Reimagining Engineering Education: An Ecological Systems Approach to Integrating Educational Technologies

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Abstract. A university's first year of engineering education is pivotal, significantly impacting student retention and success. First-year engineering students face a formidable transition, grapple with the steep learning curve of advanced technical subjects, the necessity for enhanced self-directed study habits, and the assimilation into a new social environment. Concurrently, educators and institutions encounter the challenge of delivering effective and differentiated instruction and support to an increasingly diverse student body. The integration of new educational technologies emerges as a crucial opportunity to improve personalized learning paths, strengthen engagement, and facilitate both students' and educators' navigation through these transitions. This study employs Bronfenbrenner's ecological systems theory, a multi-layered framework to understand and address the diverse influences on student development to explore the intricate interactions among technology, pedagogy, and the broader educational context. This approach highlights the critical roles of reciprocity, power dynamics, and emotional influences across the various systemic layers—from microsystems like classroom environments to macrosystems encompassing broader socio-cultural influences. This study aims to establish a holistic, supportive learning ecosystem by leveraging educational technologies like learning management systems, virtual laboratories, and AI-powered systems. These tools collectively enhance students' academic, social, and personal development, improving scholarly achievement, engagement, and overall well-being. The multi-layered framework extends beyond classroom confines, underscoring the need for comprehensive student support. This paper outlines a practical framework for adopt-

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ing various strategies to create a scalable model that improves the first-year experience for engineering students, ultimately emphasizing the importance of holistic student support by bridging theoretical constructs with practical applications.

Keywords: Engineering Education, Ecological Systems Theory, Educational Technology, Student Support Systems, Student Retention, Peer-peer Learning, Virtual learning.

1 Introduction

The first year of engineering education is often described as a crucible, testing and shaping aspiring engineers through a significant transition from the structured high school environment to the more autonomous and academically rigorous university setting [1]. This shift demands that students adjust to new learning styles and expectations, excel in time management, and transition from rote memorization to a focus on critical thinking and problem-solving [2]. Many students find this adjustment daunting, struggling to apply theoretical knowledge to practical engineering problems, leading to feelings of inadequacy and negatively affecting their motivation and academic performance [3]. These challenges are multifaceted, involving the demanding nature of engineering curricula and psychological and social adjustments as students acclimate to new environments and learning methods. Such transitions are pivotal, laying the foundation for future academic persistence and success [4]. Research highlights that the experiences and achievements during this formative first year greatly influence students' decisions to persist in their chosen fields. For engineering students, the initial hurdles of mastering complex technical subjects and developing strong problem-solving and design-thinking skills are intimidating but essential for forming their professional identities and capabilities as engineers [5].

The first year of engineering education is crucial, as it significantly affects student retention and overall academic success. This phase lays the groundwork for students' understanding and skills, shaping their entire academic path in the engineering programme. Empirical evidence consistently shows that a student's performance in their first year strongly predicts their ability to succeed in subsequent years. Therefore, educational institutions are required to implement comprehensive engagement and support mechanisms during this foundational period. These measures are vital in helping students navigate the demanding requirements of engineering studies and influencing their decision to continue in the programme [6].

The educational landscape is experiencing a significant transformation driven by the advent of sophisticated educational technologies (EdTech). These technologies offer a wide range of tools and resources specifically designed to address the unique challenges faced by first-year engineering students [7]. Interactive simulations are vital to this technological revolution, bringing abstract concepts by enabling students to visualize and manipulate engineering principles within a virtual environment. At the same time, online learning platforms offer unprecedented access to a plethora of educational materials, including video lectures, quizzes, and practice problems, empowering students to control their own learning pace and review complex topics as needed. Furthermore, collaboration tools enhance the educational experience by facilitating communication and teamwork, creating more interactive learning environments, and promoting the development of crucial communication and interpersonal skills. These EdTech are driving a shift in pedagogy from traditional, teacher-centered methods to more dynamic, learner-centered models. This transition encourages active student engagement in the knowledge-creation process. Digital tools overcome geographical and temporal limitations, enabling effective collaboration and allowing students to gain diverse perspectives [7, 8]. Adaptive learning systems enhance the learning experience by customizing content to meet individual learning preferences and needs, maximizing engagement and effectiveness. This shift in educational methods enhances cognitive activities, promotes deep mental engagement, and sustains attention, thereby nurturing critical thinking and problem-solving abilities. As these technologies become integrated into the educational framework, they profoundly impact pedagogical approaches, altering education's structure, methods, and content. Teachers transition from mere information providers to facilitators of learning, and students develop into independent thinkers capable of autonomous, critical, and creative thinking and action. The widespread integration of educational technologies challenges and redefines traditional educational boundaries and better prepares students for professional environments. By enhancing personal development and equipping students with essential skills, educational technologies enable learners to tackle future challenges with innovation [9].

While educational technologies have become increasingly common in various academic disciplines, there is a lack of sufficient documentation on their integration within an ecological systems framework, particularly in engineering education. This study addresses this gap by investigating the complex interactions among students, technologies, and the broader educational landscape [10]. Several under-explored dimensions characterize the research gap regarding the use of educational technologies within this framework. There is a notable lack of studies that systematically integrate these technologies while considering both individual learning outcomes and broader ecological influences. The dynamics between educational technologies and various systemic layers, from immediate learning environments to broader societal and cultural contexts, have not been sufficiently examined [11]. Most existing literature focuses on academic performance and student engagement, neglecting other developmental areas such as social skills, emotional well-being, and adaptability. The impact of institutional and cultural contexts on the effectiveness of these technologies is also poorly understood. Furthermore, there is a lack of longitudinal research that tracks the long-term impacts of these technologies on students' career trajectories and lifelong learning habits. Addressing these gaps will enhance our understanding of optimizing educational technologies, thereby improving the success of engineering education within a comprehensive ecological framework.

This paper studies how an ecological systems approach to educational technology integration can improve the design of first-year engineering students' learning experiences. The study aims to assess the interaction between educational technologies and various systemic layers, analyzing how tools like interactive simulations, collaborative platforms, and adaptive learning systems influence different ecological layers affecting the student learning environment. It seeks to evaluate the effectiveness of these technologies in improving academic performance and student engagement while also exploring their impact on broader developmental outcomes such as social skills, emotional well-being, and adaptability. Additionally, the study examines the role of institutional and cultural contexts in the implementation and efficacy of educational technologies, investigating how different educational settings and cultural backgrounds influence their adoption and success. Furthermore, it conducts a longitudinal analysis to determine the long-term effects of educational technologies on students' career paths and lifelong learning habits. By systematically exploring these objectives, the study aims to provide comprehensive insights into integrating educational technologies within an ecological framework, contributing to enhancing engineering education practices.

