CTE Workshop Proceedings, 2025, Vol. **12**, pp. 197–221 https://doi.org/10.55056/cte.929

STEM project design in computer microelectronics education

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Abstract. STEM education has emerged as a critical approach for developing 21st century skills in higher education students. This paper investigates the implementation of STEM project design in computer microelectronics education, focusing on the integration of virtual simulations using Tinkercad and physical implementation with Arduino microcontrollers. The research demonstrates how this dual approach enhances students' interdisciplinary skills through project-based learning. Drawing on the theoretical foundations of experiential learning, constructionism, and Technological Pedagogical Content Knowledge (TPACK), the study analyzes the stages of STEM project implementation from problem definition to final presentation. The research reveals that the combination of virtual modeling and physical prototyping creates a comprehensive learning environment that promotes critical thinking, problem-solving, and technical competencies. Assessment frameworks and implementation guidelines derived from this study provide valuable insights for educators seeking to integrate STEM approaches in technical education. The findings contribute to the broader understanding of effective STEM education methodologies while addressing the specific challenges of computer microelectronics instruction in higher education settings.

Keywords: STEM education, project-based learning, computer microelectronics, Arduino, Tinkercad, virtual simulation, physical implementation, higher education, Technological Pedagogical Content Knowledge, competency assessment, dual-environment learning, interdisciplinary education

1. Introduction

In the rapidly evolving technological landscape of the 21st century, the development of STEM (Science, Technology, Engineering, and Mathematics) competencies has become paramount for preparing future professionals. Traditional educational approaches, often characterized by compartmentalized learning of separate subjects, increasingly fail to develop the integrated knowledge and interdisciplinary skills required in modern workplaces. This challenge is particularly evident in the field of computer microelectronics, where theoretical knowledge must be seamlessly coupled with practical application across multiple disciplines.

STEM education has gained significant momentum globally as an educational approach that fosters interdisciplinary learning and collaboration. Countries including the United Kingdom, China, Australia, Israel, Singapore, South Korea, and the United States have implemented national programs focused on STEM education [14]. In Ukraine, the development of digital competencies has been recognized as a key

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priority, as evidenced by various regulatory documents including the Law of Ukraine "On Education" and the Concept for the Development of Digital Competencies. The Concept for the Development of Natural Sciences and Mathematics Education (STEM Education) through 2027 further emphasizes STEM education as a priority direction for educational development [16].

The integration of technology in higher education presents significant challenges, including resource limitations, faculty preparation, and effective pedagogical approaches [22]. Research has shown that active learning strategies, particularly project-based learning, significantly enhance student engagement and learning outcomes in STEM fields [32]. The marriage of virtual simulations with physical implementation offers a promising approach to addressing these challenges, providing students with both conceptual understanding and hands-on experience.

Virtual laboratory environments enable students to experiment safely, iterate quickly, and develop conceptual understanding before working with physical components [18]. Platforms such as Tinkercad provide accessible entry points for students to design and test electronic circuits without the constraints of physical resources [35]. However, the transition from virtual to physical implementation remains a critical step in developing comprehensive technical competencies [25].

The Arduino platform has emerged as a versatile tool for STEM education, offering an open-source, cost-effective solution for teaching electronics, programming, and design [31]. Its accessibility and flexibility make it particularly well-suited for educational settings where resources may be limited [21]. The combination of Arduino with virtual simulation platforms creates a powerful educational ecosystem that supports the full cycle of design, testing, and implementation [27].

Despite the potential benefits of integrating STEM approaches in computer microelectronics education, there remains a gap in the literature regarding effective implementation methodologies that bridge virtual and physical learning environments. Furthermore, there is limited research on assessment frameworks specifically tailored to STEM project-based learning in technical higher education contexts [2].

This paper addresses these gaps by analyzing a STEM project design approach implemented in a computer microelectronics course at Pavlo Tychyna Uman State Pedagogical University. The research examines how the integration of Tinkercad for virtual modeling and Arduino for physical implementation enhances student learning across multiple dimensions of STEM competencies. By documenting the implementation process, analyzing its theoretical foundations, and developing assessment frameworks, this study contributes to both the theoretical understanding and practical application of STEM approaches in higher education.

The remainder of this paper is structured as follows: section 2 establishes the theoretical framework underpinning STEM education and project-based learning; section 3 reviews the literature on STEM implementation, technology platforms, and assessment approaches; section 4 details the methodology of the STEM project design implementation; section 5 analyzes the findings and discusses their implications; section 6 presents a framework for STEM project design in higher education; section 7 explores future directions; and section 8 concludes with key insights and recommendations.

2. Theoretical framework

The implementation of STEM project design in computer microelectronics education draws upon several interconnected theoretical perspectives that form a robust foundation for understanding both the pedagogical principles and practical applications. This section explores how these theoretical foundations inform the integration of virtual and physical learning environments in STEM education.

STEM education represents a paradigm shift from traditional disciplinary teaching toward an integrated approach that reflects the interconnected nature of science, technology, engineering, and mathematics in real-world applications [6]. Unlike conventional educational models that compartmentalize knowledge, STEM education emphasizes the synthesis of concepts across disciplines to solve complex problems. As Sujarwanto, Madlazim and Sanjaya [33] explain, effective STEM education maintains the principles of individual disciplines while creating meaningful connections between them through authentic learning experiences.

The conceptual framework proposed by Murphy, MacDonald and Danaia [23] identifies three key interacting components essential for effective STEM education: knowledge (the nature of STEM knowing and understanding), skills (transdisciplinary competencies beyond individual STEM disciplines), and engagement (the affective domain of STEM education). This framework emphasizes the importance of addressing critical issues such as transitions and trajectories, gender equity, socioeconomic factors, and cultural diversity in STEM education – elements that significantly influence student participation and success.

Project-based learning serves as a primary pedagogical approach within STEM education, providing a structured framework for interdisciplinary learning through authentic problem-solving experiences [30]. Rooted in constructivist learning principles, project-based learning posits that students actively construct knowledge through experience and reflection rather than passively receiving information. Toma, Yánez-Pérez and Meneses-Villagrá [34] emphasize that socio-constructivist principles are particularly valuable in STEM education, as they establish connections between disciplines through scientific inquiry, engineering design, and computational thinking.

The experiential learning theory articulated by Kolb offers a valuable framework for understanding how direct experience translates into knowledge acquisition in STEM contexts. The experiential learning cycle – comprising concrete experience, reflective observation, abstract conceptualization, and active experimentation – aligns closely with the processes involved in STEM project design [3]. Students engage with concrete experiences through both virtual simulation and physical implementation, reflect on these experiences through documentation and discussions, form abstract conceptualizations about circuit behavior and programming principles, and actively experiment through iterative design and testing.

Problem-solving skill development represents a central objective of STEM project-based learning. Zeeshan, Watanabe and Neittaanmaki [40] identify specific cognitive processes that develop through STEM learning approaches, including problem definition, information gathering, solution generation, evaluation, and implementation. These processes align with engineering design thinking and computational problem-solving approaches integral to microelectronics education, creating a natural pathway for students to develop these skills through authentic project work.

The successful integration of technology in STEM education also relies heavily on teachers' development of appropriate knowledge and skills. The Technological Pedagogical Content Knowledge (TPACK) framework provides a theoretical lens for understanding the complex interplay of knowledge domains required for effective technology integration in educational settings [28]. TPACK extends Shulman's concept of Pedagogical Content Knowledge (PCK) by adding technology as a third knowledge domain, resulting in seven distinct but interconnected knowledge areas that teachers must develop to effectively integrate technology in their teaching practices.

