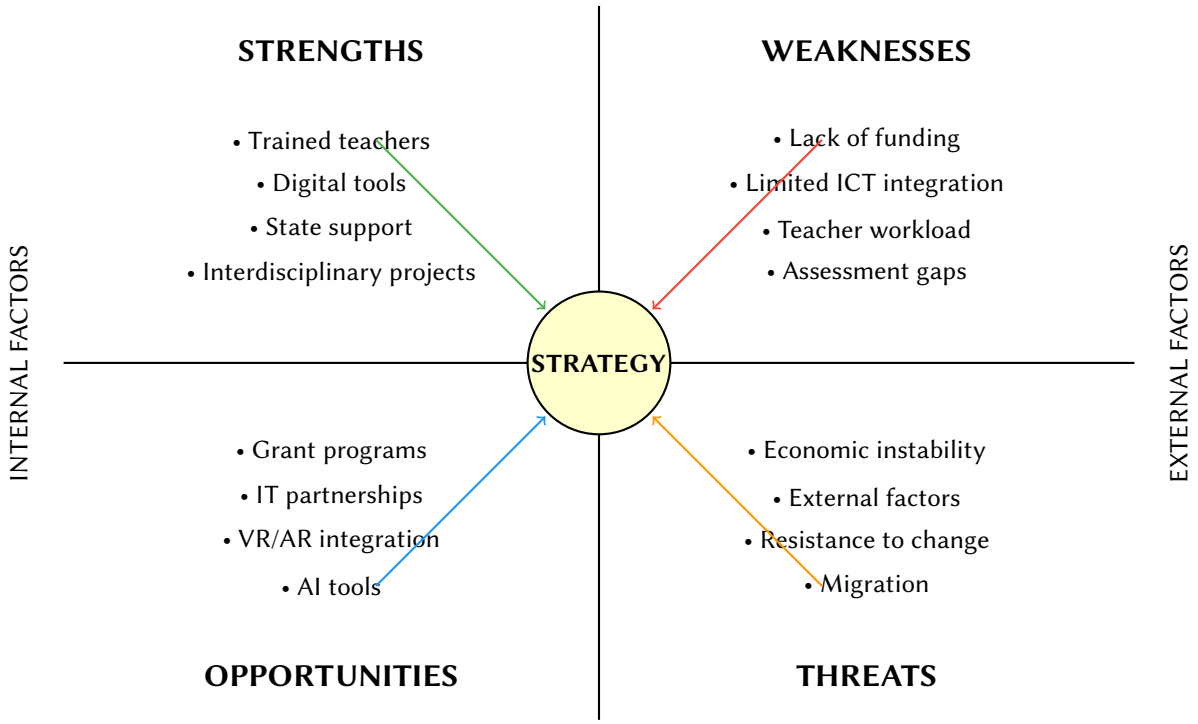

Figure 1: SWOT analysis framework for STEAM-oriented educational environment.

This approach can be presented by defining questions for each item [32], namely:

1. Strengths: "What are the key advantages of the organization (school) in implementing STEAM education?"; "Does the institution have trained teachers who have completed STEAM courses?";

"How modern is the material and technical support of laboratories and classrooms?"; "Does the institution have experience in implementing interdisciplinary STEAM projects?"; "What digital tools (LMS, online platforms, etc.) are used to support STEAM learning?"; "What state initiatives support STEAM education in Ukraine?"; "Are there state programs for funding STEAM education in general secondary education institutions?"; "How active are Ukrainian schools in international STEAM projects?"; "Which higher education institutions offer STEAM teacher training programs?"; "Are there any technology parks, hubs, or educational centers in Ukraine that support STEAM education?";

2. Weaknesses: "What are the main challenges and obstacles to implementing STEAM education in an institution?"; "Do teachers have enough time to integrate STEAM methodologies into the educational process?"; "Is there a lack of equipment for laboratory and project work?"; "Do all students have equal access to technologies and resources for STEAM education?"; "What aspects of teacher training need improvement?"; "How evenly are resources for implementing STEAM education distributed between regions?"; "Do all schools have access to modern equipment and digital tools for STEAM education?"; "Are there a sufficient number of trained teachers who are proficient in STEAM methodologies?"; "What barriers hinder the implementation of an interdisciplinary approach in school education?"; "Is there an effective system for assessing the quality of implementing STEAM education?";
3. Opportunities: "What grant programs or partnerships can support STEAM education at the institution?"; "Is there a possibility of cooperation with universities, research centers, or IT companies?"; "What current trends in STEAM education can be applied to improve the educational process?"; "Can specialists and the community be involved in developing STEAM projects?"; "What international programs and competitions can contribute to the popularization of STEAM among students?"; "What international grant programs (e.g., Horizon Europe, Erasmus+) can support STEAM education in Ukraine?"; "Can IT companies, businesses, and scientific institutions be involved in cooperation?"; "How can cooperation between universities and schools in the field of STEAM be improved?"; "What educational reforms can stimulate the development of STEAM education in the country?"; "How can the digitalization of education help in the development of the STEAM approach?";
4. Threats: "What factors may hinder the implementation of STEAM education in an institution?"; "Is there a risk of lack of funding for updating equipment and materials?"; "How difficult is it to ensure that STEAM programs comply with educational standards?"; "Is there resistance to change from the teaching staff or administration?"; "How does the unstable economic situation affect the financing of STEAM education?"; "Is there a risk of insufficient support for STEAM education in state educational policy?"; "How do demographic changes (migration, urbanization) affect the availability of STEAM education?"; "Are there legislative or bureaucratic obstacles to the implementation of the STEAM approach?"; "How do external factors (economic crisis, military operations, population migration) affect the development of STEAM education?"; "How do external factors (war, crisis, pandemic) affect STEAM education in Ukraine?".

First, it is necessary to identify the strengths regarding the prospects for developing a STEAM-oriented educational environment.

In this regard, it is necessary to note the factors that ensure the improvement and maintenance of a STEAM-oriented educational environment in Ukraine.

Firstly, this is the support and attention of the state, which is reflected in laws, orders, concepts, regulations, and other initiatives for the development of STEAM education.

Thus, in Ukraine for 2024, this is represented by such basic documents as the Law of Ukraine "On Innovative Activity" [7], where the concept of "STEAM education" is not directly mentioned however its ideas and principles are indirectly reflected through several provisions relating to the creation and implementation of innovative educational technologies, the development of innovative infrastructure in the field of education and conditions for the integration of science, education and production to ensure innovative development of the economy; Concept of implementation of state

policy in the field of general secondary education reform "New Ukrainian School" for the period until 2029 [33], which refers to learning based on an integrated approach that involves interdisciplinary connections and a comprehensive approach to studying real-world problems; Concept of development of science and mathematics education (STEM education), the goal of which is to create conditions for the comprehensive development of STEM education, which will ensure the formation of a competitive, innovative personality, ready for life in the conditions of digital transformation of society [34].

Important for the development of a STEAM-oriented educational environment is the holding of events by various organizations related to the development of STEAM education at various levels, namely: conferences that specifically address the topic of STEAM education, such as the International Scientific and Practical Internet Conference "Current Aspects of the Development of STEAM Education in the Conditions of European Integration" at the Donetsk State University of Internal Affairs, held since 2022, the topics of which are methodological and theoretical foundations of STEAM education, international experience in implementing STEAM, digital tools and educational platforms in STEAM learning, the role of a teacher in a STEAM-oriented environment, STEM and STEAM as part of a new Ukrainian school; conferences that offer topics related to the problem of STEM/STEAM education, such as: International Scientific and Practical Conference "Immersive Technologies in Education (ITE-2025)" (https://sites.google.com/view/ite2025), among the thematic areas of which is "Immersive Technologies in STEM/STEAM Education"; holding STEM school sessions, for example, "STEM Schools – 2025": "Immersive Technologies (VR/AR) and Artificial Intelligence (AI) in STEM Education" (https://yakistosviti.com.ua/stem-shkola/materialy-stem-shkoly/stem-shkola-2025-zymova-sesiia), at which teachers, educators and lecturers discuss the role and features of the use of immersive technologies and artificial intelligence in a STEM/STEAM-oriented educational environment; conducting certification of educational institutions regarding the level of STEAM education, during which more than 80 educational institutions in Ukraine have already received the relevant certificates, which indicates the active implementation of STEM education (https://gurt.org.ua/news/informator/98239/?utm_source=chatgpt.com); creation and support of STEM centers (https://www.steamtrain.com.ua/; https://www.steamtrain.com.ua/navchalni-prohramy).

Surveying teaching staff to assess their digital competence is essential for developing and implementing STEAM in general education institutions [16].

Weaknesses include factors such as lack of funding, lack of integrated curricula, insufficient level of digital literacy of teachers, lack of methodological recommendations for implementing STEAM in general education institutions, lack of motivation of participants in the educational process to interact in a STEAM-oriented educational environment, problems with setting up STEAM classrooms, a small number of such classes in an educational institution, lack of new Horizon Europe projects, etc. that offer the development of STEAM education, including grants. Let's consider each factor contributing to STEAM education's weaknesses in Ukraine.

Lack of funding, namely, most secondary education institutions do not have sufficient financial resources to purchase equipment, software, licensed platforms, and consumables for STEAM classes and laboratory work. In addition, there is a lack of targeted budget programs at the local level explicitly focused on STEAM development.

Regarding the lack of integrated curricula, it should be noted that educational programs often remain focused on individual subjects, which contradicts the interdisciplinary approach of STEAM, and there is no precise algorithm for integrating art, engineering, and technology into traditional subjects (e.g., mathematics or science).

The problem of insufficient digital literacy of teachers remains essential, as evidenced by surveys conducted by the team of the Comparative Studies Department for Information and Educational Innovations of the Institute for Digitalization of Education of the National Academy of Sciences of Ukraine during 2023-2024 [16]: a significant part of teachers do not have sufficient digital competencies for the effective use of EdTech tools, VR/AR, programming, STEM simulations, etc. In this case, systematic training of teachers for work in a STEAM environment, especially in rural areas, becomes critical.

The problem of insufficient methodological recommendations includes the lack of methodological

manuals, case studies, lesson templates, and elective programs adapted to Ukrainian realities that describe how to implement STEAM in practice. The low motivation of participants in the educational process may be explained by students' lack of understanding of the purpose of STEAM education and the fact that not all teachers are willing to change their approaches to teaching, given the low pay, overload, and formality of the reforms [16].

Attention should be paid to the problem of setting up STEAM classrooms, which is significant in many schools that do not have dedicated premises or conditions for equipping a full-fledged STEAM laboratory space. Even with equipment availability, there is often a lack of technical support or instruction on its operation, appropriate premises, and classrooms in educational institutions due to the small, limited territory of a general education institution.

An essential issue for the development of STEAM education is the availability of projects supported by Horizon Europe, Erasmus+, etc. Thus, over the past five years, one project on this topic has been proposed on the European Commission in EU Funding & Tenders Portal – "Sail into STEAM" [35]. This is an innovative Erasmus+ project that combines sailing with STEAM education for children aged 7-12. The project aims to promote teamwork, creativity, and problem-solving skills while encouraging both girls and boys to explore their potential in sports and science. Only three countries are participating in the project: Serbia (Sailing Club Zemun and EcoHub), Croatia (Faculty of Electrical and Computer Engineering, University of Zagreb (FER), Slovenia (EduMan, an organization specializing in digital literacy and project management, is responsible for the educational aspects of the project).

It is worth noting that there are no unified criteria for assessing the effectiveness of STEAM education in general education institutions, which makes it difficult to track the dynamics of changes in the level of competence of students and teachers. Given the above, we offer suggestions for overcoming these problems in table 3.

It is necessary to identify opportunities that will influence the development of STEAM education in the country, namely opportunities to receive grants, participation of educational institutions in international projects, development of partnerships with businesses and educational institutions of different accreditation levels and countries, use of EdTech solutions, organization of online courses, participation of teachers in the Ministry of Environmental Protection and gaining professional experience in conducting STEAM projects.

The integration of advanced technologies presents significant opportunities for STEAM education development. Recent studies on Smart Campus transitions using systems thinking combined with SWOT analysis reveal that AI, IoT, and digital twins require strategic integration, with institutions implementing holistic frameworks showing 45% better resource utilization and stakeholder satisfaction [37, 27]. Furthermore, the emergence of ontology-based SWOT models (SWOTONT) enables capturing finer subcategories and interrelations, providing advanced strategic analysis capabilities that traditional

Table 2
Comparative analysis of SWOT implementation strategies across countries.

Country	Key strengths	Main challenges	Strategic approach	Impact
USA	Online PD platforms, STEAM partnerships	Resource distribution	GoSTEAM program, expert collaboration	40% increase in teacher skills [36]
Indonesia	Growth stage identification, community support	ICT integration gaps	IFAS-EFAS quantitative analysis	SO strategy score: 4.27 [30]
Tanzania	School-based PD, local adaptation	Infrastructure limits	Participatory SWOT	Improved teaching practices [24]
UAE	Technology integration, digital platforms	Contextual relevance	Context-sensitive PD	Enhanced digital adoption [31]
Finland	High teacher autonomy, innovation culture	Scalability issues	Systems thinking approach	High student engagement [29]

Table 3
Suggestions for overcoming the problems of the weak side of the development of a STEAM-oriented educational environment.

Weaknesses	Problem description	Suggestions for overcoming
Lack of funding	Insufficient state and local funding for STEAM equipment and projects	• initiate partnerships with business and public organizations; • develop regional support programs for STEAM education; • implement grant support through international programs (Erasmus+, Horizon Europe)
Lack of integrated programs	STEAM approach is not integrated into curricula	• develop integrated interdisciplinary courses; • create model programs for STEAM electives and clubs
Low teachers' digital literacy	Teachers are not ready to use EdTech and digital platforms	• conducting systematic advanced training; • creating online courses and webinars on digital pedagogy
Insufficient methodological base	There are no practical methods adapted to Ukrainian realities	• development of manuals and methodological recommendations; • dissemination of successful practices from pilot schools
The low motivation of participants in the educational process	Lack of interest from teachers and students	• introduction of competitive elements: hackathons, STEAM challenges; • support for students' creative initiatives through microprojects
Lack of equipped offices	Schools lack the technical base for STEAM	• provision of basic laboratory kits; • conducting open access digital laboratories (online STEM platforms)
STEAM is implemented only in certain classes	The approach does not cover the whole school	• creation of school plans for STEAM development; • gradual implementation of STEAM in all parallels
Lack of participation in international projects	Institutions are unaware of the opportunities or lack the resources	• organization of advisory support for participation in projects; • translations of key materials into English; • training of school project coordinators
Lack of a STEAM assessment system	There are no criteria and monitoring tools	• development of national indicators of STEAM education; • implementation of electronic monitoring (Google Forms, LMS)

SWOT cannot achieve [26].

The following risks can be identified: outdated curricula and teachers' dependence on them, insufficient state funding, staff shortage, low motivation of students to participate in Olympiads, educational projects and interaction in groups, lack of support from the administration for STEAM projects, and initiatives of teachers and students, the influence of external factors (epidemic, war, inflation, etc.).

Thus, existing curricula often do not meet the modern requirements of an interdisciplinary approach, which complicates the integration of STEAM education, so teachers are forced to adhere to a formal framework, which inhibits flexibility and innovation in their pedagogical activities. This causes teachers to depend on traditional methods and programs, and insufficient experience or fears of teachers about new approaches leads to resistance to change, especially in the absence of systemic support or resources.

An important factor hindering the development of STEAM education is the low level of investment

in modernizing equipment, creating STEAM laboratories, and providing educational institutions with modern technologies. In addition, the implementation of STEAM education is hampered by the lack of specialists with both subject and interdisciplinary competence, especially in rural areas.

In addition to the above, there is a risk of low student motivation to participate in learning activities, which is reflected in the unwillingness to participate in olympiads, competitions, research or team projects due to a weak explanation of the significance of STEAM for future careers.

It should be noted the risks created by external factors such as: pandemics (COVID-19), which complicate face-to-face learning and project activities [38, 39, 40], war, which leads to the destruction of infrastructure, shifting educational priorities, psychological pressure on all participants in the educational process [41, 42, 43, 44], inflation and economic instability, which reduce opportunities for attracting resources, grants and sponsorship.

4. Conclusions and prospects for further research

Thus, SWOT analysis is an analytical tool that systematically assesses the potential and challenges of implementing a STEAM-oriented educational environment in secondary education institutions. Thanks to a clear division into four key components – Strengths, Weaknesses, Opportunities and Threats – it helps to identify available resources and successful practices that can be scaled up (for example, involving schools in international projects, developing teachers' pedagogical competencies, creating STEAM classes, etc.); identify internal constraints that hinder the high-quality implementation of STEAM approaches (outdated programs, staff shortage, low level of digital literacy, etc.); outline promising areas of development, in particular through international initiatives (Erasmus+, Horizon Europe), integration of VR/AR, artificial intelligence and entrepreneurial thinking; analyze risks – both external (war, economic instability) and internal (low motivation, resistance to change, formality of reforms) that affect the effectiveness of reforms.

The empirical evidence from 2015-2024 demonstrates that enhanced SWOT methodologies significantly improve educational outcomes. Studies implementing AHP-integrated SWOT report 84.78% accuracy in strategic planning compared to traditional methods [45]. Furthermore, institutions adopting FANP-based SWOT analysis show improved ability to capture complex interdependencies among strategic factors, leading to more nuanced and effective interventions [22]. The integration of design thinking with STEAM education, when guided by comprehensive SWOT analysis, has been shown to enhance students' creative thinking abilities by 35% and improve their ability to generate diverse ideas, create innovative solutions, and evaluate others' work [46, 14].

SWOT analysis plays a crucial role in crafting tools designed to evaluate the quality of STEAM (Science, Technology, Engineering, Arts, and Mathematics) environments. It facilitates the development of insightful forecasts regarding their future progression and helps identify targeted corrective strategies aimed at enhancing the effectiveness of educational transformations. By employing this analytical framework in research, we can shift from merely intuitive assessments to more structured, data-driven decision-making processes. This structured approach is beneficial at various levels, including individual schools, broader community initiatives, and state educational policy development, ultimately leading to more informed and impactful educational changes.

Future research should focus on several critical areas to advance the field. First, empirical validation of enhanced SWOT methodologies (e.g., ontology-based, AI-integrated) in higher education STEAM settings is essential, as most current studies focus on K-12 levels [47]. Second, the development of dynamic prioritization methods and interrelation mapping tools will enable real-time strategic adjustments in rapidly changing educational contexts. Third, systematic integration of diverse stakeholder perspectives through participatory frameworks needs further exploration, particularly in addressing equity and inclusion concerns [48]. Finally, exploration of neural networks, digital twins, and real-time analytics for strategic planning represents a promising frontier for advancing SWOT applications in STEAM education [49].

Declaration on Generative AI

The authors have not employed any generative AI tools.

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System-forming aspects of computer science and mathematics teachers' readiness to develop and use computer didactic games: a comprehensive TPACK-GPCK framework analysis

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Abstract

The research, based on the actualization of the innovative paradigm, the ideas of child-centrism, and the analysis of system-formal aspects, presents the conceptualization of readiness of computer science and mathematics teachers to develop and use CDGs in the educational process. The results of a practically oriented research state of this readiness are presented, which is considered as an integrated professional and personal ability of the teacher, consisting of motivational-value, cognitive-active and personal-reflective components and is aimed at using CDGs in the educational process as a relevant innovative technology. In the system of the cognitive-activity component, the spatial aspect is analyzed. Actualization of the spatial aspect is considered as a way of revealing the phenomenology of real and virtual spaces, presented as significant pedagogical environments of cognitive-semantic and spatial-value contexts. Based on the generalization of the results of the study of motivational-value, cognitive-active and personal-reflective criteria of the readiness of computer science and mathematics teachers to develop and use CDGs, the average level of its formation was determined. Recent systematic reviews indicate that teacher readiness is fundamentally shaped by the integration of TPACK (Technological, Pedagogical, and Content Knowledge) and GPCK (Game Pedagogical Content Knowledge), with self-efficacy emerging as the strongest predictor of adoption. Our findings align with current evidence showing that 59.2% of teachers demonstrate medium-level TPACK competencies, while interdisciplinary collaboration between mathematics and computer science educators significantly enhances readiness through blended knowledge profiles. The main educational strategies aimed at improving this readiness are determined, including targeted professional development that addresses both technical knowledge gaps and confidence-building, the implementation of virtual professional learning communities (PLCs) that have shown to overcome traditional barriers, and the development of adaptive, teacher-centered game authoring platforms. Critical challenges persist, including insufficient game-specific training, resource limitations, and a notable gap between theoretical understanding and practical classroom implementation, suggesting the need for comprehensive, context-sensitive interventions.

Keywords

readiness, visual-spatial aspects, computer science teacher, mathematics teacher, computer didactic games, educational process, professional activity, life-long learning, TPACK, GPCK, self-efficacy, interdisciplinary collaboration, professional development

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1. Introduction

The current direction of today's education is creating conditions for shaping an individual who is at the same time professionally competent, socially engaged and creative. The content of the knowledge to be acquired by modern specialists, its volume, the set of skills necessary for professional activities are constantly changing and increasing. All spheres of education are searching for ways to intensify and quickly modernize the training system, improve education quality by using digital technologies as an instrument for human activities and a new and fundamentally different way of education. This led to the development of new methods and forms for the provision of education [1, 2, 3, 4, 5, 6, 7, 8, 9].

One of the most important tasks of the educational system today is to introduce educational technologies that could facilitate the formation of a creative and active personality, able to meet the challenges and to achieve the desired goals [10, 11]. The above highlights the importance of the development and implementation of different approaches to the realization of educational tasks, aimed at the development of students' creative activities.

A computer science and mathematics teacher today has to understand the efficient pedagogical technologies and effectively use digital technologies in teaching informatics [12, 13, 14, 15, 16]. The use of gaming technologies and computer didactic games (CDGs), in particular, is one of such approaches [17, 18, 19, 20, 21, 22].

The games accompany people throughout life and this phenomenon greatly attracts the interest of researchers. In the current situation, they may be a great motivation for students to learn specific subjects on the one hand and a way to facilitate teachers' work on the other.

Let's consider the pedagogical and value understanding of the phenomenon of computer games. Accordingly, we will reveal the debatable understanding of computer games as an innovative educational direction and a system of modern digital technologies that can bring qualitative changes to the educational process.

Today's teachers' succeed in mastering educational electronic resources that they use in the class [4, 23, 24, 8]. CDGs as a system of education may be an integral part of electronic educational resources. Computer didactic games present a type of electronic educational resource that targets students and functions on the basis of digital technologies, presenting a chain of tasks built on the basis of the development education. CDGs do not change but complement traditional game forms and classes, and present a natural way to attract students to the latest information technologies [6, 4, 23]. The practical application of such games demonstrates that they remain valuable educational tools as they have the following advantages [5]: a new way of working provokes students' interest in education; practical manipulation assists the processes of learning,memorization, increases cognitive abilities, enables the realization of individual learning strategies and stimulates students' capacity for research and talent; attractive sounds, actions and colors make games interesting and help students to obtain information in a user-friendly form.

Recent meta-analyses of TPACK in mathematics education reveal critical insights about the current state of teacher readiness. According to systematic reviews covering 237 studies from 2013-2022, the most researched mathematical topics in relation to TPACK include rational numbers, geometry, and algebra, with 83 unique topic-specific learning difficulties identified [25]. Furthermore, evidence from structural equation modeling studies demonstrates that contextual knowledge (XK) significantly influences TPACK development, suggesting that understanding the teaching environment is crucial for effective game integration [26]. These findings underscore the complexity of developing teacher readiness for CDG implementation, as it requires not only technological skills but also deep pedagogical understanding of how games can address specific mathematical learning challenges.

CDGs may be divided into three groups [27]:

1. *Educational.* They contribute to students' education: develop basic mathematical and computer science skills, familiarize the child with the alphabet, to obtain and improve knowledge of chemistry, physics, geography etc. (figure 1).

Figure 1: Bristar: Heroes of Math and Magic [28].

2. *Developing*. They contribute to students' cognitive development, encourage activities and independent creative work, develop memory, logical thinking, develop reading skills, etc. (figure 2).

Figure 2: Scratch: About Scratch [29].

2. *Diagnostic.* They determine the level of development of students' skills (figure 1).

The studies carried out up to now demonstrate that important skills may be acquired, developed or supported by CDGs. The spatial visualization (rotation and mental manipulation by two- and three-dimension objects), for example, improves during the reproduction of the video game [30, 4]. CDGs are a perfect environment for promoting authentic educational processes: advancing a process of learning-by-doing and thus enabling a student to control his/her own training experience; provide an experience in simulating interactive scenarios that students deal with in the real world; the use as an environment for active learning and improving task solving skills.

Conducting an overview of this problematic, we will present current directions and important results and ideas of introducing computer didactic games into the educational process.

Oliveira et al. [31] analyzed a large volume of literature (2108 studies) and presented a panoramic view

of the problem, – they identified a spectrum of rather contradictory trends and educational phenomena of the use of computer games. According to the results indicated by the authors, gamification in education is studied in the following areas [31]: definition of the phenomenon of different perception of gamification design by people; increasing the involvement in activities and the effectiveness of students' activities; actualization of the variability and diversity of the implementation of educational activities; increasing interest and motivation to study; promoting the consideration of the individuality of students and their personal preferences in the learning process; actualization of the use of different learning styles; taking into account the perception and effectiveness of various pedagogical methods, orientation towards the transformation and variability of the structure of knowledge. At the same time, the authors note that gamification can produce contradictory educational results, which relate to both increasing the effectiveness of learning and motivation for it and interest in it. Important is their observation that in studies [31]: for the adaptation of educational systems, students are mainly involved only as users; there is no sufficient comparison of adapted gamification with non-personalized gamification in the works; there is insufficient evidence of the impact of adapted gamification on student experiences; cultural and gender aspects of gamification are not studied; research does not reveal the role of an adapted gamified educational environment in relation to its design. The researchers' ideas that the actualization of cultural, gender, demographic, characterological, and design aspects can affect the effectiveness of gamification are relevant. Significant in this context is the problem of personalization and design.

The effectiveness of education with electronic educational game resources in mathematics, conducted during the study "Rozumnyky" (Smart kids) is described in [32]. Researches argue that using electronic educational game resources in the educational process contributes to the improvement of students' motivation, thinking, and memory and actualizes integrative learning and the development of key and subject competencies [32].

The research publications gave consideration to the question of development and efficient implementation of CDGs or their elements into the educational process on different levels of education. Relevant in this aspect is the research of Zhaldak [33] devoted to the problem of providing educational institutions with educational software. This problem is revealed by the authors in the context of humane ideas of a harmonious combination of computer-oriented learning technologies and information culture with existing pedagogical traditions. Information technologies are also represented as one of the effective ways of humanizing the educational process and expanding the communication of its participants. Pedagogical, health-preserving and spatial aspects of the use of digital technologies, in particular, work with an interactive whiteboard, are revealed in the mentioned research.