This paper is organized as follows: Section 2, Literature Review, explores Bronfenbrenner's Ecological Systems Theory and its relevance to engineering education. Section 3 presents the Integration of Bronfenbrenner's Theory and Educational Technologies. Section 4 outlines practical steps for applying the proposed approach, discussing challenges and solutions, and Considerations. Section 5 summarizes the study's findings, discusses implications for student support, engineering education, and policy, and offers future research and practice recommendations. Finally, Section 6 reiterates the main findings, emphasizes the importance of integrating Bronfenbrenner's theory and educational technologies, and reflects on the potential of this approach to transform engineering education.

2 Literature Review

2.1 Bronfenbrenner's Ecological Systems Theory and Engineering Education

Overview of Bronfenbrenner's theory

Bronfenbrenner's ecological theory of human development has profoundly influenced various domains, particularly human development and educational psychology [12]. Bronfenbrenner initially crafted an ecological model to address the gaps in child development research concerning the influence of broader environmental contexts. This model has evolved into a robust framework for understanding the complex interactions within an ecosystem that impact child development [13]. A frequently employed visual representation of this concept is a diagram with a child positioned at the centre, surrounded by concentric circles representing the micro, meso-, exo-, and macrosystems [13]. Some visual representations, such as incorporating an arrow symbolizing the chronosystem, which signifies the influence of time, a component Bronfenbrenner added in 1994.

Bronfenbrenner's initial framework described these ecological systems and was later refined into the Process-Person-Context-Time (PPCT) model. This enhanced model accounts for the dynamic interactions between developmental processes, individual biological characteristics, contextual factors, and temporal elements [14].

Beyond its foundational role in developmental psychology, Bronfenbrenner's theory has significant implications for educational research. In 1977, Bronfenbrenner pioneered an ecological approach to education, emphasizing the interactive connections between learners and their environments. He critiqued the reliance on laboratory experiments in educational research and advocated for an ecologically valid methodology that holistically examines educational systems and processes. He stressed the importance of the physical settings and the evolving relationships between students and their environments, underscoring that understanding individual learning processes within educational settings hinges on the interplay between learner characteristics and their environmental contexts. His seminal work, "Ecological Models of Human Development," published in the International Encyclopaedia of Education in 1994, exemplifies his profound influence on educational research [13, 14].

Bronfenbrenner's ecological theory has been extensively applied in studies of child development and parental education and has also found applications in educational accountability, educational transitions, computer-assisted language learning, early childhood education, and higher education. For instance, Mulisa (2019) utilized Bronfenbrenner's framework to advocate for an integrated approach in higher education that emphasizes the dynamic interaction between students and their social environments, asserting that educational achievements are not solely determined by student abilities or curriculum quality [15]. This perspective necessitates that educators and practitioners employ holistic strategies to manage the multi-level socioecological factors influencing student learning effectively.

Thus, Bronfenbrenner's theory offers a detailed and comprehensive framework that aids educators and policymakers in understanding, appreciating, and effectively addressing the complex environmental factors involved in international and intercultural education [16]. This framework facilitates a deeper comprehension of the diverse cultural contexts, values, and norms that influence learners and underscores the critical interactions and relationships within intercultural settings that contribute to a student's adaptability and learning. Furthermore, it encourages students to engage actively in diverse environments, enhancing their intercultural competence.

Relevance of the theory to engineering education

Bronfenbrenner's Ecological Systems Theory is highly relevant to engineering education as it comprehensively examines the diverse environmental factors impacting student development and success. This theory extends the understanding of engineering education beyond mere academic learning to include personal and professional development influenced by immediate educational settings, familial and social support systems, broader institutional policies, cultural values, and historical changes. Such a holistic approach aids educators and policymakers in recognizing the complex interplay of these factors, enabling the development of strategies that enhance educational experiences and outcomes for engineering students.

Bronfenbrenner's ecological theory provides a valuable framework for understanding the myriad contextual factors influencing the development of first-year engineering students, particularly within the context of blended learning. Bronfenbrenner states, "All individuals are part of interrelated systems that place the individual at the centre, encompassing all systems that affect the individual"[17]. In this context, the first-year engineering student is positioned at the centre of this model, with direct influences emanating from those closest to them, such as family, friends, and academics [18]. These students are embedded within more remote systems, including political and socio-economic contexts. Bronfenbrenner's ecological theory emphasizes the importance of considering an individual's experiences and the specific characteristics of environments in understanding their development. The theory identifies five critical systems: the microsystem, mesosystem, exosystem, macrosystem, and chronosystem, which interact over time to shape the developmental trajectory of the individual [19]. The microsystem includes direct interactions and immediate environments; the mesosystem encompasses interconnections between microsystems; the exosystem involves broader social systems that indirectly influence the individual; the macrosystem includes overarching cultural, economic, and societal influences; and the chronosystem reflects the dimension of time, considering both life transitions and sociohistorical contexts, for example, improving educator-student relationships and resource availability in the microsystem, ensuring course consistency in the mesosystem, adapting university policies in the exosystem, and promoting inclusive cultural perceptions in the macrosystem. Addressing these factors can lead to more effective support strategies, enhancing engineering students' educational outcomes and well-being.

2.2 Educational Technologies in Engineering Education

In contemporary engineering education, many educational technologies (EdTech) are transforming the learning experience for students, particularly in critical first-year courses. This shift extends beyond merely offering new tools; it introduces advanced instructional methodologies, fostering innovative learning and collaboration styles.

