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Editorial Brief

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The June 2026 issue of the ASEAN Journal for Engineering Education (AJEE) presents a diverse and timely collection of thirteen scholarly contributions that collectively reflect the continuing transformation of engineering and technology education. The papers in this issue explore innovative pedagogical approaches, digital learning technologies, artificial intelligence, active learning strategies, accreditation frameworks, educational analytics, and emerging theoretical perspectives that are shaping the future of engineering education in ASEAN and beyond.

A recurring theme throughout this issue is the pursuit of deeper, more meaningful student learning through pedagogical innovation. Several papers demonstrate how active learning approaches can enhance student engagement, understanding, and problem-solving capabilities. The action research study on electronic circuit design education highlights the successful integration of simulation tools to bridge gaps between theoretical instruction and laboratory practice. Similarly, the study on microcontroller-based problem-solving workshops illustrates how Internet of Things (IoT) technologies can stimulate student motivation and experiential learning while identifying areas for further development in creative problem-solving.

The importance of structured pedagogical frameworks is further reinforced through the integration of SOLO Taxonomy with active learning strategies in chemical engineering process simulation education. The findings demonstrate how cognitive scaffolding can systematically enhance students' technical competencies and higher-order thinking skills. Complementing this perspective, the investigation into Design-Based Learning in rural Malaysian schools reminds us that effective pedagogy must be sensitive to contextual realities. By proposing a framework adapted to resource-constrained environments, the study contributes valuable insights toward more inclusive and equitable educational practices.

The growing influence of artificial intelligence and learning analytics is another major focus of this issue. The implementation of AI-driven spaced retrieval practices in advanced engineering mathematics demonstrates how emerging educational technologies can significantly improve learning outcomes and retention. Meanwhile, the comparative study of student performance prediction models highlights the practical value of interpretable machine learning approaches, emphasizing that transparency and deployability may be as important as predictive accuracy in educational settings.

Perhaps most forward-looking is the conceptual exploration of AI-Augmented Digital Twin Classrooms. Drawing inspiration from Industry 4.0 and Industry 5.0 principles, the proposed framework reimagines learning environments as intelligent, adaptive, and learner-centered ecosystems. Together with studies on educational analytics and AI-enhanced learning, this contribution signals the emergence of a new generation of engineering education environments that leverage real-time data, immersive technologies, and intelligent decision-making to personalize learning experiences.

Several papers in this issue also demonstrate the continued importance of virtual and simulation-based learning. The use of finite element analysis to support the teaching of beam structures in aerospace engineering illustrates how numerical simulations can help students visualize and understand complex engineering concepts. Likewise, the development of an open-ended virtual laboratory for environmental engineering education shows how virtual learning environments can effectively support outcomes-based education while providing flexibility and accessibility for learners. These studies highlight the growing role of virtual laboratories as complementary tools that extend learning beyond the constraints of physical facilities.

Gamification emerges as another promising avenue for enhancing student engagement. The study examining crossword puzzles as a learning intervention in engineering physics demonstrates how carefully designed gamified activities can improve conceptual understanding, technical vocabulary retention, and student participation. Such findings reinforce the value of incorporating interactive and learner-centered approaches into traditionally challenging engineering subjects.

Beyond classroom practices, this issue also addresses broader institutional and strategic dimensions of higher education. The systematic review on service quality and institutional characteristics offers a comprehensive perspective on how digital transformation and organizational identity influence student satisfaction and trust. By proposing an integrated framework for evaluating higher education services, the study contributes to ongoing discussions about institutional effectiveness in increasingly digital educational environments.

Two papers provide important theoretical and policy-oriented contributions that extend beyond immediate classroom implementation. The critical review of engineering identity traces the evolution of the field from foundational identity theories to contemporary engineering education scholarship. By identifying emerging dimensions such as belonging, agency, and professional readiness, the review offers a valuable roadmap for future research, particularly within ASEAN and Global South contexts. Meanwhile, the comparative analysis of ABET and EUR-ACE accreditation systems addresses a pressing strategic question faced by engineering programs worldwide. The proposed decision-oriented framework provides institutional leaders with practical guidance for aligning accreditation choices with organizational goals, graduate mobility aspirations, and regional priorities.

Collectively, the contributions in this issue reflect several significant trends shaping contemporary engineering education: the integration of artificial intelligence and digital technologies, the expansion of active and experiential learning approaches, the growing importance of educational analytics, the evolution of virtual and simulation-based learning environments, and the increasing attention given to identity, quality assurance, and institutional strategy. These developments underscore the need for engineering educators to continuously adapt their pedagogical practices while remaining responsive to technological advancements, societal expectations, and the changing needs of learners.

As Chief Editor, I am pleased to present this issue to our readers. The articles published herein demonstrate the vibrancy and diversity of engineering education research across multiple disciplines, educational levels, and geographical contexts. More importantly, they contribute practical insights and scholarly perspectives that can inform teaching practice, curriculum development, institutional decision-making, and future research.

I would like to express my sincere appreciation to all authors, reviewers, editorial board members, and the AJEE editorial team for their dedication and contributions. Their collective efforts continue to strengthen AJEE as a platform for advancing engineering education scholarship and fostering educational excellence throughout the ASEAN region and beyond.

Dr. Zaki Yamani Zakaria

Chief Editor,

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Integrating SOLO Taxonomy with Active Learning in Chemical Engineering Process Simulation

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Abstract
This study presents a structured pedagogical intervention that integrates Active Learning strategies with the Structure of the Observed Learning Outcome (SOLO) Taxonomy to enhance cognitive development and technical competency in a Process Simulation and Integration course for third-year chemical engineering students. The course was redesigned to align weekly learning activities with SOLO's five hierarchical levels, progressing from basic unit operations to advanced process optimization using tools such as Aspen HYSYS. Active learning techniques including hands-on simulations, team-based problem-solving, reflective journals, and gallery walks were implemented during Semester 2 of the 2022/2023 session at Universiti Malaysia Sabah (UMS), engaging 50 students in a scaffolded learning journey. Assessment data showed a 48% improvement in problem-solving proficiency, alongside enhanced software fluency and teamwork. Reflective journals and peer evaluations confirmed gains in conceptual understanding and confidence in tackling complex engineering problems. The findings underscore the value of aligning cognitive taxonomies with active pedagogical strategies to support deep learning, engagement, and real-world application. This approach offers a replicable model for engineering educators aiming to foster 21st-century skills in simulation-based courses.

Keywords: Active Learning; SOLO Taxonomy; Process Simulation; Chemical Engineering Education; Curriculum Innovation.

Introduction

The increasing complexity of engineering challenges in the 21st century, driven by digital transformation, sustainability imperatives, and the demands of cross-disciplinary collaboration, requires a fundamental rethinking of engineering education. Chemical engineering graduates today must demonstrate not only technical proficiency but also higher-order cognitive abilities such as systems integration, critical thinking, and innovative problem-solving. In response, education scholars and accrediting bodies have called for pedagogical reforms that emphasize active, student-centered, and outcome-based learning over traditional, lecture-driven instruction (Felder & Brent, 2016; Rajan et al., 2020).

Process simulation, a cornerstone of chemical engineering curricula, typically involves using platforms such as Aspen HYSYS to model, analyze, and optimize process systems. However, the conventional delivery of simulation courses often remains procedural and software-centric, with limited emphasis on cognitive development. This results in surface-level learning, where students complete isolated tasks without integrating conceptual understanding or applying engineering judgment to complex, real-world problems (Ma & Lee, 2021; Rojano et al., 2021).

A critical pedagogical gap persists: while process simulation aims to develop systems-thinking competencies, it rarely incorporates cognitive development frameworks such as the SOLO Taxonomy. Traditional engineering curricula frequently rely on Bloom's Taxonomy for outcome mapping; however, Bloom's often focuses on the difficulty of the task or the category of the cognitive process rather than the internal structural complexity of a student's response. In a simulation environment, a student may 'apply' a unit operation without understanding its relational impact on the entire system. Unlike Bloom's, which categorizes cognitive processes, SOLO provides a systematic way to evaluate how students integrate multiple parts of a simulation, such as mass balances and heat integration, into a coherent whole. This makes SOLO uniquely suited to address the 'analysis-synthesis' gap that occurs when students treat simulation as a procedural, software-centric exercise rather than an integrated engineering challenge.

To address this gap, the present study introduces an integrated pedagogical framework that combines Active Learning strategies with the SOLO Taxonomy.

SOLO, developed by Biggs and Collis (1982), organizes cognitive development into five hierarchical levels: pre-structural, uni-structural, multi-structural, relational, and extended abstract, providing a scaffolded model for designing learning activities and assessments. When paired with active learning techniques such as hands-on simulation, team-based problem-solving, reflective journaling, and gallery walks, SOLO can serve as a powerful tool for fostering both conceptual growth and real-world application (Freeman et al., 2014; Chan et al., 2017).

This paper reports the implementation of a SOLO-aligned Active Learning framework in a Process Simulation and Integration course for third-year chemical engineering students at Universiti Malaysia Sabah (UMS). The course redesign explicitly mapped weekly learning tasks to the five SOLO levels, aiming to guide students systematically from foundational knowledge to advanced process integration and optimization. Evidence from student assessments, reflective journals, and peer evaluations was used to evaluate the framework's effectiveness in enhancing software proficiency, problem-solving ability, teamwork, and confidence in decision-making.

By documenting this intervention, the study contributes a replicable model for curriculum innovation in chemical engineering education, one that aligns instructional strategies, learning outcomes, and assessments with structured cognitive development. It also offers insights into how SOLO Taxonomy can be operationalized to enrich active learning environments and prepare graduates for the complexities of Industry 4.0.

Theoretical Framework

The SOLO Taxonomy, developed by Biggs and Collis (1982), is a systematic framework used to describe the increasing structural complexity of a student's performance. Unlike other taxonomies that may focus on the difficulty of a task, SOLO defines learning as a progression from the visible 'surface' to the 'deep' understanding of a subject (Biggs & Tang, 2011). It is categorized into five hierarchical levels: **Pre-structural:** The learner lacks understanding and uses irrelevant information. **Uni-structural:** The learner focuses on a single relevant aspect of the task. **Multi-structural:** The learner identifies several relevant independent aspects but fails to integrate them. **Relational:** The learner integrates the parts into a coherent whole, understanding the relationships between components. **Extended Abstract:** The learner generalizes the integrated whole to new domains or higher levels of abstraction (Chan et al., 2017; Scott & Harlow, 2012).

Complementing this cognitive scaffold is the use of active learning, an instructional approach that emphasizes student engagement through doing, reflecting, and collaborating. Unlike passive, lecture-driven instruction, active learning cultivates deeper understanding, higher motivation, and stronger skill acquisition, critical attributes for engineering graduates navigating increasingly complex professional landscapes (Freeman et al., 2014; Prince, 2004). Activities such as hands-on simulations, peer collaboration, reflective journaling, and gallery walks foster metacognitive development and provide real-time opportunities to apply theoretical knowledge in meaningful contexts (Michael, 2006; Gómez Puente et al., 2013).

The integration of SOLO Taxonomy and active learning strategies forms a dual-pedagogical framework that aligns learning outcomes with instructional activities and assessments. In the pre-structural and uni-structural stages, students are introduced to the Aspen HYSYS interface and simulate basic unit operations through guided tutorials. As they progress to the multi-structural level, learners participate in group-based simulations of multiple operations, developing a broader but still segmented understanding of process elements. At the relational stage, students synthesize complete process flowsheets, integrating mass and energy balances while engaging in peer critique and feedback. Finally, in the extended abstract phase, learners generalize their knowledge to optimize complex systems, tackle open-ended case studies, and critically reflect on their learning journey.

Within the context of process simulation, SOLO Taxonomy enables the deliberate design of learning activities that support the development of students' ability to model, integrate, and optimize systems. Prior studies suggest that while Bloom's Taxonomy is effective for setting foundational objectives, it lacks a clear hierarchical transition for evaluating the integration of complex engineering components. SOLO identifies the critical transition from a 'multi-structural' level, knowing many isolated unit operations, to a 'relational' level, where these operations are integrated into a functional flowsheet. This structural focus is essential for fostering the systems thinking required for modern engineering practice. (Graham, 2018; Schwab, 2017).

While the SOLO taxonomy is a tool for advancing cognitive depth, it effectively accommodates broad subject knowledge by categorizing the acquisition of multiple independent concepts at the Multi-structural level before requiring their integration at the Relational level. This makes it particularly suitable for engineering disciplines that require both a wide technical vocabulary and the ability to apply that knowledge to complex, integrated systems. This section explicitly describes how the complexity of the task (from basic unit operations to full process optimization) dictates the choice of AL strategy to support that specific SOLO level.

Methodology

Course Context and Educational Setting

The Process Simulation and Integration course is a core chemical engineering undergraduate subject at the Faculty of Engineering, UMS. This course emphasizes the application of Aspen HYSYS for modeling, analyzing, and optimizing chemical processes, with a focus on integrating unit operations into complete process flows. Recognizing the challenges students face in transitioning from isolated simulation tasks to holistic system integration, the course was redesigned using a combined Active Learning and SOLO Taxonomy framework to scaffold students' cognitive development and enhance their learning experience.

Course Redesign Using SOLO-Active Learning Model

The redesigned framework aligns weekly learning activities with the five cognitive levels of SOLO Taxonomy: pre-structural, uni-structural, multi-structural, relational, and extended abstract. Each level is paired with targeted Active Learning strategies that include hands-on simulation, peer collaboration, reflective journaling, and gallery walk presentations. The structured progression allows students to build from basic operational knowledge toward complex system-level understanding and optimization, as shown in more details in Figure 1. This explains the rationale for the "structured progression," noting that pairing targeted AL strategies with SOLO levels allows students to build systematically toward high-level optimization.

The SOLO Taxonomy provides a distinct advantage over the more commonly used Bloom's Taxonomy in process simulation contexts. While Bloom's remains a useful tool for setting general learning objectives, it has been criticized for lacking a clear hierarchical transition between 'analysis' and 'synthesis' in practical application. In contrast, SOLO identifies the transition from a 'multi-structural' level (knowing many isolated unit operations) to a 'relational' level (integrating them into a functional flowsheet). This structural focus is particularly relevant to engineering education, where learners must evolve from basic conceptual understanding to advanced analytical thinking and practical application. Prior studies have validated that SOLO-based approaches are superior for fostering systems thinking because they explicitly measure the degree of integration in student work.

Week-by-Week SOLO-Aligned Learning Progression

The course progression was structured to align with SOLO Taxonomy, ensuring that students developed cognitive skills progressively (Biggs & Collis, 1982).

- *Weeks 1–3: Foundational Knowledge (Pre-structural and Uni-structural levels)*
    - Introduction to Aspen HYSYS interface and basic unit operations.
    - Hands-on exercises to simulate individual components (e.g., heat exchangers, pumps).
    - Activity: In-Class Exercise (ICE1) – Identifying unit operations and their functions.
- *Weeks 4–6: Bridging Concepts (Multi-structural level)*
    - Simulating multiple unit operations without integration.
    - Understanding energy requirements in process systems.
    - Activity: Group problem-solving on distillation sequence energy analysis (ICE4).

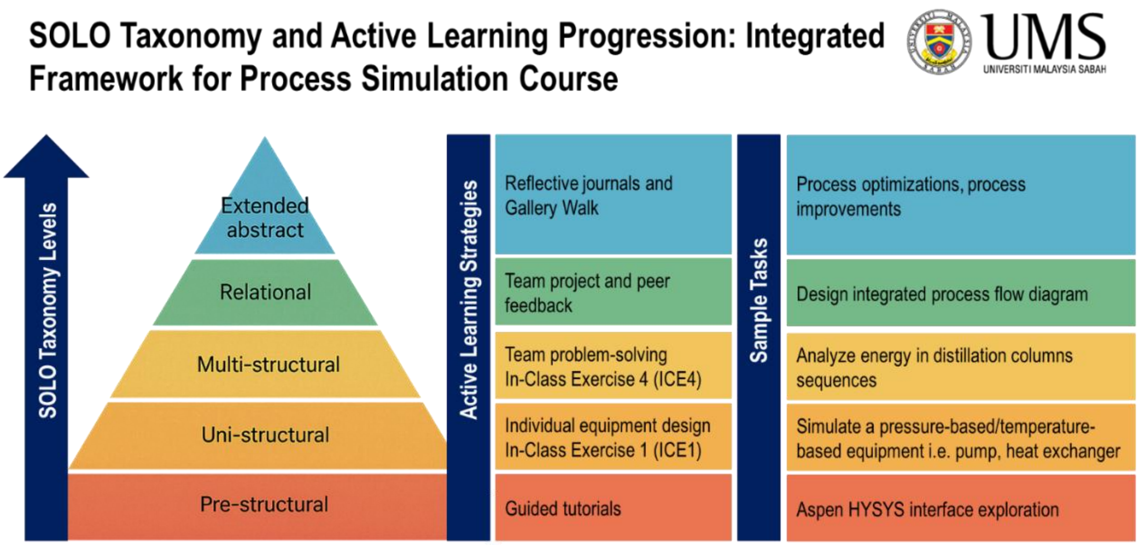

Figure 1. SOLO Taxonomy and Active Learning Progression: Integrated Framework for Process Simulation Course.

- *Weeks 7–10: Integrated Process Modeling (Relational level)*
  - Synthesizing unit operations into a full process flowsheet.
  - Performing mass and energy balance calculations.
  - Activity: Team-based project – Designing a complete process flow in Aspen HYSYS.
- *Weeks 11–14: Advanced Process Optimization (Extended Abstract level)*
  - Applying process simulation to optimize energy efficiency and reduce operational costs.
  - Reflective journal submissions and peer discussions on process improvements.
  - Activity: Gallery Walk – Presenting case studies on process optimization.

This progressive structure ensured that students moved from basic knowledge acquisition to higher-order thinking and real-world application (Chan et al., 2017; Ma & Lee, 2021).

Active Learning Techniques Applied

The course design incorporated Active Learning techniques, ensuring that students engaged with the material beyond passive learning (Freeman et al., 2014; Prince & Felder, 2006).

1. *Hands-on Simulations*
   - Students directly engaged with Aspen HYSYS to simulate unit operations.
   - Early exercises focused on understanding the impact of process parameters on performance (Michael, 2006).
2. *Team-Based Problem-Solving*
   - Groups collaborated to analyze, optimize, and troubleshoot process flowsheets.
   - Encouraged peer learning and critical thinking (Prince, 2004).
3. *Reflective Journals*
   - Students documented weekly learning experiences, challenges, and self-assessments.
   - Promoted metacognitive awareness and deeper learning (Biggs & Tang, 2011).
4. *Gallery Walks*
   - Teams presented their simulation projects and received peer feedback.
   - Encouraged discussion, critique, and real-world application of knowledge (Gómez Puente et al., 2013).

These active learning techniques increased engagement, motivation, and deeper conceptual understanding (Freeman et al., 2014).

Assessment Framework

To evaluate the effectiveness of SOLO Taxonomy and Active Learning, a comprehensive assessment framework was designed, incorporating:

- *Formative Assessments*
  - Weekly quizzes and reflective journals to track conceptual understanding and problem-solving progression.
  - Feedback sessions after team-based problem-solving activities (Biggs & Tang, 2011).
- *Summative Assessments*
  - Process simulation projects requiring students to integrate unit operations into an optimized flowsheet.
  - Process Simulation Project industrial-based complex problem-solving tasks aligned with SOLO relational and extended abstract levels (Chan et al., 2017).
- *Peer and Self-Assessments*
  - Gallery Walk evaluations where students critique peer solutions and justify their own approaches (Michael, 2006).
  - Self-reflection rubrics assessing personal growth in problem-solving and teamwork skills.

By incorporating multiple assessment types, students' learning was measured beyond memorization, focusing on progressive cognitive development and real-world application (Freeman et al., 2014). SOLO Taxonomy levels mapped to activities, strategies, outcomes as well as assessment in the process simulation course is tabulated as in Table 1.

Table 1. SOLO Taxonomy Levels Mapped to Activities, Strategies, Outcomes, and Assessment in Process Simulation Course

SOLO Level	Cognitive Focus	Learning Activities	Active Learning Strategies	Expected Student Outcomes	Assessment Methods
Pre-structural	No meaningful understanding	Introduction to Aspen HYSYS interface and navigation	Guided software tutorials, instructor-led demo	Students recognize the simulation platform but lack functional understanding	Diagnostic quiz, observation during tutorial sessions
Uni-structural	Understanding of one concept	Simulating single unit operations (e.g., pump, heat exchanger)	Hands-on exercises, ICE1 worksheet	Students describe and simulate a single unit operation in isolation	In-class exercise (ICE1), individual submission of simulation tasks

Multi-structural	Understanding of multiple concepts, but not interrelated	Simulating multiple components separately; analyzing energy usage in distillation	Group problem-solving (ICE4), collaborative modeling	Students list and operate multiple unit operations without integration	Group task (ICE4), short quiz on energy analysis for distillation columns sequences
Relational	Integration of parts into a coherent whole	Developing full process flowsheets with mass/energy balance	Team project work, peer review discussions	Students construct integrated flowsheets and justify design logic	Team simulation report, peer feedback form, rubric-based instructor evaluation
Extended Abstract	Generalizing and applying knowledge in new contexts	Process optimization, case study analysis, proposing improvements	Reflective journals, Gallery Walk presentations	Students apply concepts to new scenarios and propose improvements with critical reflection	Reflective journal rubric, Gallery Walk peer/self-assessment, open-ended exam questions

Results and Discussion

This section presents the findings and analysis of the impact of integrating SOLO Taxonomy and Active Learning in the Process Simulation and Integration course. The discussion is structured around student learning outcomes, critical thinking development, engagement levels, and a comparison with traditional teaching approaches.

Student Learning Outcomes

The implementation of SOLO Taxonomy provided a structured learning progression, guiding students from basic conceptual understanding to complex problem-solving. The week-by-week structured approach, aligned with the five levels of SOLO, allowed students to gradually build their knowledge, integrate different unit operations, and optimize full process simulations (Biggs & Tang, 2011; Chan et al., 2017).

Assessment results indicated a significant improvement in students' ability to:

- Identify and understand individual unit operations (Uni-structural level).
- Connect multiple process components within a system (Multi-structural level).
- Develop and optimize complete process flows (Relational level).
- Apply knowledge to new industrial challenges and case studies (Extended Abstract level).

Analysis of student performance in simulation-based assessments showed a progressive increase in their ability to analyze and solve engineering problems, supporting previous studies that highlight the effectiveness of SOLO Taxonomy in engineering education (Scott & Harlow, 2012; Ma & Lee, 2021).

How SOLO Taxonomy Helped Students Transition from Basic to Complex Problem-Solving

Students progressed from isolated knowledge acquisition to integrative thinking. The implementation of SOLO Taxonomy ensured cognitive development, as evidenced by:

- Higher student scores in final projects compared to initial assessments.
- Students' ability to connect theoretical knowledge with real-world applications, a key skill for engineering graduates (Freeman et al., 2014).
- Decreased reliance on memorization and an increase in logical reasoning and structured problem-solving.

Reflections from students indicated that they initially struggled with process integration but gained confidence and autonomy in simulations as they moved through the SOLO levels (Prince & Felder, 2006).