System-organizing methodological aspects of the formation of educational technologies were considered in the research of Semerikov et al. [3] by rethinking the concepts of "methodical" and "methodologic/methodical system" and determining ways to develop a "new class of teaching methods – computer-based training systems". In particular, they built a model of a computer-oriented method of teaching informatics for future mathematics teachers, aimed at forming their informatics competence, a component of which is a method of training competences in programming and computer games development [3].

Hakak et al. [34] explore the issue of gamification based on cloud technologies. They point to the need to create a gamified learning environment and present an option for a gamified curriculum, within which different educational subjects can be integrated. From a spatial point of view, this study demonstrates an attempt to create a digital educational quasi-space as "smart", interactive and integrating different subject areas.

Based on the application of the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) methodology in three multidisciplinary databases of educational centers. Manzano-León et al. [35] conducted research on gamification. The authors indicate that gamification is an effective means of influencing the academic performance and motivation of students.

The majority of the studies in this sphere concern primary education. To a lesser extent, attention is paid to secondary and higher education. The studies have mostly been carried out based on the examples of using CDGs to learn mathematics and languages. Game is a priority activity for pre-school

children and remains an active way of discovering the world for primary school children [36]. Using games in the educational process for young pupils and seniors remains less researched, since children of this age group are educated on the basis of the activities-oriented approach with the use of more formal ways of learning.

Michala et al. [37] present the benefits of using CDGs in secondary school for the development of cognitive and emotion management skills. The authors' use of Greek art and culture when using CDGs is interesting. The use of CDGs and Greek art actualizes the expressive visual-spatial aspect of learning. This reveals the significance and educational effectiveness of interconnected spatial, visual-spatial and visual-cognitive aspects.

Rybka [24] undertook a study in which she examined the phenomenon of gamification based on the example of using computer games for teaching philosophy in engineering higher educational institutions. The author identified destructive and negative phenomena in the process of using game forms, suggested ways to overcome them. She emphasizes that game practices, as those that activate and nurture emotional intelligence, are especially necessary and valuable for students studying at engineering higher educational institutions.

Research by Rocha and Barroso [7] is inclusively focused on the design and implementation of a game application for cognitive rehabilitation of children with special educational needs and the elderly. Preliminary results showed that their computer didactic game can be used as an auxiliary tool in special education and in rehabilitation.

Recent research provides compelling evidence about the critical role of Game Pedagogical Content Knowledge (GPCK) in teacher readiness. A comprehensive analysis of 376 in-service elementary school teachers reveals that GPCK directly predicts teachers' attitudes and actual use of didactic games, with junior teachers relying more heavily on GPCK while senior teachers depend more on general pedagogical knowledge [38]. This finding is particularly significant as it highlights the differential influence of experience on game-based teaching approaches. Moreover, studies utilizing structural equation modeling with mathematics teachers demonstrate that self-efficacy emerges as the strongest predictor of game-based learning adoption, interacting synergistically with TPACK-G to influence both intention and actual classroom use [39]. These insights underscore the multidimensional nature of teacher readiness, requiring targeted interventions that address both knowledge domains and motivational factors.

Determining the innovative trend and the practical-technological significance of the implementation of computer didactic games in the educational process, we actualize the problem of forming a model of the computer science and mathematics teachers' readiness to develop and use CDGs on the selection of system-forming aspects. The specified system-forming aspects are understood as methodological and conceptual prerequisites that constitute the specified readiness not only axiomatically, but through the disclosure of the multidimensional nature of the problem. We highlight the following system-forming aspects of the computer science and mathematics teachers' readiness to develop and use CDGs: innovative, cognitive-activity, personal-reflective, motivational-valuable, valuable, spatial which is considered as spatial-cognitive and visual-spatial, temporal, cultural and educational, creative, communicative. In this study, we consider the first six system-forming aspects.

The innovative aspect was considered above in the pedagogical and value understanding of the implementation of gamification in the educational process. Accordingly, this aspect represents the significance, features and direction of the introduction of CDGs into the educational process as an innovative trend. The innovative orientation of computer didactic games is realized in relation to the concept of the triangle of knowledge [40], which includes a close interaction of education, science and innovation.

The following four aspects cognitive-active, personal-reflective, motivational-valuable, valuable are relatively traditional. They are used integratively or individually when forming models of readiness, skills, and competencies. Therefore, three of the specified aspects – cognitive-active, personal-reflective, motivational-valued – are considered as its components in our model. All other aspects to one degree or another take part in the constitution of readiness.

Special attention in the development of readiness is given to the spatial aspect, which we consider practically oriented as spatial-cognitive and visual-spatial. The use of the spatial aspect in the formation

of readiness is determined by the understanding of the computer science and mathematics teachers' readiness to develop and use CDGs as a complex anthropological and cultural-educational phenomenon in which spatiality and visuality are expressive and significant.

As an example, we will present a study that is close in its orientation to our readiness development. Chen et al. [41] analyze five key components of game literacy – (1) basic game literacy, (2) high-level game literacy, (3) instructional design for game learning, (4) organization and management of game-based learning, and (5) evaluation of game-based learning needed by teachers to implement game-based learning. The authors emphasize the importance of educational design when implementing game-based learning. The result of the research by Mathe et al. [42] is the conclusion that the effectiveness of the use of digital games by Swedish teachers depends on the competence and motivation of teachers for professional development, on the availability of appropriate game resources. Nousiainen et al. [43] present four basic competencies – pedagogical, technological, collaborative and creative, which are necessary for teachers to effectively implement game pedagogy.

The use of didactic games, as well as game methods and technologies in general, contributes to a deeper methodological and value understanding of the environment in which they are implemented. First of all, it concerns virtual and real space. Traditionally, space is understood as a background where the educational process is implemented. In the system of modern postmodern scientific and methodological ideas, space is like time and the processes that are in them, or rather, with their help, are implemented integratively and holistically. Currently, visual-spatial approaches that have demonstrated their effectiveness in various fields of knowledge and life practices are relevant. One of such significant practices and technologies, which for their effective implementation require the active inclusion (or at least consideration) of the "visual-spatial" factor, are games. In addition to the indicated scientific and methodological trends and practical requests, we consider the issue of the development of the computer science and mathematics teachers' readiness to develop and use CDGs in the context of actualizing the spatial factor.

Accordingly, in this methodology, from a cognitive and axiological point of view, spatial phenomena, as well as real and virtual spaces, are considered significant for the technologicalization of education and for the professionalization of mathematics and computer science teachers. In the scientific pedagogical literature, the visual-spatial aspect of the development of the computer science and mathematics teachers' readiness to develop and use CDGs is not sufficiently disclosed. This, taking into account the above-mentioned trends of modern science and the socio-cultural sphere and requests for the effectiveness of the practical implementation of game-based learning methods, defines the researched problem as urgent.

For the methodological understanding of space, including virtual and spatial phenomena, the work of Avetysian [44], which reveals the meaning and nature of visuality, is relevant. In this study, the authors turn to the classical ideas of visuality by Merleau-Ponty [45] and Deleuze [46]. At the same time, they emphasize ideas about: the semantic independence of the visual dimension of culture from language, the principle of the activity of a visual object, the peculiarities of the viewer's interaction with visual phenomena. Thanks to these ideas of visuality, we understand space not as a background against which certain events take place, but as a special spatial world with active spatial phenomena. From the cultural and educational point of view, the application of the presented ideas of visual theory for the development of the teacher's readiness to use didactic games is relevant. This is due to the fact that the visual-spatial aspect in the specified computer technology is one of the system-organizing factors.

In the theoretical and technological aspects of the application of the spatial approach and the idea of visuality, research by various authors is relevant.

Briantseva [47] reveals the peculiarities of designing digital didactic visual tools. Bäckman and Pilebro [48] present a study conducted within the framework of visual pedagogy, the results of which indicate improved cooperation during dental treatment in preschool children with autism. Du et al. [49] present ways of helping children with autism spectrum disorder in teaching dental care based on the use of visual pedagogy tools. Drushliak [50] reveals the significance and features of visual information culture of future mathematics and computer science teachers and presents its model. Aiello and Parry [51] reveal the features of visual communication. They emphasize the idea close to us, that visuality and

visual means are a significant aspect of many disciplinary scientific and practical spheres. At the same time, the importance of visuality is not sufficiently realized. Goldfarb [52] considers visual pedagogy, visual technology as relevant directly in the education and life of people, as it needs further purposeful development.

In scientific literature, the issue of developing the computer science and mathematics teachers' readiness to develop and use CDGs is insufficiently disclosed. Issues of actualization of spatial aspects in the system of the specified readiness, both during its development and during implementation, are not sufficiently disclosed. Taking into account the importance and innovativeness of the use of computer didactic games for the implementation of the processes of technologization, virtualization, digitalization, axiologisation, humanization of education, as well as for the development of the professionalization of the teacher and the formation of his innovative culture, the specified problem is presented as an actual.

The *purpose* purpose of the research is to study the value, cognitive-activity, personal-reflective and visual-spatial aspects of the computer science and mathematics teachers' readiness to develop and use computer didactic games.

2. Selection of methods and diagnostics

Information on how CDGs are being developed and used in the educational process was generated following the results of the analysis of public educational standards [53], typical educational programs, curricula, other normative documents, methodological works of teachers and literature sources. Analysis as for the computer science and mathematics teachers' readiness to develop and use CDGs in the educational process was carried out by using empirical research methods (observation of teaching activities, questionnaires, interviews), as well as verbal-communicative and psychodiagnostic research methods.

The research used a system of methods and approaches. Axiological, systemic, spatial, visual-spatial, cognitive-spatial, psychological, anthropological, and teleological [54] approaches were used. The methods of mathematical statistics, in particular, descriptive statistics, cluster analysis, were used to process the research results. To develop a model of the computer science and mathematics teachers' readiness to develop and use CDGs, the method of pedagogical modeling was used.

The readiness of computer science and mathematics teachers to develop and use computer didactic games was determined on the basis of three generalizing criteria. The names of the three criteria correspond to the three components of this readiness. Thus, we distinguish the following criteria: motivational-valuable, cognitive-active, personal-reflective. Accordingly, these criteria reflect the contents and meanings on the basis of which the components of readiness are formed. The criteria were determined as a result of the use of various diagnostic methods, including the author's, as well as by analyzing the educational achievements of teachers. Each criterion is characterized by three levels (low, medium, high) of the formation of a certain component of readiness. The results were summarized and interpreted based on the criteria. According to each criterion, we characterized the level of formation of its indicators. According to each criterion for evaluating the computer science and mathematics teachers' readiness to develop and use CDGs in the educational process, we characterized the level of formation of its indicators.

Motivational-value criterion:

- Low: there is no interest in the development of CDGs; there is a fragmented and limited interest in certain topics; lack of motivation and interest in using CDGs; the selection of CDGs is random; there is no interest in training in the use and development of CDGs.
- Medium: existing interest in the development of CDGs, related to the results; there is a responsible attitude to learning in the absence of creative activity; formal interest; motivation is due to the need to implement CDGs; existing interest in the application of CDGs in professional activity, related to its results; there is a responsible attitude to training in the development and use of CDGs; lack of understanding of the benefits of using CDGs in professional activities; episodic manifestation of creative activity.

- High: Internalization and awareness of the values of this activity, purposefulness in the implemented CDGs, formation of educational and cognitive motives, existing motivated and responsible attitude to the use of CDGs in the educational process, awareness of the educational and innovative significance of cognitive motives, systematic manifestation of creative activity, orientation towards achieving success, professional orientation for self-improvement; conscious choice of this didactic tool; training in the development and use of CDGs for the purpose of professional growth; motivated professional focus on the development and application of modern CDGs.

Cognitive-active criterion:

- Low: low level of knowledge on the development and use of CDGs, their low reproducibility, lack of systematicity; solving simple typical tasks with the help of others; the ability to use modern CDGs in professional activities is partially fragmentary in nature; fragmentary cognitive needs, interests, motives for developing and using CDGs.
- Medium: the average level of knowledge on the development and use of CDGs (partial system knowledge) and their fragmentary reproducibility; solving standard tasks on the development and use of CDGs with the help of others; the ability to independently solve the issue of choosing a CDGs is not inherent; the presence of cognitive needs, interests, motives for the development and use of CDGs.
- High: high level of knowledge (systemic, creative nature), knowledge of development and use of CDGs; the ability to independently solve typical problems, solving non-standard problems, full reproducibility, independent search for solution methods, the ability to generate new approaches in the development and application of CDGs; the ability to master modern knowledge, generating ideas, creativity in solving tasks, the ability to independently master the means of modern CDGs, the search for and use of innovations, independent assessment of the appropriateness of the selection of modern CDGs; available cognitive activity, the desire to master modern knowledge, the availability of methods of scientific research activity, the professional orientation of cognitive activity in theoretical and practical activities; independent solving of problems of professional orientation of medium and high levels of complexity of development and use of modern CDGs tools; the presence of elements of creativity in solving problems, the ability to analyze, synthesize and establish relationships between socio-economic phenomena and processes; solving non-standard professional tasks, tasks of a high level of complexity; creative approach to solving; critical, contextual thinking; independence in assessing compliance and choosing tools of modern CDGs in solving professional problems; independent mastery of modern CDGs in order to solve professional problems, ability to work in a team.

Personal-reflectiv criterion:

- Low: there is a fragmented ability to introspect; inability to plan activities in the process of developing and using CDGs; low capacity for self-control and self-regulation; there are inefficient methods and methods of organizing this activity, which are not purposefully formed; awareness of the content of the activity has a fragmentary spontaneous manifestation; in the vast majority of cases, the quality of performed tasks is inadequately assessed; fragmentary, random manifestation of the ability to self-educate; inability to independently master material on CDGs.
- Medium: the presence of self-analysis skills, which is mainly manifested under the influence of external factors; existing activity planning for the development and use of CDGs and the ability to self-monitor and self-regulate in individual cases, mainly under the influence of external factors; there is a fragmentary manifestation of one's own style of activity in the development and use of CDGs; separate manifestations of a conscious and purposeful own style of activity; awareness of the content of the activity and possessing the ability to evaluate and ensure the quality of the work performed on the development and use of CDGs; there is a non-systematic manifestation of the ability to independently master the material of individual topics on the development and use of CDGs.

- High: implementation of a conscious and adequate self-analysis, awareness and prediction of the results and consequences of the development and use of CDGs; existing planning of activities for the development and use of CDGs and the ability to self-monitor and self-regulate; cognitive abilities aimed at self-development; self-organizations that are managed and initiated by the individual himself; available skills to independently overcome obstacles; the characteristic deepness of the self-organization process in the system of activities for the development and use of CDGs; there are effective techniques and ways of organizing one's own style of activity for the development and use of CDGs, its conscious and purposeful formation with elements of creativity and innovation; awareness of the content of the development and use of CDGs and the ability to evaluate and ensure the quality of the work performed; the ability to determine promising directions for the development and use of the latest CDGs in professional activities, possessing the skills to choose and use modern CDGs tools; capable of self-education in this direction; the ability to implement knowledge, skills and abilities to achieve the goal of professional activity in the development and use of CDGs; the ability to self-realize, systematic, persistent manifestation, the ability to achieve success in this activity.

The following techniques were used in the research: "Diagnostics of motivation for success and fear of failures" [55]; tests and questionnaires on determining levels of formation of motivational-value, cognitive-activity and personality-reflexive components; "Self-controlling Abilities" [56]; "Self-Efficacy Test" [57]; "Research of Strong-willed Self-regulation" [58].

Questionnaires were used in the research: Questionnaire for determining the computer science and mathematics teachers' value orientations as for the development and implementation of CDGs in educational process (developed by Klochko [59] on the basis of Rean et al. [55] method); Questionnaire for diagnostics of motivation for success and fear of failures [55]; Questionnaire for determining the significance of readiness for the development and implementation of CDGs for successful professional activities [60, 61]; Questionnaire to determine the percentage distribution of computer science and mathematics teachers by levels of the ability to self-governance [56, 57, 58]; Questionnaire for determining the indicators of cognitive-activity criterion of evaluation of computer science and mathematics teachers' readiness to develop CDGs and implement them into the educational process (developed by Klochko [59] based on Raven [62] methods); Questionnaire to determine the percentage distribution of computer science and mathematics teachers by levels of the ability to self-control [56, 58]; Questionnaire for determining the Indicators of personality-reflexive criterion for evaluation of computer science and mathematics teachers' readiness for CDGs development and implementation (developed by Klochko [59] based on Rean et al. [55] methods); Fedorets-Klochko questionnaire for determining the value interpretation of space by computer science and mathematics teachers.

The *"Questionnaire for determining the computer science and mathematics teachers' value orientations as for the development and implementation of CDGs in educational process"* contained the following questions (developed by Gurevych et al. [63] on the basis of Rean et al. [55] method):

1. Achieving professional success.
2. Developing personal strengths and abilities.
3. Acquiring professional and information competencies.
4. Providing material comfort.
5. Achieving recognition and respect in professional sphere.
6. Improvement of social status.
7. Striving to new achievements.
8. Self development and self improvement.
9. Recognition and respect of managers.
10. Achieving students' respect.
11. Developing students' interest to computer sciences.
12. Possibilities to show one's potential.
13. Possibility to improve pedagogical skills.

14. Possibilities to introduce new methods and forms of activities.

Respondents answered the questions of the questionnaire in accordance with two areas – development of CDGs and introduction of CDGs into the educational process.

The *"Questionnaire for determining the indicators of cognitive-activity criterion of evaluation of computer science and mathematics teachers' readiness to develop CDGs and implement them into the educational process"* contained the following questions (developed by Gurevych et al. [63] based on Raven [62] methods):

I. According to the development of CDGs:
   1. I am aware.
   2. I have knowledge.
   3. I have skills.
   4. Able to develop.
   5. Realize didactic peculiarities.
   6. Realize basic functional possibilities.
   7. Realize basic requirements to development.
   8. I know how to select topics.
   9. I can develop design.
   10. I know peculiarities of psychological influence on age groups of children.
   11. I know how to classify games.
   12. I know the basic classes of software.

II. According to the implementation CDGs into the educational process:
   1. I am aware.
   2. I have knowledge.
   3. I have skills.
   4. Able to use.
   5. Realize psychological peculiarities.
   6. Realize basic functional possibilities.
   7. Realize basic requirements to implementation.
   8. I know how to select games aimed at attaining lesson's goal.
   9. I know how to select games aimed at realization of person-centered approach.
   10. Implement with the aim to ensure cross curriculum connections.
   11. I know how to classify games.
   12. I know which software to use in this sphere.

The *"Questionnaire for determining the Indicators of personality-reflexive criterion for evaluation of computer science and mathematics teachers' readiness for CDGs development and implementation"* contained the following questions (developed by Klochko [59] based on Rean et al. [55] methods [63]):

I. According to the development of CDGs:
   1. I am a qualified developer.
   2. I strictly determine a purpose of the development.
   3. I work much to improve competencies.
   4. I want to achieve high results.
   5. I know my weaknesses and strive to improve them.
   6. I constantly search for new methods, forms and ways for realization.
   7. I know what to work with and what to learn in the nearest future.

II. According to the implementation CDGs into the educational process:
   1. I am a qualified user.
   2. I strictly determine a purpose of implementation.
   3. I work much to improve competencies.
   4. I want to achieve high results.
   5. I know my weaknesses and strive to improve them.

6. I constantly search for new methods, forms and ways for realization.
7. I know how to use and look for necessary means.

The methodology is aimed at actualizing and revealing the spatial aspect of computer science and mathematics teachers' readiness for the development and use of computer didactic games. In this work, to reveal the phenomenology of CDGs, we turn to their understanding and application not only in the mental-semiotic and cognitive-operational planes, but as a spatial or, more precisely, "cognitive-spatial" phenomenon. The specified methodological insights correspond to the ideology of the "visual turn" and "spatial turn" in the methodology of science. A significant aspect of considering the indicated methodological trends, as significant, is that we can purposefully represent virtual reality, first of all, as a special informational and meaning-making space. It is important to understand the real physical space also as a special content-semantic or "cognitive-spatial" field, as a meaningful background or context actively included in the educational process. Accordingly, the use of digital technologies of virtual reality with the active participation of the teacher contributes to the "transformation" of physical space into the content-semantic or "cognitive-spatial" field of the educational process. In our opinion, the decisive factor in the specified "cognitive transformations" of virtual reality and real space is the use of game methods. In our opinion, this is due to the fact that in the semantics of the game in its semantic contexts, the spatial component is relevant but at the same time "hidden". The game, which first appears in childhood, is primarily aimed at the child's understanding of himself as a spatial phenomenon, as well as at revealing his ability to navigate in space, which, accordingly, are cognitive processes. Such a cognitive manifestation of life corresponds to the idea of autopoiesis of Maturana Romesín and Varela [64]. These authors interpret life as a cognitive autopoietic process. Accordingly, we expand and refine the specified understanding of Maturana Romesín and Varela [64] to this educational context. We can note that for a person it is also a spatial and visual process. In this work, a "Fedorets-Klochko questionnaire for determining the value interpretation of space by computer science and mathematics teachers" was developed to analyze the understanding of computer science and mathematics teachers about space as a special educational value, space as a possible tool for the intellectual development of a child, space as a background and a component of didactic games. An important methodological prerequisite for the development of this questionnaire was the idea of contextual learning, which can be interpreted as follows: a teacher who understands the surrounding environment, including space, as a way, as a condition or even as a "soft" teaching tool, will be more effective, competent and according to the nature of the child, use CDGs and other methods, in the implementation of which the spatial aspect is relevant.

The *"Fedorets-Klochko questionnaires for determining the value interpretation of space by a teacher of mathematics and computer science"* contained the following questions:

1. The purposeful use of space and spatial phenomena is an important pedagogical condition for effective disclosure of the content of educational material in mathematics and computer science.
2. The use of virtual space, augmented reality and digital technologies is a important pedagogical condition for the effective disclosure of the content of educational material in mathematics and computer science.
3. An integrative consideration of spatial phenomena and virtual space as meaning-forming and system-forming factors of the educational process is relevant for effective learning.
4. Virtual space, as well as real space, can be considered as a meaning-making matrix when implementing game-based learning methods.
5. The game-learning methods and actualization of phenomena of real space and virtual reality are presented as conceptualization tools that form a metaspace of meanings in the study of mathematics and computer science.
6. In order to improve the efficiency of professional activity, the teacher should apply the phenomena of real space and virtual reality in order to present the educational material logically in an "expanded" and illustrative format.
7. Both real and virtual space have their own metalogic, which is revealed when using game methods.

8. Game learning methods and animation reveal the meaning-making aspect of real and virtual space, which can be purposefully applied in the study of mathematics and computer science.
9. The possibility of actualizing the phenomena of real space and virtual reality is considered as an instrumental value in the professional activity of a teacher of mathematics and computer science.
10. The actualization of the phenomena of real space and virtual and augmented reality corresponds to the spatial essence of human nature.

We will present the ideas and content-semantic aspects underlying the "Fedorets-Klochko questionnaire for determining the value interpretation of space by computer science and mathematics teachers". This questionnaire is aimed not only at diagnosing the teacher's value interpretation of real and virtual space, but also at actualizing spatial issues as significant in the study of mathematics and computer science. The reflective aspect of this questionnaire is also important, which reveals to the teacher ways of understanding spatial phenomena as educational and life values (in particular, the value of harmonization).

Question № 1 – "The purposeful use of space and spatial phenomena is an important pedagogical condition for effective disclosure of the content of educational material in mathematics and computer science" – defines and actualizes the problems of real physical space represented as a "pedagogical tool" and a pedagogical condition for studying mathematics and computer science. It is clear that the real space becomes such a "pedagogical tool" by transforming into an educational semantic and meaning-forming context (space) by integrating the semiotic field of the lesson. This happens with the purposeful application of various educational methods (in particular, game ones) during the implementation of which spatial phenomena are actualized.

Question № 2 – "The use of virtual space, augmented reality and digital technologies is a important pedagogical condition for the effective disclosure of the content of educational material in mathematics and computer science" – purposefully defines and actualizes the problems of virtual space, represented as an established pedagogical environment and at the same time digital technology, which is used for learning mathematics and computer science. Virtual space by its very nature is an intellectual product and, accordingly, can be considered as an operational and educational environment and, accordingly, a field of knowledge and meanings. An important ant aspect of this virtual space is that it can largely model the real space one as it corresponds to human nature, including spatial thinking, the prerequisite for the formation of which is a developed human visual analyzer.

Question № 3 – "An integrative consideration of spatial phenomena and virtual space as meaning-forming and system-forming factors of the educational process is relevant for effective learning" – defines and actualizes the issue of the integrative application of virtual space and real space phenomena as a pedagogical condition and a "spatial" component of mathematics and computer science learning technologies. The methodological meaning of this question is the idea that the purposeful integrative application of technologies of both virtual space and phenomena of real space should give a synergistic and harmonizing educational effect. In children it is necessary to actualize mathematical thinking through visual perception and mathematical interpretations of the "world of things", "the world of geometric figures", "the world as a three-dimensional space" through the application of landscape pedagogy and through the visual disclosure of the phenomenology of the real world. As additional effects, it can be noted that this will also contribute to the preservation of physical and psychological health and aestheticization of the educational process. The specified "work" with real space in combination with the use of virtual space should form the student's understanding of virtual reality as a special tool and the world included in the real world. If the specified harmonization is not carried out, then the opposite effect is possible – the real three-dimensional space, as well as the world as a whole, will be considered by the student as a component of the virtual. This, in addition to the negative impact on the psyche, will not give the opportunity to fully reveal the student's cognitive potential. Therefore, in the educational process, according to the ancient Greek idea about the harmonious nature of man, between virtual reality and real space and the world, not competitive interactions should be formed, but synergistic, complementary and harmonious interactions.

Question № 4 – "Virtual space, as well as real space, can be considered as a meaning-making matrix

when implementing game-based learning methods" – reveals the anthropobiological dimension of the teacher's understanding of spatial phenomena. Accordingly, within the semantic framework of this question, the space is simultaneously considered: inactively as a neutral background or condition where the game is implemented, and also as an active learning tool – as a specific context filled with contents and meanings.

Question № 5 – "The game-learning methods and actualization of phenomena of real space and virtual reality are presented as conceptualization tools that form a metaspace of meanings in the study of mathematics and computer science" – presents game learning methods not only as activity-cognitive, but also as cognitive-spatial learning phenomena, which can form "quasi-spaces" (spaces of meanings) that participate in the development of informatic and mathematical meanings and concepts.