1. Learning Management Systems (LMS) like Moodle, Blackboard, and Canvas provide a structured foundation for education, offering centralized access to course materials, assignments, and communication channels between instructors and students [20]. Simulation software such as MATLAB bridges the theoretical-practical divide by allowing students to experiment with complex engineering concepts in a virtual environment, solidifying understanding and preparing students for real-world problem-solving [21].
2. Computer-aided design (CAD) tools like AutoCAD take this approach further, empowering students to translate their designs into digital blueprints. It fosters critical skills in design thinking, visualization, and technical drawing, which are essential for aspiring engineers [22].
3. Collaboration also benefits from this technological revolution. Online platforms like Google Workspace, Zoom, and Microsoft Teams equip students with the tools to work seamlessly on projects, fostering communication and teamwork skills crucial for success in the engineering field [23]. These platforms are particularly valuable for project-based learning, where students can learn from each other and develop the ability to collaborate effectively in a team setting [24].
4. The power of artificial intelligence (AI) finds its place in EdTech as well. AI-driven systems analyze student performance and learning patterns, allowing per-

sonalized learning experiences. These systems can adapt to the difficulty level of exercises, recommend additional learning resources, and identify areas where individual students might need extra support [25, 26]. For example, ChatGPT is an artificial intelligence technology that supports engineering education by staying current with technological advancements and industry shifts [27]. It offers personalized learning experiences and tailored feedback, aligning with students' needs. ChatGPT can also create realistic virtual simulations for hands-on learning [27]. However, a notable drawback is its reliance on training data, which can perpetuate biases and spread misinformation [28]. There's also a risk of students using ChatGPT unethically, which could lead to short-term gains but long-term educational and professional setbacks [29]. ChatGPT enhances teaching and learning to prepare engineering graduates for immediate employment in a digitally driven economy. It is particularly effective for self-directed learning and can be incorporated into collaborative classroom activities, such as group research projects, to foster student interaction [30].

5. Laboratory work is integral to the engineering curriculum. An online laboratory is "a conceptual instructional space where students engage in laboratory-like activities. Students might not be physically present with the experimental equipment in this setting but can control it remotely using online technologies or engage with entirely virtual, simulated instruments" [31]. Online laboratories offer several advantages, such as facilitating experiential learning by giving students more frequent and flexible access to laboratory experiences. They allow students extended individual time to complete tasks, more efficient usage of costly equipment, and the opportunity for equipment sharing across institutions [32].
6. Virtual reality offers complete immersion through technology, enabling students to engage in a wholly computer-generated environment [33]. Immersive virtual reality necessitates using a head-mounted device that plunges the student into the experience, effectively making them feel as though they are physically present in that setting [34]. It provides a learning environment with stimuli and artefacts replicating the engineering workplace, which is especially advantageous for students who struggle to visualize abstract engineering concepts [33]. Additionally, virtual reality enhances students' understanding of concepts, problem-solving capabilities, and

skills acquisition [34]. It offers rich experiential learning opportunities and enables collaborative problem-solving when multiple students are simultaneously immersed in the same virtual scenario. Also, the cost-effectiveness of virtual reality allows students access to environments and scenarios that would otherwise be too costly or impractical to experience in person [33, 34].

While educational technology offers numerous advantages, its limitations cannot be overlooked. Computers, for instance, cannot mimic the human brain's varied and creative thought processes, which can generate new and innovative ideas beyond the capabilities of technology.

Additionally, the internet often hosts misleading or inaccurate information. The ease of fabricating achievements online necessitates diligent fact-checking before academic use. Distractions from phones and other devices during online courses can also impair concentration and degrade academic performance. Furthermore, some people are reluctant to participate in online learning due to its lack of personal interaction and the immediacy found in traditional classroom settings. They prefer direct engagement with peers in face-to-face environments to better understand the collective knowledge on a subject. However, for those interested in virtual education, a range of options exist, including distance learning, live virtual classrooms, and online video conferencing [35].

Implementing educational technology also faces challenges, including the high costs associated with acquiring and maintaining these technologies, which can be prohibitive for some institutions [36]. Technical issues and the learning curve associated with new technologies can pose additional obstacles for teachers and students [37]. Furthermore, the issues of access and equity must be carefully managed. Not every student has access to a reliable internet connection or personal devices, which can deepen educational disparities [38].

3 Integrating Bronfenbrenner's Theory and Educational Technologies

Integrating educational technology (EdTech) with Bronfenbrenner's Ecological Systems Theory provides a holistic approach to enhancing learning experiences across various levels of the educational ecosystem. Bronfenbrenner's Ecological Systems Theory offers such a framework, highlighting the multifaceted impact of technology across different environmental levels. Fig 1 captures these dynamics, showing how EdTech can be strategically integrated across all Bronfenbrenner's ecological model levels to enhance educational outcomes and bridge gaps within the educational ecosystem.

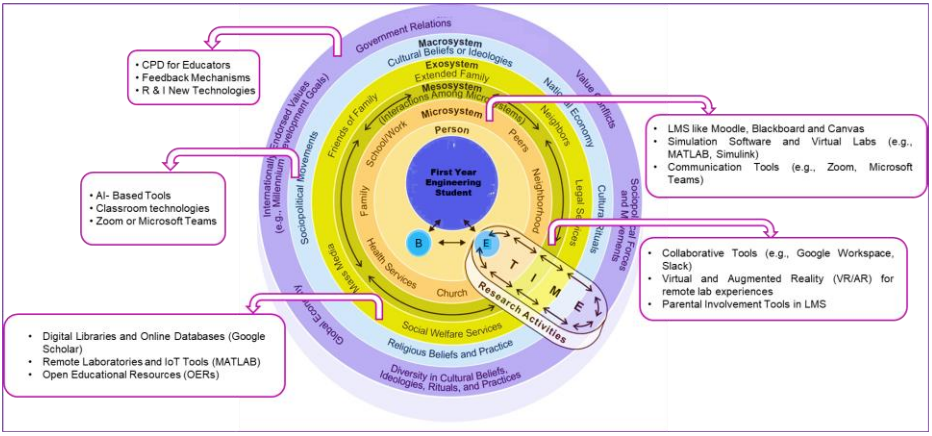

Fig. 1. Conceptual Framework of EdTech in Bronfenbrenner's Ecological Systems

Microsystem of the First-Year Engineering Student

According to Bronfenbrenner, the microsystem is defined as the pattern of activities, roles, and interpersonal relations experienced by the developing individual within a particular physical setting [39](Bronfenbrenner, 1989, p. 227). It includes an individual's immediate environment and daily engagements with lecturers, tutors, fellow students, friends, and family members. The microsystem directly and primarily influences an individual's life [18]. For first-year engineering students, the microsystem encompasses their activities and relationships within the university setting, directly impacting their development. The key participants in this setting are the students, their peers, lecturers, and tutors. Within this context, students utilize various materials and tools, including those required for digital learning [40]. Many first-year engineering students come from disadvantaged backgrounds and rural areas, often attending under-resourced schools. Also, English may not be their first language, posing a significant learning barrier [41]. As a result, these students transition from disadvantaged school systems into higher education institutions that may also be under-resourced [42].