Impact on Teamworking, Software Skills and Problem-Solving Skills

The integration of SOLO Taxonomy and Active Learning in the Process Simulation and Integration course significantly enhanced students' development in three key skill domains: teamworking, software proficiency, and problem-solving, skills aligned with the needs of modern engineering practice and Industry 4.0 demands (Graham, 2018; Schwab, 2017), as shown in Figure 2.

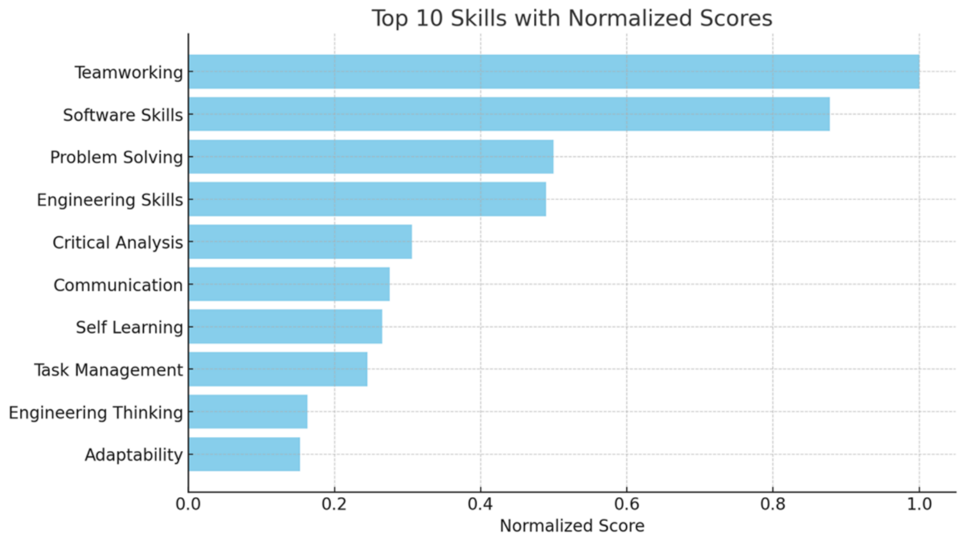

Figure 2. Top 10 skills developed during the Process Simulation and Integration course, as identified through student reflections and peer evaluations.

- *Teamworking Skills:* Collaborative problem-solving tasks, such as group simulations, peer discussions, and gallery walks, cultivated interpersonal and communication skills essential for multidisciplinary teamwork. Students reported increased confidence in contributing ideas, resolving conflicts, and reaching consensus on simulation design strategies. Peer evaluations revealed that over 85% of students actively participated and valued input from team members, reinforcing prior findings that cooperative learning environments improve collaboration and accountability (Freeman et al., 2014; Gómez Puente et al., 2013).
- *Software Proficiency:* Hands-on engagement with Aspen HYSYS across all SOLO levels, from basic tutorials to advanced system integration, helped students build operational fluency. Early in the course, students focused on navigating the interface and simulating single unit operations. By the end, they demonstrated proficiency in configuring complex flowsheets and executing mass and energy balances. The structured progression enhanced their confidence and efficiency in using engineering software tools (Ma & Lee, 2021; Rojano et al., 2021). As seen in Figure 2, 89% of students identified software skill acquisition as one of the top competencies gained.
- *Problem-Solving Skills:* The SOLO-aligned progression supported students' transition from surface-level to deep, analytical thinking. At the relational and extended abstract levels, students were required to evaluate trade-offs, optimize process parameters, and propose system-wide improvements, mirroring industrial decision-making scenarios. Assessment data showed a 32% average increase in problem-solving proficiency from pre- to post-course evaluations. Students developed not only technical solutions but also the ability to justify their decisions based on process performance and economic considerations, aligning with engineering graduate attributes (Biggs & Tang, 2011; Chan et al., 2017; Rajan et al., 2020).

Overall, the integrated framework empowered students with essential 21st-century engineering competencies, collaboration, tool mastery, and strategic thinking, critical for tackling complex challenges in professional practice.

Evidence from Assessments and Reflections

To measure the effectiveness of the framework, a combination of student assessments, reflective journals, and peer evaluations was analyzed.

1. *Assessment Data Analysis*
   - Students' pre-test and post-test scores showed an average increase of 32% in problem-solving capabilities.
   - Final project evaluations revealed that 90% of students were able to successfully integrate multiple unit operations, compared to 50% at the beginning of the course.
2. *Reflective Journal Insights*
   - Early reflections: Many students struggled with process integration and decision-making.
   - Mid-course reflections: Students acknowledged the benefits of team discussions and problem-solving activities.
   - Final reflections: Most students expressed increased confidence in tackling open-ended engineering problems.
3. *Peer Evaluations & Gallery Walk Feedback*
   - Students rated peer feedback as one of the most valuable learning experiences, supporting previous research that highlights the benefits of collaborative learning (Gómez Puente et al., 2013).

This part of the discussion justifies why AL strategies like peer review and reflective journals were necessary to bridge the gap between "knowing isolated units" (Multi-structural) and "relational understanding".

Student Engagement and Feedback

Engagement levels significantly increased compared to previous offerings of the course using traditional lecture-based teaching. This was evident from:

- Increased participation in class discussions and hands-on exercises.
- Higher attendance rates (95%) compared to previous semesters (78%), indicating increased motivation.
- Positive feedback in course surveys, where 87% of students preferred the active learning approach over traditional methods.

Students expressed that active learning activities such as gallery walks, reflective journals, and simulation-based problem-solving helped them retain concepts more effectively and apply them in different contexts (Prince, 2004).

One student commented:

"*At first, I found process simulation overwhelming, but as we progressed through the SOLO levels, I could see how everything connected. The gallery walks and peer discussions helped me understand the bigger picture.*"

This supports findings in engineering education literature, where active learning environments enhance engagement and long-term knowledge retention (Freeman et al., 2014; Ma & Lee, 2021).

The initial 50% proficiency level reported at the beginning of the course was established through a diagnostic simulation task and the first In-Class Exercise (ICE1). During this phase, which corresponds to the Uni-structural level of the SOLO taxonomy, students were evaluated on their ability to navigate the Aspen HYSYS interface and simulate individual unit operations, such as a single pump or heat exchanger, in isolation. While half of the cohort could perform these procedural tasks, they lacked the cognitive framework to integrate these components into a functioning process flowsheet.

The subsequent increase to 90% proficiency in the final project is attributed to the integrated SOLO-AL framework rather than mere subject exposure. By scaffolding the course into five hierarchical levels, the framework explicitly addressed the transition from 'Multi-structural' knowledge (knowing isolated units) to 'Relational' understanding (integrating units into a coherent system). Active learning strategies, such as team-based problem-solving and peer review, forced students to move beyond software-centric procedures to justify design logic and troubleshoot complex mass and energy balances. Furthermore, the use of reflective journals and Gallery Walks encouraged Extended Abstract thinking, enabling students to generalize their knowledge and optimize systems,a leap in complexity that is rarely achieved through traditional lecture-based instruction alone.

Conclusion

This study has demonstrated that integrating Active Learning strategies with the SOLO Taxonomy provides a powerful pedagogical framework for enhancing cognitive development, engagement, and technical competency in chemical engineering education. Through a structured progression from foundational knowledge to higher-order thinking, students in the Process Simulation and Integration course significantly improved their ability to analyze, synthesize, and optimize complex process simulations using Aspen HYSYS.

The SOLO-aligned active learning approach enabled learners to move beyond procedural knowledge, fostering deeper conceptual understanding and problem-solving proficiency. Evidence from assessments, reflections, and peer evaluations confirmed marked gains in students' software skills, team collaboration, and confidence in tackling real-world engineering challenges. The framework also contributed to higher levels of student satisfaction and motivation, reinforcing its effectiveness as a transformative instructional model.

This study contributes a replicable and scalable model that supports engineering curriculum reform by aligning teaching activities, assessment strategies, and learning outcomes with cognitive development stages. Future work may explore its adaptation in other engineering domains, longitudinal impact on graduate attributes, and integration with digital learning platforms to further strengthen student-centered and outcomes-based education.

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Conflict of Interest

The authors declare no conflict of interest.

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Abstract
Retrieval practice is an effective learning approach that involves students actively retrieving knowledge from memory after completing the lesson (like lectures, workshops, and labs), which improves memory retention and fosters long-term learning. In short, this study underpins Retrieval Practice Theory. Unlike the pre-test, which involves taking practice tests before learning new information as opposed to afterward, retrieval practice is a strategy where students are tested on questions about unit materials that they have already learned. However, a more interactive spaced retrieval practice using a new platform, such as the highly recommended AI-powered question generators like Edapp, is still limited. This new spaced retrieval practice was implemented two times per semester for mid-semester tests, and then the data was collected for analysis. Based on an engineering first-year unit, namely MATH1020 Calculus for Engineers, after implementing spaced retrieval practices in the first semester of 2024, a significant increase in the passing rate was observed, up to 20.33%. The 95% confidence intervals for the passing rates further reinforce this improvement, showing that the post-intervention cohort's performance was not only higher but also statistically more precise compared to the pre-intervention groups. This substantial improvement demonstrates the effectiveness of the newly proposed intervention.

Keywords: pedagogy, spaced retrieval, AI-driven, mathematics, student-centered approach.

Introduction

First-year engineering courses play a pivotal role in shaping the foundation of future engineers, requiring innovative teaching strategies to engage students, promote deep learning, and improve the courses' passing rates. Retrieval practice involves activities undertaken to activate prior knowledge and enhance students' learning experiences. The effectiveness of retrieval practice has been demonstrated in various educational contexts, including classrooms and online learning environments, in various fields of study (Carpenter, 2023; Van Hoof et al., 2023; Wellmann & Skillicorn, 2024). Encouraging more frequent use of retrieval practice can enhance student achievement (Wang et al., 2023).

Retrieval practice consistently benefits student learning by improving learning outcomes across various educational levels, content areas, experimental designs, final test delays, retrieval, final test formats, the timing of retrieval practice, and feedback (Agarwal et al., 2021). Recently, the efficacy of retrieval practice in university mathematics was investigated by Szabó et al. (2023), and they discovered that it is useful for students with low, average, or high mathematical competence and that it can be an efficient method of learning higher mathematics to be implemented in classes to improve students' performances. This retrieval practice can be conducted via massed practice or spaced practice, as shown in Figure 1.

Massed practice refers to conditions in which individuals practice a task continuously without rest, studying, or learning that takes place all at once over a

Yeo, W.S., Lim, M.J.Y.T., Nor, F.M., & Saptoro, A. (2026), Unlocking Learning Potential: AI-Driven Spaced Retrieval for Enhanced Pedagogy, *ASEAN Journal of Engineering Education*, 10(1), 9-14. https://doi.org/10.11113/ajee2026.10n1.214

long period. This massed practice is only one practice before the actual test, like a pre-exam. Meanwhile, spaced practice refers to conditions in which individuals are given rest intervals within the practice sessions, studying, or learning that takes place in smaller amounts of time spread out over multiple sessions. Lyle et al. (2022), Lyle et al. (2020), and Hopkins et al. (2016) found that spaced retrieval practice improved mathematical knowledge retention. This is in line with other recent research, including Ebersbach and Nazari (2020), Emeny et al. (2021), and Yazdani and Zebrowski (2006), who demonstrated spacing effects in different forms of mathematics learning.

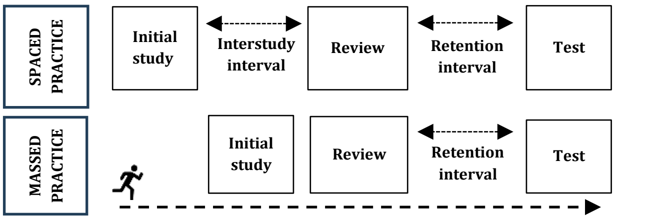

Figure 1. Massed practice and spaced practice before the test

Since students sometimes are unsure where to start, they try to cram all the information they need at the last minute, which leads to hours of wasted time staring at a blank screen, which only causes them more stress. The spaced retrieval practice enhances students' memory, with previous research finding an increased percentage in grades (YeckehZaare et al., 2022) and increasing the retention of STEM knowledge, including mathematics knowledge (Bego et al., 2017; Carpenter, 2023; Hopkins et al., 2016; Lyle et al., 2020; Lyle et al., 2022; May, 2022; Razzaq et al., 2025; Yasar et al., 2019). Honestly, Stavnezer and Lom (2019) reported that the scores for retrieval practice did not differ before and after instruction. Therefore, the effectiveness of the spaced retrieval practice on MATH1020 remains questionable. Thus, this project utilized AI-enhanced applications to improve student engagement by providing an AI-powered question generator for MATH1020 Calculus for Engineers.

Research Methodology

AI-powered online system, EdApp

In this project, the free and highly recommended AI-powered online system, EdApp, was used for the spaced retrieval practice to support the student-centered pedagogy approach in a first-year engineering course, namely MATH1020 Calculus for Engineers. The questions were generated based on the past year's tests and exam papers, and these questions were reviewed and validated by all authors. In EdApp, an action plan is provided after students answer the questions, explaining the fundamental theory behind each question and identifying the relevant teaching materials that students should review.

This project is also introduced to improve the existing online quizzes via the Pearson system and STACK in this unit, which requires the specified syntax for the final answers. The spaced retrieval practices in the project are set as multiple-choice questions, and true or false questions require working steps to get the right answer mapped to the unit learning outcomes (ULOs) and program outcome (PO). The test questions designed in this study primarily assessed students' understanding and analytical skills. Most questions required students to demonstrate conceptual understanding, interpret mathematical information, and apply appropriate solution methods to solve problems. Additionally, other e-learning platforms like Kahoot, the Pearson system, and STACK do not offer the feature to include the action plans for each question in the spaced retrieval practices.

In the meantime, the team members built a total of 20-25 questions related to the unit contents based on the pattern of the past test questions and provided them for each retrieval practice using an AI-powered question generator, namely EdApp. The range of 20–25 questions was used to provide flexibility in aligning the number of questions with the complexity and coverage of each topic. Meanwhile, all students received the same questions. The retrieval practice sessions were conducted twice, with each session lasting one hour, during scheduled revision classes after the completion of specific topics and before the actual test/exam. This activity is considered an active learning strategy because students actively retrieved previously learned knowledge through structured questions. **Figure 2** shows the operational framework of the retrieval practice sessions in this study. These initiatives are to help students prepare for the test by allowing them to practice answering questions under similar conditions to the real test. Additionally, suggested action plans were provided in the system after the spaced retrieval practices. This AI-powered system allows students to generate a certificate of completion, which serves as a complement to their learning and commitments. By utilizing the spaced retrieval practice, it was expected to assess their learning of conceptual theory and fundamental principles in this unit before the actual assessments, and improve the passing rate of the unit.

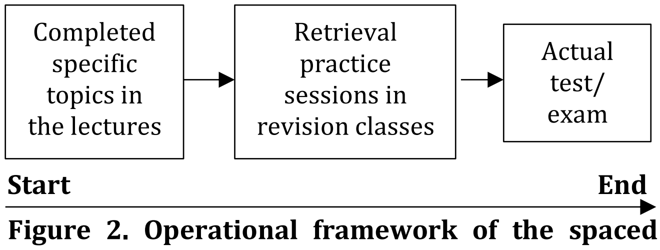

Figure 2. Operational framework of the spaced retrieval practice sessions in this study

Data collection and analysis

Data collection was conducted for semesters in the years 2023 and 2024 before and after the retrieval practices: i) the total number of students, ii) mid-semester test marks, and iii) the passing rates. To be more specific, the sample sizes were 61 students in Semester 1 of 2024, 28 students in Semester 1 of 2023, and 25 students in Semester 2 of 2023. Basically, this study used a quantitative approach to evaluate the impact of spaced retrieval practice on student performance. A quasi-experimental research design for semesters in the years 2023 and 2024, before and after the retrieval practices, was used to assess the effectiveness of the retrieval practice. The following data was collected to understand the students' activities, engagement, and learning behavior. All the collected data from learning activities were tabulated to understand their trends and patterns.

In the analysis, the relationships between sets of data and the passing rate were analyzed and compared. The percentage error, PE, displayed in (1), was used to compare the data collected before the spaced retrieval practices. Factors that affect the passing rate of the unit were identified. Moreover, the root causes of problems faced and solutions were also justified.

$$PE = \left|\frac{V_a - V_b}{V_a}\right| \times 100\% \quad (1)$$

where V_a and V_b refer to the average test marks and passing rates after and before the spaced retrieval practices, respectively.

Anonymous questionnaire survey

An online anonymous questionnaire survey for the spaced retrieval practice in the clinic classes was conducted in July 2024 for 3 weeks, and it was voluntary. The purpose of this online anonymous questionnaire survey is to gather student feedback on how they experience the spaced retrieval practice in the clinic classes of the semester. It took roughly 8 minutes to complete all questionnaire survey questions, and there is only one survey for a semester in this study. And all the participants' details remain confidential and were not collected, are non-identifiable, and are analyzed. Hence, this research project has no foreseeable risks since the participants' information was not collected or analyzed.

Results and Discussions

This study was conducted in Semester 1, 2024, on an engineering first-year unit, MATH1020 Calculus for Engineers. This unit has a lower passing rate, a high number of repeat students, and is traditionally a complex or difficult unit. The initiative of this study is to support the learning and teaching of this teaching unit so that students perform better and have a better learning experience. The following subsections are the results of the data analysis and the anonymous questionnaire survey.

Results of the data analysis

The results of the data analysis in this study are summarized in **Table 1**, which highlights the variation in students' performance due to different teaching strategies and learning approaches. As mentioned earlier in the methodology section, the numbers of students in Semester 1 of the year 2024 and Semesters 1 and 2 of the year 2023 are 61, 28, and 25, respectively. It is worth noting that the number of students in a semester did not impact the analysis, as the means of the marks were used to standardize the result data regardless of the number of students (Glass & Hopkins, 1996), ensuring fair comparisons across different groups (Wright, 2008). Hence, the student numbers were not a factor in data analysis.

From **Table 1**, the mean for the mid-semester test mark, which is out of 100 in Semester 1 in the year 2024, is higher than both Semesters 1 and 2 in the year 2023. The mean of the marks exceeding 50% indicates that students are performing above the minimum passing threshold, suggesting a generally satisfactory level of understanding and competence in the teaching unit. This concept is further supported by Kamaruddin et al. (2023), who discussed how the means of the marks are used to indicate student performance and understanding. In this study, these three-semester students have a mean of marks of 60.60-70.66, all exceeding 50 out of 100, or 50%, indicating above-average performance on the test. Nevertheless, in Semester 1 of 2024, the spaced retrieval practices facilitated better performance, with an improvement of 14.14%-14.24% in the mean of the marks compared to Semesters 1 and 2 of the year 2023. These findings support the correlation of the spaced retrieval practices and their retention benefit, where these findings are consistent with the study from Roediger III and Karpicke (2006). They adopted a similar approach to retrieval practices and demonstrated a scaling improvement in student average performance. This consistency in results suggested that the spaced retrieval approach could benefit long-term retention and understanding.

In addition, the median of the mark in Semester 1, 2024, after the spaced retrieval practices is higher than before these practices in Semesters 1 and 2, 2023, by about 14.91% and 12.38%, respectively. Moreover, note that the medians of Semester 1, 2024, are slightly higher than their means, indicating that the bulk of students achieved relatively high scores and performed well. Besides that, Table 1 shows that the passing rate of the mid-semester test in Semester 1 of the year 2024 was over 80%, which improved significantly from Semesters 1 and 2, 2023, by 15.52% and 20.33%, respectively. These significant improvements in student passing rate further verify statistically the effectiveness of spaced retrieval practice approaches on student capability to retain and apply knowledge over time.

Table 1. The obtained results *before and **after the spaced retrieval practice for the mid-semester test

Learning mode	Face-to-face learning mode				
Semester/ year	****S1 2024**	***S1 2023**	***PE* *(%)***	***S2 2023**	***PE* *(%)***
Total number of students	**61**	28		25	
Mean of the mark (Total: 100)	**70.66**	60.67	14.14	60.60	14.24
Median of the mark (Total: 100)	**71.25**	60.63	14.91	62.50	12.28
Passing rate (%)	**80.33**	67.86	15.52	64.00	20.33

*S1 and S2 are Semesters 1 and 2, respectively.

Furthermore, **Table 2** summarizes the computed 95% Wilson confidence intervals (CIs) for passing rates of the mid-semester test. In Semester 1, 2024, which is after retrieval practice, the passing rate was 80.33%, with a 95% CI ranging from 68.69% to 88.37%. This result indicates that the true passing rate of the population lies within this interval. The relatively narrower interval reflects the larger sample size (n = 61), which provides a more precise estimate. Moreover, in Semester 1, 2023 (before retrieval practice), the passing rate was 67.86%, with a 95% CI of 49.34% to 82.07%. The range of CIs is wider because of the smaller sample size (n = 28), indicating greater uncertainty in the estimated passing rate. Also, for Semester 2, 2023 (before retrieval practice), the passing rate was 64.00%, and the 95% CI was 44.52% to 79.75%. Like Semester 1, 2023, the smaller sample (n = 25) also results in a wide interval, showing less precision. In conclusion, based on our findings, it is worth noting that such retrieval practices do not merely enhance short-term memorization but foster deeper learning and understanding, leading to better academic outcomes.

Table 2. The obtained 95% confidence intervals for passing rates *before and **after the spaced retrieval practice for the mid-semester test

Semester/year	95% CI (Wilson)
****S1 2024**	68.69 – 88.37
***S1 2023**	49.34 – 82.07
***S2 2023**	44.52 – 79.75

Furthermore, to address the limitation of other e-learning platforms that do not offer the feature to include the action plans for each question in the spaced retrieval practices, EdApp, used in this study, can provide the suggested action plans in the system after the spaced retrieval practices. In this study, these action plans enable students to recap their lectures to have a better understanding of the teaching materials and allow students to focus their study efforts on those weaker areas, improving overall comprehension and knowledge. Moreover, these action plans provide immediate, tailored qualitative feedback on students' questions' responses, which explain the correct answers, highlight key concepts, and direct students to specific lecture notes for more detailed studies. Hence, these action plans reinforce their memory by re-emphasizing the key concepts and providing a deeper insight, and are less likely to be forgotten. This approach ensures that all students receive valuable knowledge in different contexts that solidify their gaps in the materials and guide them to additional learning sources and experiences.

Results from the anonymous questionnaire survey

Besides the quantitative improvements, qualitative feedback from students also provides further insight into the benefits of spaced retrieval practices. As shown in **Figures 3(a)** and **3(b)**, respectively, the survey reveals that up to 52% found these approaches exceptionally effective (very and extremely effective shown in **Figure 3(a)**) for their learning, while 72.5% of students enjoyed the spaced retrieval practices in clinic classes, which are like revision sessions (absolutely shown in **Figure 3(b)**).