Koh, Chai and Tsai [15] found that teachers' perceptions of technology integration in constructivist-oriented learning environments are significantly influenced by their technological pedagogical knowledge (TPK), technological content knowledge (TCK), and technological knowledge (TK). These findings highlight the importance of developing these intermediate knowledge forms in preparing educators to implement STEM project-based learning effectively. Polly and Byker [29] further connected TPACK development to Vygotsky's Zone of Proximal Development, emphasizing the need for scaffolded experiences that enable the integration of technology, pedagogy, and content knowledge through experiential learning opportunities.

Drawing these theoretical perspectives together, we can understand STEM project design as a complex educational approach that integrates constructivist learning principles, experiential learning cycles, problem-solving skill development, and technological pedagogical content knowledge. The dual-environment approach of virtual simulation and physical implementation creates complementary learning contexts that support different aspects of this integrated theoretical framework. Virtual environments facilitate rapid prototyping, experimentation, and conceptual understanding, while physical implementation develops hands-on skills, troubleshooting abilities, and deeper understanding of real-world constraints.

3. Literature review

The implementation of STEM project design in computer microelectronics education builds upon a rich body of research spanning multiple domains. This section explores the current landscape of STEM education globally, examines technology platforms supporting STEM learning, investigates assessment approaches for project-based learning, and identifies key challenges in effective STEM implementation.

3.1. Global implementation of STEM education

STEM education has gained significant traction globally, with diverse approaches to integrating science, technology, engineering, and mathematics into educational curricula. Jamaluddin, Razak and Rahim [14] conducted a comprehensive scoping review of STEM education in the Asia-Pacific region, identifying seven primary challenges: teaching practices, learning approaches, gender disparities, location, career interest, student enrollment, and student soft skills. Their research revealed that Malaysia and India have emerged as leading contributors to STEM education, with approximately 43.5% and 34.0% of tertiary students earning STEM degrees, respectively.

Despite increasing research output, Kurniati et al. [17] found that international collaboration among STEM researchers remains limited. Their systematic review highlighted the need for cross-country and cross-cultural research collaborations to maximize the impact of STEM research and dissemination. This finding points to an important gap in the current research landscape, suggesting that greater collaborative efforts could enhance the effectiveness of STEM education globally.

The conceptual frameworks underpinning STEM education vary across regions, reflecting cultural and educational contexts. Sujarwanto, Madlazim and Sanjaya [33] proposed a conceptual framework for STEM education based on the Indonesian curriculum, emphasizing the importance of maintaining the principles of science, technology, and mathematics while integrating the engineering design process. Similarly, Yata, Ohtani and Isobe [39] developed a framework based on Japanese subject principles, highlighting the need for cultural contextualization in STEM implementation. These diverse frameworks demonstrate how STEM education adapts to different cultural and educational contexts while maintaining core principles.

In higher education contexts, STEM implementation often emphasizes sustainability and community engagement. Zizka, McGunagle and Clark [42] examined STEM higher education institutions in the United States, finding that on-campus efforts primarily focused on environmental actions, while community engagement projects emphasized social or economic principles of sustainability. Their research identified a gap between theoretical learning in the classroom and practical application in real-world contexts – a challenge that project-based learning approaches may help address.

3.2. Technology platforms in STEM education

Technology platforms play a crucial role in supporting STEM education, particularly in fields such as computer microelectronics where hands-on experience with electronic components and programming is essential. Virtual laboratories and simulation environments have become increasingly important tools for enhancing STEM learning experiences.

Ghergulescu et al. [11] found that virtual laboratories provide valuable opportunities for students to conduct experiments in controlled environments at their own pace, addressing challenges such as limited resources, safety concerns, and geographical limitations. Lynch and Ghergulescu [20] identified key benefits of virtual labs in STEM education, including instant feedback to students, inquiry-based learning opportunities, and the elimination of hazards associated with physical laboratories.

The effectiveness of virtual labs in promoting student learning has been demonstrated in multiple studies. Pang et al. [26] conducted a systematic review of science learning using virtual simulation technologies, finding positive impacts on student motivation, autonomy, interest, and confidence. Their research highlighted the pedagogical effectiveness of virtual simulations when integrated within a broader educational framework that connects virtual experiences to learning objectives and assessment approaches.

Tinkercad has emerged as a particularly valuable platform for teaching electronics and circuit design. Tselegkaridis, Sapounidis and Papakostas [35] compared different interfaces for learning circuits and coding with Arduino, finding that students who used a graphical user interface like Tinkercad reported enhanced understanding of the interconnection of components in microcontroller circuits. The intuitive, visual nature of the Tinkercad environment appears to support conceptual understanding of complex electronic systems.

The Arduino platform has become increasingly prevalent in STEM education as an accessible and versatile tool for teaching electronics, programming, and design principles. Recktenwald and Hall [31] documented the adaptation of the Living with the Lab curriculum to the Arduino platform, finding that while Arduino offered superior technical capabilities compared to alternatives, there were initially fewer educational resources available – a gap that has been increasingly addressed in recent years.

Several studies have explored the specific educational benefits of Arduino-based learning. Chaudry [5] used Arduino Uno microcontrollers as an extra-credit activity in undergraduate physics courses, reporting increased student interest in physics and improved understanding of basic physics concepts. Marzoli et al. [21] found that Arduino improved laboratory practice in Italian upper secondary schools and positively influenced students' attitudes toward STEM subjects. These findings suggest that Arduino-based projects can enhance both content understanding and affective engagement with STEM disciplines.

Comparative analyses of different microcontroller platforms provide insights into their relative strengths for educational purposes. Pech and Novak [27] compared Arduino and Micro:bit as teaching platforms for programming and electronics education, finding that while both platforms were effective, Micro:bit was often more appropriate for beginners due to its simplicity and ease of use. This highlights the importance of selecting appropriate technologies based on student experience levels and educational objectives.

The integration of Arduino with online platforms like Tinkercad creates powerful educational ecosystems that support the full development cycle from design to implementation. Oteri [25] described a practical-based e-examination system using the Arduino e-kit for STEM electronic and mobile learning, highlighting how the combination of Arduino microcontrollers, sensors, and free cloud-based software enabled students to apply their knowledge to solve real-world problems. This integration of virtual and physical tools creates a more comprehensive learning environment that addresses multiple aspects of STEM competency development.

3.3. Assessment approaches in STEM project-based learning

Effective assessment of STEM project-based learning requires methods that address both the process and products of student work across multiple dimensions of competency. Traditional assessment approaches often fail to capture the complexity of skills and knowledge developed through interdisciplinary STEM projects.

Competency-based assessment provides a foundation for evaluating student development in STEM project-based learning. Arikan, Erktin and Pesen [2] developed and validated a STEM competencies assessment framework that addresses the multidimensional and integrated structure of STEM competencies. Their framework incorporated science, technology, engineering, and mathematics domains, using problems that required mathematical calculations as a medium for assessment. This multidimensional approach acknowledges the integrated nature of STEM competencies and provides a more comprehensive view of student development.