At the microsystem level, EdTech can directly impact the student's immediate learning environment. Tools like learning management systems, interactive software, and virtual simulations can enhance the interaction between students and teachers and between students themselves. These technologies can personalize learning experiences, provide immediate feedback, and facilitate a more engaging and interactive learning environment that mimics the dynamics of a physical classroom. These technologies bridge the gap between theoretical knowledge and practical application, fostering a more dynamic learning environment [20]. For example, circuit design and simulation tools such as Multisim or MATLAB allow students to create and test electronic circuits in a virtual environment. It helps students understand theoretical concepts through practical application.

Mesosystem of the First-Year Engineering Student

The mesosystem refers to interactions between two or more settings involving the developing individual, such as the relationships between home and school, school, and the workplace. Essentially, the mesosystem is a system of microsystems [43]. The quality of these relationships can either support or hinder an individual's development [18]. The mesosystem is significant because it emphasizes that an individual's performance in one setting, such as a university, is influenced by experiences in other settings, such as home. It is particularly relevant for first-year engineering students whose university performance is impacted by their home life and the quality of their previous education. Spaull (2019) asserts that the life chances of the average South African child are determined not by their ability or effort but by factors such as their skin colour, place of birth, and parental wealth [44]. Many first-year engineering students come from historically disadvantaged backgrounds, which affects their financial situation and the quality of their prior education. These students often face challenges in university programs due to their limited educational background and lack of exposure to digital technologies [45].

EdTech tools like VR/AR and online collaboration platforms connect different learning environments in the mesosystem. Students can collaborate on projects across geographical boundaries, blurring the lines between classrooms and laboratories. It provides a more holistic learning experience. For instance, employing integrated learning platforms like Blackboard that integrate learning materials, assignments and resources to facilitate smoother transition between the course, helping students see the connections between their learning activities. Tools like Microsoft Teams or Zoom are used for group projects and study groups, fostering collaboration and interaction between students in different sections.

Exosystem of the First-Year Engineering Student

The exosystem, part of Bronfenbrenner's systems, consists of external environmental settings that indirectly impact individuals' development [13]. Although students don't actively participate in these settings, they still affect their development. For first-year engineering students, socioeconomics is a critical factor within the exosystem [46]. Socio-economic status significantly impacts students' ability to access education and finance the necessary tools for digital learning, such as tablets or laptops. In South Africa, issues of technology affordability and accessibility remain unresolved, particularly for students from lower socio-economic backgrounds [45]. Institutional regulations influence student choices and behaviour and are also part of the exosystem [47]. These include university policies and general information, rules, and regulations that collectively shape the educational experience.

At the exosystem level, EdTech extends the reach of educational resources. Students can access online lectures from renowned professors, explore open-source educational materials (OERs), and participate in virtual workshops, regardless of physical location. It democratizes access to knowledge and empowers students to take ownership of their learning journeys [48].

Macrosystem of the First-Year Engineering Student

The macrosystem, the outermost layer of Bronfenbrenner's systems, encompasses cultural norms, values, and societal influences [18]. In South Africa, since the advent of democracy in 1994, equity and access to higher education have been widely regarded as transformational imperatives [49]. However, challenges remain for students from poor socio-economic backgrounds and those enrolled at historically disadvantaged universities, which have fewer resources compared to historically advantaged universities, impacting the quality of education and support available to students [42]. The macrosystem reflects societal trends driving the development and adoption of EdTech. Engineering education must prepare students for a technology-driven workforce as technology becomes increasingly integrated into all aspects of life. EdTech tools play a crucial role in achieving this by equipping students with the necessary technical skills and fostering a growth mindset that embraces continuous learning in the face of rapid technological advancements [50].

Chronosystem of the First-Year Engineering Student

The chronosystem captures changes or consistencies in the individual and their environment [43]. This system is particularly relevant to first-year engineering students in South Africa due to the historical context of education. Since 1994, post-apartheid South Africa has implemented laws and policies to dismantle racial segregation and make the education system more equitable [51][46]. However, the transformation process has been slow, and the schooling system still inadequately prepares many black students for higher education [2]. Additionally, inequities in higher education persist, with historically disadvantaged universities remaining under-resourced compared to historically advantaged universities [42]. Thus, although the current university experience for these students improves over previous conditions, disparities in resources and opportunities still exist.

EdTech adapts education to the evolving times highlighted in the chronosystem. Updating educational tools and methods helps institutions stay current with educational demands and workforce skills as technologies progress. This ongoing adaptation is crucial for preparing students for emerging fields and future challenges, ensuring education remains relevant and responsive to societal changes. Continuous evaluation and adaptation are essential to ensure that engineering education remains at the forefront of innovation [52].

By integrating EdTech with Bronfenbrenner's Ecological Systems Theory, engineering educators can move beyond simply incorporating technology for newness. This framework fosters a holistic approach to improving engineering education, making it more dynamic, inclusive, and effective in preparing future engineers to thrive in a rapidly changing world.

3.1 Balancing Educational Technologies with Traditional Pedagogical Methods

The integration of educational technologies into engineering education has created new opportunities for enhancing the student's learning experience. However, these advancements should not entirely replace traditional pedagogical methods. Instead, a balanced approach that blends the strengths of both can provide a more comprehensive learning environment for first-year engineering students. Educational technologies, such as learning management systems (LMS), virtual simulations, and AI-powered tools, offer flexibility, personalized learning, and interactive experiences. Adaptive platforms, for instance, allow for tailored content delivery, adjusting based on students' performance [8]. These tools promote self-paced learning and provide opportunities for students to deepen their understanding of complex concepts outside the classroom.

However, in line with the need for a balanced approach, these technologies are not viewed as replacements for traditional teaching methods. Instead, they are seen as enhancements that complement the hands-on, interactive nature of in-person learning. For instance, virtual labs and simulations allow students to explore theoretical concepts in digital environments. Still, physical lab work remains crucial for developing practical skills and confidence in handling real-world engineering equipment [22].

The decision to pursue balanced integration is supported by research demonstrating that blended learning models—combining traditional in-person instruction with digital tools—lead to better student outcomes. Studies, such as Sala et al. (2024), show that students in hybrid learning environments report greater engagement, retention, and academic success compared to those in either entirely traditional or fully digital settings [53]. This evidence highlights that an optimal approach is not to choose one over the other but to combine them thoughtfully to create a cohesive learning experience.

While the balanced approach has clear benefits, challenges in its implementation need to be addressed. A significant issue is the digital divide, where students may lack access to the necessary devices or reliable internet [19]. Additionally, resistance from educators or students more accustomed to traditional methods can hinder the successful adoption of technology.