Many students testified that the spaced retrieval approach built their confidence and had better prepared them for tests. Spaced retrieval practices offer consistent review and "run through" sessions integrated into their exam preparation, where students regularly challenge themselves, learn from the mistakes, improve competency by being procedurally fluent, and continuously accumulate successes. As such, it allows and provides collective evidence of their capabilities and eventually builds a foundation of self-trust to override their self-doubt. While all these denote psychological effects and are scientifically supported and agreed upon by researchers from Singh et al. (2022), this physiological benefit is the one in which the level of confidence could foster a positive attitude towards learning and encourage active participation. Moreover, students' perceptions of their preparedness are closely linked to their academic success. When students feel prepared, they are more likely to perform well, which creates a positive feedback loop of confidence and achievement. This relationship between preparedness and success has been extensively documented in educational research, underscoring the importance of effective study strategies like spaced retrieval practices.

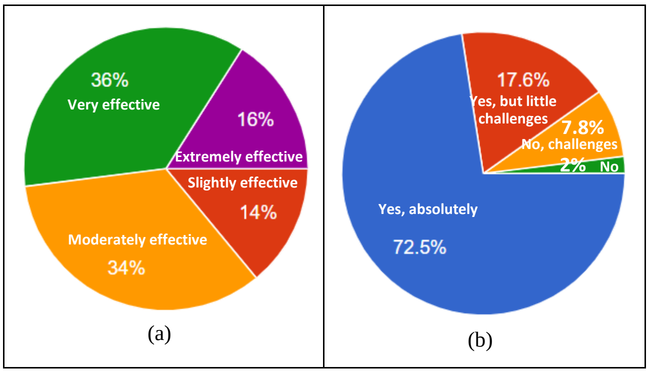

Figure 3. Survey questions for the spaced retrieval practice in the clinic classes (a) How effective has the spaced retrieval practice in the clinic classes been for you? and (b) Do you enjoy the spaced retrieval practice in the clinic classes?

Besides that, the positive reception of spaced retrieval practices also highlights their effectiveness in reducing test anxiety. These positive student perceptions suggest that the approach not only improved academic performance but also enhanced learning motivation. As students experienced better understanding and greater confidence, they became more motivated to engage consistently with the course content. Consistently engaging with the unit materials reduces the fear of the unknown or of potential failures and feeling overwhelmed by the content volume to be studied in a short range of time closer to the test dates. These ongoing engagements reframe students' perception and focus on performance rather than worry, making the learning process more manageable and less stressful.

Conclusions

In conclusion, spaced retrieval practices involve a systematic review of previously learned unit materials at increasing time intervals, suggesting that constantly recalling information by studying it multiple times over a longer period is more effective in knowledge retention than repetitive, short-term cramming. Our study has supported both quantitatively and qualitatively the benefit of integrating the spaced retrieval approach into the institutional curriculum. Our findings demonstrated a statistically significant improvement in the passing rate of the mid-semester test, indicating its reliable outcome in students grading improving instead of merely being a result of chance.

First of all, this growing body of evidence in educational psychology supports that spaced retrieval practices are a better learning strategy compared to the conventional method of massed practice, or cramming. Secondly, the spaced retrieval practices offer long-term benefits for students by establishing a habit of regular review and self-assessment. Hence, students could develop more effective study skills throughout their educational journey and beyond.

These practices provide students with a concrete knowledge base, allowing new information to be integrated and applied in the best possible way. However, this limitation of the study was investigated in a semester, which could not represent the complete success of the proposed approach as in this study. Hence, further research on the spaced retrieval practice sessions involving more semesters needs to be carried out to investigate the consistency of the findings. And eventually, this approach can be implemented in other units if the findings are promising.

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Conflict of Interest

The authors declare no competing interests.

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Improving Learning Experiences with Project Development and Problem-Solving Using Microcontroller – A Case Study

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Abstract

This paper presented an innovative teaching practice to promote problem-based learning via the Internet of Things (IoT) and Arduino microcontroller workshop. This educational research evaluates the participants' improvements in terms of the knowledge, confidence level and motivation. The participants included multi-disciplinary engineering students, who have enrolled in Electrical Systems (ELEN1000), whereby they completed all given tasks in teams and within a limited time. At the end, a total of 91 respondents' feedback was accumulated and analyzed via descriptive, *T-test* and ANOVA analysis. *T-test* 1 (p = 0.08135) found that the workshop improved participants' excitement. *T-test* 2 (p = 0.1323) explained that the workshop activities help to visualize the learned knowledge. Nevertheless, *T-test* 3 (p = 0.02) implied that the developed confidence level did not improve respondents' capability to generate spontaneous ideas. *T-test* 4 (p = 0.15999) highlighted that respondents are impressed with their capabilities after viewing the results. ANOVA Test 1 revealed that knowledge visualization significantly enhanced participants' confidence levels; however, it was insufficient to substantially improve their ability to generate spontaneous ideas for problem-solving. These findings suggest the need for additional activities that expose participants to a broader range of IoT applications. Overall, all respondents reported highly positive perceptions of the workshop and expressed inspiration to utilize microcontrollers in their future projects.

Keywords: internet-of-things, microcontroller, descriptive, *T-test*, ANOVA.

Introduction

Nowadays, there is a significant shift in learning and teaching practices of tertiary education by adopting more practical components integrated into students' learning opportunities, supported by advanced technologies. This is in accordance with the students' expectations for education practicability (Thien et al., 2022). The students' expectations are apprehensible in current practices, which are more focused on teaching knowledge and principles. Applications of knowledge began to gain attention from a few Malaysian universities. Moreover, there is a dramatic increase in engineering courses to incorporate digital technologies such as microcontrollers and Internet of Things (IoT) applications. Alvarado & Maestre (2019) constructed a replica of the famous weapon (lightsaber) of the Star Wars movie using a microcontroller. Afonso et al. (2021) adopted an innovative teaching-learning method for the automated control of robotics using microcontrollers.

Improving learning experience via applying the learned knowledge is an idea that can be a drawback to Kolb's education philosophy in 1984. Practicing the learned knowledge enhances the experience, whereby new knowledge is created through the transformation of experience (Kolb, 1984, p. 38). He presented a learning cycle that covers Concrete Experience, Abstract Conceptualization, Reflective Observation, and Active Experimentation. In the context of microcontroller, learning experience and knowledge transform can be materialized via developing circuits, deepen understand of its theory and further improve the design.

Few educators suggested that practical experiences can be consistently explored via project-based learning because this allows contemporaneously to engage the learning processes with other soft skills. Dunai et al. (2017) applied traversal skills consisting of scheduling, organizing, structure design, agile communication, teamwork and presentation for the developed project. Swart & Hertzog (2018) demonstrated the connection of microcontrollers with various sensors in an academic workshop. All literature above applied comprehensive approaches and it is good to have a few perception studies on the designed tasks; thereafter, they could be studied and referred to by other educators.

This paper recommends implementing an innovative teaching practice by applying digital technologies in an organized IoT and Arduino microcontroller workshop. This educational research evaluates the extent of improvements in terms of participants' knowledge, confidence level, and motivation after completing the assigned tasks. In common, students are relatively weak in applications due to a lack of hands-on skills. Some students were unable to answer consistently application related problems of the microcontrollers and IoT consistently in their assessments. From the students' feedback comments, more application examples are required to study and practice this topic. In light of this, a series of innovative workshops was planned by the unit lecturer to stimulate conceptual knowledge learning by providing students with the opportunity to develop projects from scratch or solve the hidden errors in both hardware and Integrated Development Environment (IDE) programming.

Microcontrollers such as the Arduino series are an open-source embedded system used for data acquisition and control applications via interacting with sensors and actuators. The microcontroller is relatively inexpensive and is being adopted in university courses (El-Abd, 2017). Arduino microcontroller is compacted with an 8-bit ATmega microprocessor, analog & digital IO pins, serial communication modules, and other interface functions. Recktenwald & Hall (2011) explained that the microcontroller realm has many advanced technologies in real-life applications and is adaptable to IoT technologies. Students gain invaluable knowledge and know-how to develop projects on a breadboard, operating with the Arduino microcontroller.

This paper presents a survey study of an innovative workshop, which provides project tasks related to the application of the Arduino microcontroller. The workshop focuses on multi-disciplinary engineering students who are enrolled in the Electrical Systems (ELEN1000) at the institution. Students are invited as participants and respondents voluntarily. The participants work in a team to develop application functions from scratch by using the Arduino and ESP8266 microcontrollers. Each task in the worksheet instruction is a dialogic scaffolding approach (Gutierez, 2021) with a few hidden errors for both hardware wiring and IDE programming. Participants discuss and incorporate all ideas from previous tasks to develop a new project from the available components. The paper is organized into various sections. The literature review explains the literature on microcontrollers in real applications and education. Methodology describes the experiment design, questionnaire model and analysis methods. This is followed by analysis and results that analyze all the feedback with descriptive, *T-test* and ANOVA analysis. Discussion further elaborates on the outcomes of all analyses. Last but not least, the conclusion of the findings with suggestions was described and the improvement in the workshop activities was discussed.

Literature Review

There are literature works on incorporating the microcontroller in teaching practices. Recktenwald & Hall (2011) introduced a hands-on curriculum to learn the microcontroller. Rosen et al. (2014) provided a preliminary skill to reflect the learning of various engineering knowledge and applications. Carlotta (2016) improved the hardware equipment by designing LEGO MINDSTORMS projects using Arduino microcontrollers. Agatolio & Moro (2017) promoted an Arduino microcontroller-based robot as an interactive learning tool. Husni & Purnama (2020) adopted a data accumulation function to an electric physics experiment board for Science, Technology, Engineering and Mathematics (STEM) education media. On the other hand, AL-Yoonus (2019) encouraged students to develop microcontroller-based projects with reusable electronic components. Besides, Istiantara et al. (2019) researched the extension of the microcontroller-based straight motion practicum media to improve students' project management and communication skills.

Arduino microcontrollers are high feasibility adopted with the industrial-based projects. Balaji et. al. (2019) developed a consistent monitoring function of the HT motor systems and controlled them wirelessly by the ESP8266. In addition, Haq et al. (2020) developed a cost-effective ultrasonic tide-measuring device by embedding a microcontroller, ultrasonic sensor and Global Positioning System (GPS) module with the IoT to upload and monitor real-time parameters on the website.

Mishra et al. (2018) incorporated an Arduino microcontroller into the cloud to monitor irrigation water usage for optimized crop growth. Veeramanickam et al. (2022) presented parking detection and monitoring by using an IoT platform at college campuses. Chew et al. (2021) and Benny et al. (2024) applied IoT principles to a Proportional-Integral-based light control system and smart detectors at the high-risk working environment, which showed that IoT technologies are well-adapted to practical applications. Moreover, Ahmad et al. (2019) concluded that participants successfully demonstrated conceptual scientific understanding by participating in microcontroller-related experimental activities. The mentioned projects significantly inspire research motivation among authors and optimize their learning experiences.

Methodology

The methodology session explains the Design of Experiment (DOE). In addition, this session also discusses statistical analysis approaches via Descriptive, *T-test* and ANOVA.

Workshop Flow

Figure 1 illustrates the flowchart of the experiment design. Participants will perform the project tasks based on the worksheet and then to test the developed functions. After the workshop, all participants were required to fill out a set of survey questionnaires. The data from the questionnaire are then analyzed via descriptive, *T-test*, and ANOVA analysis.

Questionnaire

The survey questionnaire accumulates participants' feedback after completing their tasks. The feedback is essentially reflecting how efficiently the designed workshop improves their conceptual knowledge, confidence level and motivations and others when learning the microcontroller and IDE programming. Table 1 depicts the questionnaire model for the innovative workshop.

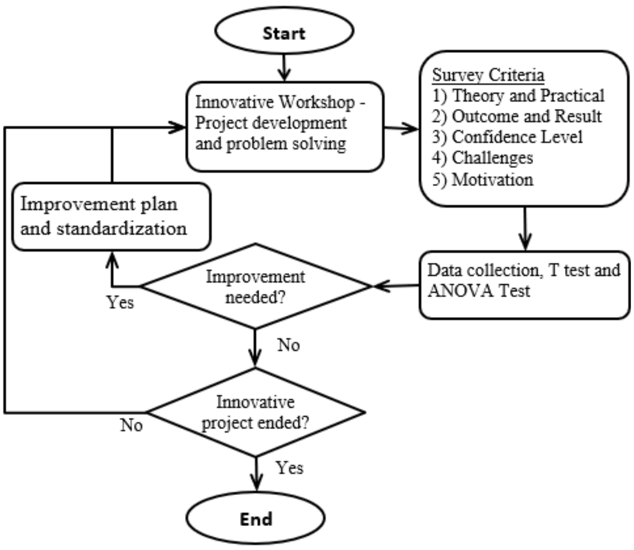

Figure 1. Flowchart - Design of experiment

Table 1. Case study questionnaire list

Criteria	Question	Content
Knowledge & practical	A	I am excited to practise while learning the microcontroller and IDE programming knowledge.
	B	The workshop activities are systematically designed to learn principles, concepts and develop ideas when studying the theory.
Outcome/ Result	C	The workshop activities allow me to immediately visualize the learned knowledge after completing each task.
	D	I have enhanced my understanding of the learned knowledge via practical activities.
Confidence level	E	The workshop enhances my confidence level via step-by-step problem-solving for IoT and microcontrollers.
	F	The workshop improves communication and co-operation among teammates while completing practical tasks.
New Challenge	G	The workshop enhances my capability to produce spontaneous ideas to tackle problems and write code.
	H	The workshop made me think of an alternative way to solve problems, which is very challenging.
Motivation	I	I am impressed by the achieved result, and escalating my interest in learning IoT and Arduino microcontroller.
	J	The workshop has highly motivated me and I will apply IoT and Arduino microcontroller in my future project.

The survey questionnaire has been provided to all participants for their feedback. The resulting score is determined by using the Likert Scale, which comprises "Strongly Agree, SA = 5", "Agree, A = 4", "Neutral, N = 3", "Disagree, D = 2", and "Strongly Disagree, SD = 1". All the results are compiled into an MS Excel spreadsheet and analyzed by descriptive, *T-test*, and ANOVA analysis.

Descriptive, T-test and ANOVA analysis

Descriptive analysis is a fundamental study of all the collected data. Descriptive analysis performs rational justification for the background study, not in a statistical way. This analysis identifies the significant similarities and differences among all the compared group variables and distributions. At first, all categorical data are compiled and observed by the researcher before commenting on the trends and factors affecting all the compared variables. Frequency and percentage distribution are common approaches used to interpret the categorical survey variables (Alreck & Settle, 1995). Data in categorical distribution can be interpreted clearly via graphical plots, charts, or diagrams. In the circumstances when the variables have too many values in a frequency table, data can be re-processed by reducing the samples during recoding recode them into categories.

The *T-test* is an inferential statistical analysis used to determine whether there is any remarkable divergence between the means of two data sets based on definite features. The *T-test* analyzes the known population means that are mathematically calculated (Crawford & Garthwaite, 2012). Zikmund (2003) described that the *T-test* analyzes the mean scores of selected interval-scaled variables or hypotheses and then tests whether there is a significant difference among the hypotheses. There are two involved hypotheses known as the null hypothesis, H_0 and the alternative hypothesis, H_a. For obtaining the p-value, the t-statistic value, t_{n-1} is to be determined by using $t_{n-1} = (x - \mu)/(s/\sqrt{n})$, where x is the sample mean, μ is the hypothesized mean, s is the sample standard deviation, and n is the sample size. After obtaining the t_{n-1} for that moment, statistical software or the t-distribution table (Statology, 2022) should be referred to for finding the corresponding p-value. For the *p*-value is less than 0.05, the two compared hypotheses are statistically different and therefore reject the H_0. In contrast, two hypotheses are not statistically different and thereby the H_0 is accepted.

ANOVA measures the mean between two or more values of the different contributing groups. The analysis of variance measures the difference between means for more than two data distributions. One-way ANOVA applies one dependent continuous variable but uses more than one independent categorical variable. In the analysis, ANOVA analyses the relation among hypotheses and determines whether there are statistical differences between the populations' means. ANOVA computes the sample variances, F-distribution statistics and eventually to determine the p-value as described by Goos & Meintrup (2016).

Designed Work Activities and Tools

The experimental design for the Arduino microcontroller and IoT tool is shown in Figure 2. All participants are creating a complete set of task step-by-step by employing the given guidelines and source code. The Arduino workshop provided comprehensive guidance on how to create a project for each team and correct all errors in the working instructions. A full set of equipment is also provided to test in real-time operations.

Analysis Results

Descriptive Analysis

The case study accumulated feedback from 91 respondents/participants, who have enrolled for the course Electrical Systems (ELEN 1000) in the year 2024. Among all the participants, 63 were male students, and 28 were female students. This probably reflects that male students prefer to learn knowledge through practical activities, rather than female students that prefers to learn conceptual knowledge, as they feel they can understand well without viewing practical examples. Interestingly, the highest number of 25 participants was from Mechanical Engineering. It is seconded by 20 participants from Electrical and Electronic Engineering, 18 participants from Chemical Engineering, 13 participants from Civil Engineering, 7 participants from Petroleum Engineering, 4 participants from Environment Engineering, and 4 students who were yet to decide on their engineering major. Among all of them, 52 participants or 57.14% were experienced users of the Arduino microcontroller. The demographics of the participants are depicted in Figure 3.

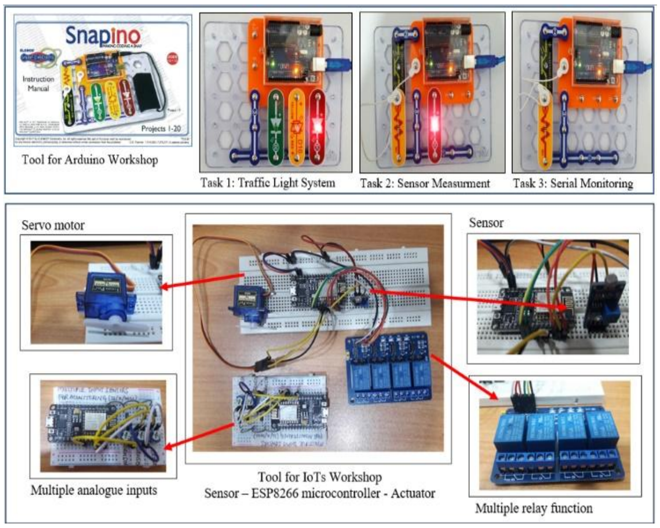

Figure 2. IoTs and Arduino microcontroller workshop activities

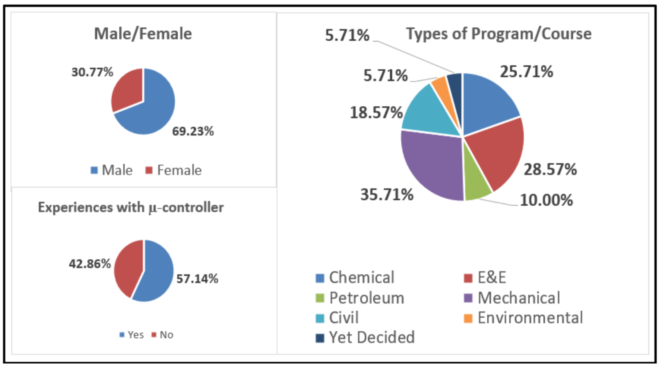

Figure 3. Research population or participants demographics

The score and percentage of every question are tabulated in Table 2. The highest-ranked percentage comes from experiencing co-operation and communication among teammates for completing tasks together (Question F). The feedback reflects that respondents prefer to study with teammates, whereby they have the opportunity to discuss and contribute their ideas in completing the given tasks.

T-test Analysis

There are two hypotheses to be analyzed by using the *T-test* analysis, which is obtainable using Ms. Excel spreadsheet. The *T-test* measures the correlation between two independent variables. All the *T-test* results are illustrated in Table 3.

T-test 1 analyzes the respondents' perceptions of the designed project to improve their conceptual knowledge, which is related to improving their determination to study the IoT and Arduino microcontroller. Question A has gained a mean of 1.61538 and a variance of 0.35042. Question B has gained a lower mean of 1.53846 and a variance of 0.27350. The analysis result of probability, p = 0.08135, which is > 0.05, therefore supports the H0 and supports the statement that the learned knowledge improves determination to study IoT and Arduino microcontroller. *T-test* 2 analyses of respondents' perception of the implemented tasks to visualize the learned knowledge with is helping them to understand the learned knowledge overall. The mean and variance of Question C are 1.5604 and 0.3602, which are greater than those of Question D. Moreover, the *T-test* produces $p = 0.1323$ (> 0.05), so accepting the tested H_0.

T-test 3 researches the correlation of the respondents on the developed confidence levels after solving the designed workshop activities, which has increased their capability to generate a spontaneous idea in dealing with the problems related to IoT and Arduino microcontroller. The mean and variance of Question G are respectively 1.89010 and 0.76557, which are greater than both values of Question E. The *T-test* also shows that $p = 0.02$ (less than 0.05), therefore, two-tested distribution are statistically dissimilar and therefore reject the H_0. *T-test* 4 analyzes respondents' insight on problem-solving process in completing given tasks (Question H) has stimulated their interests to further study IoT and Arduino microcontroller (Question I). The mean and variance of Question H are respectively 1.74725 and 0.67985 and larger than those of Question I, which gain respective values of 1.65934 and 0.53822. The *T-test* result also shows that $p = 0.159996$ (accept the null hypothesis, H_0). That means, the faced challenges of the participants have further escalated their determination to learn IoT and Arduino microcontroller.

Table 2. The respondents feedback analysis spreadsheet

Question Sequence Nu.	Strongly Agree		Agree		Neutral		Disagree		Strongly Disagree	
	Freq	***(%)***	***Freq***	***(%)***	***Freq***	***(%)***	***Freq***	***(%)***	***Freq***	***(%)***
A	50	54.95%	37	40.66%	4	4.95%	0	0.00%	0	0.00%
B	48	52.75%	40	43.41%	3	3.85%	0	0.00%	0	0.00%
C	48	52.75%	40	43.41%	3	3.85%	0	0.00%	0	0.00%
D	53	58.24%	31	34.07%	7	7.69%	0	0.00%	0	0.00%
E	37	45.71%	41	45.05%	13	14.84%	0	0.00%	0	0.00%
F	52	64.23%	35	39.01%	3	3.30%	1	0.55%	0	0.00%
G	27	29.67%	35	38.46%	9	9.89%	4	3.85%	0	0.00%
H	28	30.22%	34	37.91%	10	10.99%	2	2.20%	1	0.55%
I	47	51.10%	36	40.11%	7	7.69%	1	1.10%	0	0.00%
J	36	40.11%	40	43.96%	13	13.74%	2	2.20%	0	0.00%

Table 3. *T-test* for selected groups or data distributions

T-test	***T-test* 1**		***T-test* 2**		***T-test* 3**		***T-test* 4**	
	Question A	***Question B***	***Question C***	***Question D***	***Question E***	***Question G***	***Question H***	***Question I***
Mean	1.61538	1.53846	1.56043	1.48351	1.70329	1.89011	1.74725	1.65934
Variance	0.35042	0.27350	0.36019	0.38583	0.47765	0.76557	0.67985	0.53822
Observation	91	91	91	91	91	91	91	91
Pearson Correlation	0.56872		0.42742		0.42321		0.42550	
df	90		90		90		90	
t Stat	1.40752		1.12249		-2.08380		1	
p one-tail	**0.08136**		**0.13231**		**0.02001**		**0.16000**	
t Critical one-tail	1.66196		1.66196		1.66196		1.66196	

Note: p > 0.05 (accept the null hypothesis)

ANOVA Analysis

ANOVA analyses the closed relation among more than two compared independent variables. The *p*-value is used to determine whether the tested hypotheses are statistically significant or vice versa.