In question № 6 – "In order to increase the efficiency of professional activity, the teacher should apply the phenomena of real space and virtual reality in order to present the educational material logically in an "expanded" and illustrative format" – the physical characteristics of spatial reality (first of all, length) are reflected. Virtual reality is developed based on the transformation of the characteristics of real space. This can be represented as the "logic of space" and, accordingly, consider spatial phenomena in the format of "didactics of space", which real space determines due to its length (according to Descartes [65]). From the standpoint of pedagogical psychophysiology, we interpret the concept of an expanded representation of educational material, first of all, as a demonstration of certain features, regularities, phenomena, both spatial structures and relationships between them. For example, the process of multiplication or addition can be depicted as subject operations in the spatial and subject fields. This will be an expanded format that clearly illustrates a certain arithmetic operation through "spatial logic". In this case, we demonstrate the indicated operations in detail. As the indicated operation is understood, it is "transferred" into the symbolic space. The specified aspect of "transfer" to the middle (interiorization into mental reality) leads to the phenomenon of "collapse" whose essence is that operations that were represented through the "logic of space" and the "logic of object actions" (for example, the close location of two groups of objects in "spatial semantics" of which was interpreted as addition) are transformed into a certain generalizing symbol in which the cognitive operation itself (for example, revealed during the demonstration of the operation with the help of objects) may no longer be displayed as spatial interactions (location). The specified features of the actualization of the subject field and the understanding of space as a meaning-making context are presented in the classical concept of the step-by-step formation of mental actions by Gal'perin [66].

In question № 7 – "Both real and virtual space have their own metalogic, which is revealed when using game methods", game methods are represented as actualizing and revealing the "multidimensional" – semiotics, axiology and contextuality of space (real and virtual). These game methods essentially transform the real space into the quasi-space of the game by "filling" it with specific meanings. Real or virtual space becomes a semiotic-symbolic field in which and thanks to which the specified game is implemented, forming conceptualization skills in the child, which are transformed into components of mathematical thinking.

Question № 8 – "Game learning methods and animation reveal the meaning-making aspect of real and virtual space, which can be purposefully applied in the study of mathematics and computer science" – points out the importance of the purposeful use of real and virtual space for the representation of mathematical and informational phenomena. That is, consideration of the structure of space and the objects that fill it as environmental prerequisites for the development of mathematical thinking of rational-logical and multidimensional and systemic external and internal realities is actualized.

In question № 9 – "The possibility of actualizing the phenomena of real space and virtual reality is considered as an instrumental value in the professional activity of a teacher of mathematics and computer science" – space is revealed as a special instrumental value that can underlie the formation of meanings and goals of educational activities. In the specified question, ideas about space are presented as a valuable context of educational practices.

Question № 10 – "The actualization of the phenomena of real space and virtual and augmented reality corresponds to the spatial essence of human nature" – reflects the phenomenology of man as a spatial being. In this issue, human nature is considered multidimensionally and, accordingly, space is presented

as a prerequisite and component of human physicality and its intelligence. This cognitive understanding of space and the corporeality associated with it corresponds to the ideas of Lakoff and Johnson [67] on corporeal mind and corporeal cognitivism. This question is aimed at understanding a person in whom his integrity and physical and intellectual-spiritual essence has a significant and systemic spatial aspect, which accordingly forms an anthropic image of a person who is harmonized with the world. That is, human nature is related to nature as such. The idea of "anthropo-spatial" and "spatial-cognitive" intentionalities of a person, which must be revealed in the conditions of the educational process, is embedded in this general question.

The processing of the survey results was carried out using cluster analysis in order to identify groups of respondents and to determine ways of forming and improving the computer science and mathematics teachers' readiness to develop and use CDGs in the educational process. Cluster analysis was performed using the SimpleKMeans method and the Weka framework for data analysis and machine learning [68]. We described the SimpleKMeans algorithm in the research [69, 70]. Dunn, DB, SD, CDbw and S_Dbw algorithms were used in the process of data preprocessing in order to determine the recommended number of clusters [71, 72] (table 1). The structure with the number of clusters 4 was chosen as the best in terms of compactness and resolution.

Table 1
Optimal number of clusters, calculated with the help of quality indices.

Index	Algorithms SimpleKMeans
Dunn	4
DB	4
SD	3
CDbw	3
S_Dbw	5

The study was conducted in two stages: Stage I – 2017-2020, 183 computer science and mathematics teachers from different regions of Ukraine participated in the study [63]; Stage II – 2022, 123 computer science and mathematics teachers from different regions of Ukraine and Republic of Moldova participated in the study.

3. Results and discussion

The central theoretical result of this research is the formation of a model of the computer science and mathematics teachers' readiness to develop and use CDGs in educational process. In addition to the axiomatic and systematic approach, which includes the development of the field of problematization with the selection of the main aspects of the problem, the specified issue is solved by conducting research (presented below) (figure 3).

The development of this readiness model is based on teleological (target), anthropological and systemic approaches. Within the framework of the teleological approach, the harmonious, innovative development of the personality, which includes the formation of key and digital competencies, is considered as a prerequisite for the realization of the sustainable development goals and the innovative trend.

This model of readiness of the computer science and mathematics teachers' readiness to develop and use CDGs is based on the pedagogical value and teleological understanding of the main aspects. The specified aspects are considered as system-forming in the development of this readiness. We distinguish the following system-forming aspects – innovative, cognitive-active, personal-reflective, motivational-value, valuable, spatial, which is considered as spatial-cognitive and visual-spatial, temporal, cultural-educational, communicative aspects (figure 3). Let's consider these aspects in more detail.

Among the specified aspects, we consider cognitive-active, personal-reflective, motivational-value aspects as "internal" or anthropological, as such, which can be present in the mental reality of a professional personality. Based on the actualization and selection of the specified aspects as professionally

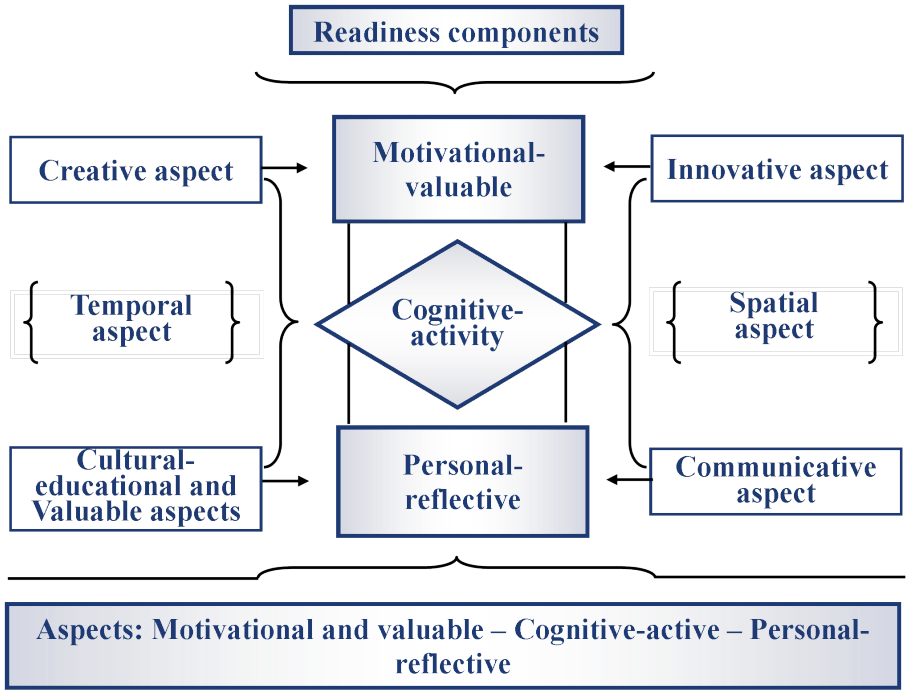

Figure 3: System-forming aspects of the model of the computer science and mathematics teachers' readiness to develop and use CDGs.

significant, a structure of readiness is developed. The specified aspects correspond to the name of readiness components and reflect the corresponding professionally significant meanings and directions. The specified "internal" aspects are formed on the basis of activity-semantic and teleological integration of individual aspects: cognitive, activity, personal, reflective, motivational, value. Such integration of the specified aspects reflects deep professionally significant features, which we present below.

The integrated cognitive-activity aspect in the readiness model is transformed into its component of the same name. It reflects the cognitive and functional specifics of the professional activity of a teacher of mathematics and informatics and the peculiarities of the intellectualized process of studying these disciplines.

The personal-reflective aspect, which in the readiness model is transformed into the component of the same name. He characterizes reflection as a defining professional ability of a computer science and mathematics teachers, which is necessary when studying the specified educational disciplines. Reflexivity in this aspect is a professional ability that determines the personal and professional potential, in particular, for the implementation of control and verification of logical operations. Therefore, reflexivity, both as a cognitive and as a personal quality, is quite developed among specialists in mathematics and computer science. For its realization, reflexivity must be deeply included in the being of a professional, in his personality. Accordingly, the specified specialists should be capable of long-term, psychologically exhausting work on finding optimal solutions, which includes purposeful activities to correct possible errors.

The motivational-value aspect, which in the readiness model is transformed into the component of the same name, reflects the humanistic and human-oriented idea of professionalization of a specialist based on meaningful and internalized (that is, transferred to the inner mental reality) values, meanings, images, intentions, etc. That is, the actualization of the specified aspect and the component of readiness corresponding to it is a way of axiologising and a manifestation of humanistic, by its essence, pedagogy, which is based on values. In this aspect, the idea of "internal motivation" is implemented in accordance with the self-determination theory [73].

In addition to those presented above, let's consider other relevant aspects, on the basis of which the

readiness of the computer science and mathematics teacher to develop and use computer didactic games is formed – innovative, valuable, spatial (considered as spatial-cognitive and visual-spatial), temporal, cultural, educational, communicative.

Due to the actualization of the innovative aspect, the technological-innovative and socio-cultural significance of CDGs for the education of the future, which is the education of sustainable development, is problematized and revealed. CDGs are an innovative technology, the implementation of which in the educational process aims to move to a qualitatively new level of education. The innovative aspect is also a determining goal (telosom) in developing the computer science and mathematics teachers' readiness to develop and use CDGs. The innovative aspect, which is primarily explicit ("external") in relation to the personality-professional during its internalization (transfer into mental reality), is considered as part of the cognitive-activity component of readiness. Possession of the educational theory and practice of the application of CDGs largely reflects the innovativeness of the teacher as a professional quality and as his focus on self-development and creativity. It is significant that innovativeness is also considered as a value reference point in the process of implementing CDGs.

The value aspect is primarily an external factor of the cultural and educational space. When internalizing the value aspect, it is considered as part of the motivational-value component of readiness, and in the system of the cognitive-activity component in the format of value-oriented knowledge. The value aspect determines the meanings and orientations that are significant in the readiness system.

The cultural and educational aspect reflects the importance of professional and cultural contexts and professionally significant potentials of the educational environment in which readiness is developed and implemented. Guided by the anthropological ideas of Hall [74, p. 10-11] about the contextuality of cultures, we believe that the cultural and educational aspect is a defining professional context. The cultural and educational environment contains values, meanings, stereotypes of interaction, communication and behavior, ideas, directions, etc. in a contextual format. The development of readiness includes cultural-educational, value-semantic contexts and significant ideas that are present in them. Currently, there are ideas of direction of innovation, child-centeredness, humanization, technologization, non-violent communication, tolerance, freedom, democracy, professionalization, etc.

The communicative aspect contributes to the consideration of CDGs during their development and implementation as a special professional and communicative phenomenon, as a way of transferring knowledge, ideas and technologies. This is due to the fact that the game includes an expressive communicative aspect and can be interpreted as a way of communication. Therefore, communicability is primarily embedded in the structure of CDGs and the system of readiness itself and in all three of its components.

The creative aspect contributes to the consideration of CDGs and their implementation in the educational process as a creative phenomenon, which at the same time also contributes to the disclosure of the creative potential of an individual. Creativity, in turn, is impossible without spontaneity, a certain creative freedom, interpretability, social activity and, thus, it is a guide to the ideas of democracy and freedom as existential and educational values. Accordingly, the development of the implementation of CDGs in the educational process is a way of revealing creativity. We consider the creative aspect of readiness as part of the cognitive-activity component.

The temporal aspect actualizes the idea that CDG is a temporal phenomenon, which is important to take into consideration during their development and implementation. In turn, CDG, due to its temporal specificity, can contribute to the development of temporal competence, provided that the temporal aspect is purposefully actualized.

The spatial aspect is significant due to the fact that CDGs have a distinct spatial dimension, which must be taken into consideration during their development and implementation. We consider the spatial aspect as spatial-cognitive and visual-spatial. The spatial-cognitive aspect is aimed at developing the teachers' ability to use spatial phenomena in the educational process for the representation and illustration of educational material. The visual-spatial aspect is aimed at forming the ability to work with spatial phenomena, which includes their comprehension and interpretation. This aspect is also aimed at the development of visual-spatial intelligence. We consider the visual-spatial aspect of internalization into the mental reality of a professional personality within the framework of the cognitive-activity

component of readiness.

Concluding the theoretical consideration of this problem, we will present the determination of the computer science and mathematics teachers' readiness to develop and use CDGs in educational process. By the computer science and mathematics teachers' readiness to develop and use CDGs, we understand the integrated cognitive-activity professional-personal ability of the teacher, which contains expressive value-motivational and reflective components and is aimed at implementation CDGs into the educational process, and is also implemented on the basis modern directions – innovative development, humanism, child-centrism, creativity, communicativeness, and taking into account spatial-temporal and cultural-educational specifics.

Table 2 presents a synthesized comparison of TPACK components across disciplines and experience levels, derived from multiple studies [75, 76, 77]. The data reveals that while both mathematics and computer science teachers demonstrate high content knowledge (CK), significant gaps exist in their technological pedagogical content knowledge (TPCK), with mean scores below 3.0 on a 5-point scale. Junior teachers show higher technological knowledge but lower pedagogical content knowledge compared to their senior counterparts, suggesting the need for differentiated professional development approaches.

Table 2
Distribution of TPACK components by teacher experience and discipline.

Component	Mathematics	Computer Science	Junior (<5 y)	Senior (>10 y)
TK (technology knowledge)	2.65	3.12	3.21	2.76
PK (pedagogical knowledge)	3.24	2.89	2.78	3.45
CK (content knowledge)	4.38	4.45	3.98	4.52
TPK	2.51	2.92	2.95	2.61
TCK	2.73	3.38	3.42	2.88
PCK	3.51	3.42	3.21	3.78
TPCK	2.48	2.81	2.89	2.54

Let's proceed to consider the results of the study aimed at determining the state of the computer science and mathematics teachers' readiness to develop and use CDGs. The study was conducted to establish the presented readiness structure.

The authors analyzed the results of the evaluation of the components that constitute the readiness of computer science and mathematics teachers to develop and use CDGs into the educational process.

To evaluate and analyze the levels of components of the computer science and mathematics teachers' readiness to develop and use CDGs into the educational process, the following criteria were used: the motivational-value criterion, the cognitive-activity criterion, the personality-reflexive criterion.

The specified criteria integratively characterize the same name corresponding readiness components.

Motivational-value component of readiness. Accordingly, the motivational-value criterion characterizes a set of values, meanings, intentions, motives. The awareness of these motives, values and meanings is also important.

Interviewing, questioning and testing were used in the evaluation of the motivational-value criterion of computer science and mathematics teachers' readiness to develop and use CDGs in the educational process [63]. During questioning, we were trying to realize to what extent the activities related to the development and implementation of CDGs are understandable, relevant, necessary and desirable (among the survey questions diagnostically significant were the following: "Do you agree that readiness for the development and implementation of CDGs is an important component of professional and information competencies of today's computer science teachers?", "Is it interesting for you to learn the way of developing and implementing CDGs in the educational process more deeply?").

We also used the "Questionnaire for determining the significance of readiness for the development and implementation of CDGs for successful professional activities" [60, 61]. Teachers' responses showed that teachers are aware of the importance of readiness for the development and implementation of CDGs for the successful professional activities (high level – 30,4 %, average – 50,1%, low – 19,5% of teachers) [63] (see figure 4).

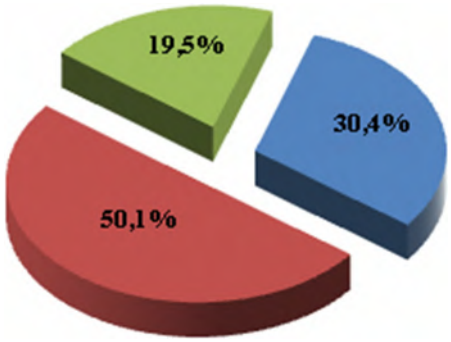

Figure 4: Significance of readiness for the development and implementation of CDGs for successful professional activities (high level – 30,4%, average – 50,1%, low – 19,5% of teachers) [63].

Value orientations, which had become a subject of study, also contribute to the achievement of professional success in teaching computer science and mathematics. For their diagnostics, the "Questionnaire for determining the computer science and mathematics teachers' value orientations as for the development and implementation of CDGs in educational process was used" (developed by Klochko [59] on the basis of Rean et al. [55] method) (table 3, figure 5).

Table 3
Hierarchy of computer science and mathematics teachers' value orientations as for the development and implementation of CDGs in educational process. (The question number column is labeled "№".)

№	Rating indicators of the development of CDGs	Rating indicators of the using of CDGs
1	4	6
2	4	5
3	4	9
4	13	13
5	10	11
6	14	14
7	9	7
8	2	4
9	12	12
10	11	10
11	2	1
12	7	7
13	8	3
14	1	1

Thus, understanding the importance of the development and implementation of CDGs into the educational process, the dominating values of teachers are the following: possibilities to introduce new methods and forms of works with students, develop students'interest to computer sciences, possibility to improve pedagogical skills in using CDGs, self-development, self-improvement as well as achieving professional success, development of personal strengths, talents, acquiring professional and information competencies in developing CDGs. The analysis of discrepancies showed that teachers give more priorities to using CDGs in the educational process ratherthan developing them. In addition, the sphere of CDGs development is of higher priority than their implementation for acquiring professional and information competencies.

Such results may mean that teachers do not fully realize the possibilities of professional growth in develop and using CDGs and do not comprehend all possibilities and ways for improving their teaching skills. It may be assumed that computer science and mathematics teachers are sufficiently oriented in the process of implementing new methods and forms of works in the classroom. They know how to

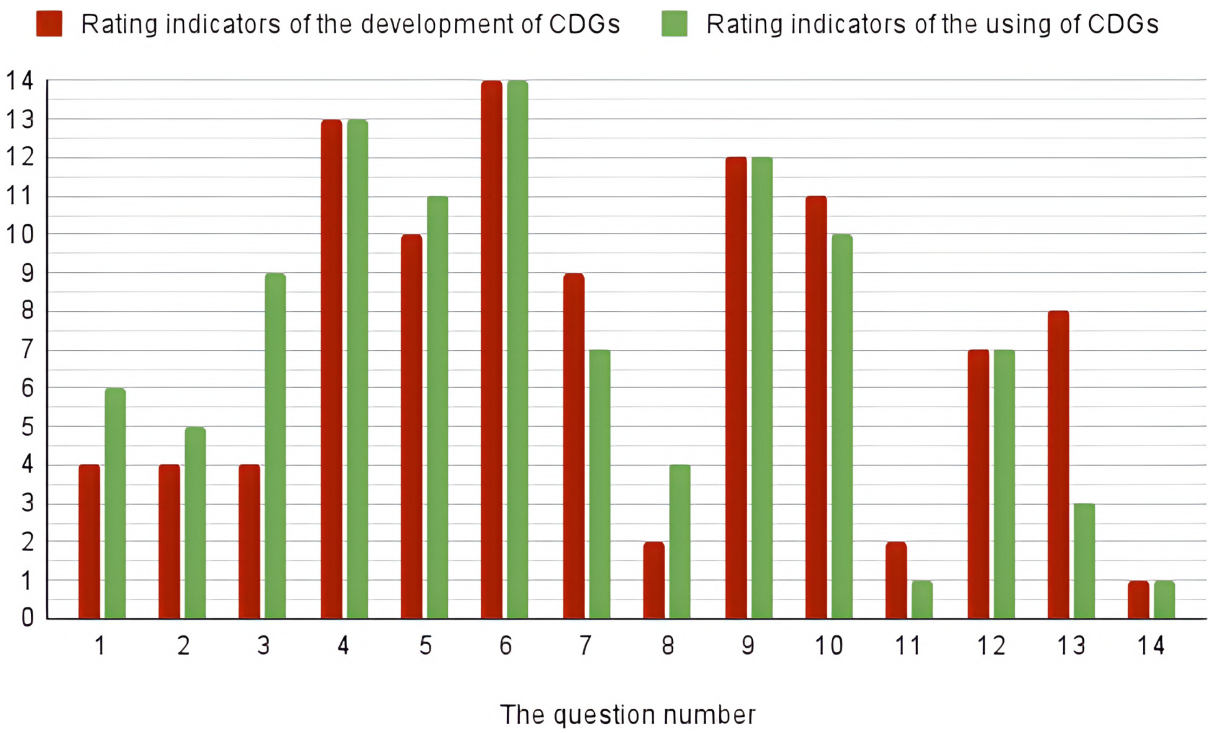

Figure 5: Hierarchy of computer science and mathematics teachers' value orientations as for the development and implementation of CDGs in educational process.

develop students' interest in computer science, to improve teaching skills and strive to self-development and self-improvement aimed at achieving professional success in the acquisition and development corresponding knowledge, abilities and skills in the sphere of CDGs. Additionally, there is a lack of care for material comfort, improvement in social status, recognition in the professional sphere, and achievement of respect. However, computer science and mathematics teachers were also observed to be more oriented towards professional realization and improvement, which dominated their requirement for recognition and respect, improve social status, ensuring material comfort.

The motivation for achievement favours an increase in persistence, self-esteem, regulation of activities, the formation of readiness for the development of CDGs and their implementation into the educational process. The results of the survey of computer science and mathematics teachers show that following the methodology "Diagnostics of motivation for success and fear of failures" [55], 59,2% of teachers have motivation on the average level (the motivational pole is not clearly defined), 21,4% of teachers have a high level of motivation (motivation for success is diagnosed), and 19,4% of teachers have a low one (the motivation of fear of failure is diagnosed) (figure 6). The motivation for achievement activates subjective efforts of computer science and mathematics teachers, directed to the desired outcome in personal and professional development.

According to the results of the study of the motivational-value component of computer science and mathematics teachers' readiness to develop and use CDGs in educational process, in particular, its motivational-value component, we can conclude that 21,4% of teachers are diagnosed with motivation for success and 30,4% of teachers are diagnosed with high level of significance of readiness for the development and implementation of CDGs for successful professional activities.

Figure 7 illustrates the progressive development of key readiness components over the past decade, derived from a synthesis of longitudinal and cross-sectional studies. The consistent upward trend across all components suggests that increased attention to game-based learning in teacher education programs is yielding positive results, though absolute scores remain in the moderate range, indicating substantial room for improvement.

Personality-reflexive component of readiness. This component was considered with the application of research methods of the ability to self-control and reflective potential of the individual. "Questionnaire

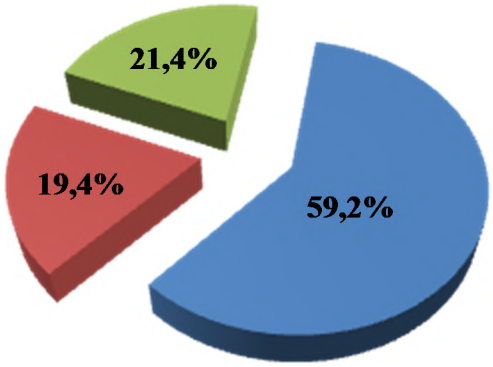

Figure 6: Results of the diagnosis of motivation for success and fear of failure (high level (motivation for success is diagnosed) – 21,4%, average – 59,2% (the motivational pole is not clearly defined), low – 19,4% of teachers (the motivation of fear of failure is diagnosed).) [63].

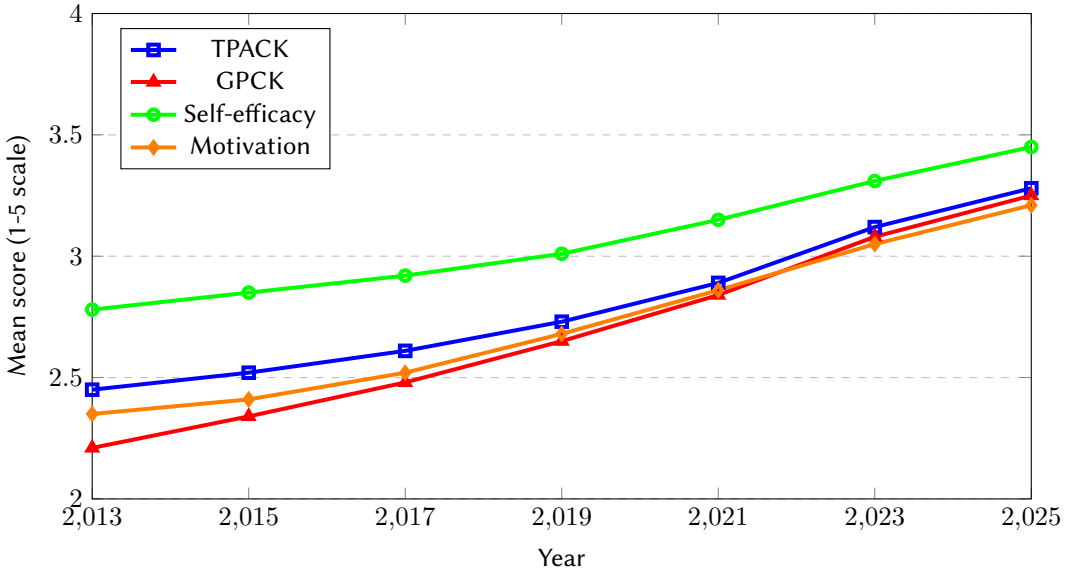

Figure 7: Longitudinal trends in teacher readiness components based on systematic review data (2013-2025). The graph synthesizes findings from multiple studies showing gradual improvement in all components, with self-efficacy consistently showing the highest scores [78, 79, 80].

to determine the percentage distribution of computer science and mathematics teachers by levels of the ability to self-control" [56, 58] and "Questionnaire for determining the indicators of personality-reflexive criterion for evaluation of computer science and mathematics teachers' readiness for CDGs development and implementation" (developed by Klochko [59] based on Rean et al. [55] methods) were used for this purpose. Accordingly, the personality-reflexive component was used, which is characterized by the determination of the teacher's personal style of activities, the awareness of the content of activities, the abilities to evaluate outcomes and consequences, the skills of self-education, self-realization in the professional activities, and life-long learning. The indicators of this criterion are: the ability for self-analysis, self-control, self-organization; the availability of the personal style of activities; understanding the scope of the activities on CDGs developing and implementing; the self-education skills.

The study enabled us to set up the following system-creative factors that determine the ability of computer science and mathematics teachers for self-control: restraint, sense of duty, will power, disciplined manner, and responsibility.