To mitigate these challenges, institutions implement measures such as technology loan programs for students and professional development initiatives for educators. These steps ensure that both students and staff are equipped to fully engage with educational technologies while maintaining the essential aspects of traditional teaching methods.

In establishing this balance, a phased approach is recommended, where institutions gradually integrate digital tools into the curriculum. Initially, lower-tech solutions, such as online platforms for course management and assignment submission, can be introduced [20]. As the educational community becomes more comfortable with these technologies, advanced tools like virtual labs or AI-driven learning analytics can be progressively incorporated [25]. This gradual integration allows for reflection and adaptation, ensuring that the combination of traditional methods and EdTech remains effective. The inclusion of feedback loops, where students and educators assess the impact of the hybrid approach, helps ensure that the balance remains beneficial and adaptable to evolving educational needs.

4 The Reimagined Support System

4.1 Implementation of Proposed Framework

The reimagined support system in engineering education focuses on an ecological systems approach, integrating many levels of support that interact dynamically. This method utilizes educational technologies to optimize learning and streamline the integration of theoretical and practical information. Collaboration among teachers, students, technology providers, and industry partners is required to establish a comprehensive educational setting. Table 1 encapsulates the proposed implementation framework for integrating educational technologies within Bronfenbrenner's Ecological Systems Theory, detailing objectives, tools, and expected outcomes for first-year engineering students at each ecological level.

Table 1. Ecological Levels and Key Strategies

Ecological Level	Objectives	Key Strategies and Tools
Microsystems	Enhance direct educational interactions between students and their immediate learning environments.	**EdTech Tools**: Interactive whiteboards, simulation software (MATLAB Simulink, AutoCAD), AR/VR for immersive learning. **Pedagogy**: Flipped classrooms, active learning where students engage in hands-on activities during class.
Mesosystem	Facilitate effective connections between different learning settings within the university.	**EdTech Tools**: LMS like Moodle or Blackboard, **Pedagogy**: Integrated projects that span multiple courses, interdisciplinary collaboration.
Exosystem	Align institutional policies and broader community interactions to support technology-enhanced learning.	**EdTech Tools**: Cloud computing services for easy access to resources, broadband infrastructure for high-speed internet **Pedagogy**: Industry-driven projects and internships facilitated by the university's partnerships.
Macrosystem	Reflect on societal and cultural norms that influence educational practices at the institutional level.	**EdTech Tools**: Global classroom technologies, e.g., virtual exchange programs using platforms like Zoom or Microsoft Teams **Pedagogy**: Emphasis on global competency skills and cultural sensitivity training in the curriculum.
Chronosystem	Address changes over time in technology and educational needs.	**EdTech Tools**: Continuous updates to software and hardware, adoption of AI and machine learning for personalized learning. **Pedagogy**: Agile teaching methods, continuous professional development for faculty.

4.2 Detailed Implementation Plan for the Proposed Framework

A structured implementation plan has been developed to ensure the practical application of the proposed framework. This plan outlines specific timelines, responsibilities, and benchmarks to guide the process across various phases of implementation. Table 2 provides a detailed breakdown of the action plan, which supports scalability and adaptability in diverse educational settings.

Phase	Timeline	Objective	Key Tasks	Benchmarks
Phase 1: Pilot Testing	0-6 months	Conduct small-scale pilot testing of the framework in selected institutions.	• Select pilot institutions and departments. • Provide initial training to educators on EdTech integration. • Set up necessary infrastructure (e.g., LMS, digital tools). • Collect initial feedback from participants.	• Infrastructure and tools successfully set up. • Completion of educator training. • Initial feedback was gathered from educators and students.
Phase 2: Full-Scale Implementation	6-18 months	Expand the framework based on pilot testing results	• Scale up implementation in more departments and institutions. • Provide ongoing professional development and technical support to educators. • Address technology access gaps (e.g., device provision, connectivity solutions). • Collect data (student performance, retention rates) to assess framework impact.	• Framework implemented across multiple departments. • Increased educator engagement. • Positive trends in student performance and retention rates. • Identified areas for adjustment and refinement.
Phase 3: Ongoing Monitoring and Adaptation	18-24 months and beyond	Establish long-term monitoring and adaptive feedback systems	• Conduct evaluations every six months to assess the framework's impact. • Implement feedback loops to adjust strategies based on feedback from educators and students. • Adapt the framework based on emerging	• Regular data collection on student outcomes. • Continuous adaptation of the framework based on evolving educational needs. • Periodic feedback from stakeholders to inform adjustments.

			technological advancements and needs.	

4.3 Methodology

Informal interviews were conducted with three educators to gather their perceptions and experiences about the proposed framework for integrating an ecological systems approach with educational technology in engineering education. The interviews were held in a relaxed and conversational setting and aimed to understand the framework's effectiveness, challenges in its implementation, and possible improvements. Educators were selected based on their varied backgrounds and experiences in engineering education to ensure a wide range of perspectives. They represented different levels of familiarity with educational technologies, teaching methodologies, and student engagement strategies.

An interview guide with open-ended questions was crafted to cover all pertinent topics, facilitating a free exchange of ideas and experiences. Each interview, lasting about an hour, was scheduled at the convenience of the participants, either in their offices or via a virtual platform. The sessions were audio-recorded with the participant's permission to capture the discussions' nuances accurately. The recordings were transcribed word-for-word, and thematic analysis was conducted to identify recurring themes, unique insights, and differing views. This analysis was crucial in assessing the proposed framework's practical impacts and collecting valuable feedback for its refinement.

Participants were fully briefed on the study's goals, the voluntary basis of their involvement, and their right to opt out at any time. The data was anonymized to maintain confidentiality and anonymity, ensuring that individual responses could not be linked back to any participant.

4.4 Potential Challenges and Solutions

During the informal interviews conducted with three educators on the proposed framework, several potential challenges were identified, along with viable solutions. First, resistance to change was noted as a significant barrier, which could be mitigated by implementing change management strategies, including training and pilot programs that allow participants to experience the benefits directly. Technological disparities among students also emerged as a concern, suggesting the need for a technology access fund and the application of universal design principles to ensure equitable learning opportunities. The complexity of integrating multiple technological platforms presented another challenge, which could be addressed by developing a centralized platform and providing ongoing IT support to educators. Funding constraints were identified as a limitation to adopting new technologies, with solutions including seeking grants, forming partnerships with tech companies, and advocating for dedicated institutional funding. Lastly, the difficulty in assessing the impact of new educational technologies on learning outcomes was discussed, pointing to the need for robust assessment mechanisms that utilize both qualitative and quantitative data to evaluate the effectiveness of technology integration. These insights underline the complexities of updating educational frameworks and the need for comprehensive strategies to overcome these challenges.