In this survey, two ANOVA tests have been conducted in the following sessions, as illustrated in Table 4.

In ANOVA 1, four groups of independent variables include workshop improves understanding (Question B), visualizing the conceptual knowledge (Question C), further enhancing confidence level (Question E), and generating spontaneous ideas (Question H). Among the compared parameters, Question H has gained the largest mean and variance, respectively, as 1.89011 and 0.76557. Whereas Question C has gained the lowest value of mean = 1.4615 and variance = 0.2957. The performed ANOVA analysis shows that *p*-value < 0.05 (*p* = 0.042606) reflects that there is a statistical difference between the four tested group variables; therefore, perception is not accepted.

ANOVA 2 analyses the respondents' perception that the practiced activities are consistent with the learned knowledge (Question B), improves their confidence level (Question E) for trying to solve given tasks (Question H). Both Question B and E gained a similar mean of 1.483516 and a variance of 0.385836. Besides, ANOVA analysis shows that *p*-value =0.368667 (> 0.05) reflects that there is no statistical difference between the three tested group variables; therefore, this perception is accepted.

Discussion

By referring to Table 2, respondents were excited and satisfied with this workshop because of providing them with an invaluable opportunity to practically learn how to develop a workable IoT system by using the microcontroller and IDE programming. 54.95% of respondents strongly agreed, and 40.66% of respondents were highly perceived (Question A) to practice the given tasks when learning conceptual knowledge. This is also reflected in Question D, whereby 52.75% of respondents strongly agreed, and 43.41% agreed, that practical activities immediately allowed them to visualize the learned conceptual knowledge. A respondent from Chemical Engineering commented that "*It was an excellent opportunity to apply what I learned from the lecture into the practical project and understand how applications in daily lives work*."

Secondly, more than 90% of respondents (Question B) perceived that the designed workshop activities are systematic and greatly helped them to understand the principles and knowledge. In the workshop, the designed tasks for instances, such as LED blinking, traffic light, night light system, and data acquisition functions, are fundamental to many engineering applications that involve microcontrollers in the design. An excited respondent from Civil Engineering commented that "*The Arduino project is very suitable for theory teaching to understand the whole electrical knowledge*."

Thirdly, the feedback showed that the workshop escalates students' interest in learning IoT and Arduino microcontroller, as they are excited by the achievements from the workshop. In Question I, 51.10% of respondents strongly agreed, and 40.11% agreed that they were impressed by their abilities and what they were capable of doing while completing the given tasks in the worksheet. A respondent from Electrical & Electronic Engineering: "*This project excites and motivates me to learn more about Arduino Programming*."

Table 4 ANOVA analysis for knowledge, visualizing result, confidence level, spontaneous idea and determination

Groups	ANOVA 1				ANOVA 2		
	Question B	***Question C***	***Question E***	***Question H***	***Question B***	***Question E***	***Question H***
Sum	140	133	155	138	135	135	125
Average	1.53846	1.46154	1.70330	1.89011	1.483516	1.483516	1.373626
Variance	0.27350	0.29573	0.47766	0.76557	0.385836	0.385836	0.325519
Source of Variation	**Between Groups**	**Within Groups**	**Total**		**Between Groups**	**Within Groups**	**Total**
SS	2.95604	128.9451	131.9011		0.73260	98.74725	99.47985
df	3	360	363		2	270	272
MS	0.98535	0.358181			0.36630	0.36573	
F	2.75098				1.001558		
***p*-value**	**0.04261**				**0.368667**		
F-crit	2.62971				3.029218		

Besides, the case study also triggered minor concerns from the respondent's feedback. Primarily, 14.48% of respondents (Question E) were neutral in commenting on enhanced confidence level via step-by-step problem solving for IoT and Arduino microcontroller. This is probably correlated with the 3.85% (Question G) respondents, who perceived that the activities in the workshop were still not adequate to improve their capabilities to produce spontaneous ideas for problem-solving. Perhaps, they have even dealt with the Arduino microcontroller and IoT before, and therefore, felt that the given tasks were not challenging them. Even a respondent from Electrical & Electronic Engineering opined that "*It is better to have the circuit diagram instead of a full image that allows students to think about how to connect the components with Arduino Microcontroller. More complex problems should be given to encourage more creative problem-solving. Ultimately, students can understand better.*"

Amazingly, this workshop has inspired most of the participants to learn further about the microcontroller and IDE programming. More than 80% of the respondents agreed (refer to Question I and Question J) that the workshop has stimulated their interest in further learning about microcontrollers and IoT, and they will consider applying the Arduino microcontroller in their future projects. A respondent from Mechanical Engineering commented that "*It is really helpful for understanding Arduino Microcontroller. I am happy to have a chance to play around with it. In the future, I will recommend it to my friends*." Besides, a student who studied Engineering First Year mentioned that "*This is fun, and I enjoyed it a lot. Please organize it again next year*."

From Table 4, ANOVA 1 analyzes the knowledge learning (Question B) after observing the result (Question C), which improves confidence level (Question E) and generates spontaneous ideas (Question H). Among them, Question N possesses the largest mean and variance values, which is also found from the *T-test* 3 analysis. Probably, few respondents feel the assigned tasks are simple and they lack more comprehensive samples to try when participating in the workshop. Nevertheless, more respondents still feel impressed by their potential and capabilities to complete given tasks in the workshop. Even so, it might be more beneficial to develop an additional worksheet with more complicated tasks to improve the engagement of the experienced participants in the future workshop.

ANOVA 2 analyzed the interrelation of three tested group covers, assigned data to improve knowledge understanding (Question B), improved confidence level (Question E), and tried to solve the given tasks with different approaches (Question H). The probability, $p = 0.368667$ (> 0.5), reflects that the three tested parameters are statistically similar; therefore, it is well to perceive that the workshop has success to enhance knowledge learning and confidence level among participants, that inspire them to strive to complete tasks with different approaches.

Overall, this is a very exciting experience to perform an innovative workshop as participants highly perceive that the workshop helps to boost their learning experience and inspiration in learning microcontroller and IoT. Invaluable findings from the *T-test* 3 and ANOVA 1 are being noted closely, whereby more workshops and comprehensive tasks could be provided for future improvement.

Conclusion

This paper presented an analysis of participants' feedback on the enhanced knowledge, hands-on, confidence level, motivation and spontaneous idea, after completing the project tasks in a designed innovative workshop. As noted, the innovative workshop is a part of the required improvement from the action plan of the student's feedback and concern in studying Arduino microcontroller and IoT. The workshop has enhanced the students' learning experience, particularly in practising the learned knowledge. The targeted population covers multi-disciplinary students who have enrolled in ELEN1000, where they are invited to participate in an Arduino microcontroller and IoT workshop. Fundamentally, the designed activities comprise hardware and software developments for traffic light, night light and data acquisition functions. Participants work in a team to develop project tasks one by one and need to solve the hidden errors to ensure the projects operate as required. Then, participants discussed with the team member how to integrate all the completed tasks to create a more inclusive function. After completing practical activities, participants are required to provide their feedback.

Overall, 91 pieces of feedback were collected from all respondents and were analyzed by using descriptive, *T-test*, and ANOVA analysis. This is favourable to the pronoun that most of the respondents are highly perceiving the innovative workshop that helps to improve their understanding and excitement in learning microcontroller and IDE programming (*T-test* 1) and prefer to learn practical activities concurrently with the conceptual knowledge because of helping them to visualize the learned knowledge (*T-test* 2). Perhaps due to the limited time for the workshop, respondents still feel their confidence level is not adequate for accessing spontaneous ideas dealing with future problems. In addition, the feedback is probably given by an excited respondent who is experienced in dealing with Arduino microcontrollers and IDE programming (*T-test* 3). Most of the respondents highly perceived that the challenges they faced in proceeding project tasks have inspired their interest to further learn microcontroller and IDE programming (*T-test* 4). The analysis is also extended by using the ANOVA method. ANOVA Test 1 found that the innovative workshop makes most of the respondents amazed at their capabilities to complete the given tasks during the workshop. However, the finding shows concern about the capability to generate spontaneous ideas. Last but not least, ANOVA Test 2 found that practical activities in the workshop are aligned with the conceptual knowledge, have improved participants' confidence levels and inspiration to thrive on tackling the assigned problem task with different approaches in the workshop.

In conclusion, the organized, innovative workshops were conducted successfully. Both the positive and negative feedback are well noted and followed up with improvements in teaching and innovative workshops in future semesters. Satisfaction and motivations of instructors are credited to the appreciation and encouragement words from all respondents, who have strongly recommended that this innovative workshop should continue for future semesters.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Student Performance Prediction Using the UCI Dataset: A Comparison of Interpretable and Ensemble Models

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Abstract

AI technologies have not only transformed teaching methods but have also provided novel solutions for education management, assessment, and personalized learning. This study examines whether complex machine learning models consistently outperform simple interpretable approaches in predicting student outcomes. Using the University of California, Irvine (UCI) Student Performance dataset, five key predictors: First period grade (G1), Second period grade (G2), Number of past class failures (Failures), Mother's education level (Medu) and Higher education aspiration (Higher), were extracted from 32 original attributes. Three models, including Linear Regression (LR), Random Forest (RF), and an Ensemble Model (EM), were evaluated across Mathematics and Portuguese subjects using MSE, RMSE, MAE, and R^2, with five-fold cross-validation to assess robustness. Experimental results demonstrate that Linear Regression achieved the best overall performance in both subjects, with R^2 = 0.779 for Mathematics and R^2 = 0.862 for Portuguese, whereas RF and EM did not yield consistent gains. Portuguese is generally more predictable than Mathematics under the same pipeline. Feature influence analysis indicates that early-term grades (G1 and G2) dominate predictive power, suggesting that the approach supports mid-semester/operational prediction rather than start-of-term early-warning. Overall, the findings highlight the practical value of interpretable models for educational analytics when transparency and deployability are important.

Keywords: Machine learning, educational data mining, performance prediction, linear regression, feature importance.

Introduction

The rapid development of artificial intelligence (AI) and machine learning has accelerated their adoption in educational data mining, where predictive analytics are increasingly used to support assessment, academic risk detection, and decision-making in teaching and learning processes (Kuleto et al., 2021; Luan et al., 2020). Between 2017 and 2021, the use of artificial intelligence in educational settings in the United States grew by 47.5% (Kuleto et al., 2021). Recent studies have demonstrated the practical applications of AI technology in several areas, including intelligent tutoring, adaptive learning systems, student behavior analysis, academic performance prediction, personalized learning and tutoring, and online education. For example, intelligent tutoring systems can provide personalized tutoring and instant feedback based on students' learning behaviors and performance outcomes (Chen et al., 2020). By analyzing data on students' learning behaviors, educators can gain insights into their learning habits and requirements, thereby facilitating the optimization of instructional design and management (Luan & Tsai, 2021). The use of virtual reality technology helps create immersive learning environments, enabling a more intuitive understanding of complex knowledge (Zafari et al., 2022). In parallel, the growing availability of educational records has made it feasible to model student outcomes using historical grades and contextual variables, potentially enabling data-informed interventions to support learners who may be at risk (Shafique et al., 2023; Vakhabova et al., 2019).

Despite this progress, a persistent practical question remains insufficiently addressed: do more complex machine learning models consistently outperform simpler and more interpretable models when applied to structured educational datasets? In educational contexts, model choice is not only an accuracy issue but also relates to transparency, ease of maintenance, and stakeholders' trust. However, existing work often focuses either on proposing a specific modelling approach or on applying highly complex models, while systematic comparisons across interpretable and more complex techniques under a controlled experimental setup are still relatively limited (Yağcı, 2022). As a result, it can be difficult for educators and practitioners to determine whether increased model complexity yields meaningful benefits in settings where interpretability and deployability are valued.

To address this gap, this study investigates student performance prediction using the widely adopted

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University of California, Irvine (UCI) Student Performance dataset (Cortez, 2008). We analyse two subjects: Mathematics and Portuguese, under the same modelling pipeline, which enables a controlled comparison of model behaviour across subject contexts. Specifically, this study first processed and analyzed the 32 influencing factors in the dataset and selected the five most critical factors to balance predictive performance and interpretability. Then, three regression approaches are compared: Linear Regression (as an interpretable baseline), Random Forest (as a non-linear model capturing interactions), and a simple ensemble model that averages heterogeneous learners. Model performance is assessed using standard error metrics (MSE, RMSE, and MAE) and R^2, together with five-fold cross-validation to estimate robustness. Additionally, this study briefly discusses the differences in predicting performance for STEM (Science, Technology, Engineering, and Mathematics) versus non-STEM subjects, which is further discussed in the discussion and conclusion sections.

Overall, this work provides practical interpretations for model selection in educational analysis through controlled comparisons and evaluations of interpretable models and more complex models on standard benchmark datasets, offering a more thorough understanding of which factors most significantly impact student performance. This approach not only improves predictive accuracy but also offers a deeper understanding of the multifaceted nature of academic success.

Methodology

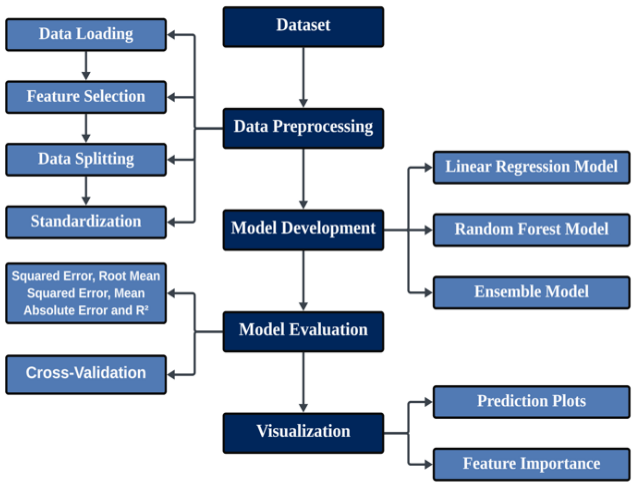

Figure 1. Methodology flowchart

Figure 1 summarizes the overall workflow of this study, which consists of five stages: (i) dataset and data loading, (ii) feature selection, (iii) data splitting and preprocessing, (iv) model development, and (v) model evaluation and visualization. The detailed procedures are described below.

Dataset and Data Loading

Dataset: This study utilizes the UCI student performance dataset (Cortez, 2008), which contains student performance information for Mathematics (Math) and Portuguese (Por) subjects, as well as 32 features related to student demographics, social and school-related factors, and academic performance. The decision to compare Mathematics and Portuguese subjects was driven by the distinct cognitive demands and teaching methods associated with STEM versus non-STEM subjects. Mathematics, as a core STEM subject, typically requires logical reasoning and problem-solving skills, while Portuguese, a language subject, involves comprehension and linguistic abilities. The two subjects are analyzed separately to examine whether model performance and influential factors remain consistent across different subject areas within the same data source. The Math and Por datasets were loaded into separate data frames for independent preprocessing and modelling.

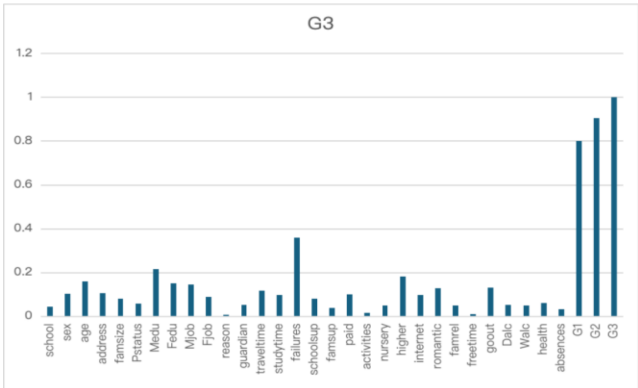

Figure 2. Feature selection for Math

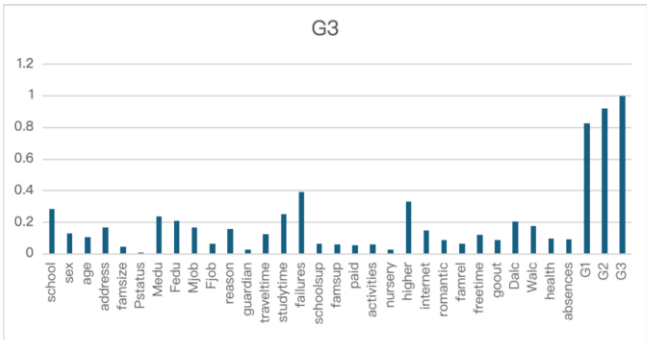

Figure 3. Feature selection for Por

Feature Selection: The prediction target is G3, representing the final grade, to reduce model complexity and maintain interpretability, a small set of predictors was selected from the original attributes. Relevant features and the target variable were extracted from the loaded 'DataFrames' to ensure that the models were trained on the most pertinent data. Figure 2 and Figure 3 show the results of the dataset preprocessing. For Math, G1, G2, Failures, Medu, Higher, and Fedu (Father's education level) are most strongly associated with the final grade. For Por, G1, G2, Failures, Higher, School, and Medu are the most important influencing factors. Therefore, the following features were selected as common predictors for both subjects: First period grade (G1), Second period grade (G2), Number of past class failures (Failures), Mother's education level (Medu) and Higher education aspiration (Higher). While some additional variables, such as Fedu and School, show relevance in individual subjects, a unified feature set was adopted to enable a fair and controlled comparison across subjects and models.

Data Splitting: Each dataset was split into training and testing sets using an 80/20 ratio. The training set was used for model fitting and cross-validation, and the held-out test set was used for final evaluation.

Standardization: To ensure all features are on the same scale, standardization was performed using 'StandardScaler'. This process scales the features to have a mean of zero and a standard deviation of one. Standardization is crucial for machine learning algorithms sensitive to the scale of input data, ensuring all features contribute equally to the training process.

Model Development

Three regression approaches were developed and compared: Linear Regression (LR), Random Forest (RF), and a simple Ensemble Model (EM).

1) Linear Regression Model (LR): Trained on standardized data, this model assumes a linear relationship between input features and the target variable. Feature coefficients were derived from training data. Performance was evaluated on test data using Mean Squared Error, Root Mean Squared Error, Mean Absolute Error, Coefficient of Determination, and Cross-Validation.

Standard Model Description: Regression assumes a linear relationship between the input features $\boldsymbol{X}$ and the target variable y. The model can be expressed as:

$$y = \mathbf{X}\beta + \epsilon \tag{1}$$

where $\boldsymbol{X}$ is the matrix of input 5 features, β is the vector of coefficients learned from the training data, y is the predicted target variable (G3), ϵ is the error term.

Training: Trained on standardized training data using the 'LinearRegression` class from 'scikit-learn'.

Prediction and Evaluation: Predictions were made on the test data, and the model's performance was evaluated using Mean Squared Error, Root Mean Squared Error, Mean Absolute Error, Coefficient of Determination, and Cross-Validation.

Feature Importance: The regression coefficient β represents the influence of each feature on the target variable.

2) Random Forest Model (RF): An ensemble learning method based on decision trees, capturing non-linear relationships and feature interactions. Multiple decision trees were built during training, and the average prediction of individual trees was outputted. Performance was evaluated using the same metrics as LR.

Standard Model Description: Random Forest constructs multiple decision trees during training and outputs the mean prediction of the individual trees. The model's prediction y is given by:

$$\hat{y} = \frac{1}{T}\sum_{t=1}^{T}\hat{y}^{(t)} \tag{2}$$

where y is the predicted target variable (G3), T is the number of trees, $\hat{y}^{(t)}$ is the prediction from the t-th tree.

The input features $\boldsymbol{X}$ are the same as in the LR.

Training: Trained on the training data using the 'RandomForestRegressor' class from 'scikit-learn'.

Prediction and Evaluation: Predictions were made on the test data, and performance was evaluated using the same metrics as LR.

Feature Importance: Analyzed to understand each feature's contribution to the model's predictions, typically using the mean decrease in impurity.

3) Ensemble Model (EM): To investigate whether combining heterogeneous learners improves predictive performance, a simple ensemble model was constructed by averaging predictions from LR, RF, and Gradient Boosting (GB). Each model was trained individually, and feature importance was averaged from RF and gradient boosting models to gain insights into feature significance. Sequential tree building corrected errors from previous trees. Final predictions were averaged from the three models, and performance was evaluated using the same metrics as the other models. This unweighted averaging strategy was intentionally adopted as a lightweight and transparent baseline ensemble to avoid additional hyperparameters, like stacking weights, that may introduce extra tuning complexity or overfitting risk under limited sample sizes.

Standard Model Description: The ensemble model combined predictions from three models, the final ensemble prediction $\hat{y}_{ensemble}$ is given by:

$$\hat{y}_{ensemble} = \frac{1}{3}(\hat{y}_{LR} + \hat{y}_{RF} + \hat{y}_{GB}) \tag{3}$$

where $\hat{y}_{ensemble}$ is the ensemble prediction of G3. $\hat{y}_{LR}$ is the prediction from the LR. $\hat{y}_{RF}$ is the prediction from the Random Forest mode. $\hat{y}_{GB}$ is the prediction from the GB. The input features $\boldsymbol{X}$ are the same as in the LR.

Training: Each model was individually trained on the training data.

Prediction and Evaluation: The final predictions were obtained by averaging the predictions from the three models.

Feature Importance: Averaged from the Random Forest and Gradient Boosting models to gain insights into the relative importance of each feature.

Model Evaluation

The following metrics were used to quantify predictive performance:

Squared Error (MSE): Measures the average squared difference between actual and predicted values.

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (4)$$

It penalizes larger errors more than smaller ones, providing a clear indication of model performance. Lower MSE values indicate better model performance.

Root Mean Squared Error (RMSE): The square root of MSE, converting the error metric back to the same units as the target variable.

$$RMSE = \sqrt{MSE} \quad (5)$$

It helps understand the prediction error in the context of the actual data. Lower RMSE values indicate better model performance.

Mean Absolute Error (MAE): Measures the average absolute difference between actual and predicted values.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \quad (6)$$

It provides a straightforward interpretation of prediction error. Lower MAE values indicate better model performance.

R^2 (Coefficient of Determination): Represents the proportion of variance in the dependent variable that can be predicted from the independent variables.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (7)$$

An R^2 value close to 1 indicates that the model explains a large portion of the variance, reflecting better prediction accuracy.

Cross-Validation (CV): To ensure the robustness and reliability of the models, k-fold cross-validation was used. This method involves dividing the training data into five subsets, training the model on four subsets, and validating it on the remaining subset. This process is repeated five times, with each subset serving as the validation set once. Cross-validation metrics (MSE, RMSE, MAE, and R^2) are averaged over the five folds to provide a more generalized performance estimate. Notably, during implementation, scikit-learn reports MSE as negative values when using scoring='neg_mean_squared_error'. We report the corresponding positive MSE values in this table for clarity.

Visualization

Prediction Plots: Scatter plots of actual versus predicted values were created for both the Math and Portuguese datasets. These plots help visualize the models' performance by showing how closely the predicted values match the actual values.

Feature Importance: Bar charts of feature importance scores were generated to understand the significance of each feature in predicting student performance. The importance scores indicate the contribution of each feature to the predictions, providing insights into the factors most influencing student grades.