The development of rubrics specifically tailored to STEM education has been documented in several studies. Eltanahy and Mansour [9] created and validated a rubric for assessing students' competencies in entrepreneurial-STEM learning contexts. Their mixed-methods approach involved faculty, assessment experts, and students, resulting in a tool that offered constructive feedback on learners' competencies and performance while establishing a more visible learning context. Huang and Jong [13] proposed a generic rubric for evaluating students' work in STEM education, identifying six dimensions: problem definition, feasibility, usability, teamwork, entrepreneurship, and overall presentation and justifications. Their work emphasized the importance of design principles in creating effective evaluation tools for STEM learning.

Authentic assessment approaches, which evaluate students' abilities in real-world contexts, have particular relevance for STEM project-based learning. Vrioni, Mavroudi and Ioannou [36] documented the development and use of rubrics for authentic assessment in STEM project-based learning activities, employing an iterative and participatory approach to create and implement assessment tools. Capraro and Corlu [4] noted that STEM project-based learning shifts the focus from summative to formative assessment, with greater attention to the interpersonal domain. Their research emphasized that authentic assessment in STEM project-based learning helps students transition from authority-imposed regulation to self-regulation of their learning – a key aspect of developing lifelong learning capabilities.

Self-assessment rubrics have shown promise in improving student project work while reducing instructor workload. Faletič [10] described the use of scientific abilities rubrics in a project laboratory course, finding that the average assessment time decreased while the quality of student reports increased when students were engaged in self-assessment. This suggests that well-designed rubrics can serve dual purposes of enhancing student learning through reflection while also making assessment more efficient for instructors.

Beyond content knowledge, STEM education aims to develop process skills such as critical thinking, problem-solving, and collaboration. Cole et al. [7] explored the assessment of process skills in STEM education, developing rubrics for critical thinking, information processing, and teamwork. Their research emphasized the importance of aligning instructional methods with assessment practices to enhance learning outcomes. Woodhall and Strong [38] developed a rubric-based assessment methodology for student design projects that linked directly to course learning objectives. Their approach emphasized the assessment of process and techniques critical to professional engineering practice rather than focusing solely on deliverables as products.

Assessment methodologies in STEM education continue to evolve as researchers and practitioners seek more effective ways to evaluate complex, interdisciplinary learning. The integration of technology in assessment, such as the use of AI and computer vision for classroom observations [1], represents an emerging frontier that may enhance the accuracy and efficiency of STEM project evaluation. These technological approaches may be particularly valuable for capturing complex process data that traditional assessment methods might miss.

3.4. Challenges and barriers to effective STEM implementation

Despite the potential benefits of STEM education, numerous challenges and barriers can impede effective implementation, particularly in resource-constrained environments. Understanding these challenges is essential for developing strategies to overcome them.

The preparation and support of faculty represent significant challenges in STEM implementation. Weng, Jong and Chiu [37] identified lack of pedagogical content knowledge (PCK) and external support as the main challenges facing teachers implementing STEM education. Their research highlighted the need for targeted professional development to enhance teachers' ability to integrate STEM disciplines effectively. Zhang, Zhou and Zhang [41] conducted a meta-analysis of interventions to promote teachers' perceptions about STEM education, finding that curriculum-based interventions and professional development programs had the strongest effect on improving teachers' STEM knowledge. Their analysis showed that in-service teachers were inclined to benefit more from interventions in both STEM knowledge and STEM teaching skill perceptions compared to pre-service teachers, suggesting the importance of contextualizing professional development within authentic teaching practice.

Nelson and Brennan [24] proposed the LENS (Learning Environments Nurture Success) model for engineering faculty development, which aligns with evidence-based characteristics of effective learning environments for engineering students. Their model addresses academic rigor, focus on learning, instructional support, quality of teaching, student-faculty relationships, and student engagement. This comprehensive approach to faculty development acknowledges the multifaceted nature of effective STEM teaching and provides a framework for enhancing faculty capabilities across multiple dimensions.

Resource limitations present significant challenges to STEM implementation, particularly in contexts where access to technology and materials may be constrained. Hossain, Deehan and Gibbs [12] found that teachers in STEM classrooms frequently face challenges including limited time, insufficient funding, restricted access, and inadequate training and professional development opportunities. These resource constraints can significantly limit the types of STEM activities that teachers can implement, potentially reducing the effectiveness of STEM education.

Technology adoption in higher education faces numerous barriers, as documented by Mirriahi, Dawson and Hoven [22]. Their research using social network analysis identified key actors within departmental social networks who can facilitate technology adoption. Lubis and Yus [19] mapped knowledge and research trends on technology adoption in higher education, finding significant growth in research interest but persistent challenges in implementation. These challenges highlight the need for strategic approaches to technology adoption that address both technical and social dimensions of educational change.

The literature review reveals a rich body of research on STEM education implementation, technology platforms, assessment approaches, and implementation challenges. While significant progress has been made in understanding effective STEM education practices, gaps remain in our understanding of how to integrate virtual and physical learning environments effectively, particularly in resource-constrained contexts. The following sections build upon this literature to describe and analyze the implementation of STEM project design in computer microelectronics education.

4. Methodology

4.1. Educational context

The implementation of STEM project design took place within the course "Fundamentals of Computer Microelectronics" offered as part of the "Secondary Education (Informatics)" educational program at Pavlo Tychyna Uman State Pedagogical University. This elective course, provided to third-year undergraduate students, builds upon their existing foundational programming skills and understanding of basic algorithmic structures.

The educational context presented both opportunities and constraints for STEM implementation. Students brought valuable prior knowledge of programming concepts and logical structures, creating a foundation for more advanced learning. However, their experience with hardware components and electronics varied considerably, requiring flexible instructional approaches. The institutional context included computer laboratories with internet access, essential for the virtual simulation component, but only a limited set of Arduino components for physical implementation – a common resource constraint in many educational settings.

As an elective course within a teacher preparation program, the implementation needed to develop not only technical competencies in microelectronics but also pedagogical skills that students would need as future informatics teachers. This dual focus on technical and pedagogical development created a rich learning context that aligned with the broader goals of STEM education in teacher preparation programs.

4.2. STEM project design process

The STEM project design process incorporated key elements of project-based learning while addressing the specific requirements of computer microelectronics education. The process was structured to be inherently iterative, with students revisiting earlier stages as needed based on testing results and emergent challenges. This iterative approach aligned with engineering design thinking and reinforced the problem-solving nature of STEM education.

The design process began with problem definition, where students formulated technical specifications that clearly defined the project topic, objectives, specific tasks, and completion timelines. This stage required students to articulate the problem to be addressed and the expected outcomes, fostering critical thinking and planning skills. Students then engaged in resource research, investigating existing implementations of similar projects and identifying relevant resources, platforms, and approaches. This stage supported the development of research skills and critical analysis of existing solutions.

Component selection followed, with students selecting appropriate Arduino components for their projects based on their research. This stage required students to apply interdisciplinary knowledge to make informed selections, considering functionality, compatibility, and resource constraints. Students then moved to schema design and prototyping, developing electronic circuit designs and prototypes using the Tinkercad platform. This stage focused on translating conceptual understanding into practical circuit designs, fostering spatial reasoning and technical design skills.

The programming stage involved developing code to control the Arduino components, applying programming concepts to implement project functionality. This stage integrated computational thinking with electronics knowledge, creating authentic contexts for applying programming skills to physical systems. Finally, students documented their design process, implementation challenges, and solutions, creating comprehensive technical documentation that emphasized communication skills and reflective practice.