5 Discussion

Integrating an ecological systems approach with educational technologies in engineering education has substantial prospects and poses diverse challenges. Insights gained from informal interviews with three educators offer a more profound comprehension of the practical consequences, aiding in forming strategic implementations and essential policy revisions. However, the small sample size of three educators and the qualitative nature of this study highlight some limitations, such as the need for a broader participant base and quantitative validation in future research. Expanding the sample size to include more educators from diverse educational contexts will allow for a more comprehensive understanding of the framework's applicability and effectiveness. Additionally, incorporating quantitative metrics like student performance and retention rates will strengthen the validation of the framework in future iterations.

The proposed framework holds the capacity to transform engineering education by improving interactivity and customization of learning experiences. Educators have observed significant enhancements in student involvement and enthusiasm due to technology-integrated learning settings' interactive and immersive character. This strategy not only conforms to contemporary pedagogical trends but also caters to the varied learning requirements of students, promoting inclusiveness and enriching the educational experience across different ecological levels. For example, while virtual simulations provide students with immersive environments, physical labs remain indispensable for hands-on skill development, ensuring students gain both theoretical and practical knowledge.

Adopting advanced technologies in education brings up difficulties, such as the complications of integrating these technologies and the requirement for extensive IT assistance. These problems require systematic training and resource distribution, ensuring educators are adequately prepared to handle new tools and platforms. Furthermore, the unequal distribution of technical resources among students emphasizes the need for rules that guarantee fair access to all essential learning materials, bridging gaps across all levels of the ecological system.

The knowledge acquired emphasizes the necessity for specific policy measures. It is recommended that educational institutions reassess their financial allocations to more effectively support the implementation of new technologies and finance continuous professional development for instructors. Moreover, it is crucial to implement policies that target the reduction of technical disparities. These policies guarantee that all students, irrespective of their socio-economic background or ecological context, have equal access and may fully take advantage of educational technological breakthroughs.

Using an ecological systems approach in conjunction with educational technology can potentially influence student retention and achievement significantly. Enhancing the engagement and relevance of learning improves students' chances of sticking to their studies and attaining superior results. The efficacy of these advantages relies heavily on the efficient execution of the suggested framework and ongoing assessment and improvement of the associated procedures. It necessitates an adaptable strategy considering temporal changes and the interdependence of different ecological levels, guaranteeing that technological incorporation is sensitive to the developing educational environment.

To appropriately utilize the revolutionary capabilities of technology in education, it is crucial to have a strong and flexible framework that aligns with Bronfenbrenner's ecological systems theory. This framework comprises three interrelated pillars: infrastructure and accessibility, teacher training and professional development, curriculum integration and pedagogical adaptation.

Infrastructure and Accessibility (Microsystem): It is essential to create a dependable technology infrastructure that immediately affects the students' immediate learning environment. Substantial investments are required to provide access to high-speed internet and modern technology, ensuring equitable access across all ecosystems, from urban to rural areas. This microsystem support ensures that individual learners and instructors possess the technology resources required for efficient digital learning.

Teacher Training and Professional Development (Exosystem): Educators require thorough instruction in the most up-to-date educational technologies and data literacy to adjust and employ technology proficiently within their educational settings. This training, often driven by decisions made at the institutional or district level, prepares educators to effectively incorporate technology into their teaching practices, influencing the overall educational environments in which they work. Additionally, a phased implementation approach is considered, beginning with pilot programs in select departments over a 6–12-month period, as shown in Table 2. Following successful pilot studies, institutions can scale up the framework, ensuring all educators receive the necessary training and support. Regular evaluations should occur every six months to assess the framework's effectiveness in improving student retention and achievement.

Curriculum integration and pedagogical adaptation at the macrosystem level refers to incorporating curriculum content and adjusting teaching methods to meet the needs of a more extensive educational system or framework. Modifying the curriculum and teaching approaches to incorporate technology demonstrates the more comprehensive cultural values and trends towards digital literacy and interactive learning. This adaptation is demonstrated by transitioning from traditional lecture-based models to interactive, student-centred learning environments seamlessly incorporating technology into teaching and learning processes. The alterations occurring at the macrosystem level significantly impact how education systems adapt to the problems and opportunities presented by the digital age.

Furthermore, it is crucial to establish a comprehensive monitoring and evaluation system (Chronosystem) to consistently evaluate the efficacy of technological integration and make any adjustments as needed. This component encompasses the transformations and progressions that occur as technological improvements evolve and educational requirements alter.

Finally, promoting inclusivity and equity in the availability of technology-enhanced education (Mesosystem) facilitates the connections between many locations, including the home, school, and community settings. All individuals involved in education must work together to create inclusive policies and support systems and ensure that all students, regardless of their background, may take advantage of technological improvements. Taking a complete strategy and using Bronfenbrenner's ecological lens is essential to utilize technology and sustainably improve learning outcomes successfully.

The framework's sustainability will also depend on its scalability and adaptability to changing educational and technological landscapes. Institutions must adopt flexible strategies that allow for the ongoing refinement of educational technologies based on student and educator feedback. Although this study focuses on engineering education, the principles of the framework can be applied across disciplines, offering opportunities for innovation in fields like health sciences, business, and the arts.

As such, the combination of an ecological systems approach and educational technology in engineering education has the potential to revolutionize the learning process. However, it is crucial to carefully evaluate the educational advantages, technological obstacles, policy consequences, and potential effects on student achievement and retention. Ongoing adjustment and assistance are essential to fully achieving this groundbreaking method's advantages.

6 Conclusion

Integrating the ecological systems approach with educational technology in engineering education highlights a transformative pathway for enhancing teaching and learning environments. This investigation, enriched by informal interviews with educators, has underscored both the vast potential and the significant challenges inherent in such a framework. As revealed through discussions, adopting this approach can improve student engagement, personalized learning experiences, and better preparation for real-world engineering challenges.

However, this endeavour is not without its complexities. Challenges such as technological disparities, resistance to change, and the need for robust infrastructure and support systems need strategic attention. Addressing these issues requires a collaborative effort involving educators, policymakers, and technology specialists to ensure the framework's effective implementation and sustainability.