Result

Quantitative comparison

Table 1. K Cross-Validation (K =5) for Math

	MSE	RMSE	MAE	R^2
LR	4.532	2.129	1.281	0.779
CV of LR	3.662	1.913	1.866	0.827
RF	4.784	2.187	1.398	0.767
CV of RF	4.535	2.087	2.087	0.784
EM	4.671	2.161	1.329	0.772
CV of EM	4.535	2.087	2.087	0.784

Table 2. K Cross-Validation (K =5) for Por

	MSE	RMSE	MAE	R^2
LR	1.347	1.161	0.725	0.862
CV of LR	1.705	1.166	1.277	0.804
RF	2.161	1.470	0.823	0.778
CV of RF	2.337	1.506	1.506	0.780
EM	1.633	1.278	0.767	0.833
CV of EM	2.337	1.506	1.506	0.780

The results presented in Table 1 and Table 2 demonstrate the performance of three machine learning models—Linear Regression (LR), Random Forest (RF), and an Ensemble Model (EM)—in predicting student grades for Mathematics and Portuguese, using K-fold cross-validation (K=5). Across both subjects, LR achieves the best overall balance between accuracy and robustness, consistently attaining the highest R^2 and the lowest error metrics. Notably, the advantage of LR is observed not only in the single train–test split results but also in the CV estimates.

For the Mathematics data set, Linear Regression yielded the lowest MSE of 4.532, and R^2 value of 0.779. In comparison, the Random Forest model exhibited higher error metrics, with an MSE of 4.784 and R^2 value of 0.767. The Ensemble Model performed moderately, with an MSE of 4.671, and R^2 value of 0.772. These results suggest that while the Ensemble Model outperforms the Random Forest, it still falls short of the Linear Regression model's performance. For the Portuguese data set, Linear Regression also outperformed the other models, , with an MSE of 1.347, and a high R^2 value of 0.862. The cross-validation results reaffirm this, with an R^2 value of 0.804.

Comparing the two subjects, the models achieve higher predictive accuracy on Portuguese than on Mathematics, as reflected by higher R^2 and lower absolute error levels. This indicates that, under the same modelling pipeline and predictor set, the Portuguese outcomes are more predictable from the selected features, whereas Mathematics appears to exhibit relatively higher residual variability. This cross-subject difference supports the decision to report results for both datasets separately rather than assuming a single universal performance profile.

Regarding model complexity, RF does not provide a consistent improvement over LR, and the simple averaging ensemble (EM) yields intermediate performance rather than surpassing the best individual model. This suggests that, for this structured dataset with a compact predictor set, adding non-linear model capacity (RF) or combining heterogeneous learners (EM) does not necessarily translate into superior generalisation. Instead, the performance pattern favours a simpler and more interpretable approach.

Prediction Behaviour

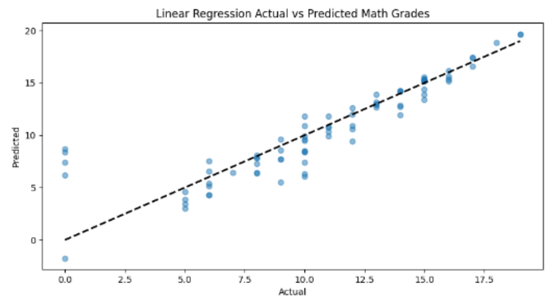

Figure 4. LR actual vs predicted Math grades

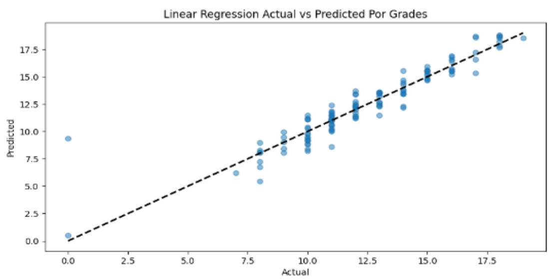

Figure 5. LR actual vs predicted Por grades

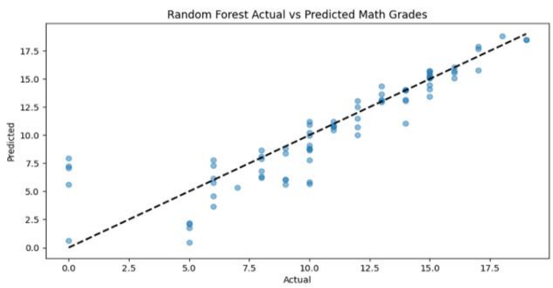

Figure 6. RF actual vs predicted Math grades

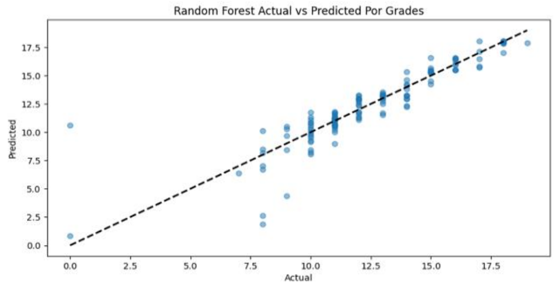

Figure 7. RF actual vs predicted Por grades

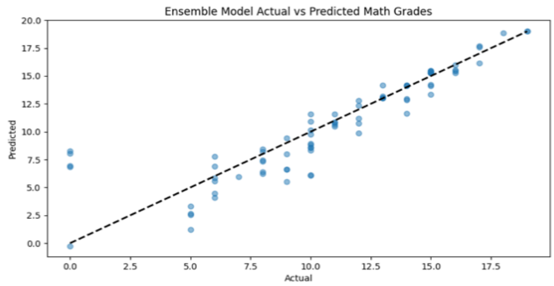

Figure 8. EM actual vs predicted Math grades

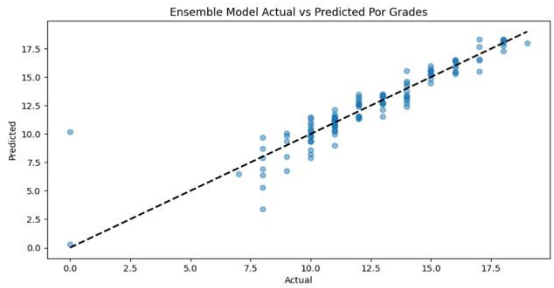

Figure 9. EM actual vs predicted Por grades

The results presented from Figure 4 to Figure 9 provide scatter plots of actual versus predicted grades for each model and subject. The x-axis represents the actual grades, and the y-axis denotes the predicted grades. Data points are scattered around a diagonal dashed line, indicating the line of perfect prediction where actual grades match the predicted grades. Overall, all models produce predictions that follow the diagonal trend, indicating meaningful learning of the grade patterns. However, clear differences are visible in the concentration and dispersion of points around the ideal prediction line.

Consistent with the quantitative metrics, LR exhibits tighter clustering around the diagonal, indicating smaller and more uniformly distributed residuals. In contrast, RF shows slightly larger dispersion, particularly for Mathematics, implying that the additional model flexibility may introduce variance without delivering a corresponding gain in predictive accuracy. The ensemble model generally follows the same trend as the base learners and reduces neither dispersion nor systematic deviations sufficiently to outperform LR, which aligns with the tabulated results.

A further qualitative observation from the scatter plots is that prediction errors tend to be more noticeable at the extremes of the grade range, where data are sparser. This behaviour is expected in educational datasets and highlights that predictive performance is strongest in the densest grade regions.

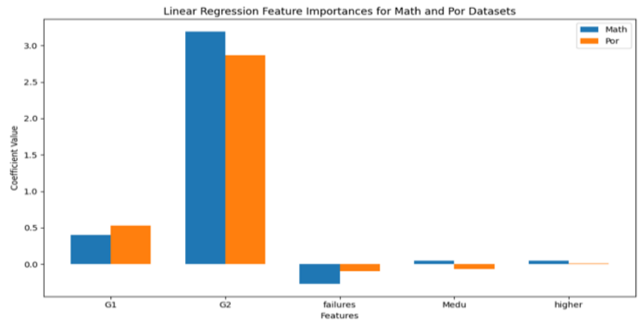

Figure 10. LR Feature Importances for Math and Por Datasets

Meanwhile, Figure 10 compares feature importance for predicting grades using Linear Regression. The x-axis lists features: G1, G2, failures, Medu, higher, and the y-axis shows coefficient values, indicating each feature's importance. Blue bars represent math, and orange bars represent Portuguese. A clear and consistent pattern emerges across both subjects: G2 is the dominant predictor, followed by G1, while Failures, Medu, and Higher contribute comparatively smaller effects. This indicates that earlier-term academic performance carries the strongest predictive signal for final outcomes, whereas demographic or aspiration-related variables provide additional but secondary explanatory power. Importantly, the feature influence pattern is broadly consistent across Math and Por, supporting the use of a unified predictor set for fair model comparison. At the same time, the observed subject-level differences in overall predictability (Table 1 and Table 2) suggest that even with similar dominant predictors, the mapping from early indicators to final performance can vary by subject context, motivating subject-specific reporting and interpretation.

Discussion

This study compared three regression approaches: Linear Regression (LR), Random Forest (RF), and a simple averaging Ensemble Model (EM), for predicting students' final grades (G3) in Mathematics and Portuguese using the UCI Student Performance dataset. Overall, the results show that LR provides the most favourable performance–simplicity trade-off, achieving the strongest predictive accuracy across both subjects while remaining highly interpretable. In contrast, the more complex RF model and the simple ensemble do not consistently improve predictive performance, suggesting that increased model complexity alone does not guarantee better generalisation in this structured educational dataset. The linear regression model has demonstrated certain effectiveness in predicting students' performance, providing educators with a possible tool for designing personalized learning plans and allocating educational resources, ensuring that intervention measures can be implemented in a timely and effective manner to improve educational outcomes in different subjects and student groups.

Comparing the two subjects, the models generally achieved higher predictive performance for Portuguese than for Mathematics, indicating that, under the same modelling pipeline and predictor set, Portuguese outcomes are more predictable from the selected features. This difference should be interpreted cautiously; it does not necessarily imply that one subject is inherently easier to predict in general. Rather, it may reflect subject-specific grading patterns, noise levels, or relationships between early and final assessments within this dataset, which, to some extent, suggests that there may be different features for STEM module and non-STEM module predictions.

A key methodological implication concerns the practical interpretation of "early intervention." Although the use of G1 and G2 improves predictive accuracy, it also means that the model primarily supports a mid-semester or operational prediction scenario, like predicting final grade after early assessments are available, rather than a true "early-warning" system at the very start of the academic term. Future work aimed at earlier-stage prediction would need to rely more on non-grade features, such as engagement proxies, attendance, learning behaviour signals, and formative assessments. It should explicitly evaluate the trade-off between interpretability and accuracy under that constraint.

In addition, there are several limitations that should be acknowledged. First, the study was derived from a specific educational context; therefore, generalisation to other regions or educational systems should be made with caution. Second, the ensemble approach was intentionally kept simple to serve as a transparent baseline. More advanced ensembling strategies, for instance, stacking with learned weights, could yield better performance but would introduce additional complexity and tuning requirements, which may reduce interpretability and increase the risk of overfitting under limited sample sizes. Third, while the reported improvements are consistent across evaluation metrics and cross-validation, the study does not claim that complex models are ineffective in educational prediction broadly. Instead, the results indicate that for structured datasets with strongly predictive prior-performance features, simpler models may be sufficient and preferable.

Overall, this work contributes a measured empirical perspective: rather than assuming that more sophisticated machine learning models will always outperform simpler alternatives, the findings suggest that model selection in educational analytics should be driven by data characteristics and deployment requirements, with interpretability and practicality considered alongside predictive accuracy.

Conclusion

Using the UCI Student Performance dataset, students' final grades in Mathematics and Portuguese was predicted by comparing three different machine learning models, linear regression, random forest, and integrated models. The findings indicate that Linear Regression outperforms the other models, achieving the highest R^2 values and the lowest MSE, RMSE, and MAE values in both subjects. This suggests that Linear Regression is particularly effective at capturing key features to develop accurate predictive models for student performance. However, the results also highlight the challenges in creating a universally accurate model for different subject modules. The comparative analysis between Mathematics and Portuguese datasets suggests that distinct features may be necessary for predicting performance in STEM versus non-STEM subjects. Across both subjects, prior academic performance indicators (G1 and G2) are the most influential predictors, highlighting the central role of early-term achievement in forecasting final outcomes.

Future research can extend this work in three directions. First, to support truly early-stage intervention, models should be evaluated using predictors available at the start of the term and compared under the same interpretability–accuracy lens. Second, validation on more diverse datasets and educational contexts would strengthen generalisability and improve relevance to broader regional practices. Third, while advanced ensembles and deep learning methods may be beneficial for larger and more complex data sources, their added value should be assessed against the practical costs of deployment, transparency, and maintenance, particularly in educational settings where interpretability and accountability are essential.

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https://github.com/JiajunGuo1027/AI-Driven-Student-Performance-Prediction-and-Analysis-of-Influencing-Factors.git

Conflict of Interest

The authors declare that there is no conflict of interest associated with the publication of this manuscript.

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Bridging Gaps in Electronic Circuit Design Education: An Action Research Study

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Abstract
This paper presents an action research project aimed at improving the performance of second-year students in electronic circuit design, as part of their practice in the undergraduate module MEC104 at Xi'an Jiaotong-Liverpool University. Several issues have been identified through observations by module leaders and feedback from students, including gaps between lectures and lab sessions, safety concerns, and lengthy debugging periods. To address these challenges, this study proposed integrating the TinkerCAD simulation tool into the module, outlining a three-step action research plan. The results and analysis indicate a positive impact of the simulation-based approach on student learning and performance in electronic circuit design.

Keywords: STEM Education, Technology-enhanced learning and teaching, Curriculum Design.

Introduction

A. Teaching Electronics Design in MEC104

The action research reports enhancing the performance of electronic circuit design for second-year students taking the MEC104 as practice. The MEC104 module, "Experimental, Computer Skills and Sustainability," offers a comprehensive learning experience in electronic engineering at the School of Advanced Technology, Xi'an Jiaotong-Liverpool University, which also covers fundamental experimental techniques, computer literacy, and engineering sustainability. This module targets on second-year engineering students and carries 5 credits. In addition to lectures on sustainability topics, the module primarily focuses on experimental electronics design, which consists of three projects: a Digital Clock project, a Smart Car project, and an Open Project. These projects account for 70% of the total marks for the module's assessment, highlighting the importance of electronic circuit design for students participating in this module.

B. Features of Teaching Electronic Design in MEC104

1) Very hands-on topics

Module MEC104 is designed to provide students with a highly interactive and experimental learning experience. With a strong focus on hands-on learning, this module is particularly valuable for second-year students who may not have extensive background knowledge or practical experience in electrical engineering. By emphasizing experiential learning, students can actively participate in the learning process, enabling them to develop a deeper understanding of the subject matter.

2) Continuous lab projects on a weekly basis

One of the key features of MEC104 is the incorporation of continuous lab projects throughout the semester. By assigning weekly lab projects, students are encouraged to consistently practice and apply their theoretical knowledge in a practical setting. This approach promotes continuous learning and helps students develop the necessary skills to succeed in the field of electrical engineering. Moreover, the regular lab projects enable students to build upon their previous work, reinforcing their understanding of the concepts and fostering a systematic approach to problem-solving.

3) Systematic design skills

A primary goal of MEC104 is to equip students with systematic design skills that can be applied in real-world scenarios. Recognizing the importance of industry expectations, this module aims to bridge the gap between academic learning and practical applications. By honing their design skills, students are better prepared for future careers in electrical

Zhang, T., Lu, Y., Chen, Y., Wu, H., Sun, J., Leach, M., & Lim, E. G. (2026), Bridging Gaps in Electronic Circuit Design Education: An Action Research Study, *ASEAN Journal of Engineering Education*, 10(1), 31-36. https://doi.org/10.11113/ajee2026.10n1.217

engineering and can meet the demands and standards of the industry. This emphasis on systematic design not only enhances their technical abilities but also cultivates a professional mindset necessary for success in their chosen field.

C. Conventional Teaching Pattern of MEC104

The pedagogical approach adopted in the instruction of MEC104 can be delineated into two primary components: lectures and laboratory sessions. During the lectures, instructors impart theoretical concepts and concisely overview electronic components. Subsequently, students actively engage in the practical application of their acquired knowledge during laboratory sessions. Here, they are tasked with the design of electronic circuits and are required to troubleshoot and rectify any issues encountered until the circuits operate as intended.

D. Challenges of Teaching MEC104

After observation in the classroom, several challenges that need to be addressed:

1) Large class size

The large class size limits individual attention and interaction, creating a heavy workload for module leaders and teaching assistants. Hands-on learning strategies should be incorporated to overcome this challenge, promoting group activities and collaborative projects. This fosters peer-to-peer learning and engagement within the classroom.

2) Safety issues

In subjects like electrical engineering, safety is crucial due to the inherent risks of working with circuits and equipment. The trial-and-error approach can lead to safety hazards, especially for inexperienced students. Neglecting safety concerns compromises student well-being and creates an unsafe learning environment.

3) Gap between lecture and lab

The gap between theoretical concepts taught in lectures and their practical application in labs can be challenging for students. Lack of integration between lecture material and lab projects hinders knowledge transfer and the development of practical skills. Bridging this gap is essential for a comprehensive understanding of the subject.

4) Long debugging time

Debugging is integral to engineering projects, including electrical engineering. However, lengthy debugging periods frustrate students and impede progress. Extended debugging time demotivates students, impacts their confidence, and limits exploration of alternative solutions or further coursework aspects.

Based on the past feedback from students, we also identified that the students have the following problems with MEC104.

- Limited design practices
- Difficult in applying theory to practice
- Confusion in debugging
- Frequent damage to hardware parts

All these points are due to the character of MEC104 that hands-on experience is required to get a high performance, but the hands-on experience is limited from lab sessions. Such giant gap between theory and practice leads to unsatisfactory performance from students.

Literature Review

A. Methodology on Simulation Based Education

Engineering students frequently engage with complex real-world systems, such as electronic circuits, robots, and deep neural networks (Kutz et al., 2016). These systems often possess high dimensionality, with thousands of parameters that can significantly impact their behavior (Kutz et al., 2016). Additionally, real-world complex systems are subject to external perturbations and internal uncertainties, which pose challenges in engineering education. University practices often fall short of meeting the requirements outlined by teaching standards, resulting in students having limited understanding of these complex systems. Consequently, graduates often require additional training before effectively applying their engineering skills in practical settings (Gruler et al., 2019).

Previous studies have highlighted the potential of virtual simulation platforms to improve students' comprehension of abstract concepts and enhance their learning experiences through repeated exploration (Juan et al., 2017). Simulation-based education (SE) emerged as a valuable tool for enhancing learning experiences as early as the 1960s (Schild, 1968), and it has since evolved across various fields in higher education, including engineering, nursing, and business management (Campos et al., 2020).

The growing popularity of SE can be attributed to advancements in personal computing devices, which now possess the capability to provide precise simulations of real-world environments (Faria et al., 2009). Such accurate simulations enable students to practice in realistic environments, accumulate valuable experience, and deepen their theoretical understanding. Another factor contributing to the popularity of SE is the integration of gaming elements, which increases student engagement and fosters a more enjoyable learning experience (Cai et al., 2016). SE can be designed in a pedagogically engaging manner, incorporating competitive elements where students must solve specific issues and surpass their peers to achieve notable accomplishments. This approach holds particular appeal for current students (Pasin & Giroux, 2011; Stanley & Latimer, 2011; Deshpande & Huang, 2011). Comprehensive reviews on related topics can be found in previous works (Campos et al., 2020; da Silva et al., 2019).

Given that the module under consideration falls within the sciences, technology, engineering, and mathematics (STEM) realm, it is essential to explore the role of SE in STEM education. Previous research has indicated that SE can bridge the gap between theory and practice, enhancing understanding and performance in business training (Riley, 2012). It has also been suggested that SE offers valuable experience with extensive training capacity, addressing the challenges of traditional physically constructed and costly laboratories (Alnoukari et al., 2013). Recent studies have successfully employed SE to simulate factory operations, providing students with a comprehensive understanding and potentially serving as a training tool for future workers (Frantzén & Ng, 2015). Furthermore, the use of an electronic circuit simulator has been shown to significantly improve students' performance (Mavinkurve & Patil, 2016). Similar simulation platforms have been employed to replicate real-world environments in military training, further highlighting the effectiveness of SE (Bruzzone & Massei, 2017). In summary, SE has emerged as a valuable tool for bridging the gap between theory and practice in STEM education.

The key benefits of SE include increased student motivation (Klug & Hausberger, 2009), valuable experience within a safe practice environment (Ören et al., 2017), enhanced problem-solving and decision-making skills (Tzimerman et al., 2014), and the cultivation of critical thinking in learning activities (Pirker & Gütl, 2015). However, SE also presents certain drawbacks, including potential distractions, the need for specialized training, and challenges in assessment (Ören et al., 2017). Nonetheless, it has been suggested that these drawbacks can be mitigated through careful project design (Campos et al., 2020).

B. Simulation Tools Selection

For the electronics design, evaluation, and simulation, or simply for understanding electrical circuits, various platforms, such as EasyEDA, PartSim, EveryCircuit, Falstad, DoCircuits, LTspice, OrCAD PSpice, fritzing, GEDA, NI Multisim or Proteus, can be found. However, these programs require installation, which can be a potential user barrier. Additionally, they are not very user-friendly and can be quite challenging for beginners. Another limitation is that these tools do not allow teachers to monitor their students' progress remotely, even if they are in the same room.

Nonetheless, it is possible to do so with the TinkerCAD platform. The efficacy of this platform compared to other simulation software available for engaging engineering students in learning key hands-on laboratory skills was also demonstrated recently (Abburi et al., 2021). The results from some other works show that this platform can provide similar experiences as conventional laboratory activities (Shalannanda, 2020) or can be used to indicate that students have positive intentions to learn programming and computing-electronic skills (Vidal-Silva et al., 2019). Hence, TinkerCAD platform is a potentially suitable candidate for conducting the project

Action Research Methodology

A. Research Question

Based on the review and analysis above, the research question is identified:

To what extent does the TinkerCAD simulation tool bridge the gap between theory and practice in electronic product design (including enhancing familiarity with electronic circuits, improving assembling and debugging experience, and improving student performance)?

B. Action Research Plan

Based on the research question and contents of the MEC104, we have devised an action research plan comprising three projects from easy to difficult using TinkerCAD. Step-by-step guidance has been provided to students.

1) Starting simulation project – Digital Clock

To familiarize students with the simulation platform, we have designed a preliminary project wherein students are tasked with designing a digital clock. Detailed operational instructions are provided to guide students, and the lab sessions are utilized to ensure that all students complete the project. This exercise enables students to become acquainted with the process of designing, assembling, and debugging electronic circuits.

2) Design project with a pre-selected topic – Smart Car

In this phase, students are required to undertake a design project centered around a pre-selected topic: a smart car system. Following a procedure similar to the starting project, students go through the design, assembly, and debugging processes. Once the simulated project is completed, students are encouraged to assemble the electronic circuits physically. Drawing on their experience from the simulation platform, they can employ the simulation results as a guide for hands-on debugging. If students encounter any unclear issues, they can attempt to replicate the bugs within the simulation and then seek solutions. Furthermore, since all students are working on the same topic, they are encouraged to engage in discussions and collaborate to identify solutions.