4.3. Implementation phases

The implementation progressed through several distinct phases, each with specific learning objectives and activities. The orientation phase introduced students to STEM project methodology, sample projects, and the Tinkercad and Arduino platforms. This phase established a foundation for subsequent work and helped students develop a vision for their projects.

The project definition phase engaged students in developing technical specifications, defining project scope, establishing evaluation criteria, and creating project timelines. This phase emphasized planning and project management skills, essential competencies for both academic and professional success. The resource exploration phase involved research on existing implementations, analysis of component specifications, exploration of Arduino libraries, and documentation of findings. This phase developed research skills and helped students build the knowledge base needed for successful project implementation.

The virtual design phase focused on the development of circuit schematics in Tinkercad, virtual component configuration, simulation testing, and documentation of design decisions. This phase provided a low-risk environment for students to experiment with circuit design and troubleshoot issues before working with physical components. The physical implementation phase involved the assembly of physical Arduino components, configuration of development environments, code upload, hardware testing, and troubleshooting. This phase developed hands-on technical skills and provided authentic problem-solving experiences as students addressed the challenges of physical implementation.

The documentation and presentation phase engaged students in compiling comprehensive project documentation, creating visual aids, preparing presentations, and reflecting on challenges and solutions. This phase developed communication skills and fostered metacognitive reflection on the learning process.

Each implementation phase incorporated elements from multiple STEM disciplines, creating authentic contexts for interdisciplinary learning. Science concepts from physics and electronics, technology tools such as Tinkercad and integrated development environments, engineering design processes and problem-solving methodologies, and mathematical concepts for circuit calculations and programming logic were integrated throughout the project process.

4.4. Tinkercad virtual environment

The Tinkercad online platform served as the primary virtual environment for the STEM project implementation. Several key features made it particularly suitable for this educational context. Its cross-platform compatibility ensured accessibility for all students regardless of their personal computing resources, as it requires only a web browser and stable internet connection. The intuitive graphical interface allowed students to build electronic circuits through an intuitive, drag-and-drop interface, reducing the initial technical barrier to entry.

Tinkercad's comprehensive component library provided models for most popular electronic components, enabling students to design complex circuits without physical limitations. The platform's circuit simulation capabilities, including electronic circuit simulators, sensor simulators, and external interaction tools, allowed students to test their designs without physical components. The visual code editor for programming Arduino boards supported both block-based and text-based programming approaches, accommodating different programming experience levels. Additionally, the platform provided examples of completed STEM projects with circuits and code, serving as references and inspiration for students.

Figure 1 shows a sample circuit design in the Tinkercad environment (reproduced from the original paper).

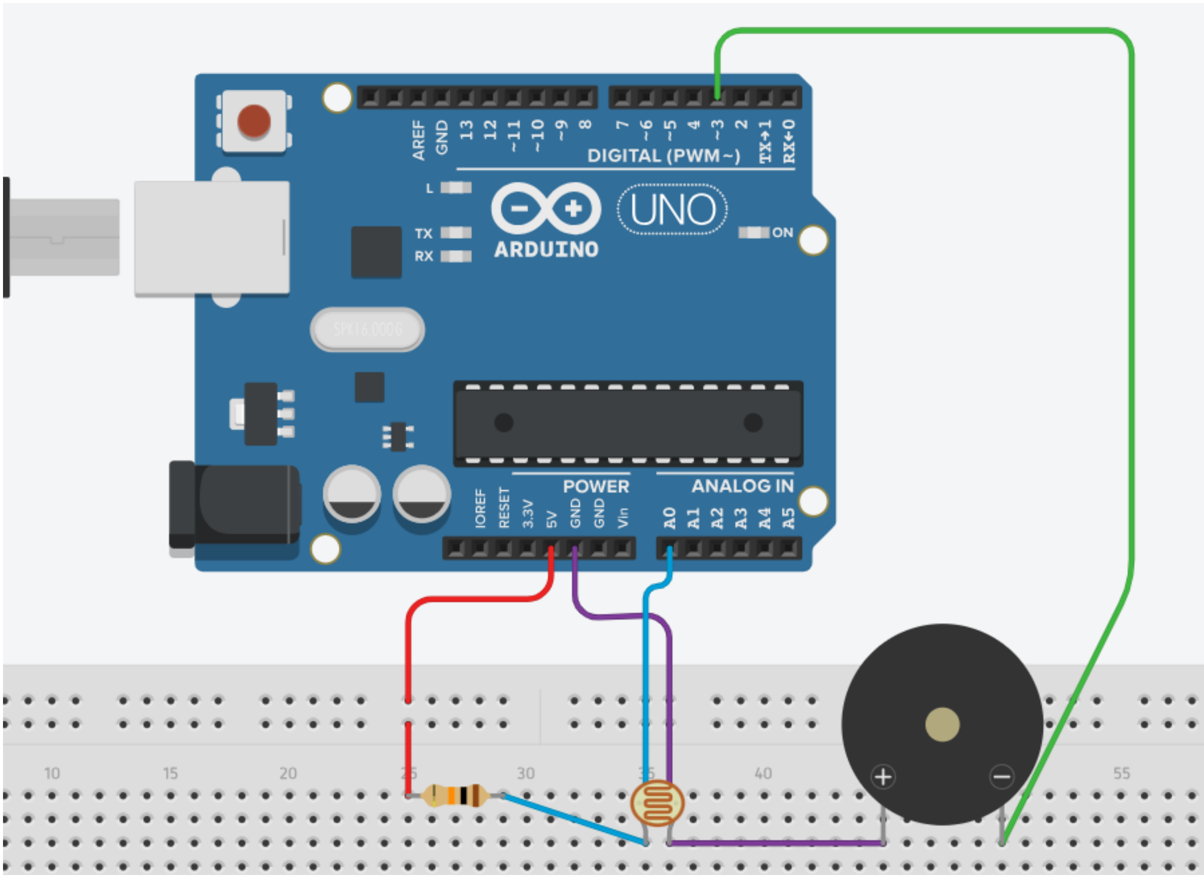

Figure 1: Example of circuit connection in Tinkercad.

The Tinkercad environment enabled students to rapidly prototype and test their circuit designs before committing to physical implementation. This approach aligned with the principles of experiential learning by providing a low-risk environment for concrete experience and reflective observation before moving to active experimentation with physical components.

4.5. Physical implementation with Arduino

Following successful virtual simulation in Tinkercad, students proceeded to physical implementation using Arduino microcontroller boards and components. This phase required students to apply knowledge from informatics and computer architecture to install and configure the integrated development environment (IDE) for Arduino programming, correctly connect the Arduino board to their computer, configure appropriate port settings in the operating system, upload program code to the Arduino board, assemble physical components according to their circuit design, and test and troubleshoot the physical implementation.

Figure 2 shows an example of a STEM project implemented on an actual Arduino board (reproduced from the original paper).