The potential for enhanced student retention and success further motivates the pursuit of this integration, indicating that when executed well, the benefits extend beyond academic performance to include more profound educational satisfaction and career readiness. Nonetheless, the path forward must include continuous assessment and adaptation. Institutions must proactively gather feedback, apply iterative improvements, and remain adaptable to the evolving technological landscape.

References

1. Andrews, J., Knowles, G., Clark, R.: Excellence in Engineering Education for the 21st Century: The Role of Engineering Education Research. (2019)
2. Zulu, C.: An exploratory study of first-year students at a historically black university campus in South Africa: their academic experiences, success and failure. Africa Educ. Rev. 5, 30–47 (2008). https://doi.org/10.1080/18146620802121576
3. Karataş, F.Ö., Bodner, G.M., Unal, S.: First-year engineering students' views of the nature of engineering: implications for engineering programmes. Eur. J. Eng. Educ. 41, 1–22 (2016). https://doi.org/10.1080/03043797.2014.1001821
4. Kloot, B., Rouvrais, S.: The South African engineering education model with a European perspective: history, analogies, transformations and challenges. Eur. J. Eng. Educ. 42, 188–202 (2017). https://doi.org/10.1080/03043797.2016.1263278
5. Froyd, J.E., Wankat, P.C., Smith, K.A.: Five Major Shifts in 100 Years of Engineering Education. Proc. IEEE. 100, 1344–1360 (2012). https://doi.org/10.1109/JPROC.2012.2190167
6. Burton, L.J., Dowling, D.G.: Key factors that influence engineering students' academic success: A longitudinal study. 2009 Res. Eng. Educ. Symp. REES 2009. (2009)

7. Dr. Neeraj Yadav: The Impact of Digital Learning on Education. Int. J. Multidiscip. Res. Arts, Sci. Technol. 2, 24–34 (2024). https://doi.org/10.61778/ijmrast.v2i1.34
8. Haleem, A., Javaid, M., Qadri, M.A., Suman, R.: Understanding the role of digital technologies in education: A review. Sustain. Oper. Comput. 3, 275–285 (2022). https://doi.org/10.1016/j.susoc.2022.05.004
9. Christodoulou, A., Angeli, C.: Adaptive Learning Techniques for Personalized Educational Software in Developing Teachers' Technological Pedagogical Content Knowledge. Front. Educ. 7, (2022). https://doi.org/10.3389/feduc.2022.789397
10. Chugh, R., Turnbull, D., Cowling, M.A., Vanderburg, R., Vanderburg, M.A.: Implementing educational technology in Higher Education Institutions: A review of technologies, stakeholder perceptions, frameworks and metrics. Educ. Inf. Technol. 28, 16403–16429 (2023). https://doi.org/10.1007/s10639-023-11846-x
11. Leal Filho, W., Raath, S., Lazzarini, B., Vargas, V.R., de Souza, L., Anholon, R., Quelhas, O.L.G., Haddad, R., Klavins, M., Orlovic, V.L.: The role of transformation in learning and education for sustainability. J. Clean. Prod. 199, 286–295 (2018). https://doi.org/10.1016/j.jclepro.2018.07.017
12. Vélez-Agosto, N.M., Soto-Crespo, J.G., Vizcarrondo-Oppenheimer, M., Vega-Molina, S., García Coll, C.: Bronfenbrenner's Bioecological Theory Revision: Moving Culture From the Macro Into the Micro. Perspect. Psychol. Sci. 12, 900–910 (2017). https://doi.org/10.1177/1745691617704397
13. Shelton, L.G.: The Bronfenbrenner Primer. Routledge, New York, NY : Routledge, 2018. (2018)
14. Tong, P., An, IS: Review of studies applying Bronfenbrenner's bioecological theory in international and intercultural education research. Front. Psychol. 14, (2024). https://doi.org/10.3389/fpsyg.2023.1233925
15. Mulisa, F.: Application of bioecological systems theory to higher education: Best evidence review. J. Pedagog. Social. Psychol. 1, 104–115 (2019)
16. Johnson, E.S.: Ecological Systems and Complexity Theory: Toward an Alternative Model of Accountability in Education. Complicity An Int. J. Complex. Educ. 5, (2008). https://doi.org/10.29173/cmplct8777
17. Allen, K.P.: Classroom Management, Bullying, and Teacher Practices. Prof. Educ. 34, 1–15 (2010)
18. Hayes, N., O'Toole, L., Halpenny, A.M.: Introducing Bronfenbrenner. Routledge, Abingdon, Oxon ; New York, NY : Routledge, 2017. | Series: Introducing Early Years Thinkers (2017)

19. Govender, S., Immenga, C., Gachago, D.: Designing Systems with Care: Responding to Inequality in an Online Course in South Africa. J. Appl. Instr. Des. (2023). https://doi.org/10.59668/722.13023
20. Kasabova, G., Parusheva, S., Bankov, B.: Learning Management Systems as a Tool for Learning in Higher Education. Izv. J. Union Sci. - Varna. Econ. Sci. Ser. 12, 224–233 (2023). https://doi.org/10.56065/IJUSV-ESS/2023.12.2.224
21. Wen, Z.: Research on the Application of Virtual Simulation Software in the Course of Building Environment. Proc. 2021 2nd Int. Conf. Ment. Heal. Humanit. Educ. 2021）. 561, 617–620 (2021). https://doi.org/10.2991/assehr.k.210617.150
22. May, D., Alves, G.R., Kist, A.A., Zvacek, S.M.: Online Laboratories in Engineering Education Research and Practice. In: International Handbook of Engineering Education Research. pp. 525–552. Routledge, New York (2023)
23. The Role of Collaboration Tools in Digital Transformation, https://www.trigyn.com/insights/collaboration-tools-digital-transformation
24. Vali, I.: The Impact of Technology on Collaborative Learning. Presented at the April 10 (2023)
25. Xu, Z.: AI in education: Enhancing learning experiences and student outcomes. Appl. Comput. Eng. 51, 104–111 (2024). https://doi.org/10.54254/2755-2721/51/20241187
26. Kaledio, P., Robert, A., Frank, L.: The Impact of Artificial Intelligence on Students' Learning Experience. SSRN Electron. J. (2024). https://doi.org/10.2139/ssrn.4716747
27. Qadir, J.: Engineering Education in the Era of ChatGPT: Promise and Pitfalls of Generative AI for Education. IEEE Glob. Eng. Educ. Conf. EDUCON. 2023-May, (2023). https://doi.org/10.1109/EDUCON54358.2023.10125121
28. Zhai, X.: ChatGPT: Artificial Intelligence for Education. Support. Instr. Decis. Mak. Potential An Autom. Scored Three-Dimensional Assess. Syst. (2022). https://doi.org/10.13140/RG.2.2.35971.37920
29. Hasanein, A.M., Sobaih, A.E.E.: Drivers and Consequences of ChatGPT Use in Higher Education: Key Stakeholder Perspectives. Eur. J. Investig. Heal. Psychol. Educ. 13, 2599–2614 (2023). https://doi.org/10.3390/ejihpe13110181
30. Montenegro-Rueda, M., Fernández-Cerero, J., Fernández-Batanero, J.M., López-Meneses, E.: Impact of the Implementation of ChatGPT in Education: A Systematic Review. Computers. 12, 153 (2023). https://doi.org/10.3390/computers12080153
31. May, D.: Cross Reality Spaces in Engineering Education – Online Laboratories for Supporting International Student Collaboration in Merging Realities. Int. J. Online Biomed. Eng. 16, 4–26 (2020). https://doi.org/10.3991/ijoe.v16i03.12849