3) Open project with a free topic

Upon completion of the smart car project, students are granted the freedom to embark on a new project based on their individual interests. The design procedure mirrors that of the smart car project, with the distinction that students must now independently complete the project as the topics vary. Throughout this phase, instructors and teaching assistants provide only general guidance, fostering an environment where students are motivated to find solutions through their own efforts.

A common thread across all projects is that students must first complete the simulations before proceeding to the physical experimentation stage. Debugging within the simulation platform proves highly efficient, allowing for multiple trial runs within a short timeframe and enabling students to accumulate experience through simulated debugging processes. Moreover, the safety issues in the practical hands-on lab sessions can be significantly reduced since students gain much experience during the practice in the simulation.

Therefore, as shown in Figure1, the traditional teaching pattern has been transferred to a new simulation-based teaching pattern with a middle stage. The proposed simulation-based teaching approach allows students to acquire valuable experience during the simulation stage before the hardware practice in the lab, which distinguishes it from traditional teaching methods.

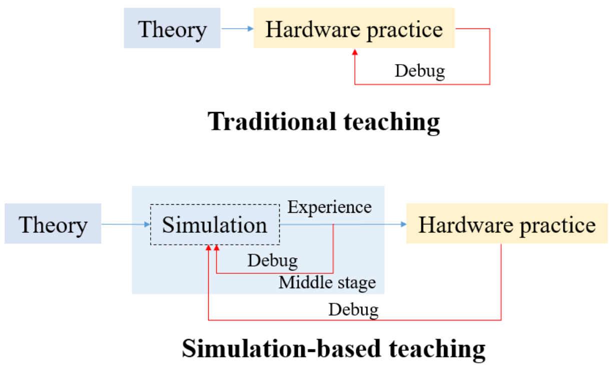

Figure 1. Proposed teaching pattern with simulation middle stage

Results and analysis

A. Student Feedback

To evaluate the outcomes of integrating simulation-based teaching into MEC104, we employed anonymous questionnaires to gather feedback from the students. The questions included in the questionnaires are:

- Is TinkerCAD helpful when designing electronic circuits?
- Please evaluate the most helpful point by using the simulation platform TinkerCAD.

92 responses were collected. The following section evaluates the collected results in Figure 2.

Approximately 89% of the participating students found TinkerCAD to be beneficial in the design of electronic circuits. This indicates that simulation-based teaching is valuable in delivering the content of MEC104.

Figure 3 clearly illustrates that the aspect of TinkerCAD that students found most helpful is its assistance in practicing circuit assembly. This is likely because assembly is a new skill for students and is the foundation for constructing electronic circuits. Furthermore, approximately 36% of the students identified debugging as the most helpful aspect of TinkerCAD. This aligns with the objectives outlined in the action plan, as the simulations provide students with valuable debugging experience, which can then guide them when debugging physical circuits.

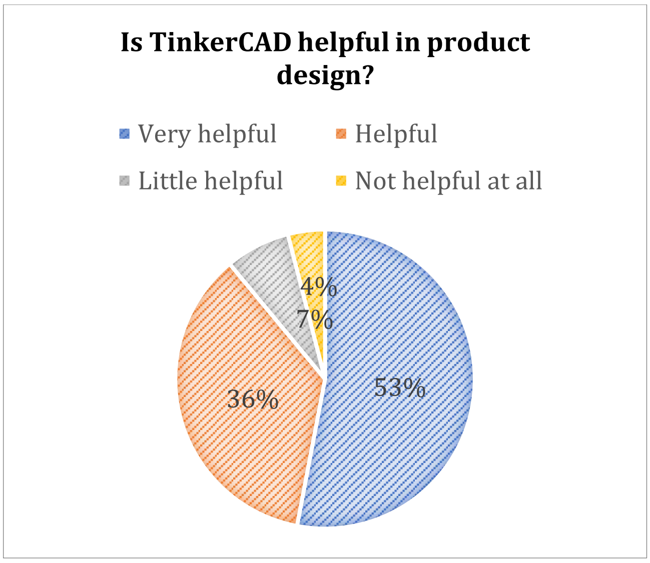

Figure 2. Students' feedback on survey question 1

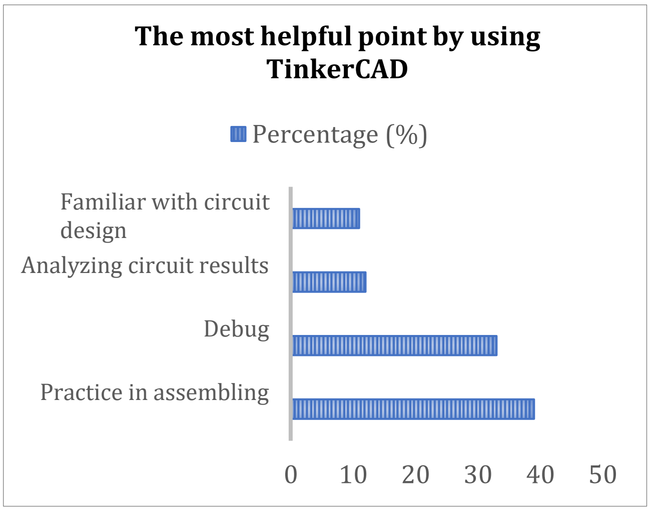

Figure 3. Student feedback on survey question 2

B. Student Assessment Performance

During the pandemic, temporary changes were made to the assessment methods. However, in the academic year 2022-2023, the assessments were reverted to the original format. Therefore, we compare the data from the 2022-2023 academic year with that of the 2018-2019 academic year to analyze the impact of the action research in Figure 4.

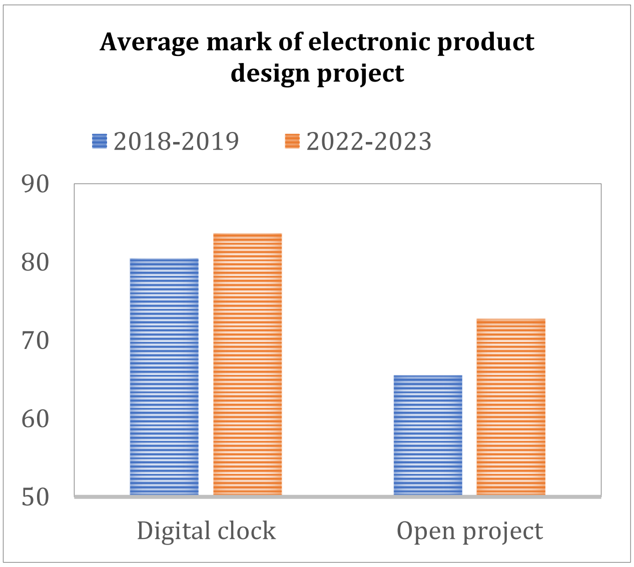

Figure 4. Average mark of electronic product design project

To ensure fairness in grading, we have employed the same marking guidelines for all assessments. Upon analyzing the marks depicted in Figure 4, we have observed an improvement in both the smart car and open project assessments. This demonstrates the benefits of integrating simulation-based teaching into MEC104. Specifically, students achieved higher scores in the smart car project due to a higher completion rate, indicating that more students successfully completed the project. Moreover, students received higher marks in the open project because they could implement more complex functionalities in their designs. With the assistance of TinkerCAD, students have gained more experience in electronic circuit design and have become more confident in incorporating intricate features into their own projects.

Based on the feedback obtained through the questionnaires and the assessment results, the integration of simulation tool into the teaching of MEC104 has proven to enhance students' comprehension of the module's content and improve their performance in electronic circuit design.

Discussion and Future Work

After analyzing the above results, the following aspects have been reflected upon and discussed, along with future directions for improvement.

1) Introducing a virtual simulation platform has shown to be effective in improving students' performance in MEC104. In the future, it is recommended to integrate simulation demonstrations into the teaching process further. This can help students gain more hands-on experience and enhance their understanding of the concepts.

2) The aspect of practicing circuit assembly was identified as the most helpful by students. To capitalize on this, it is suggested that a specific simulation project be introduced during lectures that focuses on familiarizing students with circuit assembly techniques. This can help students develop the necessary skills and confidence in this area.

3) The use of simulations has proven to be beneficial in guiding students through the debugging process. As a future direction, it is recommended that specific debugging techniques using simulations be introduced and demonstrated. This can provide students with valuable experience and enhance their troubleshooting abilities.

4) Students have found that simulations help get acquainted with electronic components. To leverage this advantage, it is proposed to integrate simulations when introducing each electronic component in order to make the theoretical concepts more intuitive and tangible for students.

By implementing these future steps, it is expected that the integration of simulation-based education in MEC104 can be further optimized to enhance student learning outcomes and improve their overall performance in electronic circuit design.

Conclusion

This paper presents an action research plan to examine the impact of integrating simulation-based teaching into the teaching of electronic circuit design. The plan consists of three sequential steps designed to progressively familiarize students with the simulation platform and facilitate their experiential learning. The findings and assessment results indicate that students perceive the simulation-based education approach as beneficial for acquiring knowledge and skills in electronic circuit design. Furthermore, the results demonstrate an improvement in students' experience on electronic design and overall performance because of utilizing the simulation platform. Therefore, it is evident that integrating the TinkerCAD simulation tool can effectively bridge the gap that exists between lectures and lab sessions, which could enhance the teaching of electronics design.

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Conflict of Interest

The authors declare that there is no conflict of interest associated with the publication of this manuscript.

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Design-Based Learning (DBL) Under Contextual Constraints: A Framework for Form 3 Design and Technology Education in Rural Malaysia

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Abstract
Design-Based Learning (DBL) has been widely promoted as a learner-centred pedagogy that engages students in creative, hands-on, and problem-solving tasks. In Malaysia, DBL aligns closely with the Design and Technology subject (Rekabentuk dan Teknologi – RBT) introduced under the Secondary School Standard Curriculum (KSSM). However, most DBL models are often conceptualised in well-resourced environments that assume access to specialised tools and digital technologies. Limited empirical research has examined how the approach is enacted in under-resourced rural settings. This qualitative study explores how DBL is enacted, adapted, and constrained in rural school contexts in three rural secondary schools in Kudat, Sabah. Drawing on semi-structured interviews with nine RBT teachers, including three school administrators who also teach RBT, and six Form 3 RBT students, alongside document analysis, the study employed inductive thematic analysis to examine classroom realities and contextual challenges. Four interrelated themes emerged: inadequate material and infrastructural resources, tensions in integrating theory and practice, difficulties in assessing design processes, and limited professional and community support. Guided by constructivist, place-based, and social learning perspectives, these findings were interpreted to develop a contextualised DBL framework that responds to the realities of under-resourced rural settings. The proposed framework emphasises pedagogical flexibility, process-oriented assessment, and enabling support structures to support more inclusive and sustainable DBL implementation. This study contributes to the literature by extending existing understandings of Design-Based Learning through an examination of how DBL is reshaped by contextual constraints in rural and under-resourced secondary school environments. The study contributes to ongoing efforts to reduce educational inequities in line with the Malaysia Education Blueprint 2013–2025 and aligns with Sustainable Development Goals 4, 5, 9, 10, and 17 by advancing equity, innovation, and collaborative learning in underserved communities.

Keywords: Design-Based Learning, Design and Technology, rural education, technical and vocational education and training

Introduction

Design-Based Learning (DBL) involves students applying theoretical knowledge to solve real-world design problems, fostering an understanding of both technical and practical skills (Clavert & Paloposki, 2015). DBL involves students working on the design of artifacts, systems and innovative solutions in project settings (Fayonto et al., 2024). This method is particularly effective in promoting deep learning and problem-solving abilities among students (Gómez Puente, van Eijck, and Jochems, 2015). Moreover, the hands-on nature of DBL projects (Radulescu et al., 2021) fosters a sense of accomplishment and satisfaction (Kasliwal et al., 2023). For example, in DBL, students actively engage in problem exploration, idea generation, prototype construction and iterative evaluation, thereby creating learning experiences that are more authentic and meaningful (Aksela and Haatainen, 2019; Kangas et al., 2021). The projects should be open-ended and multidisciplinary to encourage comprehensive learning (Gómez Puente et al., 2015), thus incorporating design thinking to foster creativity, empathy and collaborative problem solving is highly encouraged (Gómez Puente, van Eijck, & Jochems, 2013). Fried et al. (2020, 2021), for example,

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found that biomimicry projects enabled students to connect biological concepts with real-world problem-solving without compromising foundational theoretical understanding. Similarly, Gonzalez-Almaguer et al. (2021) demonstrated that integrating Design Thinking and Design of Experiments (DOE) strengthens students' systematic reasoning and problem-solving abilities.

Globally, DBL has shown promise in enhancing student engagement, interdisciplinary learning outcomes and development of essential 21st century skills (Aksela and Haatainen, 2019; Kangas et al., 2021; Veldhuis et al., 2022; Kasliwal et al., 2023). In this study, Design-Based Learning (DBL) is conceptualised as a learner-centred pedagogical approach characterised by authentic design challenges, iterative problem-solving processes, integration of theory and practice, collaborative learning, and process-oriented assessment, based on DBL characteristics outlined by Gómez Puente et al., (2015). This differentiates DBL from general project-based learning because DBL requires iteration, reflection, and process evidence. Moreover, in DBL, teachers act as facilitators, guiding students through the design process and helping them develop problem-solving skills (Gómez Puente et al.,2015). They provide scaffolding to support students' learning and encourage them to take ownership of their projects.

DBL seems to align closely with the aspirations of the Malaysian Secondary School Standard Curriculum (KSSM), particularly in the Design and Technology (RBT) subject. This subject was introduced in 2017. Prior to the introduction of this subject, the Living Skills (or *Kemahiran Hidup*) subject was taught from 1989 to 1991 (Transition Program) and Integrated Skills in accordance with the objectives of the Integrated Secondary School Curriculum (KBSM) from 1991 to 2016, which was then changed to the RBT subject starting in 2017 until now. The RBT subject focused on developing students' skills so that they would be more confident, selective, and productive in the world of technology, as well as instilling positive values. This subject was taught in lower secondary schools according to KBSM to replace elective subjects such as industrial arts, commerce and entrepreneurship, home economics, and agricultural science. However, RBT was introduced in 2017 to replace KHB because RBT emphasizes higher-order thinking skills (HOTS), problem-solving, innovation, and the use of the latest technology in line with the Malaysian Education Plan 2013-2025.

According to the Curriculum and Assessment Standard Document (DSKP), RBT emphasises project-based learning, product development, and the application of contemporary technologies (Ministry of Education Malaysia, 2016). The curriculum is fundamentally interdisciplinary, integrating elements of Science, Technology, Engineering, and Mathematics (STEM) with creative and reflective components, thus promoting mastery of technical skills, design, innovation and critical thinking through iterative design cycles. This marks a significant shift from traditional content-driven instruction towards a more contextual, experiential, and design-focused pedagogy.

The Form 3 RBT syllabus covers three core domains: Application of Technology (Mechatronic Design), Product Development, and Design in Business, which are purposefully aligned with the principles of Design-Based Learning (DBL) and Project-Based Learning as mandated in the KSSM curriculum. These domains operationalize the Design Cycle by engaging students in problem analysis, idea generation, conceptual design, prototype construction, testing, and documentation. The Mechatronics domain embeds DBL through activities that require students to identify system components, analyze existing mechanisms, propose design improvements, and evaluate their functionality. The Product Development domain serves as the central DBL context, guiding students through customer needs analysis, design conceptualization, production planning, product fabrication, and performance testing thereby fostering critical, creative, innovative, and entrepreneurial competencies. The Design in Business domain extends the design process into commercial relevance by requiring students to analyze marketing strategies and create promotional materials that enhance the marketability of their products. Collectively, these domains position DBL as an essential pedagogical core through which students develop authentic design, problem-solving, and evaluative capabilities within real-world contexts. Overall, the RBT curriculum articulates a clear vision for embedding DBL within secondary education and aligns closely with Malaysia's shifting technical and vocational education (TVET) agenda that is increasingly oriented towards creativity, flexibility, and technological fluency.

This study is significant because it highlights the practical realities and contextual constraints that influence the implementation of Design-Based Learning (DBL) in rural secondary schools. While DBL has been widely discussed in well-resourced educational environments, limited empirical research has examined how the approach is enacted in under-resourced rural settings such as those in Sabah. By documenting the lived experiences of teachers and students, this study provides important insights into the structural, pedagogical, and institutional challenges that shape DBL implementation in rural contexts. The findings contribute to implementation research by demonstrating how contextual factors influence pedagogical enactment and by proposing a contextualised DBL framework that can guide teachers, school leaders, and policymakers in strengthening design-based learning practices in rural Malaysian schools.

DBL Challenges in Rural and Under-resourced Contexts

The implementation of DBL in rural schools remains far from ideal. Remote locations in Sabah are very different settings that contrast sharply with the typical Western, urban, tech-centered classroom where most educational innovations are usually tested (Mohamad et al., 2018; Pariyar et al., 2019). For example, studies show that rural schools face severe resource limitations, including outdated infrastructure and inadequate devices (Sepadi et al., 2025; Maja, 2024). Moreover, teachers often struggle with the technical complexity of integrating new technologies into their classrooms, which hinders effective integration of technology (Sepadi et al, 2025; Ndjama & Ajani, 2025) and dealing with technical issues (Ga et al., 2024). This leads to students in rural schools having fewer opportunities to engage in hands-on, real world related project, which are crucial for developing problem-solving and critical thinking (Ali & Lande, 2018). The lack of access of necessary tools and resources further limits their ability to prototype and explore collaboratively (Ayer, Leicht, & Smith, 2012). Nevertheless, encouraging students to engage in collaborative prototyping projects can improve their understanding of the design process and enhance their ability to communicate design ideas (Ali & Lande, 2018; Hansen, Eifler, & Deininger, 2021).

Similar constraints may also be evident in rural Sabah as reported by past studies. Sabah remains one of Malaysia's most underdeveloped states, particularly in terms of infrastructure, technology, and communication systems. According to Deenerwan (2024), Sabah remains one of the states with the highest concentration of underperforming districts in national examinations. Rural schools in Sabah often record lower performance levels compared to urban areas, influenced by a lack of exposure to alternative teaching methods and insufficient educational resources (Ong & Mohd Tajuddin, 2021; Deenerwan,2024; Jafar et al., 2022).

While higher education institutions nationwide are shifting toward digital and interactive pedagogies, including virtual platforms and hands-on learning models such as Design-Based Learning (DBL), schools in Sabah are expected to keep pace despite limited resources and structural disadvantages. This expectation places rural teachers and students at a disadvantage, especially in subjects like Design and Technology (RBT), where DBL requires access to digital tools, internet connectivity, and prototyping equipment. These inequities risk undermining the effectiveness of DBL and widening existing educational disparities. Thus, this research is conducted in Sabah due to the well-documented educational disparities between rural and urban regions in Malaysia, particularly in student performance and resource accessibility. Furthermore, the lack of exposure to alternative teaching methods, such as design-based learning, compounds the challenges faced by rural learners. Therefore, this study explores the unique challenges of implementing DBL in rural Sabah schools, especially in Kudat, the Tip of Borneo. This study seeks to further explore the critical need of design based pedagogical models tailored to the rural Sabah context, thereby contributing to the national goal of reducing education inequality as outlined in the Malaysian Education Blueprint 2013–2025. Moreover, little is known about incorporating local values and community needs can make learning more relevant and impactful (Mohamad et al., 2018). Thus, targeted contextual research and focused interventions are therefore essential, especially for rural schools that continue to experience systemic disadvantages.

DBL and the RBT Curriculum in Malaysia

The Design and Technology (RBT) subject in Malaysian secondary schools seems to provide a naturally conducive ecosystem for the implementation of Design-Based Learning (DBL), as both emphasise project-based learning, technological application, and product development. However, little is known how to effectively implement DBL in rural areas. Moreover, teachers need professional development to effectively implement DBL. For example, Gómez Puente et al., 2015 suggested that training should focus on experiential learning cycles and the application of DBL frameworks. This is to ensure teachers encourage students to explore and innovate, rather than direct teaching (Clavert & Paloposki, 2015).

Another notable issue concerns teachers' mastery of technological tools and design methodologies. Research shows that the structure of the RBT curriculum which emphasises design processes, the use of technologies such as Arduino, and the development of functional products naturally corresponds with the phases of DBL (Ajit et al., 2022; Barak, 2020). Nonetheless, many teachers encounter limitations in both technical and pedagogical competencies. However, a significant number continue to rely on textbooks and express limited confidence in operating tools such as CAD software or mechatronic components. In large classroom settings, limited tools and space often require DBL activities to be organised through staggered stations or mini-sprints, a practice consistent with Barak's (2020) observations on adapting DBL for resource-constrained environments. Besides, teachers need professional development and support to effectively implement DBL (Veldhuis et al., 2022). This includes training in facilitating open-ended projects and integrating multidisciplinary activities. This is crucial as designing effective DBL projects requires careful consideration of the project's scope, complexity, and relevance to ensure they are challenging yet achievable for students.

Moreover, the open-ended and non-standardised nature of DBL assessment presents further hurdles, often leading to inconsistencies or uncertainty among teachers (Dumitrescu & Stănescu, 2022). This is due to the challenge of assessing DBL projects which can be complex, as it involves evaluating both the process and the final product (Gómez Puente et al., 2013). These issues highlight a widening gap between curricular aspirations and classroom realities, underscoring the need for enhanced teacher training and clearer assessment mechanisms. The integration of Outcome-Based Education (OBE) has been shown to enhance alignment between learning outcomes, design activities, and assessment practices (Zhang et al., 2021). The use of dual-layer rubrics one focusing on process elements (ideation, collaboration, reflection) and another on technical competency (safety, documentation) can support more equitable and formative assessment strategies (Hennessy & Mueller, 2020). Similarly, Lovejoy et al. (2021) demonstrated that interdisciplinary approaches within DBL, such as combining art and technology, enhance content connectedness and student motivation.

In terms of activity design, Huang et al. (2020) found that short DBL modules, such as sensor or actuator tasks conducted over two to three weeks, are sufficient to strengthen students' practical understanding of systems. Studies also advocate for the use of low-cost kits, locally sourced materials, and the establishment of community tool banks as medium-term strategies to address resource limitations in rural schools (Ajit et al., 2022). However, emerging evidence suggests that when DBL is contextualized to local realities, such as incorporating community-based design problems and using low-cost materials, can significantly enhance students' creative confidence and engagement (Saaya et al., 2023).Despite these challenges, research also highlights the potential of DBL to enhance student engagement, creativity and understanding of technical concepts when the approach is contextualised to the local environment (Saaya et al., 2023). Hence, there is a pressing need to develop a DBL implementation guide specifically tailored for rural schools such as those in Kudat. Such a guide must consider real constraints, local resources, cultural practices and the existing capacity of teachers and infrastructure. Beyond supporting RBT teachers in planning and conducting instruction, the guide can also assist schools, administrators and policymakers in strengthening the DBL ecosystem more systematically. Moreover, this study contributes to engineering education by demonstrating how DBL within the RBT subject can serve as an early platform for developing engineering design thinking, problem-solving, and prototyping skills among secondary school students. By contextualising DBL implementation in rural oriented classrooms, the study highlights how foundational engineering competencies can be nurtured even in resource-constrained educational environments.