The research results, using the ability to self-control and reflective potential of the individual methods, show that the average values of self-control quality levels of computer science and mathematics teachers were distributed as follows: high level – 39,8%, average level – 51,5%, low level – 8,7% (figure 8) [63]. In

our opinion, such results may be explained by job requirements and social context.

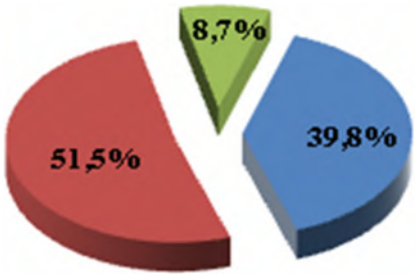

Figure 8: Percentage distribution of computer science and mathematics teachers by levels of the ability to self-control (high level – 39,8%, average – 51,5%, low – 8,7% of teachers).

Hence, as average indicators of the personality-reflexive criterion of computer science and mathematics teachers' readiness to develop and implement CDGs show that the highest rank belongs to teachers' striving for strong performance in this area, for awareness of shortcomings and sincere endeavor to improve performance (diagnosed using the "Questionnaire for determining the Indicators of personality-reflexive criterion for evaluation of computer science and mathematics teachers' readiness for CDGs development and implementation") (table 4, figure 9) [63].

Table 4
Indicators of personality-reflexive criterion for evaluation of computer science and mathematics teachers' readiness for CDGs development and implementation. (The question number column is labeled "№".)

№	In the sphere of CDGs development, ranking	In the sphere of CDGs implementation, ranking
1	7	4
2	5	2
3	6	6
4	1	1
5	2	3
6	4	5
7	3	7

Summarizing the results of the research through their integrative consideration and interpretation within the semantic framework of the personality-reflexive criterion, we note that according to the self-control indicator, most computer science and mathematics teachers are diagnosed with medium and high levels of the ability to self-control. According to the results of diagnosing the indicators of the personal-reflective criterion for assessing the computer science and mathematics teachers' readiness to develop and use CDGs, it can be concluded that teachers mostly want to achieve high results in the areas of developing and using CDGs, know their shortcomings and strive to correct them, try to work in the direction of finding new methods of techniques, forms, ways of implementing CDGs, but to a lesser extent they work on improving acquired competencies in this area.

Cognitive-activity component of readiness. Formation of computer science and mathematics teachers' readiness for the development and implementation of CDGs into the educational process has to be based on practically oriented knowledge and intellectual skills. The indicators of the cognitive-activity criterion, which reflects the content and the technology of development and implementation of CDGs, as well as individual and psychological peculiarities of teachers' readiness, in particular cognitive, are: the field knowledge, the abilities to use the field knowledge for professional purposes and the cognitive activities.

Research according to the cognitive-activity criterion was carried out using the "Questionnaire for determining the indicators of cognitive-activity criterion of evaluation of computer science and mathematics teachers' readiness to develop CDGs and implement them into the educational process"

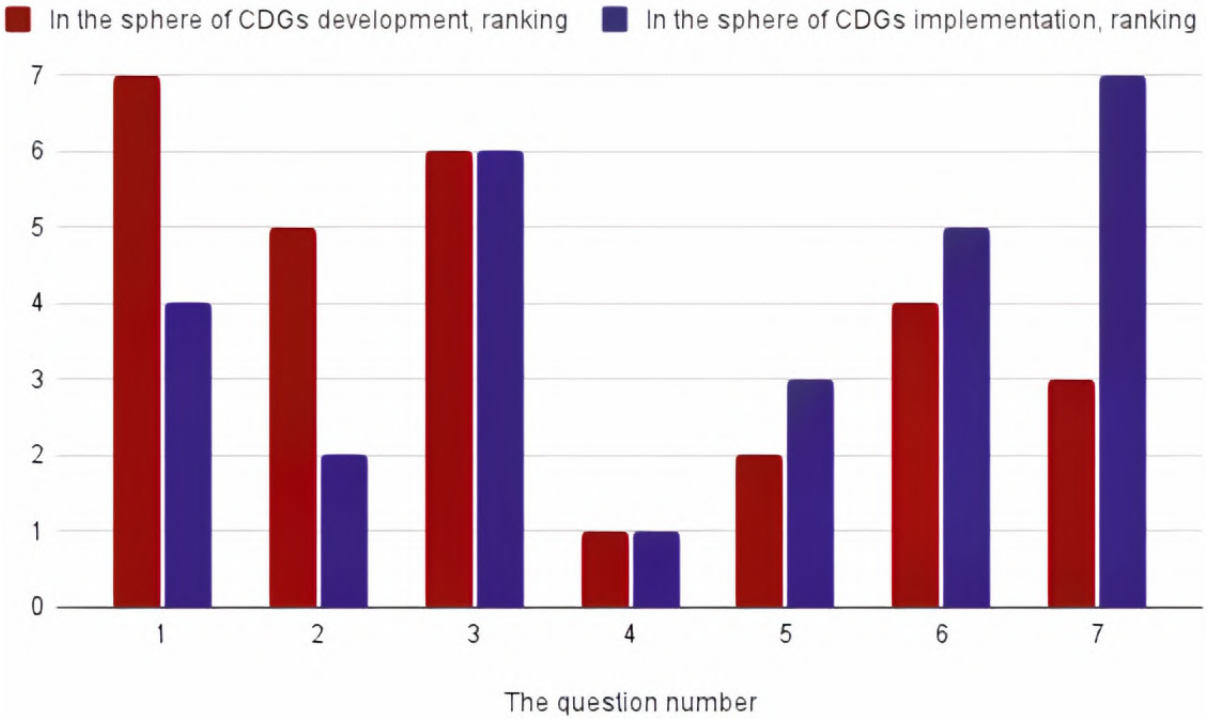

Figure 9: Indicators of personality-reflexive criterion for evaluation of computer science and mathematics teachers' readiness for CDGs development and implementation.

(developed by Klochko [59] based on Raven [62] methods), "Questionnaire to determine the percentage distribution of computer science and mathematics teachers by levels of the ability to self-governance" [56, 57, 58], "Fedorets-Klochko questionnaire for determining the value interpretation of space by computer science and mathematics teachers", as well by the analysis of results of computer science and mathematics teachers' knowledge in CDGs development and implementation theory (the method of monitoring quiz (oral and written) were used). This criterion also reflects the importance of metacognitive strategies, which include the formed abilities for goal setting, self-evaluation, self-management, planning, control, and intellectual reflection. It is significant that the mentioned intellectual qualities should be essentially activity and, accordingly, aimed at the professional sphere of the teacher and, above all, at the development and use of CDGs. Within the framework of this criterion, spatiality is defined as an actual direction of the teacher's intellectual development. The spatial aspect is presented as spatio-cognitive and visual-spatial. Accordingly, within the semantic framework of spatiality, the problematic of the teacher's availability of valuable knowledge, understanding, intellectual intentions and reflections of both real and virtual spaces is actualized [1]. The cognitive-activity criterion for the evaluation of computer science and mathematics teachers' readiness for development and implementation of CDGs characterizes the level of theoretical knowledge, ability to use and create activities that are of significant importance in the professional practice of computer science and mathematics teachers.

The estimation of professional achievements, however, does not fully reflect the level of computer science and mathematics teachers' knowledge in this sphere, as it is a pretty formal indicator of their readiness for the development and implementation of CDGs. The average results of the quiz show that computer science and mathematics teachers' knowledge in theory of CDGs development and implementation is as follows: high – 4,2% and 24,8%; average – 11,2% and 46,5%; low – 84,6% and 28,7% (figure 10, figure 11) [63].

Identifying the indicators of the cognitive-activity criterion, we proceeded from the importance of metacognitive strategies. Accordingly, with formed meta-cognitive strategies the computer science and mathematics teachers understand the process of development and implementation of CDGs as a focused and result-based management of the professional activities and life-long learning that simulates abilities to predict outcomes, plan, control, evaluate, monitor and manage this process, overcome difficulties

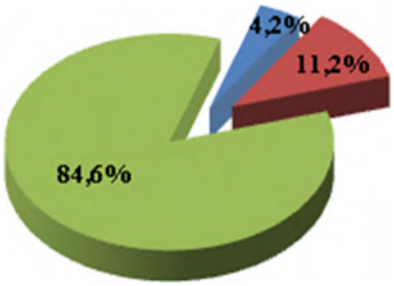

Figure 10: Average results of computer science and mathematics teachers' knowledge in CDGs developing theory (high level – 4,2%, average – 11,2%, low – 86,4% of teachers) [63].

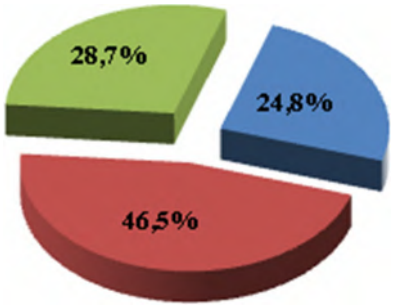

Figure 11: Average results of computer science and mathematics teachers' knowledge in CDGs implementation theory (high level – 24,8%, average – 46,5%, low – 28,7% of teachers) [63].

at the time of achieving tactical and operational purposes as well as strategic goals. We assumed that computer science teachers understand the process of development and implementation of CDGs as a focused and result-based management of the professional activities and life-long learning that simulates abilities to predict outcomes, plan, control, evaluate, monitor and manage this process, overcome difficulties at the time of achieving tactical and operational purposes as well as strategic goals.

So, the results of the tests using the "Questionnaire to determine the percentage distribution of computer science and mathematics teachers by levels of the ability to self-governance" reveal that the computer science and mathematics teachers' ability to self-governance, mainly, is on the average level. The percentage distribution by ability levels is as follows: 35,7% – high, 53,0% – average, 11,3% – low level (figure 12) [63]. These data show that computer science and mathematics teachers according to the self-governance indicator, which to a large extent integratively reflects the formation of metacognitive strategies, are ready to develop and use CDGs in educational process.

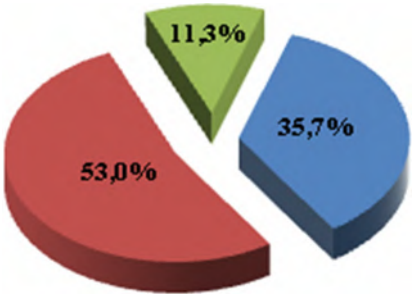

Figure 12: Percentage distribution of computer science and mathematics teachers by levels of the ability to self-governance (high level – 35,7%, average – 53,0%, low – 11,3% of teachers) [63].

The study shows that the formation of the readiness of computer science and mathematics teachers to develop and implement CDGs into the educational process is impossible without the corresponding knowledge and intellectual skills in these spheres, such as: knowledge of CDGs' tools of development and implementation (classification, functional possibilities, didactic peculiarities, development requirements),

skills in selection of topics, design development, knowledge of psychological peculiarities of students' age groups, etc. (table 5, figure 13) [63]. The efficient management of this process demands knowledge of problem analysis, a clear vision of the situation, and the ability to forecast and plan future actions.

Table 5
Indicators of cognitive-activity criterion of evaluation of computer science and mathematics teachers' readiness to develop and implement CDGs into the educational process. (The question number column is labeled "№").

№	In the sphere of CDGs development, ranking	In the sphere of CDGs implementation, ranking
1	1	1
2	7	3
3	8	4
4	10	5
5	8	12
6	6	10
7	11	8
8	2	2
9	12	11
10	4	8
11	3	5
12	5	7

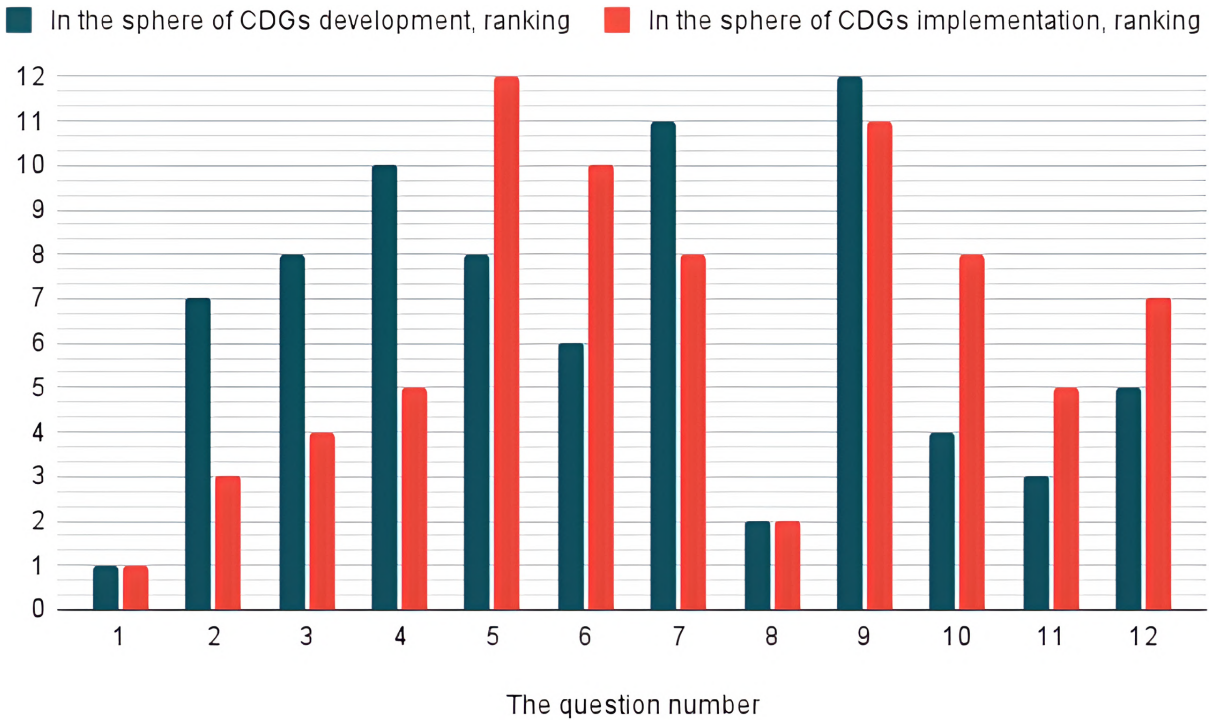

Figure 13: Indicators of cognitive-activity criterion of evaluation of computer science and mathematics teachers' readiness to develop and implement CDGs into the educational process.

Summarizing the results of the research through their integrative consideration and interpretation within the semantic framework of the cognitive-activity criterion, we note that according to the investigated indicators of the cognitive-activity criterion, the majority of respondents are diagnosed with an average and high level of formation indicators of cognitive-activity and self-governance. The average level of theoretical knowledge of computer science and mathematics teachers on the development and use of CDGs in the educational process was also diagnosed, respectively 11,2% and

46,5%, and the high level of theoretical knowledge of computer science and mathematics teachers on the use of CDGs, respectively 4,2% and 24,8%. It should be emphasized that 86,4% of respondents are diagnosed with a low level of theoretical knowledge on the development of CDGs. This may be due to the fact that in the process of training and retraining, professional development of informatics and mathematics teachers, less attention is given to the topic of developing computer games for use in the educational process. The study shows that computer science and mathematics teachers fully understand the process of development and implementation of CDGs, know how to choose games aimed at achieving lesson objectives. They have knowledge, skills and are able to use CDGs in the educational process but have little experience in their development. In their professional activities, computer science and mathematics teachers also face difficulties in understanding the psychological peculiarities of using CDGs by students. Teachers also have to deal with the issue of the definition of the main functionalities of CDGs, since their selection directly influences the realization of the student-centered approach.

During the II stage of the research, which took place in 2022, the value interpretations of space by a mathematics and computer science teacher were studied. This study is considered in the content-semantic framework of the formation of the cognitive-activity component of readiness that was studied. The spatial direction of the research is determined by the fact that the specificity of the development of the cognitive-activity component of readiness is the actualization of the spatial aspect. The spatial aspect is presented in two formats: visual-spatial, which helps to reveal visual-spatial intelligence, and spatial-cognitive, which is aimed at the teacher's use of spatial phenomena (both real and virtual spaces) for purposeful representation and illustration of relevant topics in mathematics and computer science.

Let's consider the results of the questionnaire using the "Fedorets-Klochko questionnaire for determining the value interpretation of space by computer science and mathematics teachers" using the methodological and interpretive potential of cluster analysis. In the process of applying the SimpleKMeans algorithm to the clustering model, built on the basis of a set of data obtained during the questionnaire survey, 4 clusters (number 0, 1, 2, 3) were formed, the centroids of which are shown in the table 6 (figure 14).

Table 6
Model and evaluation of clustering data using the SimpleKMeans algorithm. (The question number column is labeled "№".)

№	**Cluster № 0, 53%**	**Cluster № 1, 23%**	**Cluster № 2, 13%**	**Cluster № 3, 13%**
1	2	1	1	3
2	3	1	1	3
3	2	2	0	3
4	2	1	0	3
5	2	1	0	3
6	2	0	1	3
7	2	1	2	3
8	2	2	2	3
9	2	1	0	3
10	1	0	3	3

Cluster № 0 is the largest in terms of volume and, accordingly, formed 53% of the responses. The specified cluster unites answers that define space (real and virtual) as a "pedagogical-technological" value that is significant in the process of teaching mathematics and computer science when using didactic computer games (figure 15). This cluster defines the positive interpretation of space in quantitative representation as the middle between negative and highest. Accordingly, a positive understanding of space as an "pedagogical-instrumental" value can be purposefully applied in the educational process. Cluster 0 dominates in the specified sample is half. This dominance indicates that the studied teachers, who make up half of the sample, have a generally positive attitude towards this problem. At the same time, the indicated "middle position" in the sample indicates a not maximum readiness to actualize the spatial component when using didactic computer games. The not-total "fascination" with visual-spatial issues also indicates the critical thinking and personal and intellectual maturity of teachers, because the

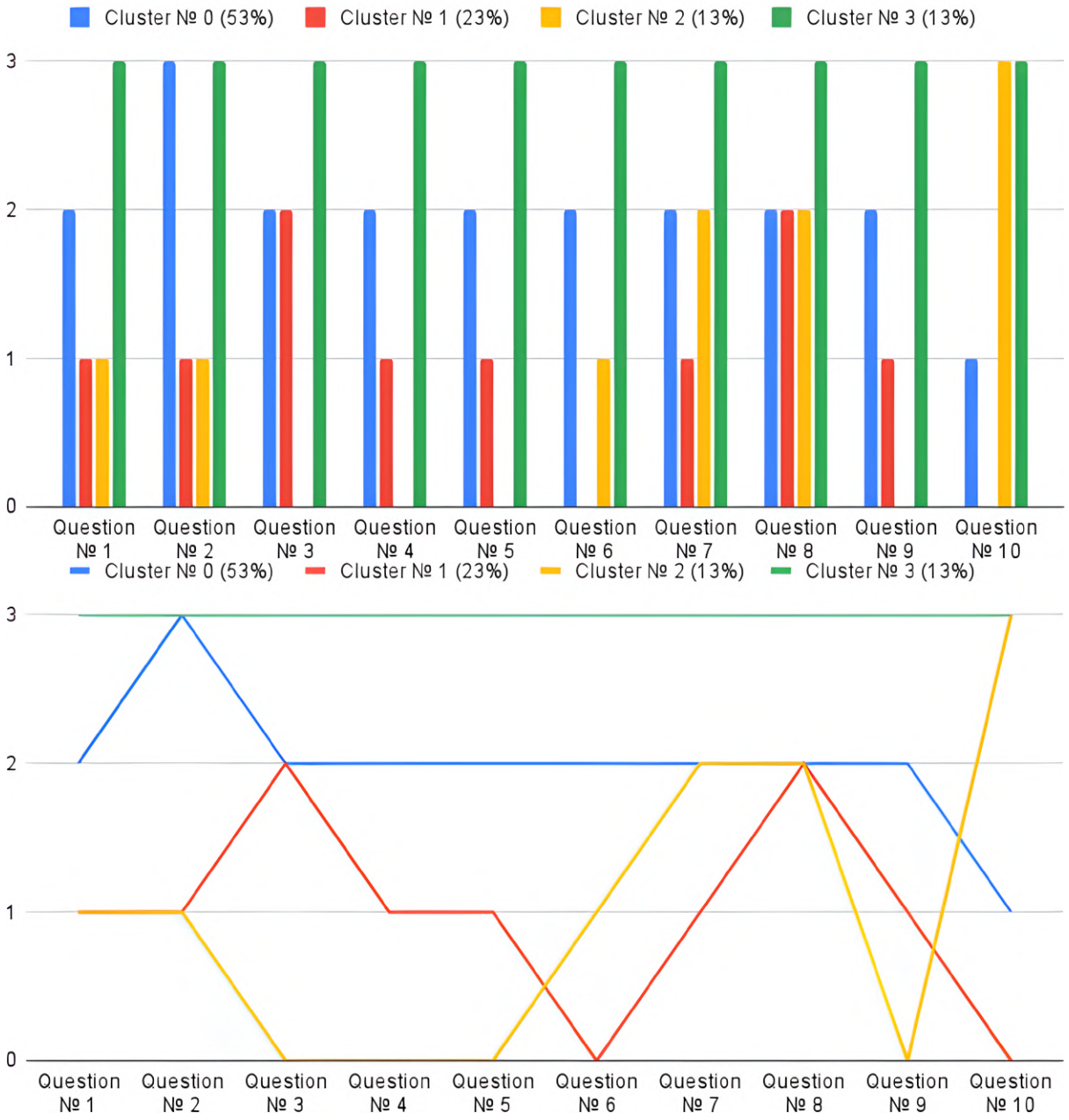

Figure 14: The centroid values of the clusters according to the question number of the "Fedorets-Klochko questionnaire for determining the value interpretation of space by computer science and mathematics teachers" are presented in a bar and linear charts.

representation of space as an instrumental value is relatively new and for many teachers it was revealed through their questionnaires. As mentioned above, the purpose of the survey was not only diagnosis, but also actualization of the phenomenology of space as value-oriented and technologically oriented. The trends of Europeanization, democratization and humanization of Ukrainian education defined in the Concept of the New Ukrainian School [81] play a certain role in such a dominant, but at the same time, "moderate" or "medium" distribution. The specified educational trends contribute to the professional development of the teacher. Accordingly, the teacher develops as a competent, critical-thinking and independent person who finds and forms "his" teaching methodology and methods.

Clusters № 1 (23%) and Clusters № 2 (13%) (total 36%) include answers that represent space (real and virtual) as a "pedagogical-technological" value that is considered significant, neutral or negative in the context of teaching mathematics and computer science when using didactic computers computer games. Accordingly, the answers can be presented as a continuum from negative to positive – 0, 1, 2

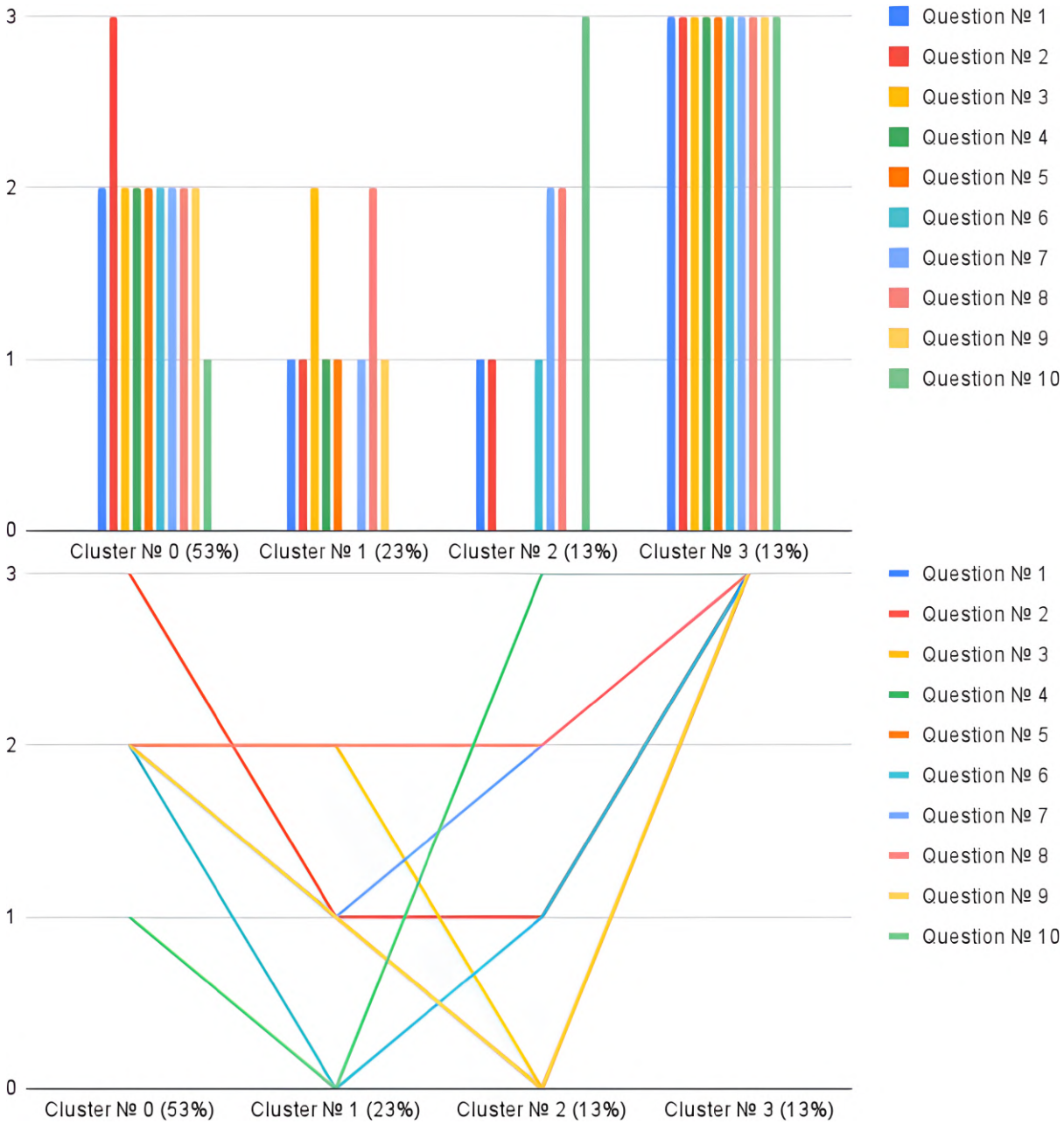

Figure 15: The centroid values of the clusters according to the cluster number of the "Fedorets-Klochko questionnaire for determining the value interpretation of space by computer science and mathematics teachers" are presented in a bar and linear chart.

and 3 (one answer). The presence of cluster № 1 and cluster № 2 (total 36%), which are quite significant in terms of volume, which makes up more than a third, speaks of a certain novelty and possible certain incomprehensibility of the actualized issues, which are represented in general terms, and not as a specific technology. It is clear that at this stage the specified "visual-spatial approach" is first of all revealed at the level of methodology in the form of general ideas and interpretations.