32. Kist, A.A., Hills, C., Maiti, A.: The Role of Online and Traditional Laboratories in the Context of Modern Engineering Curricula. Presented at the (2024)
33. Bairaktarova, D., Valentine, A., Ghannam, R.: The Use of Extended Reality (XR), Wearable, and Haptic Technologies for Learning Across Engineering Disciplines. In: International Handbook of Engineering Education Research. pp. 501–524. Routledge, New York (2023)
34. Lawson, A.P., Martella, A.M.: Critically reflecting on the use of immersive virtual reality in educational settings: What is known and what has yet to be shown? J. Appl. Learn. Teach. 6, 121–133 (2023). https://doi.org/10.37074/jalt.2023.6.2.35
35. Mcpherson, T.: Digital Youth, Innovation, and The Unexpected. (2008)
36. Sprenger, D.A., Schwaninger, A.: Technology acceptance of four digital learning technologies (classroom response system, classroom chat, e-lectures, and mobile virtual reality) after three months' usage. Int. J. Educ. Technol. High. Educ. 18, 8 (2021). https://doi.org/10.1186/s41239-021-00243-4
37. Baniasadi, T., Ayyoubzadeh, S.M., Mohammadzadeh, N.: Challenges and Practical Considerations in Applying Virtual Reality in Medical Education and Treatment. Oman Med. J. 35, e125–e125 (2020). https://doi.org/10.5001/omj.2020.43
38. Gottschalk, F., Weise, C.: Digital equity and inclusion in education: An overview of practice and policy in OECD countries. Organ. Econ. Co-operation Dev. 1–73 (2023)
39. Waugh, M., Guhn, M.: Bioecological Theory of Human Development. In: Encyclopedia of Quality of Life and Well-Being Research. pp. 398–401. Springer Netherlands, Dordrecht (2014)
40. Nguyen, L.T., Kanjug, I., Lowatcharin, G., Manakul, T., Poonpon, K., Sarakorn, W., Somabut, A., Srisawasdi, N., Traiyarach, S., Tuamsuk, K.: How teachers manage their classroom in the digital learning environment – experiences from the University Smart Learning Project. Heliyon. 8, e10817 (2022). https://doi.org/10.1016/j.heliyon.2022.e10817
41. Omidire, M.F.: Experiencing language challenges in a rural school: implications for learners' life aspirations. Early Child Dev. Care. 190, 1619–1637 (2020). https://doi.org/10.1080/03004430.2019.1660963
42. Mlambo, D.N., Mahlaba, S. Mphurpi, J.H. and Buys, T.: African Journal of Development Studies (AJDS) Special issue on Reimagining the Developmental State in South Africa The Changing Environment in South Africa's Higher Education Institutions Due to the COVID-19 Pandemic : Reference from Historically Bla. African J. Dev. Stud. 6, 351–271 (2023)

43. Bronfenbrenner, U.: Ecological models of human development. Husen, T. Postlethwaite, T.N. (Eds.), Int. Encycl. Educ. (2nd ed. 3, 1643–1647 (1994). https://doi.org/10.4324/9780203730386-13
44. Spaull, N.: Equity: A Price Too High to Pay? In: South African Schooling: The Enigma of Inequality. pp. 1–24. Springer International Publishing, Cham (2019)
45. Dlamini, R.: Complex Inequalities and Inequalities in Education. Altern. Interdiscip. J. Study Arts Humanit. South. Africa. 39, (2022). https://doi.org/10.29086/2519-5476/2022/sp39a9
46. Hannaway, D., Steyn, M., Hartell, C.: The Influence of Ecosystemic Factors on Black Student Teachers' Perceptions and Experience of Early Childhood Education. South African J. High. Educ. 28, 386–409 (2014)
47. El Zaatari, W., Maalouf, I.: How the Bronfenbrenner Bio-ecological System Theory Explains the Development of Students' Sense of Belonging to School? SAGE Open. 12, 215824402211340 (2022). https://doi.org/10.1177/21582440221134089
48. Heradio, R., de la Torre, L., Dormido, S.: Virtual and remote labs in control education: A survey. Annu. Rev. Control. 42, 1–10 (2016). https://doi.org/10.1016/j.arcontrol.2016.08.001
49. Maringe, F., Chiramba, O.: Equity, access and success in higher education in times of disruption: Contemporary and future imaginaries. South African J. High. Educ. 36, 1–5 (2022). https://doi.org/10.20853/36-4-5285
50. Holmes, R.M., Gardner, B., Kohm, K., Bant, C., Ciminello, A., Moedt, K., Romeo, L.: The relationship between young children's language abilities, creativity, play, and storytelling. Early Child Dev. Care. 189, 244–254 (2019). https://doi.org/10.1080/03004430.2017.1314274
51. Jandrić, P., Knox, J., Besley, T., Ryberg, T., Suoranta, J., Hayes, S.: Postdigital science and education. Educ. Philos. Theory. 50, 893–899 (2018). https://doi.org/10.1080/00131857.2018.1454000
52. Lim, T., Gottipati, S., Cheong, M.L.F.: Educational Technologies and Assessment Practices. Presented at the April 26 (2024)
53. Sala, R., Maffei, A., Pirola, F., Enoksson, F., Ljubić, S., Skoki, A., Zammit, J.P., Bonello, A., Podržaj, P., Žužek, T., Priarone, P.C., Antonelli, D., Pezzotta, G.: Blended learning in the engineering field: A systematic literature review. Comput. Appl. Eng. Educ. 32, (2024). https://doi.org/10.1002/cae.22712