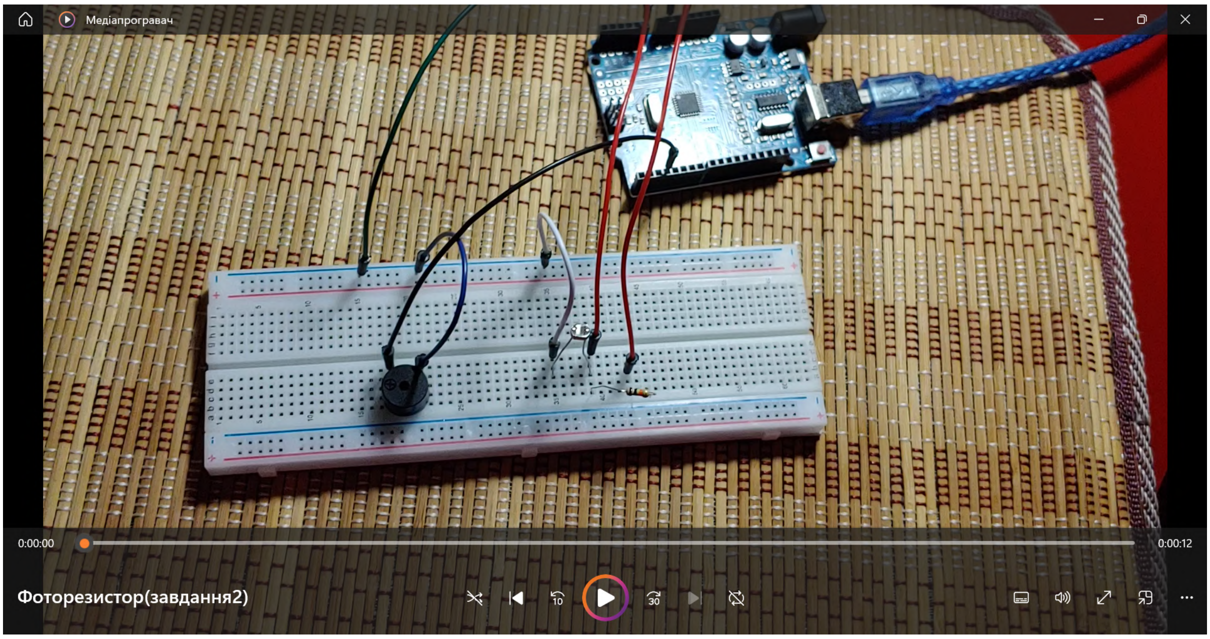

Figure 2: Implementation of STEM project on a real Arduino board.

The physical implementation phase presented unique challenges compared to virtual simulation, requiring students to account for physical constraints of components and connections, variations between simulated and actual component behavior, hardware-specific debugging requirements, real-world electrical considerations (resistance, voltage, current), and practical wiring and connection techniques. These challenges provided valuable learning opportunities, enhancing students' problem-solving skills and deepening their understanding of electronic principles through direct experience.

4.6. Documentation and assessment approach

The STEM project implementation incorporated a comprehensive documentation and assessment approach that emphasized both process and product evaluation. Throughout the project, students documented their work through technical specifications, circuit schematics, code documentation, implementation records, testing documentation, and reflective analysis. This extensive documentation created a rich record of the project development process and supported assessment of both technical and process skills.

The assessment approach incorporated both formative and summative elements. Formative assessment provided ongoing feedback during design and implementation phases, focusing on process improvements and technical refinements. Summative assessment evaluated final projects based on technical functionality, design quality, documentation completeness, and presentation effectiveness. Assessment criteria were aligned with the learning objectives and STEM competencies, emphasizing both technical skills and broader capabilities such as problem-solving, communication, and collaborative work.

5. Analysis and discussion

The dual-environment approach, incorporating both virtual simulation in Tinkercad and physical implementation with Arduino, revealed distinctive advantages and challenges for each environment. The virtual environment excelled in accessibility, providing universal access via web browsers without special hardware requirements and offering unlimited component availability. It presented a gentler learning curve with an intuitive interface, drag-and-drop functionality, and built-in examples. Perhaps most importantly, the virtual environment enabled risk-free experimentation with rapid iteration cycles and the ability to test extreme scenarios without fear of damaging components.

In contrast, the physical environment presented greater accessibility challenges, being limited by physical component availability and potential cost constraints. It involved a steeper initial learning curve, requiring physical dexterity and more complex troubleshooting. However, the physical environment provided authentic learning experiences that more closely resembled real-world engineering work. It offered tangible, real-world feedback across multiple sensory channels (visual, auditory, tactile) and developed practical technical skills that would transfer directly to professional contexts.

The comparative analysis reveals complementary strengths and weaknesses between virtual and physical implementation environments. The sequential progression from virtual to physical implementation leveraged these complementary strengths, allowing students to develop conceptual understanding and refine designs in a low-risk environment before tackling the additional challenges of physical implementation. This approach aligns with Bruner's scaffolding theory, providing appropriate support structures that are gradually removed as students develop competence.

5.1. Pedagogical implications of the STEM project approach

The implementation of STEM project design in computer microelectronics education revealed several important pedagogical implications that align with and extend current understanding of effective STEM education practices. The STEM project approach facilitated authentic integration of knowledge across science, technology, engineering, and mathematics domains. Students needed to apply concepts from electrical theory, circuit behavior, and physical principles; use software tools, programming languages, and digital interfaces; employ design methodology, prototyping, and iterative refinement; and utilize algorithmic thinking, circuit calculations, and logical operations.

This integration occurred naturally through the project requirements rather than being artificially imposed, demonstrating how project-based approaches can create authentic contexts for interdisciplinary learning. The integration also revealed the interconnected nature of these knowledge domains, helping students recognize how concepts from one discipline inform and enhance understanding in others.

The STEM project implementation supported the development of multiple competency dimensions. Technical skills including circuit design, programming, and troubleshooting were developed alongside cognitive skills such as problem-solving, critical thinking, and systems thinking. Professional skills including documentation, project management, and communication were enhanced through the project process. Personal skills including persistence, adaptability, and self-regulation were fostered through the challenges encountered and overcome. Collaborative skills including teamwork, peer learning, and knowledge sharing were developed through both formal and informal interactions during the project.

The implementation revealed the importance of balancing structured guidance with student autonomy in STEM project-based learning. The structured phases of the project provided scaffolding that supported student progress, while the open-ended nature of project definition and implementation fostered autonomy and creativity. This balance is particularly important in STEM education contexts where students may have varying levels of prior knowledge and confidence. The observation aligns with findings by Smith et al. [32], who identified principles of problem-based learning in STEM education that emphasize the importance of flexible knowledge, skills, and capabilities alongside structured support.

5.2. Analysis of student skill development

The STEM project implementation revealed patterns of student skill development across multiple dimensions. While quantitative data on skill development was not collected, qualitative observations suggest that students progressed through several developmental stages in key skill areas.

Initially, students exhibited tentative engagement with the project, characterized by limited technical vocabulary and heavy reliance on provided examples. As they progressed, they developed more robust conceptual understanding, demonstrated through improved technical communication, better understanding of component functions, and increased ability to follow established patterns. More advanced stages of development were marked by analytical application, where students demonstrated independent circuit design, systematic troubleshooting approaches, and adaptation of existing code for new purposes. The most advanced stage involved creative innovation, where students developed novel design solutions, integrated multiple components in original ways, and independently framed problems to be solved.

The progression through these stages was not uniform across all students or skill areas, with some students demonstrating advanced capabilities in certain domains while requiring more support in others. This observation aligns with the Sustaining STEM framework [23], which emphasizes the importance of addressing transitions and trajectories in STEM education.