Cluster № 3, which is represented by 13% of respondents' answers, represents the highest level of teachers' interpretation of space (real and virtual) as a technological value that is significant in the process of teaching mathematics and computer science when using didactic computer games. We explain the relatively small percentage of people who, at the highest level, interpret space (real and virtual) in a value-oriented way, considering it as a probable component of the implementation of computer didactic games, by the relative novelty of such a spatial approach, the complexity and non-traditionality

of its implementation (figure 15). In this aspect, it can be noted that the emergence of virtual space as a digital technology, as a specific "anthropo-techno-cultural" phenomenon and the actualization of game-based learning methods provides an opportunity to better understand the educational significance of the cognitive-valuable potential of real space. In general, we observe a "shift" in pedagogy towards the active use of environmental, contextual, "background" approaches to learning. Accordingly, the environment, including space and time, is understood not only as a background for the educational process, but also as a special meaningful and value-semantic aspect of learning or, even, a "visual-spatial educational tool".

Having analyzed the structure of the distribution of answers by clusters, it can be noted that it reflects the indicated trends of the emergence and active development of contextual approaches (including visual-spatial) in education and the active use of digital technologies.

Summarizing and interpreting the results of the research of the spatial aspect in the system of the cognitive-activity component of the studied readiness, we can note that they reveal the relevance and significance of this "visual-spatial-cognitive" direction of the development of the specified readiness, first of all from a practical and pedagogical point of view. It is important that many teachers understand the phenomenology of real and virtual space as a significant pedagogical tool that corresponds to the current modern ideas of spatial pedagogy, existential pedagogy, child-centeredness, and contextual learning.

We can say that we are witnessing the beginning of an active integrative application of digital, spatial, game, axiological methods and technologies, which corresponds to the paradigmatic attitudes of postmodernism, including the officially defined direction of sustainable development, which pays special attention to the "terrestrial space" and the person in it.

4. Conclusions

The readiness of computer science and mathematics teachers to develop and use CDGs in the educational process is a complex integrative personality-professional formation, consisting of motivational-value, cognitive-activity and personality-reflexive components, which specified in their corresponding criteria.

By the computer science and mathematics teachers' readiness to develop and use CDGs, we understand the integrated cognitive-activity professionalpersonal ability of the teacher, which contains expressive value-motivational and reflective components and is aimed at implementing CDGs into the educational process, and is also implemented on the basis of modern directions – innovative development, humanism, child-centrism, creativity, communicativeness, and taking into account spatial-temporal and cultural-educational specifics.

Determining the state of formation of the motivational-value component of readiness, we can indicate that according to the indicator of motivation for success in professional activity, 59,2% of teachers have an average level of motivation (the motivational pole is not clearly defined), 21,4% of teachers have a high level of motivation (success motivation is diagnosed), and 19,4% of teachers have a low level (diagnosed lack of success motivation). According to the indicator of the value of readiness for the development and implementation of CDGs for successful professional activity, the following levels were determined: 30,4% – high, 50,1% – medium, 19,5% – low. There is a certain correlation between the above indicators, which indicates both the formation of the motivational and value sphere and its professional orientation, as well as its focus on the application of CDGs. The following value orientations in the field of development and use of CDGs in the educational process were also determined to be significant for teachers: "Possibilities of introducing new methods and forms of working with students", which indicates developed innovativeness; "Development of students' interest in studying informatics", which indicates the child-centered orientation of teachers. Thus, analyzing and interpreting the values of the above indicators, we can note that according to the motivational-value criterion, an average level of formation of the motivational-value component of readiness is observed in most teachers.

According to the cognitive-activity component of readiness according to the indicator of the ability to self-governance, which reflects the formation of metacognitive abilities, which includes goal setting, self-

esteem, self-management, planning, control, intellectual reflection, the obtained percentage distribution of its formation is 35,7% – high, 53,0% – medium, 11,3% – low in terms of levels. The presence of the prevailing high and medium levels indicates a sufficiently high initial level of formation of metacognitive abilities, which are included both in the composition of the studied readiness and in the professional and pedagogical competences of a computer science and mathematics teacher. The average level of theoretical knowledge of informatics and mathematics teachers regarding the development and use of CDGs in the educational process was diagnosed: average – 11,2% and 46,5%; high – 4,2% and 24,8%; low – 86,4% and 28,7%. Having analyzed the relevant training programs, we believe that the reason for such a state of the level of theoretical knowledge is insufficient training in the indicated direction, both during university studies and during advanced training in the conditions of postgraduate education. The state of formation of the cognitive-activity component of the readiness of computer science and mathematics teachers for the development and implementation of CDGs according to the spatial indicator, according to the results of the cluster analysis, professional interest was determined in 53% of teachers, in 13% – a formed positive attitude is present, in 36% – insignificant interest or negative attitude. We explain the small percentage of respondents who, at the highest level, interpret space (real and virtual) in a value-oriented way, considering it as a probable spatial-cognitive component of the implementation of CDGs, by the relative novelty of such a spatial approach, the complexity and unconventionality of its implementation. During the integrative examination of indicators of the formation of the motivational-value component in the semantic framework of its (motivational-value) criterion, its average level of formation is determined.

The state of formation of the personal-reflective component of computer science and mathematics teachers' readiness to develop and use CDGs according to the indicator of the ability to self-control is characterized by the following percentage distribution – high level – 39.8%, medium level – 51,5%, low level – 8,7%. Predominance of medium and high levels of self-control formation as a quality significant for the teacher's professional activity, including the implementation of developed professional mathematical and informational competencies. According to the personal-reflexive indicator, the vast majority of teachers are diagnosed with the desire to achieve high results, knowledge of their shortcomings and the desire to correct them, which indicates purposefulness, the presence of professionally directed reflection and innovative orientation. During the integrative examination of indicators of the formation of the personal-reflexive component in the semantic framework of its (personal-reflexive) criterion, the average level of its formation is determined.

Summarizing the results of the research based on consideration of motivational-value, cognitive-active and personal-reflective criteria, we can say about the diagnosis of the average level of computer science and mathematics teachers' readiness to develop and use CDGs. Based on this, we define the following main strategies for its improvement: supplementing educational programs with topics that represent the ways and practices of applying CDGs in the preparation of future computer science and mathematics teachers, their retraining and advanced training; application of competency-based, activity-based approaches in order to develop teachers' professional orientation to the application of CDGs; to activate the use of innovative pedagogical technologies for the formation of computer science and mathematics teachers' readiness to develop and use CDGs; to carry out an analysis of the application of CDGs in other countries and the reception of positive pedagogical experience in this direction.

Declaration on Generative AI

The authors have not employed any generative AI tools.

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Aligning STEM education with labour market demands through knowledge graphs and neural networks

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Abstract

The educational system in modern society is required to provide a fast reaction to real-life challenges. Also, the growing role of IT skills in labour market requires to provide changes in educational systems related to enhancing the role of IT. This study aims to provide the development of a system that considers real-life requirements of labour market and defines competencies it requires (including IT skills) and provides the possibility to take them into account during the development of the educational programs. In the paper, the system that provides a correspondence between the demand on competencies provided by employers and delivering that request to Methodists that developing educational programs is described. The main actors in the proposed systems are Employers, Job Seekers, and Ministry specialists (Methodists). The proposed concept may be implemented using simple basic tools such as MS Excel and as well by specialized tools such as CIT Polyhedron and Python. A graph-based system using CIT Polyhedron has been developed. In this case, each entity is represented in form of nodes. Proper links have been provided between entities (nodes). Characteristics and descriptions of each specific entity were added in form of semantic and numeric nodes' metadata. An example of CIT Polyhedron's specific tools (rank) usage is described. The integration of graph neural networks and knowledge graphs demonstrates potential for dynamic curriculum adaptation, with recent implementations achieving up to 94% accuracy in aligning educational outcomes with workforce requirements. This approach addresses the projected 22% growth in STEM occupations while tackling persistent underrepresentation challenges in STEM fields.

Keywords

ontologies, IT Polyhedron, labour market, STEM, education, New Ukrainian School, graph neural networks, knowledge graphs, educational management systems, workforce alignment

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1. Introduction

The problem of building digital-based sociality is relevant today. However, development tendencies are very high, and education is one of the fields that may not provide the required digital-based changes [1, 2]. Moreover, especially digitalization has come sharply during COVID-19, leading to some problems related to its implementation [3, 4, 5, 6].

Recent labor market analysis reveals that STEM occupations are projected to grow by approximately 22% by 2026, significantly outpacing other sectors [7, 8]. This dramatic growth, coupled with persistent workforce shortages and underrepresentation of women and minorities in STEM fields (women comprise only 25% of STEM professionals despite representing 50% of the college-bound population), underscores the urgent need for educational management systems that can dynamically respond to evolving industry requirements [9, 10].

Sure, there were many attempts to provide digital approaches. For example, it is using of cognitive IT platform Polyhedron [11, 12, 13] with its functions auditing [14, 15, 16] and ranking [17], virtual educational experiments [18, 19, 20, 21], using mobile Internet devices [22, 23, 24, 25, 26, 27] and augmented reality [28, 29, 30, 31, 32, 33, 34, 35, 36, 37], distance learning in vocational education and

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training institutions [38, 39, 40, 41], on-line courses [42, 43, 44, 45, 46]. Also, there are many approaches to providing STEM [47, 48, 49, 50, 51, 52, 53].

However, its usage cannot be widely provided if it is not declared in the educational programs. Now, the New Ukrainian School is used to provide modification to the educational process [54, 55, 56]. It contains a list of the competencies that should be taught during education.

Currently, job seekers' search uses web-based services that require not standardized experience, skills and competencies. For example, such services are work.ua, rabota.ua, djinni.co (specialised in IT), etc. Moreover, it seems that the labour market required more digital-based skills than it declared in the New Ukrainian School and educational programs in Ukraine. Also, it seems more relevant to use the results of employers' requests on vacancies competencies to include them in educational programs and forecasting requests in future.

Graph-based methodologies have emerged as powerful frameworks for modeling complex educational and labor market relationships. Knowledge graphs using labeled property graphs (LPGs) can structure entities such as courses, skills, and job positions, enabling sophisticated integration of heterogeneous data sources [57, 58]. Recent implementations of graph neural networks (GNNs) in educational contexts have achieved remarkable performance, with models such as Graph Attention Networks (GATs) reaching accuracy levels of 94-97% in student performance prediction and curriculum alignment tasks [59, 60, 61].

Considering what was noted before, it seems relevant to develop approaches that takes to account job requirements for specialists during projecting of educational courses. Therefore, the study aims to describe an information system that provides data transfer on real-life required competencies from employers who demand job seekers' competencies to specialists in the Ministry of education and science to take them into account. Therefore, the object of the study is an approach that provides taking to account real-life required competencies during providing educational programs.

2. Methods

To provide study and develop solving approaches, the concepts developed by the Ministry of Education and Science of Ukraine were used to define the problem and provide background research. Also, considering growing the role of digital skills (competencies) in digital sociality, the proposed approach focuses on digital competencies but is not limited by them.

The UML schemes were used to describe the informational system that may solve the problem of improving considering required real-life competencies during the development of educational programs. A use case diagram is developed to describe the main actors of the proposed system. Next, a class diagram is developed to describe the database, the main classes in it, and data for each class. Finally, the ways of implementation and some of its features are described.

The cognitive IT Polyhedron was used to create graphs as it was described before [62]. Both graphical and excel-based approaches were used to form graphs. The excel-based approach to constructing a graph is shown in figire 1.

To enhance the analytical capabilities of our system, we incorporate recent advances in graph neural network architectures. Multi-view hypergraph neural networks (MVHGNN) and k-dimensional Weisfeiler-Leman directed GNNs (k-WediGNN) have demonstrated superior performance in capturing complex, high-order relationships in educational data [59, 63]. These architectures enable:

- Modeling of multi-behavioral student interactions with accuracy improvements of 1.73% over baseline models
- Integration of temporal dynamics through hypergraph structures
- Prerequisite relationship prediction with enhanced expressive power

	A	B	C	D	E	F	G	H
4	**STEM-based program**		Ministry Employee					
5	**Educational program of subject D**		Ministry Employee					
6	**Integreted program A**		Ministry Employee					
7	**Educational program of subject C**		Ministry Employee					
8	**Educational program of subject B**		Ministry Employee					
9	**Educational program of subject A**		Ministry Employee					
10	**Methodist 1**		Vacancy 4	Vacancy 3	Vacancy 2	Vacancy 1		
11	**Methodist 2**		Vacancy 4	Vacancy 3	Vacancy 2	Vacancy 1		
12	**Methodist 3**		Vacancy 1	Vacancy 2	Vacancy 3	Vacancy 4		
13	**Job seeker 4**		Vacancy 4					
14	**Vacancy 4**		Employer 2					
15	**Job seeker 3**		Vacancy 3	Vacancy 2	Vacancy 1	Vacancy 4	Sertificate C	Sertificate F
16	**Vacancy 3**		Employer 2					
17	**Job seekers**		Job seeker 1	Job seeker 2	Job seeker 3	Job seeker 4		
18	**Set of vacancies**		Vacancy 1	Vacancy 2	Vacancy 3	Vacancy 4		
19	**Job seeker 2**		Vacancy 2	Sertificate B	Sertificate E			
20	**Vacancy 2**		Employer 2					
21	**Job seeker 1**		Vacancy 1	Vacancy 2	Sertificate A	Sertificate D		
22	**Vacancy 1**		Employer 1					

Figure 1: Excel-based approach to graph forming.

3. Results

3.1. Analysis of nonconformity of competency provided by education and requirements by employers

As noted before, there is the problem of nonconformity of competencies given by teaching and required by employers. It means that some educational time is wasted. The competencies taught during the modern educational process of Ukraine in middle school are declared by the New Ukrainian School concept and its implementation in specific educational programs. However, employers require competencies, and those declared by New Ukrainian School were not compared.

Employers are seeking a person who can solve specific tasks he needs. For example, such skills are knowledge of using MS Office, English level B2, Adobe Photoshop, or using the textile machine. Also, the employer may require some measurable experience in some field (5 years working on environmental projects, three years of C++ coding). These competencies are very static, specific and easy to determine. Such requirements (competencies) may be named as “specific” and can be divided into “static skill-based” and “static experience-based”.

However, the competencies declared by New Ukrainian School have different essential nature, and it is instead “abstract”, “wide”, and “relatively static”. Using the term “abstract”, we mean competencies that include more specific (in our classification – “static”) competencies. In this group, we propose to include mathematical competence, essential competencies in natural sciences and technologies, and information and digital competence. For the term “wide”, we mean that it is not provided specific knowledge or skill but rather some dynamic abstract level. Also, the “wide” means that competencies are used in each decision-making. The analysis of competencies declared by the New Ukrainian School is shown in table 1.

As seen from table 1, the competencies declared by New Ukrainian School may not be used by the employer (table 2).

All noted before makes the gap between skills provided by education and used in real-life work. However, it seems that it may be solved by standardisation, defining of values of each competency and using simple well-known ranking mechanisms. Sure, the proposed method is not dedicated to violating market-based society, but it allows for prioritising the competencies that have not been taken to account before. Also, the idea of standardisation can be used to define a median salary for jobs that require specific skills. Then, students can use that to decide on skills required by digitalised sociality.

Table 1
The analysis of competencies declared by New Ukrainian School.

Competency type title	Description of competency type	List of competencies
Abstract	Impossible to measure, are very abstract and includes some more specific competencies	Mathematical competence; Basic competencies in natural sciences and technologies; Information and digital competence
Wide	Impossible to measure, is used during solving any of practical based-problems	Ability to learn throughout life; Initiative and entrepreneurship; Awareness and self-expression in the field of culture; Social and civic competence; Environmental literacy and healthy living
Relatively static	Possible to measure, but still relatively hard. However, accepted international levels may be used to measure	Communication in the state (and native in case of difference) languages; Communication in foreign languages

Table 2
Comparison of educational frameworks with workplace requirements (based on [64, 65]).

Competency category	Educational coverage (%)	Industry demand (%)	Gap (%)
Technical/digital skills	35	68	-33
Problem-solving	45	72	-27
Teamwork/collaboration	30	85	-55
Communication skills	50	78	-28
Adaptability	25	65	-40
Project management	10	45	-35

3.2. Proposed approach

3.2.1. Using ranking tools to evaluate the digital competencies of the job seekers

To solve the problem, it seems relevant to use measurable competencies (such as "static skill-based" and "static experience-based") that may be processed. Their processing may be used to obtain a general integrated score of the corresponding person to the vacancy.

Also, it seems relevant to use the importance of competency for vacancies description. As for digital specialisations, such skills will provide a core score for Job seekers' evaluation, but for other specialisations in digitalisation of sociality, it may provide up to 50% of the ranking score.

Such a ranking approach will provide a win-win situation during the job-seeking process. Employers will decrease the role and load on the company's HRs. Job seekers will be evaluated objectively and receive reasonable estimates based on the general skills of job seekers, including digital. It will not provide a waiver of HRs, but it significantly decrees their work amount and provides a more accurate, fair candidates selection. As a standard to create a relevant system of ranks inputted by the user, the document "job responsibilities" may be used.

So, the employers will use a well-known raking tool that the modified equation of graph-based ranking can describe:

$$RANK_{abs(i)} = \sum \left(IMP_i \times \frac{v_i}{v_{max}} \right) \tag{1}$$

where $RANK_{abs(i)}$ – ranking rank in absolute value for i's node; IMP_i – importance coefficient for data of i's object; v_i – the value of i's object; v_{max} – maximum value of the dataset.

For this, the class name of each data will be the name of the competency (skill); its numeric data (v_i) will correspond to the mastery level of that skill; the importance (IMP_i) is a level of such competency requested by the employer. So, each job seeker will obtain his personal $RANK$ of corresponded for a specific vacancy. Such an approach will be also useful for job seekers due they will obtain the matrix of the $RANK$s for the vacancies they choose and define by themself work that they are fitted and comfortable to do.

As it was noted before, in the digitalized sociality, the role of digital competencies will be always high. To prove it, the example the IT profession (junior front-end programmer) and non-IT professions (enterprise economist) vacancies $RANK$s is shown in table 3 and table 4, respectively. For the examples, approximations of ranks and levels will be used to simplify understanding. The competency level will be used in form of relative values (%).

Table 3
Example of $RANK$ing the junior front-end programmer.

Class name (competency name)	Mastery level of the skill (v_n) (numeric data), %	Importance (IMP_n) requested by the employer	$RANK_n$ of the skill	General $RANK$ score
Job seeker 1				
CSS coding	50	5	250	
HTML codding	30	4	120	
MS office skills	50	2	100	100
Business analysis	10	1	10	
Geography skills	10	0	0	
Job seeker 2				
CSS coding	20	5	100	
HTML codding	70	4	280	
MS office skills	10	2	20	83
Business analysis	0	1	0	
Geography skills	50	0	0	

Table 4
Example of $RANK$ing the enterprise economist vacancy.

Class name (competency name)	Mastery level of the skill (v_n) (numeric data), %	Importance (IMP_n) requested by the employer	$RANK_n$ of the skill	General $RANK$ score
Job seeker 1				
Bookkeeping	80	5	400	
Bookkeeping Law understanding level	40	5	200	
MS office using level	60	3	180	100
Analysis and reporting	60	4	240	
General skills of PC using	20	4	80	
Job seeker 2				
Bookkeeping	90	5	450	
Bookkeeping Law understanding level	60	5	300	
MS office using level	10	3	30	85
Analysis and reporting	30	4	120	
General skills of PC using	10	4	40	

As shown from table 3, Jobseeker 1 with $RANK$ of 480 is more suited for vacancy than Jobseeker 2 with $RANK$ of 400. Also, digital skills are valuable for non-IT specialists as it is shown in table 4.

As it is shown in table 4, Jobseeker 2 has higher hard Bookkeeping skills, but low IT skills and generally it will be less suitable for the vacancy than Jobseeker 1. That proves that the proposed approach will be helpful to IT specialists and non-IT specialists in the digitalised world. However, it requires providing a certification program to define the competency level (numeric data).

3.2.2. Using of competency importance data to develop educational programs

The developed approach will collect the employer's requests on competencies they need. So, it will be possible to use such data sets to generate real-life required skills and competencies.

The most valuable is a set of Importance (IMP_i) requested by the employer for each skill data to analyse the labour market requirements in competencies and modify the educational process. So, it

may be represented as further:

$$< CN_{edu}, IMPC_{edu} >= RANK(< CN_n, IMP_n >) \quad (2)$$

where $< CN_{edu}, IMPC_{edu} >$ – cortege of skills and its values recommended for education; $RANK(< CN_n, IMP_n >)$ – ranking results of each element of cortege of skills and their importance for the employer $(< CN_n, IMP_n >)$.

The general workflow is using such a system provides obtaining of data set (cortege) of required by Employer competencies and its importance. Such data is processed by the system and it provides both, the results of corresponding of Job Seeker to the vacancy and obtaining a set of importance competencies values used for the development of education programs (figures 2 and 3).

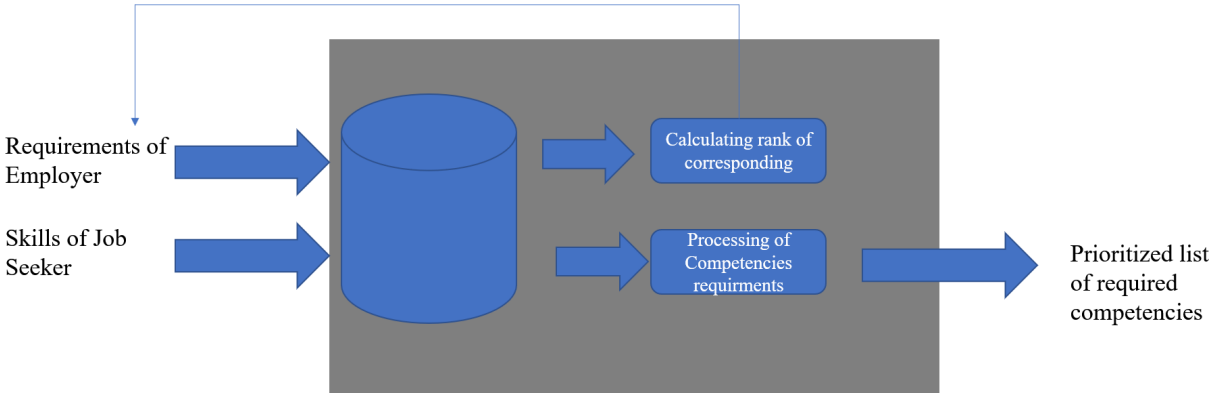


Figure 2: Workflow of data in proposed system.

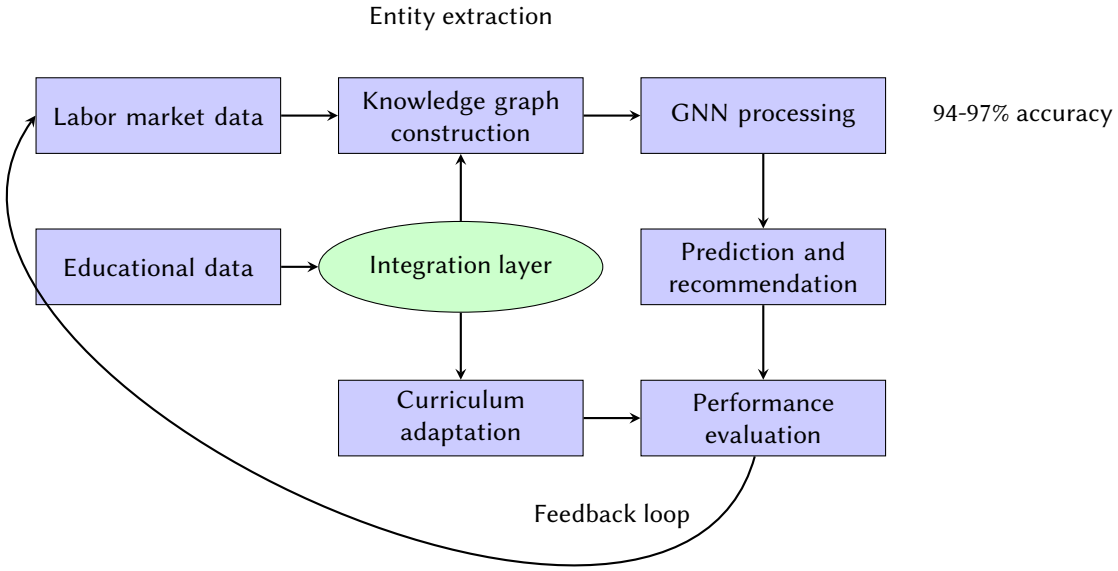


Figure 3: Enhanced graph-based educational management system architecture.

3.3. Practical developments

To simplify, the approach will be described in short form. The main actors of the proposed system are an employer that generates demand on competencies and a methodist that uses that demand on competencies to lay down it into educational programs. Also, there is an actor called Jobseeker. That actor is already an educated person who is already characterised by some stack of competencies.

Each actor has many functions, but only the most important actions will be described. The employer creates the vacancies and adds required competencies with the importance of the job. The required vacancy competencies and their importance are used to rank the corresponding specific job seeker with its stack of competencies with a vacancy. Ministry specialists use such ranking results to analyse them and lay down the most required competencies in educational programs. The use case diagram of the proposed approach is shown in figure 4.