Theoretical Framework Guiding This Study

Consistent with qualitative research traditions, theoretical perspectives were used to interpret emerging themes and inform framework development rather than to predefine analytic categories or test theoretical propositions. Design-Based Learning (DBL) is a complex pedagogical approach that integrates cognitive processes, contextual conditions, and social interactions in the construction of knowledge. In rural secondary school settings, where limitations related to infrastructure, resources, and professional support are prevalent, the enactment of DBL cannot be adequately understood through pedagogical description alone. A theoretical framework is therefore necessary to support qualitative sense-making of how DBL is experienced, adapted, and constrained in practice. This study adopts a multi-theoretical framework drawing on Constructivism, Place-Based (Situated) Learning, and Social Learning Theory to guide interpretation of participants' experiences and to inform the development of a contextualised DBL framework for Form 3 RBT education in rural schools.

Design-Based Learning aligns well with constructivist principles by promoting active, collaborative, and contextually relevant learning experiences (Fitriani, Shefeld, & Koul, 2025). Moreover, the iterative nature of DBL, combined with real-world problem-solving and scaffolding, supports the constructivist view that knowledge is actively constructed through meaningful engagement and social interaction (Clavert & Paloposki, 2015; Asrifan et al., 2025). This alignment enhances learning outcomes, critical thinking, and professional development, preparing learners for future challenges (Clavert & Paloposki, 2015; (Özüdoğru, 2025). Within the RBT context, DBL enables theoretical concepts to be embedded within hands-on design tasks, supporting meaningful integration of theory and practice.

Next, place-based and situated learning theories emphasise that learning is inherently shaped by the physical, social, cultural, and material contexts in which it occurs (Lave & Wenger, 1991; Sobel, 2004), Lave and Wenger (1991) and Sobel (2004) emphasise that learning is shaped by participation in authentic practices and local contexts. Moreover, Arvaja (2007) found that different backgrounds and contextual resources influence how students create and interpret context, negotiate meanings, and engage in knowledge construction activities.

In addition, Social Learning Theory (SLT) by Bandura (1986) highlights that learning occurs through observation, imitation, and modeling. It posits that people can learn new behaviors and skills by observing others, which involves attention, retention, reproduction, and motivation (Saka, 2024). These steps are interrelated and collectively influence learning. Consequently, teachers who adopt SLT should design instruction with these stages in mind, recognise their role as behavioural models, and intentionally structure learning environments that sustain learners' attention, support memory retention, facilitate behavioural reproduction, and enhance motivation. This principle is crucial in DBL, where students often learn by observing instructors or peers demonstrating design processes and technique (van Diggelen et al., 2021). Teachers act as models and provide the necessary support to help students progress through their design projects (van Diggelen et al., 2021). DBL requires teachers to adopt facilitative roles and develop new pedagogical and technical competencies, which can be challenging in rural contexts where access to professional development and peer support is limited. From a social learning perspective, sustained DBL implementation depends on collaborative support structures such as professional learning communities, school leadership involvement, and community partnerships. In this study, social learning theory informs interpretation of findings related to limited professional and community support, reinforcing the view that DBL enactment is a collective endeavour rather than an individual teacher responsibility. Thus, taken together, constructivism, place-based learning, and social learning theory provide a complementary framework for interpreting DBL implementation in rural RBT classrooms. Constructivism explains how learning occurs through active engagement, iteration, and reflection; place-based learning explains how local contexts and resources shape pedagogical enactment; and social learning theory explains how collaboration and institutional support mediate practice. These theoretical perspectives guided interpretation of the study's findings and informed the development of the contextualised DBL framework proposed in this research. Consistent with qualitative research traditions, these theories were employed as interpretive lenses to support sense-making of participants' experiences rather than as prescriptive frameworks to predetermine categories or test theoretical propositions.

This study addresses the following research question:

(i) What are the critical challenges and contextual needs for implementing Design-Based Learning in Form 3 RBT education in rural Kudat, and (ii) how can a conceptual framework be developed to support its effective enactment?

Accordingly, the research question is framed to explore the processes, challenges, and contextual needs associated with DBL enactment, rather than to measure outcomes or implementation fidelity. Rather than evaluating the effectiveness of DBL, this study adopts an interpretive qualitative approach to capture in-depth perspectives of teachers and students and to explore how Design-Based Learning is enacted and experienced within the contextual realities of rural secondary school settings. Thus, by examining the experiences of teachers, students and school administrators in Kudat, this study aims to design a pedagogical guide for implementing DBL in Form 3 RBT in Kudat, drawing on qualitative findings from teachers, students and school administrators. This initiative is expected to help close the gap between curriculum aspirations and classroom realities, while supporting the objectives of the Malaysia Education Blueprint (PPPM) 2013–2025 and contributing to Sustainable Development Goal 4, which emphasises quality, inclusive and equitable education.

Conceptual Framework of Design-Based Learning Implementation in rural school contexts

Design-Based Learning (DBL) is described through pedagogical models that emphasise iterative design processes, problem solving, and authentic learning. Gómez Puente, et.al (2015) propose a widely recognised framework that structures DBL around several design phases, including problem analysis, idea generation, prototype development, testing, and evaluation. Together, these stages support conceptual understanding while also developing practical design skills.

In Design and Technology (RBT) education, this framework aligns closely with the Malaysian curriculum, where students analyse problems, generate ideas, construct prototypes, and evaluate product functionality. The iterative process allows theoretical knowledge to connect with hands-on activities, making learning more meaningful through authentic design tasks.

However, many DBL frameworks assume well-resourced environments with advanced technologies and specialised facilities. Thus, drawing on the literature on Design-Based Learning (DBL), rural education, and contextualised pedagogical practices, this study proposes a conceptual framework to guide the investigation of DBL implementation in rural RBT classrooms. See Figure 1.

The framework integrates insights from prior research with the contextual realities of rural secondary schools to examine how teachers and students experience, adapt, and respond to DBL practices. It also provides a structured lens for analysing current teaching practices, implementation challenges, and the needs of teachers and students in resource-constrained environments. By synthesising these elements, the framework guides the identification of contextualised strategies for DBL implementation and supports the development of a pedagogical guide tailored to rural Design and Technology education. The framework begins with rural school contextual conditions, which represent the environmental and structural factors influencing teaching and learning in rural settings, including limitations in infrastructure, resources, and technological access.

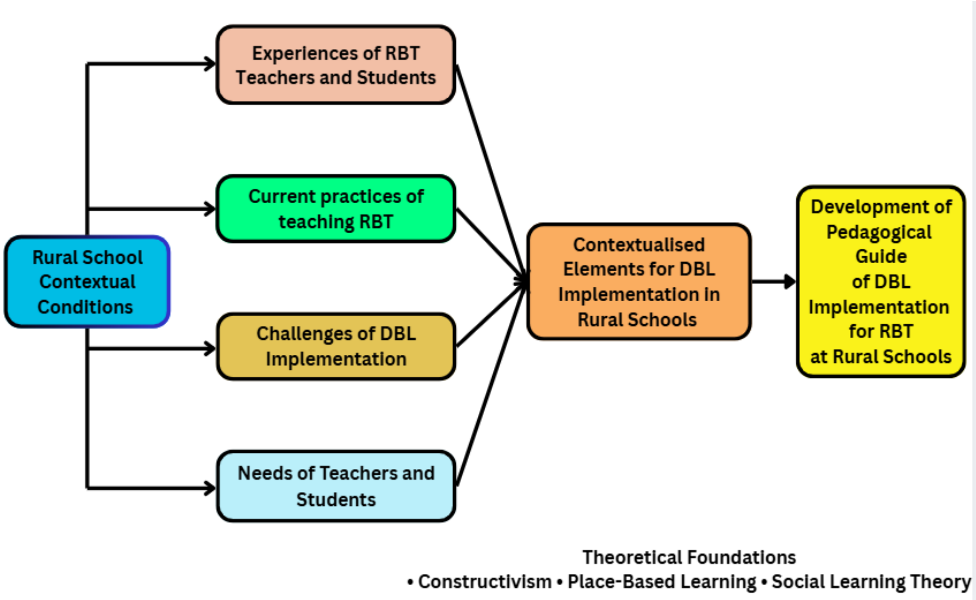

Figure 1. Conceptual framework

Within this context, the study explores four key dimensions derived from teachers' and students' perspectives: experiences of RBT teachers and students, current practices of teaching RBT, challenges of DBL implementation, and the needs of teachers and students. These dimensions represent the primary sources of empirical insights gathered through interviews and document analysis.

The findings from these dimensions are synthesised to identify contextualised elements for DBL implementation in rural schools, which reflect practical strategies and pedagogical approaches suited to rural learning environments. These elements ultimately will inform the development of a pedagogical guide for DBL implementation in RBT classrooms, aimed at supporting teachers in implementing design-based learning effectively in rural secondary schools (which is not covered in this study).

Methodology

Research Design

This study employed a qualitative research design to explore the key challenges faced by nine RBT teachers, including three school administrators who also teach Form 3 RBT and six Form 3 RBT students (15-year-olds) who have taken this subject since they were in Form 1(13 years old). The qualitative approach was selected to enable an in-depth examination of how teachers and students experience, interpret and make sense of DBL within environments characterised by limited resources, restricted access to technology, and various infrastructural constraints. This research design provides flexibility to investigate the complex issues surrounding DBL implementation in rural RBT classrooms, including inadequate facilities, financial and material constraints, contextual suitability, and levels of student engagement.

Participants

Participants were purposively selected based on their direct involvement in the teaching, administration, and learning of Form 3 Design and Technology (RBT), ensuring that multiple perspectives on DBL enactment could be captured (Table 1). The participants of this study consisted of the Heads of TVET Program at schools who also teach RBT and RBT teachers who had experience teaching RBT subjects between 2 to 8 years in rural secondary schools in Kudat. This sample helps to understand the challenges teachers face at various levels from multiple perspectives, thus providing richer data.

Table 1. Participants Head of TVET and RBT Secondary School Teacher

Pseudonyms	Category	School	Sex	Overall Teaching Experience (years)	Years of Experience Teaching RBT
Sari	(TVET Programme Head)	1	F	28	8
May	(TVET Programme Head)	2	F	11	8
Won	(TVET Programme Head)	3	M	17	2
Ken	RBT Teacher	3	M	9	8

Jamal	RBT Teacher	3	M	15	8
Maria	RBT Teacher	1	F	28	8
Massa	RBT Teacher	1	F	28	8
Kaya	RBT Teacher	2	M	2	2
Minah	RBT Teacher	2	F	18	6

In addition to the teachers, we also interviewed six rural secondary school students studying in three rural secondary schools in Kudat who studied RBT subjects from form 1 to form 3 (Table 2). This is to gain a deeper understanding of the challenges and requirements in the implementation of DBL for form 3 RBT subjects in the schools involved.

Table 2. Participants Head of TVET and RBT Secondary School Teacher

Pseudonyms	School	Sex	Age	Years of Experience Learning RBT
Kay	1	F	15	3
Glo	1	F	15	3
Jel	2	M	15	3
Joe	2	F	15	3
Syed	3	M	15	3
Zani	3	F	15	3

Data Collection

This study was conducted using a qualitative approach. Semi structured interviews were conducted with RBT teachers and students taking RBT to find out about current teaching practices, challenges faced in the implementation of Design-Based Learning (DBL) and critical needs to overcome the challenges faced. In addition, interviews with school administrators who were also RBT teachers were also conducted to understand the perspective of the school leadership on the challenges of DBL implementation as well as to identify the needs to improve the implementation of DBL. Semi-structured interviews were used to elicit participants' experiences and perceptions of DBL implementation. The interview sessions were conducted at the school, after school hours and each session lasted approximately 30 minutes. Data collection continued until thematic saturation was reached, whereby no substantively new insights emerged from additional interviews. All interviews were audio recorded and transcribed verbatim to ensure the accuracy of the transcription process and data analysis. Next, document analysis of lesson plans, RBT project logs and student work, and curriculum documents provided contextual and informal observation of instructional evidence was used to support data triangulation. Trustworthiness of the findings was enhanced through data triangulation across teachers, students, and documents, systematic analytic procedures, and the use of verbatim excerpts to support transparency and confirmability. Ethical considerations included informed consent, confidentiality through the use of pseudonyms, and sensitivity to participants' professional and learning contexts.

Pedagogical Process of DBL Implementation

Within the participating schools, Design-Based Learning (DBL) activities followed an iterative design process aligned with the principles of the RBT curriculum. The pedagogical process typically involved several interconnected stages. First, students engaged in problem analysis, where they identified real-world design problems related to everyday needs or community contexts. This stage involved brainstorming sessions, needs identification, and discussion of possible design directions. Second, students proceeded to idea generation and conceptual design, where they developed sketches, proposed solutions, and discussed alternative design ideas with peers and teachers. Third, students engaged in prototype development, during which they constructed physical or digital prototypes using available materials such as recycled resources, basic workshop tools, or low-cost kits. Fourth, prototypes were subjected to testing and evaluation, where students examined the functionality, durability, and effectiveness of their designs. Finally, students documented their design process through design logs, sketches, reflections, and reports, which provided evidence of iterative learning and design improvement. This pedagogical process allowed theoretical concepts from the RBT curriculum to be integrated with hands-on design activities, thereby reflecting the iterative and experiential nature of Design-Based Learning**.**

Data Analysis

The audio-recorded interviews were transcribed verbatim and subsequently analysed using thematic analysis, a widely adopted qualitative method that enables the identification of patterns, themes, and categories within the data (Braun & Clarke, 2021). During the analysis process, all interviews were transcribed word-for-word to ensure accurate representation of participants' responses. The transcripts were then coded, and the codes were organised into themes based on similarities and conceptual relationships. Thematic analysis was conducted inductively to allow patterns and themes to emerge from the data, after which constructivism, place-based learning, and social learning theory were applied at the interpretive stage to deepen understanding of the findings and inform the development of the contextualised DBL pedagogical guide. Furthermore, thematic analysis allowed for a comprehensive understanding of participants' lived experiences, offering rich insights into the challenges faced by teachers and students in implementing DBL for the Form 3 RBT subject in rural secondary schools, as well as the specific needs required to strengthen DBL practices in such contexts by experienced DBL practitioners. Through this approach, the study generated a holistic understanding of DBL implementation in rural areas.

Findings and Discussion

This section presents and interprets the findings derived from interviews with RBT teachers, school administrators and Form 3 RBT students from three rural secondary schools in Kudat, Sabah. Using inductive thematic analysis, four interrelated themes were identified that reflect how Design-Based Learning (DBL) is enacted, adapted, and constrained in rural school contexts. The themes reflect material, pedagogical, assessment-related, and systemic conditions that shape DBL practice. Rather than treating these themes as isolated barriers, the discussion interprets them through constructivist, place-based, and social learning perspectives to explain how contextual realities influence DBL implementation and to inform the development of a contextualised DBL framework.

Theme 1: Resource Constraints and Contextual Adaptation of DBL

Findings indicate that limited workshop facilities, outdated equipment, and restricted access to materials significantly shape how DBL is enacted in rural RBT classrooms (Table 3). From a place-based and situated learning perspective, these constraints should not be viewed solely as deficiencies, but as contextual conditions that define the boundaries within which learning occurs. DBL models are often conceptualised in well-resourced environments that assume access to specialised tools and digital technologies. In contrast, teachers and students in this study described the need to modify project ideas, delay activities due to shared equipment, and rely on low-cost or recycled materials to complete design tasks.

These adaptations illustrate how DBL is recontextualised rather than abandoned in rural settings. Teachers actively adjusted design activities to align with locally available resources, reflecting situated learning principles where meaning-making emerges through engagement with familiar tools and materials. However, such adaptations were often constrained by systemic issues, including inflexible funding structures and curriculum expectations that do not adequately account for rural disparities. This finding extends existing DBL literature by demonstrating that resource constraints reshape the form and depth of design activity, reinforcing the need to conceptualise DBL as a flexible pedagogy whose authenticity is grounded in contextual relevance rather than technological sophistication.

Table 3. Recommendations based on Theme 1: Limited Workshop Facilities and Inadequate Infrastructure

Sample Excerpt	Recommendations
"The RBT workshop still uses Kemahiran Hidup subject's equipment... many machines are also damaged... the equipment used to produce products is limited..." (Tcr. Ken, L85–95) "…The equipment is indeed insufficient, so many activities cannot be carried out... if you get into the topic of coding, without a computer and the internet, it cannot be implemented." (Tcr. Jamal, L70–80) "The main difficulty is the lack of materials in the RBT workshop... the original project idea had to be changed." (Glo, L46–54) "We have to wait our turn to use the equipment... the process of preparing the project is slow.." (Kay, L55–60)	Improve workshop facilities and provide minimum basic equipment every year. Establish a community tool bank with the Parent Teacher Association/ community. Use low-cost DBL kits and alternative materials. Arrange a workshop schedule to minimize congestion. Integrate design activities using local materials and do-it-yourself projects/ kits.

Theme 2: Financial Constraints and the Scope of Design Activity

Closely linked to infrastructural limitations were financial constraints arising from limited per capita grant allocations, which restricted schools' ability to procure materials and technologies required for DBL projects. This was due to the insufficient PCG allocation (RM6 per student) limits the ability to purchase materials, tools, and technology required for DBL projects. Projects often must be simplified or conducted using recycled materials Teachers reported having to simplify design tasks, reduce the number of projects conducted, or substitute intended materials with recycled alternatives. Students similarly expressed that insufficient materials affected their ability to fully execute design ideas (Table 4).

From a place-based learning perspective, these financial constraints further highlight how local resource ecosystems shape pedagogical enactment. While the use of recycled materials and small-scale projects reflects adaptive practice, persistent funding limitations risk narrowing the scope of design experiences and reducing opportunities for iterative experimentation. Rather than reflecting pedagogical inadequacy, these constraints point to structural inequities embedded within funding models that disadvantage rural schools. This finding underscores the importance of school–community collaboration and external support mechanisms as mediating strategies that can expand the material affordances available for DBL without compromising contextual authenticity.

Table 4. Recommendations based on Theme 2: Limited Funding and Financial Constraints

Sample Excerpt	Recommendations
"Only one 3D printer can be purchased using PCG... not all students can use it... it takes 3 days to complete one product.." (Tcr. Ken, L100–110) "Epoxy resin is too expensive... RM50 for 1 liter... cannot afford to buy it all the time..." (Tcr. Jamal, L115–120) "There are many projects, but the budget is insufficient... can only do one DBL project per class..." (Tcr. May, L145–150) "We do not have enough materials... we cannot properly execute the project..." (Joe, L60–65) "If tools are not available, you have to change the original idea... use recycled materials." (Zani, L51–52)	- Apply for external grant (CSR of Corporate Companies, District Education Office, STEM NGOs). Using a small-scale but meaningful project model. Systematically utilize recycled materials & community resources. Train teachers to plan low-cost DBL. Encourage school-community collaboration for material sponsorship.

Theme 3: Integrating Theory and Practice in DBL Instruction

Another prominent theme concerned difficulties in balancing theoretical instruction with hands-on design activities. Teachers described challenges in allocating sufficient time for practical work due to syllabus demands, large class sizes, and limited access to equipment. As a result, DBL activities were sometimes positioned as supplementary to theory-heavy instruction rather than as the central mode of learning. Students, however, consistently expressed greater engagement and understanding when involved in practical, design-oriented tasks (Table 5).

From a constructivist perspective, this tension reflects a misalignment between DBL's emphasis on learning through active engagement and traditional instructional practices that prioritise content transmission. Constructivism posits that conceptual understanding is constructed through experience and reflection, suggesting that theory is most meaningful when embedded within design activity. The findings therefore indicate that challenges in integrating theory and practice are not simply a matter of teacher preference or skill but are shaped by structural conditions that limit opportunities for sustained design engagement. Addressing this tension requires pedagogical strategies that embed theoretical concepts within design tasks, as well as systemic support that allows DBL to function as a core instructional approach rather than an add-on.

Table 5. Recommendations based on Theme 3

Sample Excerpt	Recommendations
"The topic of RBT (*Reka Bentuk dan Teknologi*) has many theories... so the DBL (Design Based Learning) activity becomes just an additional activity." (Tcr. Massa, L25–35) "I use a two-in-one approach... the theory goes into the project once..." (Tcr. May, L60–70) "Sometimes bored because busy listening to the teacher explain the concepts..." (Jel, L40–45) "It was fun to work on a 3D project... more understanding and creative." (Zani, L60–65)	Integrating theory into design activities (embedded theory). Using micro-prototyping to save time and cost. Providing DBL lesson templates for teachers. Increasing teacher training in theory practice integration. Using digital simulation if physical materials are insufficient.

The excerpts presented in Table 5 illustrate how teachers experience tension in balancing theoretical instruction and hands-on design activities. For example, Teacher Massa explained that the theoretical content within the RBT syllabus often requires substantial instructional time, which consequently reduces opportunities for extended design activities. This suggests that DBL is sometimes positioned as an additional activity rather than the central pedagogical approach. Similarly, Teacher May described using a "two-in-one" approach in which theoretical explanations are embedded within project tasks. This strategy reflects teachers' attempts to reconcile curricular demands with DBL principles. Student responses further reinforce this theme. While some students expressed boredom when lessons were dominated by teacher explanations, they reported higher engagement when participating in design projects. Taken together, these excerpts indicate that the challenge lies not merely in teacher preferences but in structural constraints such as time allocation, curriculum demands, and limited workshop access, which shape how theory and practice are integrated in DBL instruction.

Theme 4: Assessment Practices and Process-Oriented Learning

Assessment emerged as a critical challenge in DBL implementation, with teachers often relying on final products as the primary basis for evaluation due to time constraints, large class sizes, and the absence of structured assessment tools. Teachers experience difficulty assessing DBL holistically due to time constraints, large class sizes, and lack of structured rubrics. Assessment often focuses on the final product rather than the entire design process (ideation, iteration, teamwork, reflection). Students feel their effort throughout the process is not fairly evaluated.

Students perceived this emphasis as inequitable, as their effort, iteration, and problem-solving throughout the design process were not consistently recognised. From a constructivist learning perspective, product-focused assessment conflicts with DBL's process-oriented philosophy, which values ideation, experimentation, collaboration, and reflection as integral components of learning. The findings suggest that assessment challenges are rooted in systemic misalignments between DBL pedagogy and prevailing assessment cultures that prioritise efficiency and observable outcomes. In resource-constrained rural contexts, these misalignments are further intensified, potentially undermining DBL's transformative potential. Process-oriented assessment strategies, such as design checkpoints, reflection journals, and simplified rubrics, offer practical pathways to align assessment with DBL principles while remaining feasible within existing constraints (Table 6).