The development of programming skills in particular showed interesting patterns, with students transferring previously acquired programming knowledge to the new context of microcontroller programming. This transfer was not always straightforward, as students needed to adapt their understanding to the constraints and capabilities of the Arduino platform. The concept of “near transfer” from cognitive learning theory provides a useful framework for understanding this process, where knowledge from one domain is applied to a similar but distinct context.

5.3. Theoretical connections

The implementation findings can be analyzed through several theoretical lenses, providing deeper insights into the learning processes involved in STEM project design. The implementation demonstrated clear connections to Kolb’s experiential learning cycle. Students engaged in concrete experiences through both virtual simulation and physical implementation, reflected on these experiences through documentation and discussions, formed abstract conceptualizations about circuit behavior and programming principles, and actively experimented through iterative design and testing.

The cyclical nature of this learning process was particularly evident in the iterative refinement of projects, where students revisited earlier stages based on testing outcomes and new insights. This observation aligns with findings by Collins and Redden [8], who documented the improvement of estimating abilities through experiential learning in a construction context. The iterative nature of the learning process appears to be a critical factor in developing more sophisticated understanding and skills.

The implementation revealed the interplay between technological, pedagogical, and content knowledge domains described in the TPACK framework. Faculty needed to integrate knowledge of Arduino platforms, Tinkercad, and programming environments; project-based learning approaches, formative assessment methods, and scaffolding techniques; and electronics principles, programming concepts, and design methodologies. This integration created a learning environment that supported students' development of similar integrated knowledge.

The implementation also embodied key principles of constructionist learning theory, particularly through the creation of tangible artifacts (Arduino projects) as expressions of conceptual understanding. Students constructed knowledge through the active process of designing, building, and refining their projects. This constructionist approach is particularly well-suited to computer microelectronics education, where abstract concepts can be made concrete through physical implementation. The dual-environment approach provided multiple pathways for this constructionist learning, allowing students to build understanding through both digital and physical construction activities.

5.4. Analysis of challenges and mitigation strategies

The implementation revealed several challenges consistent with those identified in the literature, along with effective strategies for addressing them. Resource limitations, particularly regarding the availability of Arduino components and accessories, represented a significant challenge. This aligns with findings by Hossain, Deehan and Gibbs [12], who identified resource constraints as a common challenge in STEM implementation across educational contexts.

The dual-environment approach provided an effective mitigation strategy by allowing students to develop and test designs virtually before requiring physical components. This approach optimized the use of limited physical resources while maintaining educational quality. Additionally, the implementation emphasized reusable components that could be reconfigured for multiple projects, maximizing the educational value of available resources.

Variations in students' prior knowledge of electronics and hardware concepts presented challenges for project implementation. Some students required additional support to bridge knowledge gaps, particularly regarding circuit principles and component characteristics. Effective mitigation strategies included providing supplementary learning resources tailored to specific knowledge domains, utilizing Tinkercad's built-in tutorials and examples to support self-directed learning, facilitating peer learning through informal knowledge sharing, and implementing just-in-time instruction addressing specific technical concepts as needed.

The integration of virtual simulation with physical implementation presented challenges related to differences between simulated and real-world behavior. Students sometimes encountered unexpected discrepancies when transitioning from Tinkercad to physical Arduino implementation. Mitigation strategies included explicit discussion of simulation limitations and potential discrepancies, structured comparison activities highlighting differences between virtual and physical environments, documentation requirements specifically addressing transition challenges and solutions, and incremental implementation approaches starting with simpler components.

5.5. Relationship to existing literature

The findings from this implementation both align with and extend the existing literature on STEM education and project-based learning. The implementation confirms several key findings from previous research: the value of project-based approaches for developing integrated STEM knowledge and skills [30]; the effectiveness of virtual laboratories in providing controlled environments for experimentation [11]; the importance of authentic assessment approaches that align with the collaborative and iterative nature of STEM work [36]; and the utility of Arduino platforms for enhancing student interest and understanding in STEM subjects [21].

The implementation extends the literature by providing insights into the specific benefits of integrating virtual and physical learning environments in a sequential implementation approach. While previous research has examined these environments separately, this implementation demonstrates how their integration creates a comprehensive learning experience that leverages the strengths of each environment while addressing its limitations.

Additionally, the implementation contributes to understanding how STEM project design can be effectively implemented in resource-constrained educational contexts, providing practical strategies for maximizing educational impact with limited materials and technology access. This addresses a gap identified by several researchers regarding the challenges of STEM implementation in diverse educational settings.

6. Framework for STEM project design in higher education

Based on the theoretical foundations, literature review, and implementation analysis, this section presents a comprehensive framework for STEM project design in higher education. This framework integrates key elements of effective STEM education with practical implementation strategies for computer microelectronics and similar technical fields.

The proposed framework builds on the theoretical model presented earlier, integrating insights from implementation and aligning with established principles of effective STEM education. The framework encompasses five interconnected dimensions, each with specific components that contribute to effective STEM project design: pedagogical foundations, implementation components, assessment approaches, support structures, and integration strategies.

The pedagogical foundations dimension encompasses the theoretical underpinnings that inform the educational approach, including constructivism, experiential learning, and project-based learning principles. These foundations provide the conceptual basis for understanding how students learn through STEM projects and guide instructional design decisions.

The implementation components dimension addresses the practical elements that structure the learning experience, including virtual simulation, physical implementation, and documentation processes. These components create the concrete learning activities through which students develop STEM competencies.

The assessment approaches dimension incorporates methods for evaluating and supporting student learning, including formative assessment, authentic evaluation, and competency rubrics. These approaches ensure that assessment aligns with the complex, interdisciplinary nature of STEM learning.

The support structures dimension encompasses the resources and systems that facilitate student success, including resource repositories, technical support, and peer learning opportunities. These structures address common challenges in STEM implementation and enhance the effectiveness of the learning environment.

The integration strategies dimension focuses on approaches for connecting STEM projects to broader educational and professional contexts, including curriculum alignment, interdisciplinary connections, and professional relevance. These strategies ensure that STEM projects contribute meaningfully to broader educational goals rather than existing as isolated experiences.

6.1. Key components of effective STEM project design

Within the comprehensive framework, several key components are essential for effective STEM project design in higher education. These components address the specific needs and challenges identified in the literature and implementation analysis.

The integration of virtual simulation and physical implementation environments represents a core component of effective STEM project design, particularly in technical fields such as computer microelectronics. This dual-environment structure creates a progressive learning pathway from conceptual understanding to practical application, addresses resource constraints by optimizing the use of physical components, provides multiple learning modalities that accommodate diverse student needs, and develops both virtual and physical implementation skills relevant to professional practice.

The implementation sequence should generally progress from virtual simulation to physical implementation, with opportunities for iteration between environments as needed. This approach allows students to develop conceptual understanding and refine designs in a low-risk virtual environment before addressing the additional complexities of physical implementation.

Effective STEM project design requires a balance between structured guidance and student autonomy. The framework incorporates structured project phases that provide scaffolding for student progress while allowing flexibility in project definition and implementation approaches. The recommended project phases include project definition and specification, research and resource identification, conceptual design, virtual prototyping, physical implementation, testing and refinement, and documentation and reflection.

Within this structured framework, students should have flexibility to define specific project topics, select implementation approaches, and make design decisions based on their interests and goals. This balance supports the development of both technical skills and student agency, essential for fostering both competence and confidence.