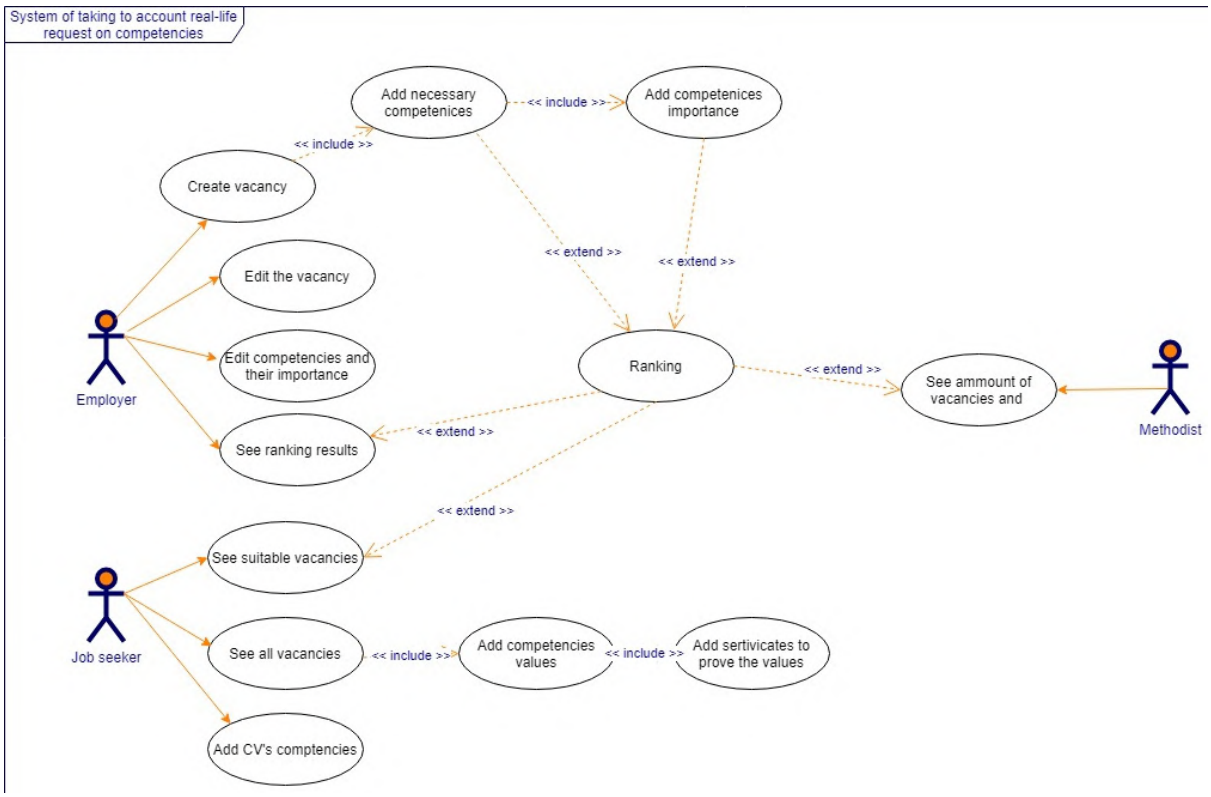


Figure 4: Use case diagram of proposed approach.

The classes that correspond to actors and actions are used to create such a system. First of all, some classes describe actors themselves, and they are Jobseeker, Employer and Ministry Employee. Each of such classes has person identifiers due they describe actors. Each Job seeker has its personalised set of competencies called the "Job seeker's set of the competencies". Each Job seeker's set of competencies consists of competencies (skills), competency's (skill's) level and certificates that prove it.

Each Employer is looking for a Job seeker, and finding it creates a vacancy. Each employer can create multiple numbers of Vacancies, and it creates a library of them called Set of Vacancies. Each vacancy has data about competencies and their importance to provide Vacancy's activities well. Job seeker's set of competencies provides a ranking that defines corresponding of its to Vacancy's RequiedCompetency and CompetencyImportance.

Set of Vacancies with its data CompetenciesAndImportance is used by Ministry employees (Methodists) to modify the educational program with an array of StudiedCompetenices. The list of database entities in the form of a class diagram is shown in table 5 and figure 5.

The proposed Use case diagram and Class diagram will be useful to developing real-life systems.

3.4. Implementation

3.4.1. Possible approaches

The proposed concept may be implemented using simple basic tools such as MS Excel and by specialised tools such as KIT Polyhedron [66, 67] and by using Python.

Table 5
Description of the classes of UML class diagram of proposed system.

Name of class	Attributes of class
Job seeker	+ ID: int + name: string +Job seeker's set of the competencies: array(Competency (skill), Competency's (skill's) level) AddNewCompetency(string): text AddCompetency's(skill's)Level: int AddCertificate:link display(set of the competencies): list(set of the competencies)
Competency's (skill's) level	+ ID: int + value: int
Competency (skill)	+ ID: int + name: string
Certificate	+ ID: int + name: int +file: link +authority:name
Job seeker's set of the competencies	+sertificates: list(certificates) + SetOfCompetencyLevel: array Competency (skill); Competencies(skills)level
	Display(Competency(skill)): list(Competency(skill)) Display(Competency's(skill's) level): Competency's (skill's) level
Ranking	++ ID: int + rank: int
Employer	+ get(Job seeker's set of the competencies):array (Job seeker's set of the competencies) + get (RequiedCompetenices): array(RequiedCompetenices): + get (CompetenicesImprotance) array (CompetenicesImprotance) + Id: int + name: text
	+create(Vacancy):array(Vacancy) +display(Job seeker's set of the competencies)
Vacancy	+ Id: int + name: text + Desription: text + RequiedCompetenices:array + CompetenicesImprotance:array
Set of the vacanieses	+Vacancynames(Vacancyname): array +CompetenciesAndImportance (VacancyRequiedCompetenices);VacancyCompetenicesImprotance:array
Ministry employee	+ Id: int + name: text + displayRequiedCompetenices:array + displayCompetenicesImprotance:array + modify
Educational program	+ users: list(User) + TextOfProgram: text + StudiedCompetenices:array

Also, the proposed approach seems relevant to use in a stack with modern semantic graph-based technologies [68, 69] and neural networks to provide analysis and predictions.

Recent implementations demonstrate that hybrid frameworks combining GNNs with reinforcement learning and natural language processing achieve superior performance. For instance, the integration of Large Language Models (LLMs) for entity extraction with GNN-based recommendation systems has

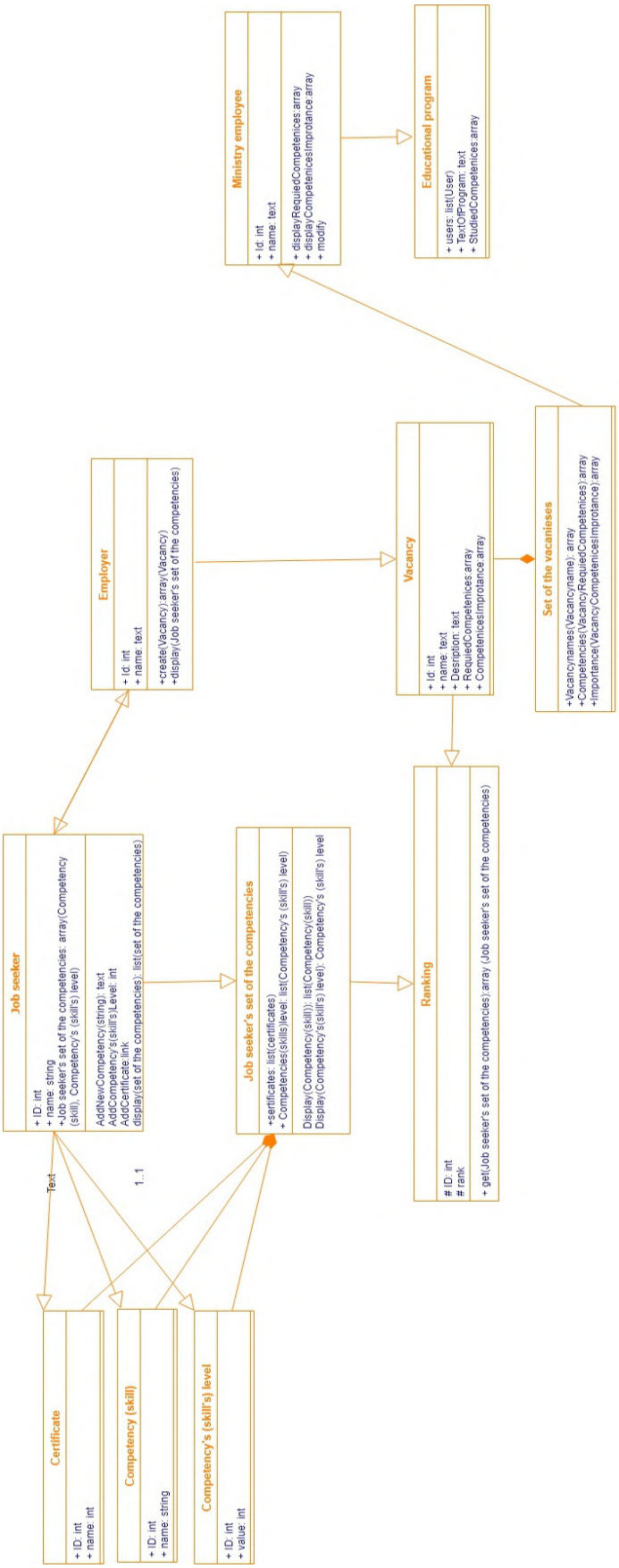


Figure 5: UML Class diagram of the proposed system.

shown accuracy improvements of 15-20% over traditional approaches [63, 70]. Advanced architectures like the Dual Graph Ensemble Knowledge Tracing (DGEKT) model have achieved state-of-the-art performance in predicting student learning trajectories and aligning them with workforce requirements [71].

Sure, while using simplified tools such as MS Excel or Google Sheets, it will not be an informational and communicational system, and it will not be possible to communicate with it using API. However, it will be possible to provide all required functions. For the Excel-based approach, libraries of skills "CompetencyName" will be located in a separate sheet and used as a drop-down list.

Also another vital question to be solved is data collection. Using google forms to create vacancy profiles and cortege on importance and competencies is the simplest way. Such google form can collect Vacancy's "name", "Description", "RequiedCompetenices", and "CompetenicesImprotance". Another form may be used to collect data on a Job seeker's set of competencies.

Sure, it is the most common and straightforward way. The system will be created using full-stack (back end and front end) development in real life. However, MS Excel-, Graph- and Phyton-based tools will be developed to make concept proof tests in further studies.

In any form of its implementation, the proposed approach will be helpful and provide an effective way to consider real-life required competencies. Comparing approaches to create a system that takes to account job requirements for specialists during projecting of educational courses educational programs with real-life labour market demand is shown in table 6.

Table 6
Comparing approaches to create a system that takes to account job requirements for specialists during projecting of educational courses educational programs with real-life labour market demand.

Name of approach	Requiring to write specific code	Possibility to provide noted database structure in full-scale	Integrated ability to provide raking without writing specific code
Excel-based	No	No	No
Graph-based	No	Yes	Yes
Python-based	Yes	Yes	No

As seen from table 6, the Excel-based approach is simple to provide, but it does not provide possibly to provide noted database structure in full-scale. On the other side, a python-based approach is a full-scale approach that gives the possibility to provide any system, but it requires a vast number of resources. Thus, the most perspective to use is a no-code cognitive IT Polyhedron to provide such a system. Also, the advantage of Polyhedron has integrated audit and ranking tools.

3.4.2. Graph-based approach

One of the advantages of the graph-based approach is a visualisation of entities (in the form of nodes) and their links. Thus, it is possible to implement a UML diagram to represent the database in the form of a graph in full-scale. Also, taking into account the specificity of graphs built using cognitive IT Polyhedron (however, it will be relevant for most graph-based approaches), some classes will be represented not in the form of nodes but in the form of semantic or semantic numeric data of some entities. For example, competency (skill) and its level will be represented in the form of metadata of nodes vacancies or job seekers (depending on the variant of realisation). For this case, competency (skill) will be the class name of the node, and its value will be the value of such a class. Such an approach provides the possibility to provide a ranking. However, competencies (skills) also will be represented in the form of nodes (separate entities) to provide additional structurisation.

The first data structural component is a set of competencies. Each specific competency has been directed on the "Set of competencies" link to represent its dependence on this class. A general view of the structural component "set of competencies" is shown in figure 6. Each competency is linked with the Job seeker whom it owns, a certificate that it proves and a vacancy that is required.

The built graph also represents Job seekers and Vacancies branches. All specific Job seekers are linked to the "Job seekers" node (figure 7a). Each vacancy is linked with the "Set of vacancies" node to

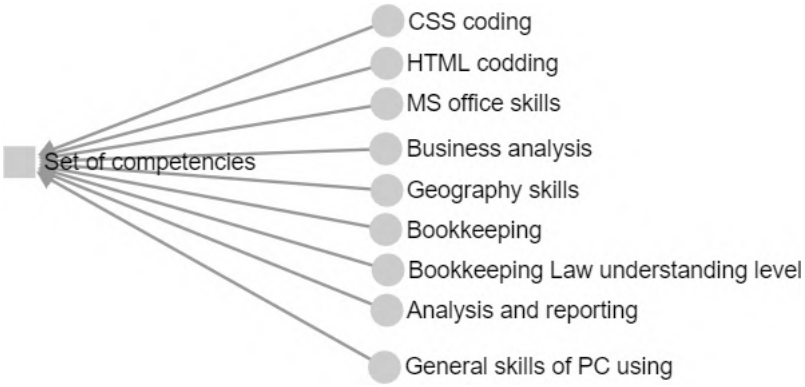


Figure 6: Element "Set of competencies" of proposed graph-based system.

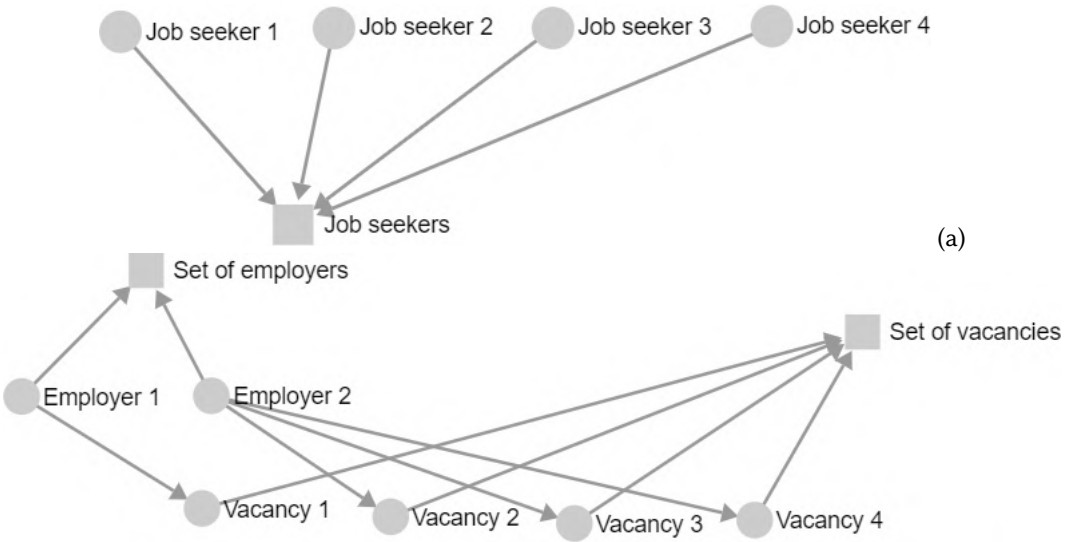


Figure 7: Element "Set of vacancies" (a) and "Set of employers" of the proposed graph-based system.

show its belonging and a specific employer who provided such vacancy. All employers are linked with the Set of employers node (figure 7b).

The primary users of demand analysis shown at graph's node "Education management institution". Vacancies are linked with members of education management institutions. Education management institution is the root node linked with ministry employee that in turn linked with Methodists who develop educational programs. Ministry employees form all educational programs. That is why they are linked. Each multiplicity of educational programs is linked to the "Educational programs" node. Educational programs additionally may be represented as a form of nodes of this graph that represents elements of specific programs themselves or have a link to the specific ontology-based educational program (figure 8).

The proposed system is integral is maybe used for decision making. All entities in the form of graph's nodes are linked as noted before:

- Job seekers with vacancies and with competencies and certificates that it proves;
- competencies with certificates that prove job seekers and vacancies
- vacancies with job seekers, required competencies, employers who provide it and methodists who form educational programs;
- job seekers are linked with competencies and certificates and with vacancies they responded on;
- methodists are linked with vacancies that describe real-life demand on competencies and with ministry employees who form educational programs.

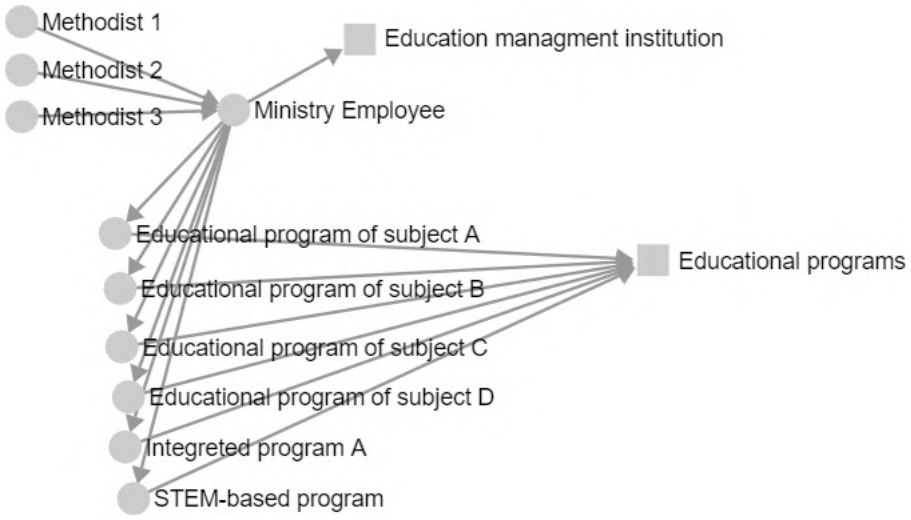


Figure 8: Elements "Educational management institutions" and "Educational programs" of the proposed graph-based system.

A general view of the proposed graph-based solution for taking to account real-life required competencies is shown in figure 9.

Both job seekers and vacancies have metadata. Job seekers' metadata are the skill level that job seekers own, and vacancies' metadata are skills and competencies that are required (figure 10a and b).

The ranking is possible to provide in both ways, to evaluate which vacancy fits the best chosen by a specific job seeker and to evaluate which job seeker fits the best for the proposed vacancy. The type of ranking depended on users' requests. The user chooses factors that he requires to rank and their importance for him. So, if he chooses the factors that correspond to competencies that require vacancy and chooses the importance of such factors for this job, the system will rank job seekers to their relevance to this vacancy; on the opposite, if the job seeker chooses competencies that require for jobs (for example, Require HTML codding), he will rank existing vacancies and find which of them fits him best (figure 11).

Methodists and Ministry employees may use a table view of the graph with or without filtering the data. A table view of the generated graph used by the Methodists and Ministry employees is shown in figure 12.

Therefore previously, the connection between education and the practical labour market was not provided systematically. And now it is proposed to use ontologies to produce such connections. In this case connection will be provided by connection relative nodes by graph's edges. The proposed approach will be much more efficient in case of its usage in complexes with forecasting systems such as regression or neurolar networks. However, it is important to collect such data to forecast and ontologies are used to provide it.

4. Discussion

Currently, the labour market requires specialists with soft skills, hard skills, critical thinking, creativity, project management and other skills. The approach that provides it is STEM/STEAM, but no trivial (as for the Ukrainian educational system) approaches that foresees not-project based and not-real-life based education. The proposed graph will be very effective to modernise both trivial educational programs (as it will highlight the skills and knowledge that are not used in employing process) and STEM-based education.

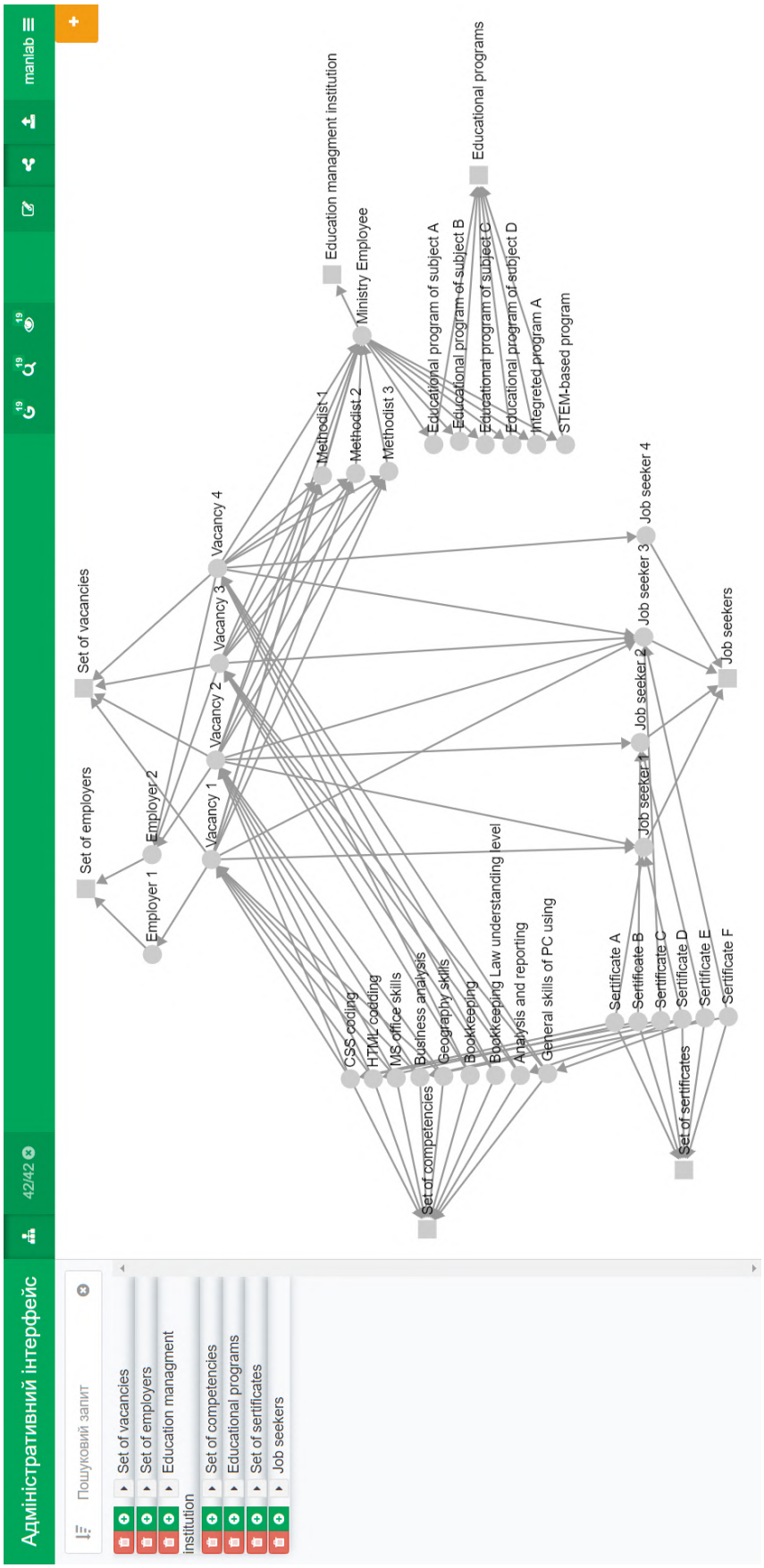


Figure 9: Developed a graph-based approach to taking to account real-life demand in the labour market.

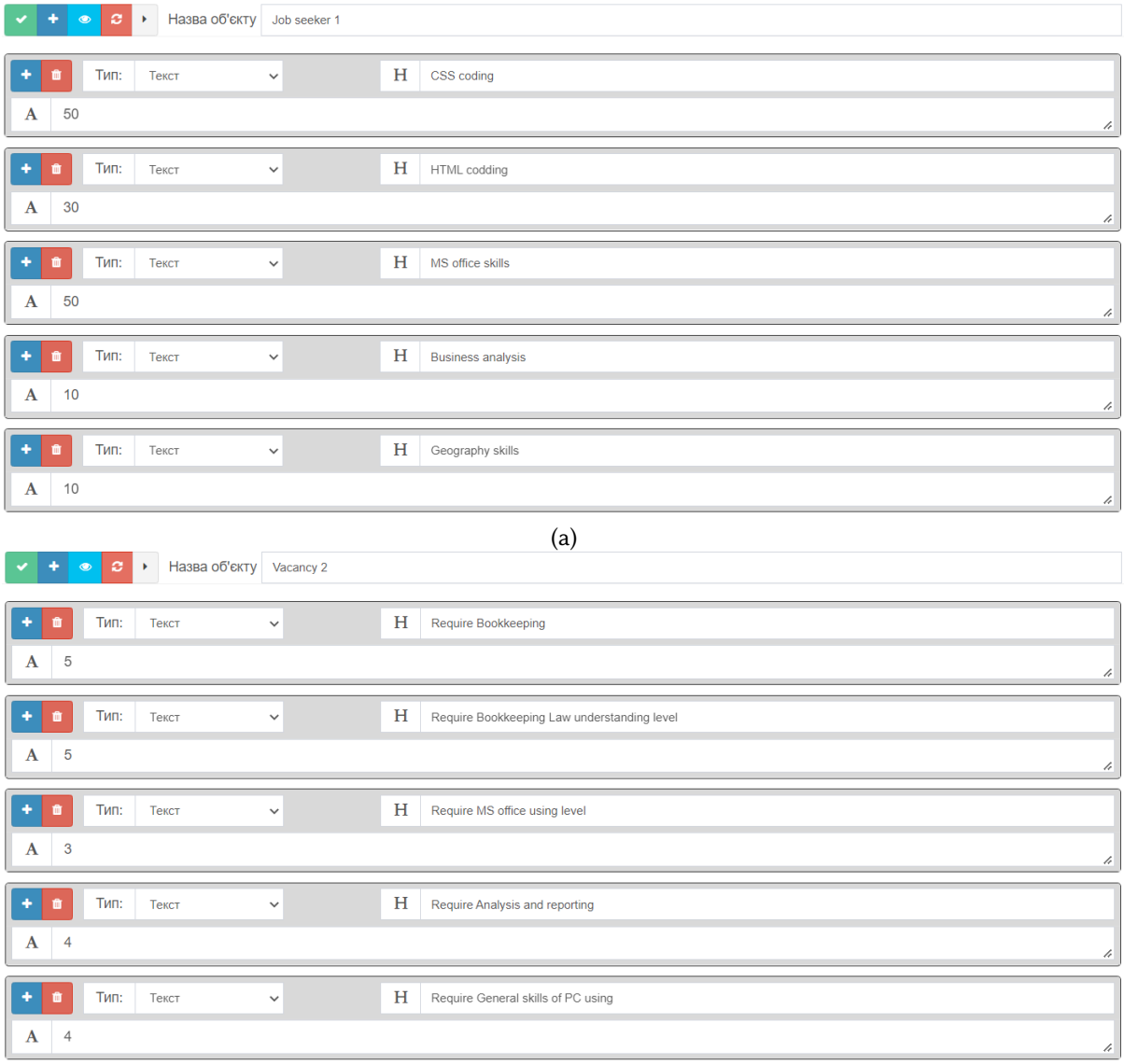


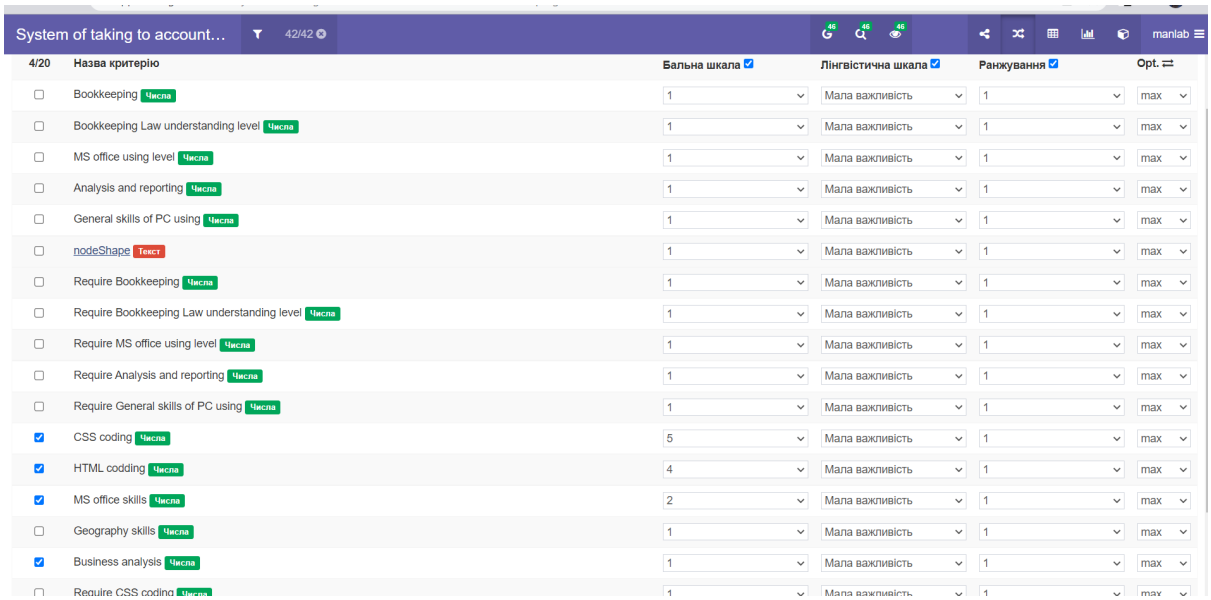
Figure 10: Metadata in graphs' elements.