Effective STEM project design requires assessment approaches that align with the interdisciplinary, iterative nature of STEM work. The framework incorporates an integrated assessment system with multiple components: formative assessment providing ongoing feedback throughout the project process; process documentation creating structured requirements for documenting project development; authentic product evaluation assessing final projects based on functionality, quality, and alignment with real-world standards; and reflective analysis engaging students in self-assessment of their learning process and outcomes.

This integrated approach acknowledges both the process and product dimensions of STEM projects, creating a more comprehensive view of student learning and development. By evaluating both how students work and what they produce, this assessment approach provides richer insights into competency development than traditional product-focused assessment.

6.2. Assessment framework with rubric dimensions

Assessment represents a critical component of effective STEM project design. Based on the literature review and implementation analysis, the framework includes a comprehensive assessment approach incorporating multiple dimensions of STEM competencies.

An effective assessment rubric for STEM projects in computer microelectronics would address dimensions including problem definition, technical design, programming, implementation, integration, documentation, interdisciplinary application, and innovation. For each dimension, the rubric would define performance levels from beginning to exemplary, with clear criteria for each level.

In the problem definition dimension, beginning performance might involve a vague problem statement with limited connection to real-world contexts, while exemplary performance would demonstrate a comprehensive problem statement with well-defined parameters and explicit connection to significant real-world contexts.

The technical design dimension would assess circuit design quality, ranging from basic functionality with inefficiencies or errors at the beginning level to sophisticated circuit design showing optimization and elegance at the exemplary level. Similarly, the programming dimension would evaluate code structure, documentation, and use of programming concepts.

The implementation dimension would assess students' ability to physically implement their designs, ranging from requiring significant assistance to demonstrating exemplary independent implementation with professional-level construction quality. The integration dimension would evaluate how effectively students connected virtual and physical environments, from limited integration with significant discrepancies to seamless integration with sophisticated understanding of environment differences.

Documentation quality would be assessed from basic coverage of minimal project elements to exemplary thorough, well-organized, and professional documentation. Interdisciplinary application would evaluate how effectively students integrated concepts from multiple disciplines, from limited application without articulated connections to sophisticated application with insightful integration of disciplinary perspectives. Finally, the innovation dimension would assess originality and creativity, from following established patterns closely to demonstrating exceptional creativity with novel approaches to technical challenges.

This assessment approach addresses multiple dimensions of competency development, providing a more complete picture of student learning than traditional assessment methods focused primarily on technical knowledge and skills.

6.3. Implementation guidelines for educators

Effective implementation of STEM project design requires careful planning and preparation. The framework provides practical guidance for educators implementing STEM projects in higher education settings, addressing preparation, implementation, and evaluation phases.

In the preparation phase, educators should assess available resources, develop project templates, establish technology infrastructure, create resource repositories, and prepare assessment tools. This preparation ensures that the necessary foundation is in place for successful project implementation.

During the implementation phase, educators should provide structured introduction to project methodology, support project definition, facilitate progressive development, implement just-in-time instruction, conduct regular check-ins, foster peer learning, and document the implementation process. These activities create a supportive learning environment that balances guidance with student autonomy.

In the evaluation phase, educators should conduct comprehensive assessment, facilitate reflection, showcase student work, gather implementation feedback, and refine their approach for future implementations. This reflective practice enhances both student learning and continuous improvement of the educational approach.

The framework also addresses scalability considerations, recognizing that STEM project design must be adaptable to different educational contexts, class sizes, and resource environments. Key considerations include resource scaling, group size adjustment, complexity calibration, support structure expansion, and assessment adaptation. By addressing these considerations, educators can implement effective STEM projects across a range of educational settings.

Technology selection criteria provide guidance for choosing appropriate virtual simulation platforms and physical implementation technologies. These criteria include accessibility, educational alignment, integration capability, scalability, resource efficiency, and professional relevance. These criteria help educators make informed decisions about technology tools that support project objectives while addressing contextual constraints.

Finally, the framework addresses curriculum integration, emphasizing the importance of aligning STEM projects with broader curriculum standards and educational objectives. Strategies for this integration include standards mapping, competency alignment, progressive integration, interdisciplinary connections, and professional preparation. These integration strategies ensure that STEM projects contribute meaningfully to broader educational goals rather than existing as isolated experiences.

7. Future directions

The implementation and analysis of STEM project design in computer microelectronics education suggest several promising directions for future development and research.

7.1. Emerging Technologies and their integration

Rapid technological advancements offer new possibilities for enhancing STEM project-based learning. Several emerging technologies show particular promise for integration in STEM education. Extended Reality (XR) technologies, including virtual reality (VR), augmented reality (AR), and mixed reality (MR), offer immersive learning experiences that could bridge virtual and physical implementation environments. Li, Shen and Sukenik [18] research on immersive virtual labs suggests that these technologies can enhance both in-person and online education by providing interactive experiences that simulate physical environments, potentially creating more seamless transitions between virtual and physical learning contexts.

Advanced Internet of Things (IoT) platforms enable more sophisticated connected projects that integrate multiple devices and data sources. These platforms could extend the capabilities of Arduino-based projects to include networked communication, data collection, and remote control functionality, creating more authentic learning experiences that reflect contemporary technological practices. Artificial Intelligence integration offers possibilities for intelligent assistance for debugging, automated assessment of code quality, and adaptive learning pathways. The work of Adeika, Abiodun and Owolabi [1] on AI and computer vision-enhanced classroom observations suggests promising applications for STEM education assessment, particularly for capturing complex process data that traditional assessment methods might miss.

Digital fabrication technologies such as 3D printing, laser cutting, and other digital fabrication tools could enhance the physical implementation phase of STEM projects, allowing students to create custom components and enclosures for their Arduino projects. These technologies would extend the design process to include physical form factors, creating more comprehensive design experiences.

The integration of these technologies would require careful consideration of accessibility, learning curve, and educational alignment. Research is needed to develop effective pedagogical approaches that leverage these technologies while maintaining focus on core learning objectives rather than technological novelty for its own sake.

7.2. Research gaps and opportunities

The implementation and analysis revealed several research gaps that offer opportunities for further investigation. Longitudinal impact assessment represents an important area for future research, examining the long-term impact of STEM project experiences on students' academic trajectories and professional development. Longitudinal studies could track how STEM project competencies transfer to other educational contexts and workplace settings, providing more robust evidence of educational effectiveness.

Comparative pedagogical approaches offer another fruitful research direction, examining how variations in project structure, guidance levels, and assessment methods affect learning outcomes across diverse student populations. This research could help identify optimal approaches for different educational contexts and student characteristics.

The specific challenges and optimal strategies for transitioning between virtual simulation and physical implementation environments require more detailed investigation. This research could inform more effective integration of these complementary learning contexts and help address the challenges observed in the current implementation.

Assessment methodology validation represents an important research opportunity, particularly regarding the evaluation of interdisciplinary competencies and process skills that may be difficult to measure through traditional assessment approaches. Validation studies of rubrics and other assessment tools could enhance the reliability and validity of STEM project assessment.

Research on inclusive STEM education is particularly important, examining how STEM project approaches can be designed to be inclusive and effective for diverse student populations. This research should address potential barriers related to prior experience, cultural background, gender, and learning preferences, ensuring that STEM education benefits all students.

These research opportunities could significantly enhance our understanding of effective STEM education practices and inform more refined implementation approaches that address the diverse needs of students and educational contexts.