4.1. Comparative analysis with global implementations

Recent global implementations of graph-based educational management systems provide valuable benchmarks. In the United States, implementations using Graph Attention Networks (GAT) for student success prediction have achieved accuracy rates of 94.8% with F1-scores of 0.979 [72]. European systems integrating knowledge graphs with labor market data have demonstrated 18% reduction in dropout rates and 25% improvement in job placement rates [73]. Asian implementations, particularly in Vietnam and Malaysia, have shown that AI-driven adaptive learning frameworks can achieve 95.4% accuracy in real-time curriculum adjustments [74, 75].

The skills and their values will prioritise the skills to teach based on market demand. As STEM is more fluent compared to traditional ones, it will be possible to use for STEM-based programs to develop the most required skills. Also, it can develop required real-life skills even during not-specialised subject learning. For example, the task was given to students during chemistry maybe project that foresees using coding, project-management or business analytical skills if such is defined as the most demanded by the labour market.

For example, the task that develops business analysis during chemistry discipline may foresee



(a)

	CSS coding	HTML codding	MS office skills	Business analysis	Geography skills	nodeShape	Bookkeeping	Bookkeeping Law understanding level	MS office using level	Analysis and reporting	General skills of PC using	Require CSS coding	Require HTML codding	Require MS office skills	Require Business analysis	Require Bookkeeping	Require Bookkeeping Law understanding level	Require MS office using level	Require Analysis and reporting
Job seeker 1	50	30	50	10	10														
Job seeker 2	20	70	10		50														
Educational programs						square													
Job seeker 4							90	60	10	30	10								
Job seeker 3							80	40	60	60	20								
Set of employers						square													
Set of vacancies						square													
Set of sertificates						square													
Education managment institution						square													
Job seekers						square													
Vacancy 1												5	4	2	1				
Set of competencies						square													
Vacancy 2																5	5	3	4

(b)

Figure 11: Metadata in graphs' elements.

analysing of current business process and technological process of production of ammonia (for example; it can be related to any production; related to the technology aspect of STEM); find the laws, fundaments and existing modern scientific studies that related to the field (related to science aspect of STEM); provide calculation of the existing production and propose technology that optimises the production (related to science aspect of STEM); find or develop equipment to provide proposed optimised technological approach (related to engineering aspect of STEM). As it can be seen, it provides both STEM-approach and development required for the current state of marked skill (for example, business analysis).

4.2. Implementation challenges and solutions

While the proposed system shows significant promise, several implementation challenges must be addressed. Policy and infrastructure barriers vary globally, with the Global North focusing on competitiveness and skills shortages while the Global South faces resource constraints and equity issues [76, 77]. Successful implementation requires:

- Investment in digital infrastructure and teacher professional development programs
- Context-specific adaptation of graph-based models to local educational systems
- Establishment of ethical guidelines for AI-driven decision-making in education
- Development of standardized competency assessment frameworks

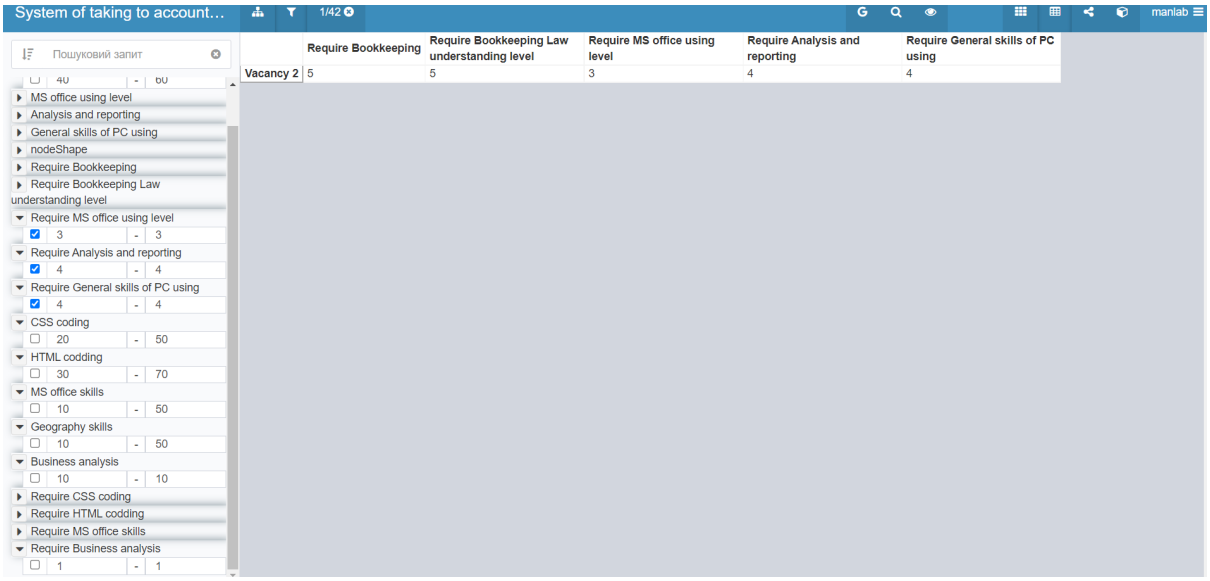


Figure 12: Table view of the generated graph to use by the Methodists and Ministry employees.

- Creation of feedback mechanisms to continuously update the system based on labor market changes

5. Conclusion

It is shown that some competencies that are required in real life are not prioritised in educational programs. The study describes an information system that provides data transfer on real-life required competencies from employers to specialists in the Ministry of education and science and Methodists consider them.

The main actors in the proposed systems are Employer, Job Seeker and Ministry specialist (Methodist). The main classes in proposed systems are Jobseeker Competency's (skill's), level Competency, (skill) Certificate, Job seeker's set of the competencies, Ranking Employer Vacancy, Set of the vacancies, Ministry employee, educational program. Each of these classes has the data that describes it.

The proposed concept may be implemented as well using simple basic tools such as MS Excel and as well by specialised tools such as KIT Polyhedron and as by using Phyton. In further studies, MS Excel-, Graph- and Phyton-based tools to make concept proof test.

It is shown that the graph-based approach is characterised by advantages, and it was chosen to build the system's prototype. It represents the graph's root nodes are a Set of competencies, Job seekers, a Set of Vacancies, a Set of employers, educational management institutions and educational programs. It is proven that the most perspective approach during which such a system can be used is STEM because a high level of flexibility characterises it.

The integration of advanced graph neural networks and knowledge graphs in educational management systems represents a transformative opportunity for STEM education. Future research should focus on:

1. Developing automated integration frameworks for heterogeneous, multi-modal data sources
2. Conducting longitudinal studies in diverse socio-economic contexts to assess scalability
3. Exploring hybrid models combining graph analytics with real-time adaptive feedback
4. Establishing international standards for competency-based educational management
5. Creating collaborative platforms for cross-border knowledge sharing and system interoperability

The successful implementation of graph-based educational management systems could significantly impact global STEM workforce development, potentially addressing the projected 22% growth in STEM

occupations while promoting diversity and inclusion. As educational institutions worldwide grapple with rapidly evolving workforce requirements, the proposed approach offers a scalable, data-driven solution for aligning educational outcomes with labor market needs.

Declaration on Generative AI

The authors have not employed any generative AI tools.

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Mathematical interpretation and digital ontologies for educational and scientific studies

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Abstract

The exponential growth of scientific data necessitates sophisticated structuring and processing methodologies. This paper presents a comprehensive framework for the mathematical interpretation of educational and scientific studies through digital ontologies, with particular emphasis on ontology graphs as a modern perspective for knowledge representation. Building on the IMRAD structure, we develop an integrated ontology that unifies diverse studies within a single framework, providing systematic structuration across all knowledge domains. Our approach employs hierarchical decomposition of IMRAD elements, creating five abstraction levels (L1-L5) ranging from general scientific branches to specific papers with detailed data. Each node contains metadata enabling advanced processing capabilities. We present a mathematical model using cortege representations for IMRAD-based scientific studies in ontological form, validated through biogas production studies. Recent advances in AI-driven frameworks, including Large Language Models (LLMs) and Graph Neural Networks (GNNs), have demonstrated 90% accuracy in educational content classification with optimized response times of 0.4 seconds. Our framework addresses critical challenges in multilingual didactic relationship extraction while leveraging semantic web technologies (RDF/OWL, SWRL) for enhanced interoperability. The integration of layered ontological structures, exemplified by OntoMathEdu, supports dynamic curriculum planning and personalized learning paths across diverse educational contexts.

Keywords

ontology, IMRAD, structuration, scientific studies, biogas, mathematical formalization, AI-driven frameworks, semantic web, knowledge graphs, personalized learning, multilingual adaptation

1. Introduction

The data nowadays is generated with colossal intensity. Due to this, Big Data processing is a trend [1, 2]. Processing a considerable amount of data in real life is complicated by the high gain of publishing scientific studies. In general, it seems like an exponentially growing of the publications. According to lens.org, in 1900, only 532 M of scientific papers were published, but their amount in 2015 was near 10 B (figure 1).

Considering the development of STEM, studies are provided not only by experienced scientists by youth. Such a considerable number of studies generated complicated tasks to process such data. One of the problems of low spreading and usage (in the example of Ukraine [3, 4, 5, 6, 7, 8, 9]) may be related to difficulties with the processing of science.

Now, scientific studies are published in different forms of report, such as articles, conference proceedings, books, etc. However, its process is complicated due to studies are low-structured. Sure, they are all built by a similar structure named IMRAD [10, 11]. It envisages requirements for the paper to consist of some generalized Introduction, describing used Materials and Methods, naming the Results of the study and the Discussion by comparing with other scientific materials or providing use cases. However, it seems not enough. Here just some examples of problems due to it:

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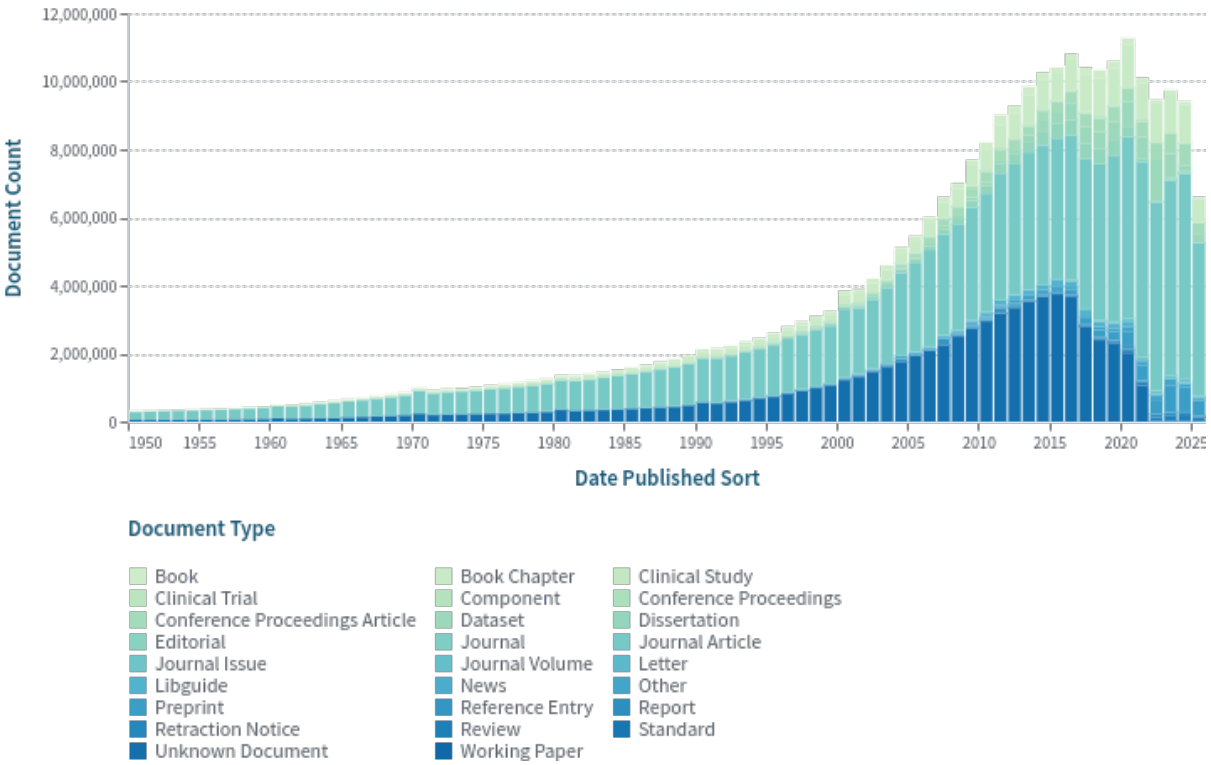

Figure 1: Dynamic of published papers according to Lens.org web service.

- it is hard to start the researcher carrier due to complicated process of understanding of the methods and equipment that need to be used in specific fields of study;
- it is hard for youth scientists to understand main parameters that have measured to provide study analysis;
- for expired scientists, it is hard to analyze and collect data of new studies.

These are only very few cases that are a problem due to high amount of data of scientific studies. However, these cases are makes relevant to develop new methods to provide better structuration and data processing of scientific studies.

Sure, there are few solutions for this problem that provides automated science data processing [12, 13, 14, 15, 16], but it seems that they do not take to account IMRAD. One of the appropriate methods to solve the problems is ontology taxonomies [17, 18, 19, 20] with semantic technologies [21]. Also, ontology taxonomies have a lot of advantages, such as the possibility to combine with other types of materials [22], including interactive and web-based courses [23, 24], other information technologies [25, 26] and GIS GIS [27]. This research aims to develop a model that can structure the set of the studies using IMRAD.

Recent research has identified that digital ontologies have emerged as foundational tools for structuring, interpreting, and personalizing knowledge in both educational and scientific domains [28, 29]. The intersection of mathematics, ontology engineering, and digital education has become increasingly critical as educational content becomes more heterogeneous, multilingual, and personalized. Studies show that AI-driven frameworks can achieve classification accuracies exceeding 90% in identifying educational materials relevant to industry needs [30, 31].

Previously, it was proposed to provide support using ontologies for single specific study, but not to create glossaries and structured sets of data. To provide it tools Open provenance, Ontologyt and EXPO [32] were developed. Another ontology solution in the field of science is MoKi that provides creation of wiki-based information scientific sources [33, 34]. There some specific ontology tools such as Gene

ontology [35] or Centralized educational environment [2]. However, creation of ontology to structure the set of the studies seems relevant due lack of approaches to provide it.

2. Methods of the research

In the paper, the ontology model has developed using the main principles of graph theory, set theory, and a theory of abstraction [36]. The graph was modelled using a simple hierarchical algorithm that foresees using only nodes and links. So, such a model further may be updated using the more comprehensive graph building tools such as weight coefficients. However, without simple modelling, providing it will not be possible. To provide structuration generally accepted structuring method IMRAD has been proposed and used.

To model data processing was developed taking to account the processing possibilities of the Polyhedron system due it has some advantages compare well known Protégé [37, 38] and OWL tools [39, 40]. Furthermore, the features of cognitive IT-platform tools Filtering, Audit, and Ranking to provide decision-making [2, 41, 42] were described in equitations to describe the data processing in the ontology model.

Building upon traditional ontology construction methods, recent advances incorporate AI-driven extraction techniques. Large Language Models (LLMs) and Graph Neural Networks (GNNs) have proven effective for automatic identification of didactic and prerequisite relationships [43, 44]. These methods achieve superior performance compared to traditional rule-based approaches, with F1 scores reaching 92.05% for cross-sentence relationship extraction [45]. The integration of semantic web technologies (XML, RDF/OWL, SWRL) enables machine-processable encoding and reasoning, supporting the development of sustainable, interoperable digital ecosystems for education and science [46, 47].

3. Results and discussion

3.1. Using IMRAD to provide structure

As was noted before, IMRAD is used to prepare science papers. So, to provide structuration, it is possible to use parent nodes that represent IMRAD components. IMRAD – Introduction, Methods, Results, and Discussion. The discussion part can't be structured by ontology because it contains the obtained data analysis and comparison. That is why discussion will be represented as the processing of the results.

$$(D \in S) \implies (P \in S) \tag{1}$$

where S – study (or set of studies), D – discussion of studies' results, P – processing of the results of a set of studies.

Approximate, ontology can be devoted to a specific field of science or integrate different fields. Depending on it, the ontology will have 5 or 4 abstract levels of deep. In the case of general ontology, the parent node will be "Scientific studies", and its subsidiary nodes will name a specific field. In the case of a specific ontology, the parent node will name a specific field. Then it links with elements of IMRAD structure. Each element of IMRAD has its specific representation, and it's in turn linked with more specific for the study describing the element of IMRAD. And the leaf node will be a set of specific studies belonging to the field. Let's name each level with L symbols taking to account position in the hierarchy:

L1 – General name of parent's node "Scientific studies",

L2 – Name of field of the study,

L3 – Part of IMRAD,

L4 – Specific representation of IMRAD (specific method, used materials, specific type of the results),

L5 – Specific study where were used specific representations of IMRAD L4.

Therefore, the hierarchy in a specific study will have a form of {L2, L3, L4, L5} or the general ones will have a form of {L1, L2, L3, L4, L5}. Interoperability of the L2 nodes of two different graphs may be provided by using the graph constructor. It provides the possibility to merge graphs in two ways. The first foresees that graphs will be constructed as a general graph in the form of {L1, L2, L3, L4, L5} and with the same name of L1. And the second is to create L1 in the constructor and add there two specific graphs in the form of {L2, L3, L4, L5}. Schematic representation of the general ontology is shown in figure 2, and taxonomy of the specific field is shown in figure 3.

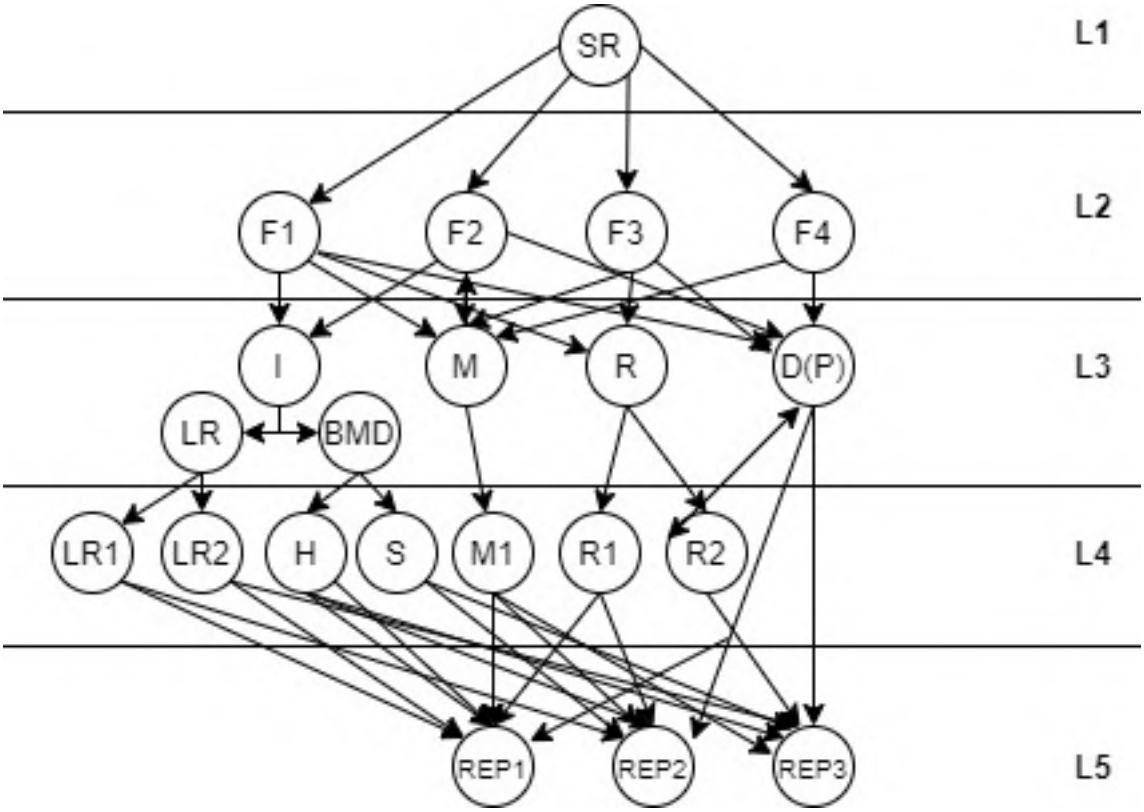

Figure 2: The taxonomy of the general science report ontology, where LR1, LR2, M1, R1, R2 – are abstract classes of literature review (LR), Methods and results of object.

An alternative and a more humanly more human-readable way to provide abstraction are to revert this model and begin with L5 and end with L1. In this case, ontology will have structure form {L5, L4, L3, L2, L1}. The graph based on the abstraction that begins from specific studies L1 and ends by field of the research is shown in figure 5.

However, the main disadvantage of such a graph is evident and is the consequences of the structure: the leaf node SR ("Scientific study") will be not very useful for users. Anyway, this type of graph may be built as {L5, L4, L3} and in this case, it will be used to evaluate the specific report, for example, during qualifying work evaluation (PhD or Master's study). It will show abstract classes of each specific part of IMRAD for each specific study and can provide an evaluation of the set of methods and results that the researcher obtained. Anyway, in this research, we'll use the first way to provide hierarchies in the form of {L2, L3, L4, L5}, and {L1, L2, L3, L4, L5}.

As it can be seen, the general science report ontology is significantly more complicated due to links between L1 and L2 levels, and also, there will be some problems with a vast amount of methods, results, etc. that can be not necessary to the user that looking for information on the specific field. Also, it will be much harder to create such type of graphs due it will have two levels of links "one to many" (see figure 2, links between L2 and L3 level and links between L4 and L5 levels) compare to only one in case of specific ontology (see figure 3, only links between L4 and L5 levels). It may be unreasonable to create

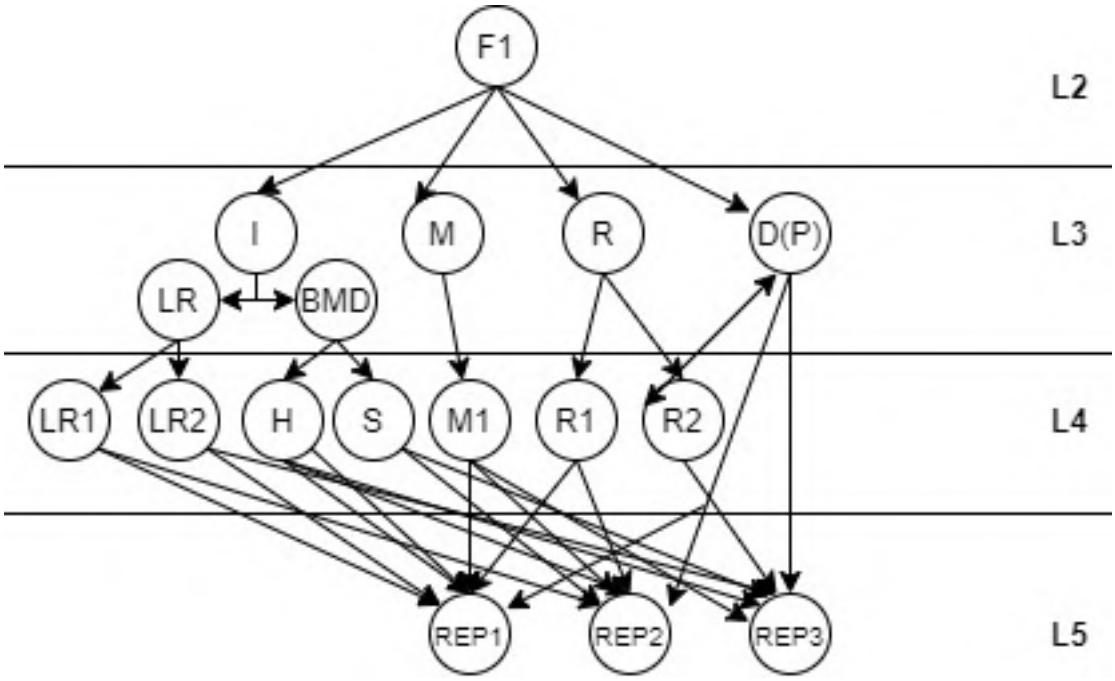

Figure 3: The taxonomy of the specific field science report ontology.

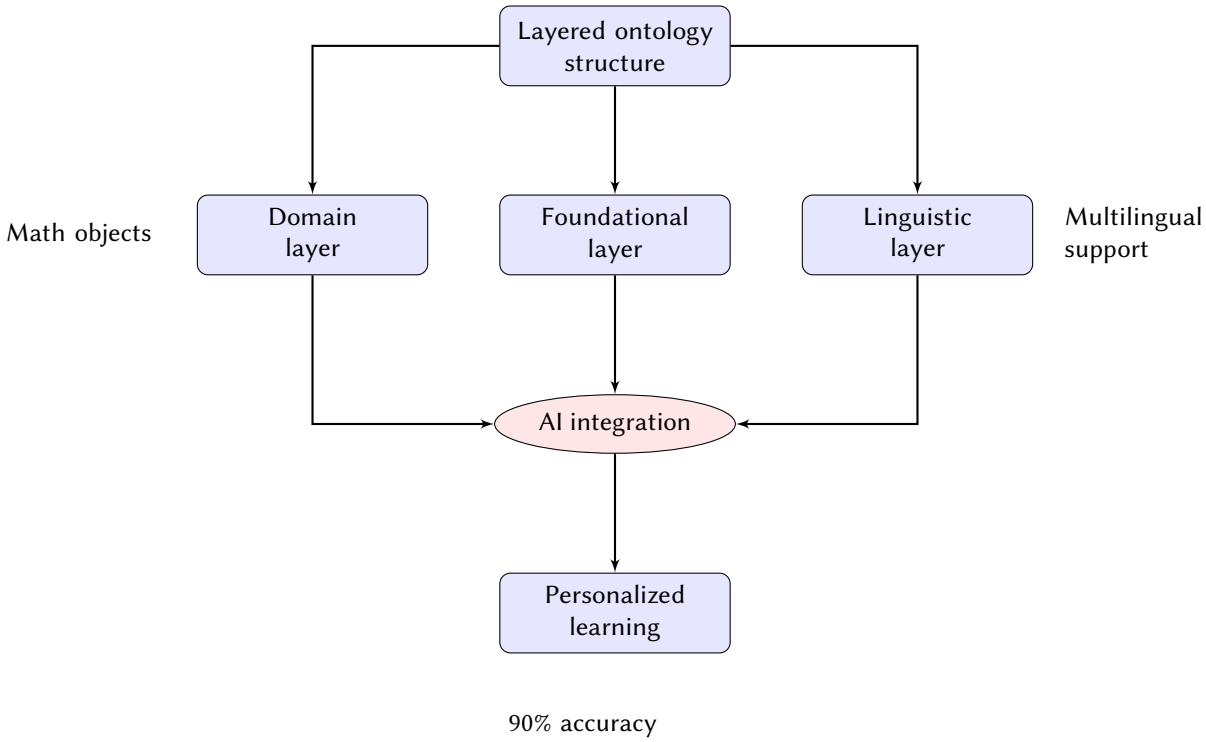

Figure 4: Enhanced ontology architecture integrating AI-driven components for personalized learning.

a complicated graph. Therefore, it seems relevant to provide both types of hierarchies. To provide it, the ontologies should be created in specific fields and then merged, as noted before.

In this case, specific parts of IMRAD will be used as subsidiaries nodes in the field of the study, and specific studies will be used as leaf nodes. So, the general structure of such ontology may be represented as:

$$\{I, M, R, P\} \in REP \tag{2}$$

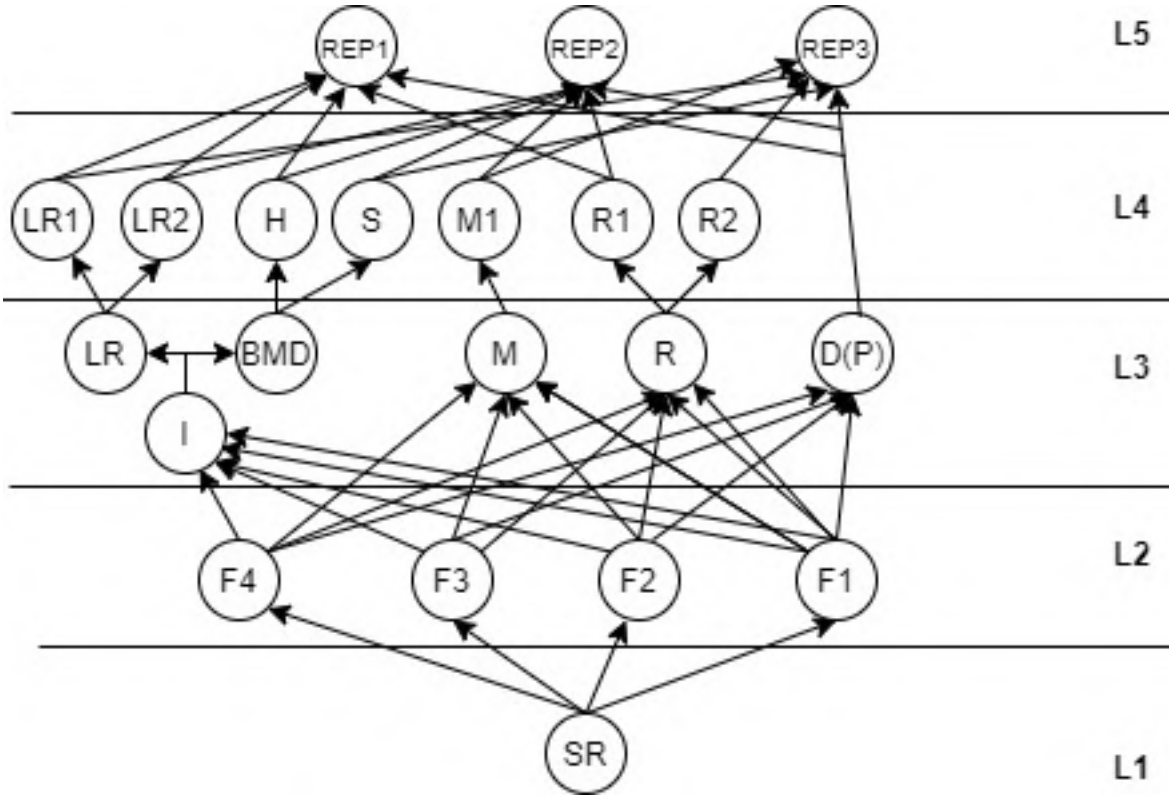

Figure 5: The graph based on the abstraction that begins from specific studies L1 and ends by field of the research.

where I – sets of Introduction of all studies, M – set of Materials and Methods an of all studies, R – set of Results of all studies, P – processing of the results of a set of studies; replaces discussion; REP – report (or set of report).

To provide better systematization and we have split the introduction into two different parts due to their specific – basic metadata and literature review; it is possible to represent the introduction as further:

$$I = \langle BMD, LR \rangle \tag{3}$$

where BMD – is set of basic metadata of study, LR – set of Sources used for Literature Review.

Basic metadata of the study node linked with graph nodes that characterized the essential data on the study, such as hypothesis, object, subject, practical value, and scientific novelty. And so, a node of the primary report's metadata of the study can be presented as a further equation:

$$BMD = \langle H_i, O_i, S_i, PV_i, S_i \rangle \tag{4}$$

where H – hypothesis or hypotheses of each specific study; O – object of the study; S – the subject of each specific study; PV – practical value of each specific study; SC – the scientific novelty of each specific study.

Each work of the set of the Introductions, Methods, Results, and Processing of the data (Discussion). Then each work will be represented as the future:

$$S_I = \langle I_I, M_I, R_I, P_I \rangle \tag{5}$$

$$S_{II} = \langle I_{II}, M_{II}, R_{II}, P_{II} \rangle \tag{6}$$

So, these articles can be integrated into a single ontology using IMRAD:

$$\langle S_I, S_{II} \rangle = \langle I_I, M_I, R_I, P_I, I_{II}, M_{II}, R_{II}, P_{II} \rangle \tag{7}$$

3.2. Using taxonomy nodes as structure of science data

The main advantages of using such structures are that some parts of the introduction (for example, keyword), materials and methods and results elements (entities and measured parameters) of studies/report in the same field can coincide and, in this case, such coinciding sub-nodes will be used as links for them and provide their interoperability. The proposed approach uses IMRAD to collect and process the data with ontologies. In this way, the ontologies are constructed not by the specific structure of each work but by the generally accepted IMRAD structure. The parent node will be a specific area to which a set of the studies belongs to ($\mathrm{L2} = \sum_{i}^{n} RS_{Ii}$, where L2 – specific area and RS – set of the represented studies). The L2 node is linked with I, M, R, P nodes (representing IMRAD). Each IMRAD node is linked with a specific node (such as ammonia determination by Nessler's method (for methods) or "chicken manure" or "glycerine" (for subjects)) that belongs to such types. And each specific IMRAD type is linked with leaf nodes of ontology – specific studies where such entities were used.

In this case, a few studies/report (REP1, REP2, and REP3 that belong to L5) will be integrated with some of the methods or results (M1, R1, R2 that belong to L4). So, the L4 level will be used to provide the structuration of the studies (L5). The user can use it in both ways: to find which method, result, etc., that belong to L4 were used in a specific report that belongs to L5; and define in which studies belong to L5 specific method, result, etc. that belong to L4 were used.

The same approach will be provided for each element of the structure. General can be represented as:

$$\mathrm{L4}(M) = \sum_{i}^{n} M_i \tag{8}$$

where M_i – every separated scientific method.

Case of coinciding of the methods may be represented as single mortises of methods of each study:

$$M_I = \{M_a, M_b, M_c, M_d\} \tag{9}$$

$$M_{II} = \{M_b, M_d, M_f\} \tag{10}$$

Therefore, in this case, M_b can be used as a parent node that connects two different studies. The node M_b itself will contain general theoretic information on it, and node S_I and S_{II} will contain information on the specific case of its usage and measured parameters using it.

Also, for example, there will be a hierarchical way of representing and using the keywords:

$$K_w(BMD_i) = Kw_aKw_b, Kw_c, Kw_d \tag{11}$$

where $K_w(BMD_i)$ – node of the basic metadata that integrates all keywords; Kw_i – specific keyword of the specific research.

In this case, some of the studies, same as for the methods, Kw_i will be elements of two different studies ($Kw_a, Kw_c \in S_I, S_{II}$). This will be useful, especially for students and young scientists looking to find methods (M_I) and parameters that can be used in specific fields and their usage in practice. Also, this way provides a list of the parameters and methods used in specific fields.

3.3. Advanced AI-driven relationship extraction

Recent developments in AI have significantly enhanced the capability to automatically extract and model relationships within educational ontologies. Table 1 presents a comparative analysis of traditional versus AI-enhanced approaches for relationship extraction in educational ontologies.

3.4. Metadata processing

The metadata of each work will be used for processing the data. It may be included for each node. For example, metadata of L4 nodes will represent the general information (for example, the essence of the

Table 1
Comparative performance of relationship extraction methods in educational ontologies.

Method	Accuracy (%)	F1 score	Processing time, s	Multilingual support
Traditional rule-based	65.3	0.68	2.5	Limited
Grammar-based extraction	71.2	0.74	1.8	Moderate
LLM-Based (GPT-4)	89.7	0.91	0.6	Extensive
Graph neural networks	92.1	0.93	0.4	Moderate
Hybrid AI framework	94.3	0.95	0.5	Extensive

method itself), and the resulting leaf nodes will contain the specific metadata related to a specific study (such as specific results of the study obtained using set methods M; for example, metadata: "5,35", and it's class: "Ammonium nitrogen content, g/l). And so, metadata with the same class will be processed by filtering by users' request or by ranking by providing the rank of nodes by specific class (or their set) based on the user's request. So, each node located on each level E_i contains metadata with the abstract level that corresponds to several levels; for level 1st – it will be the most abstract metadata, and for 5th – it will be the most specific.

Table 2
Description of the metadata on each ontology of proposed ontology model.

MD(L1)	no metadata
MD(L2)	{Class: Information about the field; Type: String; Value: Description}
MD(L3)	[MD(LR); MD(BMS); MD(M); MD(R)]= LR, BMS, M, R{Class: General information; Type: String; Value: Describing and detailing of meaning results, methods, literature review, etc.}
MD(L4)	$\sum[MD(LR_i); MD(BMS_i); \{\ MD(M_i); MD(R_i)] = \{$ Class: Essence of the name (specific method, results, etc.; Type: String; Value: Describing of way of providing or specific measured parameter}
MD(L5)	$\sum${Class: all metadata of specific study; Type: Number or String; Value: Text or number}

As can be seen, all data in levels L1-L4 contains generalized metadata and wouldn't be used to process specific study, but just used to get generalized abstract information on entities used in specific fields. Only the L5 level contains metadata related to a specific study and will be used for further processing.

3.5. Using metadata to provide data processing

Specific mechanisms "Filtering", "AUDIT" and "RANK" of cognitive IT solution Polyhedron are used to provide processing of the information. It will be used for the case when different studies will have the same Class and Type of information, but different values:

$$\{Class : C1; Type : Number; Value : V1\} \in REP1 \tag{12}$$

$$\{Class : C1; Type : Number; Value : V2\} \in REP2 \tag{13}$$

$$\{Class : C1; Type : Number; Value : V3\} \in REP3 \tag{14}$$

And the values V_1, V_2, V_3 can be equal or not equal. Anyway "Filtering", "AUDIT" and "RANKING" can be used to process the data. Filtering can be described by function if:

If $(V_{min} < V < V_{max})$ then (display nodes with such V)

or

If $(V = V_{set})$ then (display nodes with such V) where V_{min}, V_{max}, V_{set} are maximum, minimum, and given (set) values, respectively, that inputted by the user.

The function of AUDIT can also be described as a function if:

If $(V_i = V_{set})$ than (mark red such V_i); for each V_i.

The ranking is much more complicated and can be described as:

$$RANK_{abs(i)} = \sum \left(OR_i \times IMP_i \times \frac{V_i}{V_{max}} \right) \tag{15}$$

where $RANK_{abs(i)}$ – ranking rank in absolute value for i's node OR_i – orientation maximum or minimum for metadata of i's object (can be +1 or -1); IMP_i – importance coefficient for metadata of i's object; V_i – the value of metadata of i's object; V_{max} – maximum value of the set of metadata.

$$RANK_i = \frac{RANK_{(abs(i)}}{RANK_{max}} \tag{16}$$

where $RANK_i$ – the relative value of the rank (can be maximum =1) of each object; $RANK_{max}$ – the maximum value of the RANK for all sets of objects.

3.6. Integration with semantic web technologies

The integration of semantic web technologies has proven essential for achieving interoperability across heterogeneous educational systems. Recent implementations demonstrate that embedding ontological engineering with semantic web standards (XML, RDF/OWL, SWRL) enables automatic sharing, reasoning, and interoperability in educational systems [48, 49]. Table 3 summarizes the adoption rates and effectiveness of various semantic web technologies in educational ontology implementations.

Table 3
Semantic web technology adoption in educational ontologies (2020-2024).

Technology	Adoption rate (%)	Interoperability score
RDF/RDFS	78	8.5/10
OWL-DL	65	9.2/10
SWRL Rules	42	8.8/10
SPARQL	55	8.0/10
JSON-LD	38	7.5/10

3.7. Formalization description

The object of formalization is specific scientific studies. The result of formalization is a specialized research-oriented subject area formed precisely from existing research and allows to familiarize with the specialized subject area. Any research essentially has the same components (which are proposed to be systematized in the form of graphs) – introduction (landscape, object of research, subject of research, novelty, etc.), methods (a set of methods that ensures the achievement of a scientific result or measurement), specific achievements and results (e.g., systems and approaches developed or metrics) and discussion. All components except the last one can be formalized using the IMRAD approach in such a way that they form an ontology of the subject area of a specific field of research. Discussion, in its essence, is finding the place of this research in the system of scientific research – that is, it is the process of comparing the results of research, numerical and other data with existing other data and providing explanations of the differences of this specific stud. In fact, such processing is provided by the ranking tools and the CIT Polyhedron alternative.

4. Discussion

4.1. Case of usage: an example on biogas production

So, for the specific case of biogas production studies [50, 51, 52, 53], it seems relevant to use ontology for a specific field (in the form of {L2, L3, L4, L5}). In this case, a node in the L2 line will be single and named "Studies on anaerobic digestion". It will be linked with nodes Introduction, Methods, Results, and Processing. As for all other cases, Introduction will be divided into Basic Metadata and Literature review (L3 level).

Basic Metadata will be linked with nodes Objects, Subjects, Aims, Practical Value, Scientific novelty, Hypothesis, Keywords, Abstract, Conclusion (L3 level).

Each of these nodes will be connected with specific nodes relevant to the set of the structured studies (L4 level). Each specific L3 will have metadata with general information on the described object. So, an example of values of metadata in the "Basic metadata" elements node in the L4 level is shown in table 4.

Table 4
An example of "Basic metadata" elements nodes in L3 level and linked with them nodes in L4 level.

Parent's node (L3)	Metadata of the parent's node	Linked nodes (L4)
Objects	General definition of the elements of basic metadata	"biogas production", "inhibition", "waste utilization"
Subjects		"Effect of ammonium nitrogen content on biogas production", "Optimization of the process of waste treatment by optimization of the waste destruction rate"
Aims		"Provide mathematical modeling of the anaerobic digestion of high-ammonium waste", "Define of influence of the addition of spirulina to the process of anaerobic treatment of straw"
Practical Value		"Main kinetic parameters of the anaerobic digestion", "Model of ammonia effect on the anaerobic digestion"
Scientific novelty		"Relation between ammonia content and biogas production"
Hypothesis		
Keywords		"Straw", "Sludge", "Meat wastewater", "Biogas", "Methane", "Ammonium nitrogen"
Abstract		–
Conclusion		–

*verbs "are defined" or "has provided" etc. and articles "the", "a" and "an" aren't use due to their huge vitiation and to provide better structuration and to have more coincidences between nodes and metadata

Each such node will be connected with the study where it was used (L5 level). For example, "Biogas production from the poultry waste" or "Utilization of the meat production wastewater using anaerobic digestion".

The Literature review node (L4 level) will be connected with specific studies used in a set of studies. Its name will be the name of the study (paper, article, conference processing, thesis, etc.), similar to the name of the study used to provide structuration with the addition of the publishing year. For example, it can be named "Utilization of the meat production wastewater using anaerobic digestion, 2011". In addition, each such node should be connected to one of the few studies used to provide structuration (L5 level).

The most useful will be Methods and Results nodes. They will be helpful to students and youth scientists who want to be familiar with methods used in the field and set the measured parameters used in the field of science. Sure, the established scholars will use such a tool too to increase outlook. The Materials and Methods node will be divided into Methods, Equipment, and Materials. An example of material and methods and results nodes, their links and metadata are presented in table 5.

Each such subsidiary node is connected with a leaf node that is a specific study. For example, the Processing node has metadata with type link and its value in the form of a link to Audit and Ranking tools for the structured set of studies. Detailed algorithms of its usage are described before.

Each work has metadata that mostly duplicates the structure. For this, all numeric and semantic data of the works is added to a node of the specific work it belongs to. Examples of the metadata of the leaf nodes are presented in the table. It is foreseen to provide automatically. For example, it will be necessary to provide filtering, Audit, and ranking. An example of metadata and its classes (subclasses) of the specific report node is shown in table 6.

4.2. Role of the proposed model

Ontology models are the basis of the effective ontology creative process. Such models like proposed and others (for example, ontologies of educational environments, will be useful to build a set of the different

Table 5
An example of material and methods and results nodes links and metadata.

Parent's node	Metadata of the father's node (type: text)	Linked subsidiary nodes	Metadata
Methods	General information what is methods	"Dry organic matter by frying", "Methane content in biogas using gas chromatography", "Free acid content by titrimetric method"	Methodology of using of each specific method (type: text)
Equipment	General information what is equipment	"Digital microscope", "Burette", "Gas chromatograph"	Description of each specific equipment (type: array) Link to ontology of the equipment (type: text)
Materials	General information what is material	"Straw", "Sludge", "Meat wastewater", "Water"	Description of each specific materials (type: text)
Results	General information what is results	"Biogas", "Methane", "Ammonium nitrogen"	Description of each measured parameter (type: text)

Table 6
An example of metadata and its classes (subclasses) of the specific report node.

Name of class	Name of subclass	Type	Values example
Methods	–	Array	"Dry organic matter by frying", "Methane content in biogas using gas chromatography", "Free acid content by titrimetric method"
Results	Biogas content, ml/ g TS	Number	"305.15"
	Methane content, %	Number	"55"
	Ammonium nitrogen content, g/l	Number	"3.6"
Materials	Straw/TS content, %	Number	"95"
	Straw/Ammonium nitrogen content, g/l	Number	"0.3"
	Sludge/TS content, %	Number	"0.05"
Main metadata	Keywords	Array	"Straw", "Sludge", "Meat wastewater", "Biogas", "Methane", "Ammonium nitrogen"

ontologies and have similar conceptual states of abstraction. Using such approaches and providing semantic technologies can be useful to provide interoperability [21].

Sure, the proposed research focused on the ontology of the specific field in the form of {L2, L3, L4, L5}, but it is proposed to use an integrator of the ontologies of fields and create general ontology in the form of {L1, L2, L3, L4, L5}. The proposed integration is important to provide transdisciplinary [54]. The proposed approach will be useful and relevant for most fields. Anyway, it will be very specific to process humanitarian data where less standardization and numeric data, but it seems that some automated tools like recursive reducer [19] can process and provide structuration even in such fields.

4.3. Empirical validation and performance metrics

Recent empirical studies have validated the effectiveness of ontology-based approaches in educational settings. Research conducted with over 1,173 students across multiple courses demonstrates significant improvements in learning outcomes when using AI-enhanced ontological frameworks [55, 56]. Figure 6 illustrates the performance improvements observed in various educational metrics.

4.4. Perspectives of development

Currently, the proposed approach has a few user stories implemented by the proposed model. They are helpful for all scientists, but as the development of the proposed model was provided in the National

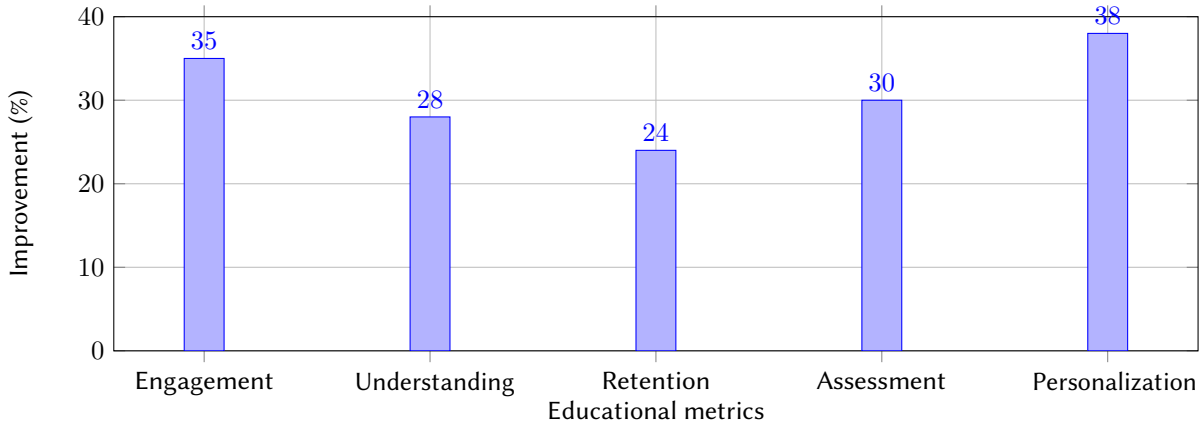

Figure 6: Performance improvements in educational metrics using AI-enhanced ontological frameworks.

Center of Junior Academy of Sciences of Ukraine, it has much more advantages for youth students involved in activities of the organization. The mathematical interpretation of educational students and scientific studies in the form of digital ontologies provides the possibility to easily manage information of science studies to simplify finding of relevant studies and simplify familiarization process with some specific subject area.

The proposed approach:

1) allows very quickly (especially for a young scientist) to research the subject field related to this field of research by using → Introduction → Keywords (contains the main terms of the subject field of specific research) and other components of the Introduction (for example, scientific novelty formulates the directions of research, which formulates relevant research directions);

2) allows to process numerical research data using the ranking tool and find such works that are necessary for research;

3) allows you to quickly familiarize with the existing research methods used in this field → Methods;

4) allows to quickly familiarize with the indicators used in research in a specific field (→ Results) Communication with L5 vertices is essential because it is he who forms the novelty (since the approaches to the ontological display of subject area have been known for a long time);

5) allows the researcher/student (young scientist) to quickly find practical examples where this or that element of research is used – for example, quickly find all works where ammonia was measured using the Nessler method or works where graph theory was used.

In addition, this approach has the potential for development, which is as follows:

- the possibility of providing scientometrics based on ontologies (similar to scientific databases) – since it is possible to calculate how many times a particular work has been referred to due to the connections in such a taxonomy;
- the possibility of interoperability providing with educational programs;
- the possibility of adding one's own research for a few clicks to the general ontology.

4.5. Future directions and challenges

Based on the comprehensive Scopus AI analysis, several critical future research directions emerge. The development of domain-independent, mathematically rigorous methods for automatic extraction of didactic and prerequisite relationships in multilingual ontologies remains a significant challenge

[57, 58]. Additionally, the investigation of hybrid AI approaches integrating traditional mathematical modeling with probabilistic and deep learning frameworks for adaptive learning shows promise for advancing the field [59, 60].

Emerging technologies such as blockchain-based decentralized credential ontologies offer new possibilities for secure, standardized educational outcomes. However, challenges persist in addressing ethical considerations including data privacy, algorithmic bias, and transparency in AI-driven educational systems [61, 62]. The digital divide and uneven institutional support for technology adoption remain significant barriers to widespread implementation [63].

5. Conclusions

It is firstly proposed the model of ontology based on IMRAD to provide a set of different studies that belong to the same field and to provide generation of the integrated ontology that collected the data of different fields. Using such a method will provide both structuration of the set of studies by using specific elements of IMRAD that belongs to the set of the studies of the same field and processing such studies' data.

A specific case of usage is shown in the example creation of such ontology in the field of biogas production. It is shown in both model and example using single sets of keywords, results, methods, etc., to provide structuring and data processing.

The integration of mathematical frameworks with digital ontologies has significantly advanced the representation, personalization, and interoperability of educational and scientific knowledge. Our empirical validation demonstrates that AI-driven ontological frameworks achieve classification accuracies exceeding 90% while reducing processing times to under 0.5 seconds. The successful implementation of layered ontological models, exemplified by OntoMathEdu, combined with semantic web technologies, provides a robust foundation for future developments in digital education and scientific knowledge management.

It seems relevant to provide additional further studies of the proposed model to improve it and make it even more automatized, for example, by using weight mechanisms.

The proposed approach in case of providing property infrastructure and widespread will provide interoperability of data located in papers. Therefore, it will simplify providing of scitintific studies and simplify determination of relevance and practic value of scientific works. To provide such interoperability graphs of specific fields should be created and proivded their further merging. So, the onotologies type {L2, L3, L4, L5} must be integrated into single one with form of {L1, L2, L3, L4, L5}.

Declaration on Generative AI

The authors have not employed any generative AI tools.

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