7.3. Theoretical extensions

Several theoretical extensions could enrich our understanding of STEM project-based learning in higher education. An integrated competency development model could provide a more comprehensive theoretical framework explaining the relationships between STEM project experiences and the development of specific competencies across technical, cognitive, professional, personal, and collaborative domains. This model could inform both educational design and assessment approaches by articulating the mechanisms through which different project experiences contribute to competency development.

An adaptive expertise framework could extend existing theories of expertise development to address how STEM projects contribute to adaptive expertise – the ability to apply knowledge flexibly in novel situations – rather than routine expertise limited to familiar contexts. This theoretical extension would be particularly valuable for understanding how STEM education prepares students for rapidly changing technological environments where adaptation is essential.

A technology integration ecology framework could conceptualize the complex interactions between technological tools, pedagogical approaches, learning environments, and student characteristics in STEM education contexts. This framework would provide a more nuanced understanding of how technologies like Tinkercad and Arduino interact with pedagogical approaches and student characteristics to create effective learning environments.

Boundary crossing theory offers another promising theoretical lens, helping to understand how students navigate the transitions between disciplinary domains, virtual and physical environments, and educational and professional contexts in STEM projects. This theoretical perspective could provide insights into the challenges and strategies associated with these transitions, informing more effective educational approaches.

These theoretical extensions could provide more robust conceptual foundations for STEM education research and practice, informing more effective implementation approaches that address the complex nature of interdisciplinary learning in technology-rich environments.

7.4. Policy implications and workplace preparedness

The implementation and analysis suggest several policy implications for higher education institutions seeking to enhance STEM education, as well as opportunities for enhancing workplace preparedness through STEM project-based learning. Resource allocation models require reconsideration to recognize the specific requirements of STEM project-based learning, including technology infrastructure, physical components, technical support, and appropriate learning spaces. These models should account for both the initial investment and ongoing maintenance costs associated with effective STEM education.

Faculty development initiatives specifically designed to build STEM teaching capabilities represent an important policy consideration. These initiatives should address technological pedagogical content knowledge (TPACK) and project-based learning facilitation skills, providing faculty with the competencies needed to implement effective STEM projects. Curriculum integration policies that support interdisciplinary learning, flexible assessment approaches, and project-based methodologies across STEM disciplines are essential for creating the institutional environment in which STEM project-based learning can flourish.

Technology infrastructure planning should support the dual-environment learning approach, ensuring access to both virtual simulation platforms and physical implementation technologies. This planning should consider both immediate needs and future technological developments that may enhance STEM education. Industry partnership frameworks can connect STEM projects to workplace contexts, providing authentic problems, technical expertise, and potential pathways to professional opportunities for students.

STEM project-based learning has significant potential to enhance workplace preparedness, particularly in technical fields that require both disciplinary knowledge and broader capabilities. Future directions for this integration include industry-aligned project frameworks that mirror professional practices, professional competency mapping that explicitly connects educational experiences to workplace requirements, work-integrated learning models that create smoother transitions between educational and professional contexts, professional portfolio development that helps students showcase their competencies to potential employers, and entrepreneurship connections that help students develop business perspectives alongside technical skills.

These policy and workplace integration directions recognize that effective STEM education should prepare students not only for academic success but also for professional contributions in increasingly technology-driven industries.

8. Conclusion

This paper has examined the implementation of STEM project design in computer microelectronics education, focusing on the integration of virtual simulations using Tinkercad and physical implementation with Arduino microcontrollers. The research has demonstrated how this dual-environment approach enhances students' interdisciplinary skills through project-based learning while addressing practical constraints in educational settings.

The analysis revealed several key findings with implications for STEM education in higher education settings. The integration of virtual simulation and physical implementation creates complementary learning environments that support different aspects of skill development. Virtual environments excel in accessibility, rapid iteration, and risk-free experimentation, while physical environments provide authentic experiences, multi-sensory feedback, and practical technical skill development. This complementary relationship creates a more comprehensive learning experience than either approach alone could provide.

STEM project-based learning supports the development of competencies across multiple dimensions, including technical skills, cognitive skills, professional skills, personal skills, and collaborative skills. This multidimensional development aligns with the needs of both academic progression and workplace preparation, creating educational experiences that prepare students for the complex challenges they will face in professional contexts.

Effective STEM project implementation requires a balance between structured guidance and student autonomy. The implementation demonstrated how structured project phases can provide necessary scaffolding while allowing flexibility in project definition and approach, supporting both skill development and student agency. This balance is particularly important in educational contexts where students bring diverse prior knowledge and experience levels.

The dual-environment approach offers effective strategies for optimizing limited educational resources, using virtual simulation to maximize design and testing before requiring physical components. This approach makes STEM implementation more accessible in resource-constrained educational contexts, an important consideration for institutions with limited technical resources.

STEM projects facilitate authentic integration of knowledge across disciplinary boundaries, helping students recognize and apply connections between science, technology, engineering, and mathematics domains. This integration occurs naturally through project requirements rather than being artificially imposed, creating more meaningful interdisciplinary learning experiences.

This research makes several theoretical contributions to the understanding of STEM education and project-based learning. The integrated theoretical model synthesizes key elements from STEM education, project-based learning, and technological pedagogical content knowledge frameworks, providing a more comprehensive conceptual framework for understanding STEM project implementation. The dual-environment learning theory developed through this research extends existing theories of technology-enhanced learning to address the specific context of STEM project-based learning, offering insights into how virtual and physical learning environments can be integrated in a complementary manner.

The comprehensive framework for STEM project design presented in this paper provides educators with a structured approach to implementing effective STEM projects, addressing pedagogical foundations, implementation components, assessment approaches, support structures, and integration strategies. The detailed assessment rubric offers a practical tool for evaluating student work across multiple dimensions of STEM competencies, supporting more comprehensive and meaningful assessment of project-based learning.

Despite these contributions, several limitations should be acknowledged. The implementation was conducted with a specific group of students in a particular educational context, potentially limiting the generalizability of findings to other student populations or institutional settings. The research did not include a comparative analysis with other instructional approaches, making it difficult to determine the relative effectiveness of the STEM project approach compared to alternatives. The analysis relied primarily on qualitative observations rather than quantitative measures of learning outcomes, limiting the ability to make definitive claims about the impact on specific competencies.

STEM education represents a critical approach for developing the knowledge, skills, and dispositions required for participation in an increasingly technological society. The implementation of STEM project design in computer microelectronics education demonstrates how interdisciplinary, project-based approaches can enhance student learning across multiple dimensions of competency. The integration of virtual simulation and physical implementation environments offers a particularly promising approach for STEM education, leveraging the complementary strengths of each environment while addressing practical constraints in educational settings.

The framework for STEM project design presented in this paper provides a comprehensive approach that educators can adapt to their specific contexts, addressing pedagogical foundations, implementation components, assessment approaches, support structures, and integration strategies. By implementing this framework with attention to local needs and constraints, educators can enhance STEM education in ways that prepare students for both academic success and professional contributions.

As we continue to develop and refine approaches to STEM education, it is essential to maintain focus on both the technical competencies that enable specific applications and the broader capabilities that support lifelong learning and adaptation in rapidly changing technological landscapes. The STEM project approach examined in this paper represents one promising pathway toward this integrated development, worthy of further implementation, research, and refinement.

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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