Table 6. Recommendations based on Theme 4

Sample Excerpt	Recommendations
"Time is not enough, so I assess what can be seen... I evaluate the student's product achievements and effectiveness... Is the product durable... and the finish" (Tcr. Ken, L150–160) "I also look at the reports and functions, but in the end I still look at the final result... that's the easiest to evaluate." (Tcr. Jamal, L165–175) "We tried to assess from the beginning,the idea, sketches, the process of making..but when there are many students, there is no time to observe everything.." (Pn. Sari, L180–190) "We have been trying from the beginning... but the teacher only looks at the final result. It feels like a waste of effort... we have to change a lot of times because it doesn't work.." (Joe, L80–85) "Sometimes creative ideas are not valued... the teacher only monitors to avoid missteps." (Glo, L90–95)	Developing a DBL Process Rubric (idea → sketch → prototype → reflection). Incorporating formative assessment such as reflection journal, logbook, sketches and process videos. Using individual + team rubrics to ensure fairness. Implementing mini checkpoints at each design phase to address time constraints. Providing training to teachers on process-based & evidence-based assessment. Utilizing simple technology like Google Forms to record the process.

Theme 5: Professional and Community Support as Enabling Conditions

This theme highlights the role of sustained professional development and community engagement as critical enabling conditions for effective Design-Based Learning (DBL) implementation in rural secondary schools. The findings indicate that continuous teacher training, professional learning communities (PLCs), and collaboration with local stakeholders are essential to compensate for limited resources, facilities, and expertise commonly faced in rural contexts. Limited professional development opportunities and community support were identified as additional factors constraining DBL sustainability.

Social learning theory provides a lens to interpret these findings, emphasising that learning and innovation are socially mediated processes supported through collaboration and shared practice. DBL requires teachers to adopt facilitative roles and develop new pedagogical and technical competencies, which can be difficult to sustain in rural contexts where teachers often work in isolation. The findings indicate that DBL enactment depends not only on individual teacher effort, but also on meso-level support structures such as school leadership, professional learning communities, and partnerships with parents and local organisations. Initiatives such as community tool banks and collaborative planning reflect social learning principles by distributing expertise and resources across a broader educational ecosystem. This interpretation extends existing DBL research by foregrounding the importance of collective and institutional responsibility in sustaining pedagogical innovation in under-resourced settings (Table 7).

Table 7. Recommendations based on Theme 5

Sample Excerpt	Recommendations
"If there are DBL courses and PLCs, teachers will be more prepared and can share experiences and ideas." (Teacher Joliwin, L200–205) "With more frequent DBL training, teachers can implement DBL with greater confidence." (Teacher Jamalit, L190–195) "Design-based learning can be more effective when teachers collaborate with the community." (Expert Tony, L85–90)	Provide continuous, practice-oriented professional development on DBL tailored to rural RBT teachers. Strengthen Professional Learning Communities (PLCs) at district and state levels to facilitate peer support and sharing of best practices. Foster partnerships with local communities, small industries, NGOs, and educational agencies to support materials, expertise, and contextualised DBL projects. Integrate community and professional support into a sustainable ecosystem for DBL implementation in rural schools.

Taken together, the findings demonstrate that DBL implementation in rural RBT classrooms is shaped by the interplay of contextual constraints, pedagogical practices, assessment norms, and support structures. Constructivism explains the importance of active, process-oriented learning; place-based learning highlights how local material and financial conditions shape pedagogical enactment; and social learning theory underscores the role of collaboration and institutional support in sustaining practice. These perspectives informed the development of the contextualised DBL framework proposed in this study.

Based on the findings of this study, the DBL implementation can be contextualized as a layered and adaptive process that begins with contextual realities and is mediated by enabling support structures. Rather than assuming ideal conditions, it reframes constraints as design parameters and emphasises pedagogical flexibility, process-oriented assessment, and collective responsibility. In doing so, the framework extends existing DBL models by offering a theoretically informed and empirically grounded approach for supporting inclusive and sustainable DBL enactment in rural secondary school contexts.

Figure 2 presents a contextualised Design-Based Learning (DBL) framework derived from the study's qualitative findings and informed by constructivist, place-based, and social learning perspectives. The framework conceptualises DBL enactment as a nested and adaptive process shaped by contextual conditions in rural schools. Rather than assuming ideal instructional settings, contextual constraints form the outer conditions within which pedagogical practice occurs. Enabling support structures mediate between these conditions and classroom practice, influencing how the core DBL pedagogical process is enacted. Learning outcomes are understood as emergent rather than guaranteed, reflecting the interaction between context, support structures, and iterative design-based learning processes.

Recognising contextual limitations enables DBL to be reframed as a flexible pedagogy rather than a resource dependent approach, particularly in rural and under resourced settings. Recent studies emphasise that instructional effectiveness is strongly shaped by alignment between pedagogy, learner characteristics, and available resources, rather than by technology alone (Nik Abdul Majid et al., 2025). A key contribution of the framework lies in its emphasis on enabling support structures as mediating mechanisms between constraints and pedagogical practice. Resource adaptation, professional learning, and curriculum flexibility collectively enhance teachers' capacity to enact DBL in constrained contexts. This shift foregrounds systemic and institutional responsibility, rather than relying solely on individual teacher agency. Evidence from rural education contexts indicates that sustained pedagogical innovation requires structured professional development and organisational support, particularly where access to resources is limited (Daminar & Galusan, 2025). At the core of the framework, the DBL pedagogical process reinforces constructivist and experiential learning principles by prioritising iteration, reflection, and problem solving within authentic contexts. From a constructivist perspective, challenges related to balancing theoretical instruction with practical activities and assessing

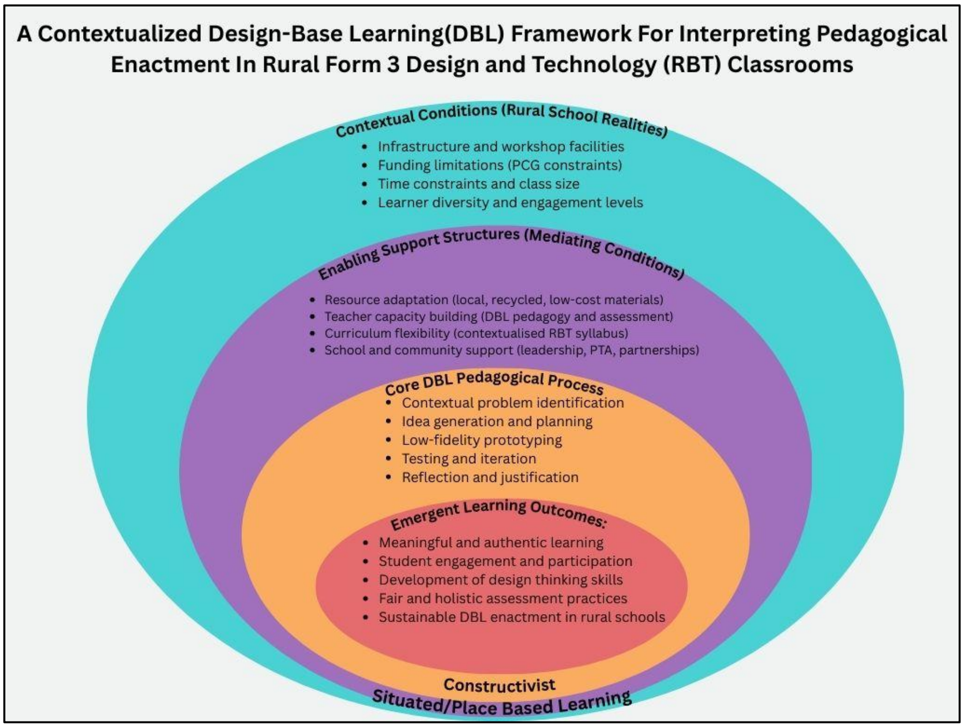

Figure 2. A Contextualised Design-Based Learning (DBL) Framework for Interpreting Pedagogical Enactment in Rural Form 3 Design and Technology (RBT) Classrooms

learning beyond final products reflect tensions between traditional instructional practices and process-oriented learning. Constructivism therefore provides a lens to interpret the importance of iteration, reflection, and formative assessment in supporting students' learning journeys within DBL environments.

Importantly, the findings demonstrate that effective DBL does not depend on sophisticated technology. Meaningful learning can occur through low fidelity prototyping, locally available materials, and community relevant design challenges. This might seem counterintuitive. Still, recent research in rural learning environments similarly shows that students demonstrate stronger engagement when learning activities are hands on, contextualised, and connected to their lived experiences (Tagare et al., 2026).

In rural secondary schools in Sabah, DBL implementation is strongly affected by limited workshop facilities, restricted funding, and reduced access to digital technologies. This theoretical perspective frames such constraints not simply as deficits, but as contextual conditions that shape how DBL can be meaningfully enacted. The use of locally available materials, recycled resources, and community-relevant design problems reflects situated learning principles and supports the enactment of authentic DBL despite resource limitations. Place-based learning thus legitimises pedagogical adaptation and contextual alignment in rural DBL practice.

The framework's focus on expected outcomes extends beyond technical skill acquisition. By foregrounding process oriented assessment, it values students' learning journeys, collaboration, and reflective thinking. In a way, this addresses persistent concerns regarding product focused evaluation, which can disadvantage learners in resource constrained contexts. Process based assessment has been shown to support more equitable learning opportunities by recognising diverse forms of participation and progress, particularly in heterogeneous and rural classrooms (Nik Abdul Majid et al., 2025).

From a policy and sustainability perspective, the framework aligns with several Sustainable Development Goals. It supports SDG 4 (Quality Education) by promoting inclusive and equitable learning opportunities for students in rural settings. It also contributes to SDG 9 (Industry, Innovation and Infrastructure) through the development of adaptable design thinking and innovation skills. In addition, by encouraging the use of local and recycled materials in learning activities, the framework aligns with SDG 12 (Responsible Consumption and Production), reinforcing sustainability principles within everyday pedagogical practice.

The recommendations presented in Tables 3–7 were derived through an iterative analytic process during thematic analysis. After identifying key themes related to resource constraints, financial limitations, pedagogical integration, assessment challenges, and support structures, the researchers examined patterns across teacher and student responses to identify potential strategies suggested implicitly or explicitly within the data. For example, teachers frequently described adapting DBL activities using recycled materials and simplified projects, which informed recommendations related to low-cost design kits and community resource utilisation. Similarly, teachers' reported difficulties in assessing design processes led to recommendations concerning process-oriented rubrics and formative assessment checkpoints. Thus, the recommendations were not externally imposed but emerged inductively from participants' experiences and were further interpreted through the theoretical lenses of constructivism, place-based learning, and social learning theory.

Conclusion

This study examined how Design-Based Learning (DBL) is enacted within the contextual realities of under resourced, rural secondary schools offering Form 3 Design and Technology (RBT) in Kudat, Sabah. Through an interpretive qualitative approach, the findings reveal that DBL implementation in rural contexts is shaped by an interrelated set of material, pedagogical, assessment-related, and systemic conditions. While teachers and students demonstrate strong awareness of DBL's process-oriented and experiential learning principles, persistent constraints related to infrastructure, funding, instructional time, assessment practices, and professional support significantly influence how DBL is enacted in practice.

This study highlights several substantive challenges that affect the implementation of Design-Based Learning (DBL) in rural secondary schools in Kudat. The findings indicate that limitations in teacher professionalism, inadequate infrastructure, contextual constraints related to students and the wider community, as well as the inherent pedagogical complexities of DBL, collectively hinder its effective enactment in RBT classrooms. Nevertheless, the study also demonstrates that DBL holds strong potential when it is contextualised to local realities particularly through the use of community-based problem scenarios, low-cost materials, and design tasks that resonate with rural livelihoods. Importantly, the study has developed a conceptual framework and a set of guiding principles for implementing DBL in rural contexts, grounded in Constructivism, Place-Based Education, and Social Learning Theory. The findings also extend engineering education literature by illustrating how pedagogical approaches commonly used in engineering design education, such as iterative design, prototyping, and reflective evaluation, can be adapted to secondary education. In doing so, the study positions rural RBT classrooms as an important entry point in the engineering education pipeline that fosters early engineering thinking and innovation skills. This framework offers practical direction for teachers, school leaders, and policymakers seeking to strengthen equitable, meaningful, and context-responsive engineering design education in rural Malaysia. It also provides a foundation for future efforts to enhance DBL implementation in ways that better reflect the unique needs, assets, and lived experiences of rural learners.

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Conflict of Interest

The authors declare no conflict of interest

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Digital Twin driven classrooms: A case study of an AI-augmented conceptual framework for adaptive learning

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Abstract
The rapid expansion of digital education has improved access to learning but has also revealed persistent limitations related to personalization, real-time adaptability, scalability, and learner engagement. Many existing digital learning platforms and AI-based tools operate as isolated solutions, offering limited integration and treating learners as passive recipients of instruction. To address these challenges, this paper proposes a conceptual framework for AI-augmented Digital Twin classrooms (AIDTC) that reconceptualizes the classroom as an intelligent cyber-physical learning system. The framework was developed through a structured synthesis of interdisciplinary literature spanning Digital Twin theory, cyber-physical systems, artificial intelligence in education, and immersive learning. Drawing on advances in digital engineering and Industry 4.0/5.0 principles, the framework integrates Digital Twin modeling, artificial intelligence, immersive learning technologies, and human-in-the-loop orchestration within a layered architecture. Continuous synchronization between learner interactions and dynamic digital representations enables proactive instructional adaptation based on real-time behavioral, cognitive, and contextual data. The proposed architecture comprises four interconnected layers perception, cognition, immersion, and orchestration supporting data capture, intelligent reasoning, immersive learning delivery, and transparent pedagogical control. The study adopts a conceptual framework development approach supported by a single case study to demonstrate how the framework can be applied in a higher-education setting. While empirical generalization is beyond the scope of this work, the case demonstrates the internal coherence, feasibility, and applicability of the proposed framework. Overall, the AIDTC framework offers a future-ready blueprint for developing intelligent, ethical, and learner-centered digital classrooms that extend beyond conventional online and hybrid learning paradigms.

Keywords: Digital Twin, AI in education, Immersive learning, Cyber-physical systems, Smart classrooms, Digital education architecture.

Introduction

In recent years, the global education sector has undergone a rapid transformation fuelled by the accelerated adoption of digital technologies. The COVID-19 pandemic served as a major inflection point, catalysing the shift from traditional in-person classrooms to remote, hybrid, and technology-enabled learning environments. However, this rapid digital migration has also exposed fundamental limitations in the current ecosystem of digital education. While platforms such as Learning Management Systems (LMS), video conferencing tools, and Massive Open Online Courses (MOOCs) have enabled broader access, they often fail to provide personalization, real-time responsiveness, and deep engagement (Al-Fraihat et al., 2018, Picciano, 2017). In most cases, these platforms treat learners as passive consumers rather than active participants in an adaptive, data-driven educational system.

The next frontier in educational innovation demands more than digitizing content it requires reimagining the classroom as an intelligent, cyber-physical system. This is where the emerging paradigm of Digital Twin technology, widely applied in industries such as aerospace, manufacturing, and healthcare, offers profound potential. A Digital Twin is a virtual replica of a physical entity that synchronizes in real-time with its counterpart using sensor data, analytics, and simulations. In engineering contexts, Digital Twins enable predictive maintenance, performance optimization, and scenario-based testing (Tao et al., 2019a). When translated to education, this concept opens the possibility of creating real-time, dynamic representations of learners and classrooms allowing instruction to adapt continuously based on behavior, performance, and engagement signals (Rasheed et al., 2021).

Complementing this is the rise of artificial intelligence (AI), particularly in domains such as intelligent tutoring systems, learning analytics, and

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adaptive assessment. AI can provide scalable decision-making, detect patterns across vast learner datasets, and support timely feedback loops (Baker, 2009). However, most current applications of AI in education operate as standalone tools rather than integrated components of a holistic, intelligent system. By integrating AI with Digital Twin models and immersive interfaces, we can construct learning environments that not only reflect the learner's cognitive and behavioural states but also act on them intelligently adjusting content, pacing, collaboration, and instructional strategies in real time (Pinkwart, 2016).

Despite significant advances in artificial intelligence in education, prior research has largely focused on standalone intelligent tutoring systems, adaptive assessments, or learning analytics dashboards that operate as isolated solutions. While these approaches have demonstrated localized benefits, they often lack integration with immersive learning environments and do not support continuous synchronization between learner behavior, intelligent reasoning, and instructional adaptation. Similarly, immersive learning technologies are frequently deployed as independent interventions rather than as components of an integrated, data-driven learning architecture. As a result, there remains a clear research gap in the form of a cohesive, system-level framework that integrates artificial intelligence, Digital Twin modelling, immersive learning, and human-in-the-loop orchestration within a unified cyber-physical classroom environment.

This paper introduces the AI-Augmented Digital Twin Classroom (AIDTC) as a conceptual framework that unifies these technologies into a multi-layered, cyber-physical learning environment. The AIDTC envisions the classroom as a smart system with four core layers: perception, cognition, immersion, and orchestration. Through this architecture, a learner's real-time interactions captured through behavioural logs, affective cues, and performance data are processed by AI models that dynamically update the learner's Digital Twin. This twin, in turn, informs personalized instructional flows delivered through immersive virtual environments such as 3D classrooms or metaverse platforms (Dede & Richards, 2022). Instructors interact with the system through orchestration dashboards, receiving recommendations for pedagogical strategies, learner grouping, and adaptive interventions.

Framing the classroom as a Digital Twin system enables a shift from reactive to proactive pedagogy, where learning pathways are not just designed in advance but evolve as learning unfolds. This aligns closely with the principles of Industry 4.0 and 5.0, where real-time data integration, system interoperability, and human-machine collaboration are central to innovation (Hecklau et al., 2016). Furthermore, this paradigm supports the goals of Education 5.0, which emphasizes human-centric learning, ethics, personalization, and digital empowerment (Magruk, 2019).

The purpose of this conceptual paper is not to present empirical results, but to offer a transdisciplinary framework that bridges educational theory, digital engineering, and AI-enabled design. It articulates the foundational components, theoretical assumptions, and architectural layout of an intelligent Digital Twin classroom and outlines strategic implications for future implementation. The AIDTC model serves as a blueprint for researchers, educational institutions, and edtech developers seeking to create resilient, scalable, and transformative digital learning experiences that extend far beyond conventional online instruction. Accordingly, this study adopts a single case study approach to demonstrate the practical application of the proposed framework within a real higher-education learning context.

This study is positioned as the development of a theory-driven conceptual framework for AI-Augmented Digital Twin Classrooms, rather than a review paper or an empirical evaluation study. The framework is derived through a structured synthesis of interdisciplinary theoretical literature and is supported by a single descriptive case study to illustrate its practical applicability in an authentic educational context. The case study is intended to demonstrate framework operationalization rather than to provide statistical validation of learning outcomes.

Literature review

The proposed AI-Augmented Digital Twin Classroom (AIDTC) framework is grounded in multiple complementary theoretical foundations spanning adaptive learning, artificial intelligence in education, immersive learning, and Digital Twin modelling. These theories collectively inform the structure, functionality, and pedagogical logic of the framework.

Adaptive learning theory provides a foundational basis for personalizing instructional pathways based on learner behavior, performance, and engagement. Learning management systems and early adaptive platforms demonstrated the potential for differentiated instruction but were largely limited to rule-based adaptation and post-hoc feedback (Al-Fraihat et al., 2018; Romero & Ventura, 2020). Contemporary adaptive learning models emphasize continuous monitoring, real-time feedback, and dynamic adjustment of instructional strategies, highlighting the need for architectures capable of closing the feedback loop between learner data and pedagogical action.

Artificial intelligence in education (AIED) extends adaptive learning by enabling automated reasoning, pattern recognition, and predictive modelling. Intelligent Tutoring Systems represent a key theoretical lineage within AIED, demonstrating how learner models can be used to deliver individualized feedback and scaffolding (VanLehn, 2011). However, many AIED implementations remain narrowly scoped, operating as standalone systems without integration into immersive environments or broader learning ecosystems. This limitation underscores the need for system-level frameworks that embed AI-driven reasoning within integrated instructional architectures.

Immersive learning theory further informs the AIDTC framework by emphasizing experiential, situated, and collaborative learning. Virtual and augmented reality environments have been shown to enhance engagement, conceptual understanding, and skill acquisition, particularly in engineering and professional education contexts (Radianti et al., 2020). From a theoretical perspective, immersive learning aligns with constructivist and experiential learning models, which stress active knowledge construction through interaction. However, immersive technologies are often implemented as isolated interventions rather than as adaptive components within data-driven instructional systems.

Digital Twin theory provides the unifying systems-level foundation for integrating adaptive learning, AI reasoning, and immersive environments. Originating in digital engineering, Digital Twins enable continuous synchronization between physical entities and their virtual representations using real-time data, analytics, and simulation (Tao et al., 2019b). In educational contexts, learner Digital Twins extend this concept by modelling cognitive, behaviour, and engagement-related learner states over time (Rasheed et al., 2021). Unlike static learner profiles, Digital Twins support continuous updating, prediction, and scenario-based instructional adaptation.

Recent conceptual models have explored Digital Twin applications in smart classrooms, demonstrating the feasibility of learner modelling and adaptive content delivery (Rasheed et al., 2022). However, existing approaches often lack a comprehensive architecture that integrates AI reasoning, immersive learning delivery, and human-in-the-loop instructional control. The AIDTC framework builds on these theoretical foundations by embedding Digital Twin principles within a layered cyber-physical architecture that supports continuous data capture, intelligent interpretation, immersive experience delivery, and transparent pedagogical orchestration.

By synthesizing these theoretical perspectives, the AIDTC framework addresses a critical gap in current educational research: the absence of an integrated, theory-driven conceptual framework capable of unifying adaptive learning, artificial intelligence, immersive environments, and Digital Twin modelling within a single coherent system.

Framework development

The AI-Augmented Digital Twin Classroom (AIDTC) framework was developed using a theory-driven conceptual design approach that integrates established principles from Digital Twin theory, cyber-physical systems, artificial intelligence in education, and constructivist learning theory. The primary objective of the framework is to address limitations in existing digital learning systems, particularly their lack of real-time adaptability, system-level integration, and learner-centric personalization.

The foundational theoretical concept underpinning the framework is Digital Twin theory, originally developed in industrial and engineering domains. A Digital Twin is defined as a dynamic virtual representation of a physical entity that is continuously synchronized using real-time data (Tao et al., 2019; Tao et al., 2020). In manufacturing and smart systems, Digital Twins enable monitoring, prediction, and optimization through closed feedback loops. In the educational context, this concept is extended to represent learners and learning environments as evolving digital entities that reflect cognitive, behavioral, and contextual states (Rasheed et al., 2021). This extension enables continuous learner modelling rather than static profiling.

The second theoretical pillar is cyber-physical systems (CPS) theory, which emphasizes tight integration between physical processes, computation, and control through feedback mechanisms (Lee, 2008). CPS principles inform the framework's closed-loop architecture, where learner interactions in physical or digital spaces generate data that are processed by intelligent systems and translated into adaptive instructional responses. This approach aligns with system-of-systems thinking widely adopted in Industry 4.0 and smart infrastructure research (Boyes et al., 2018).

From a pedagogical perspective, the framework draws on constructivist and learner-centered learning theories, which emphasize active knowledge construction, experiential learning, and continuous feedback (Picciano, 2017). These theories justify the integration of immersive learning environments and adaptive instructional pathways, ensuring that technological intelligence supports meaningful learning rather than automated content delivery.

The integration of these theoretical concepts resulted in a layered framework architecture designed to balance system modularity with continuous interaction. The framework consists of four interconnected layers: perception, cognition, immersion, and orchestration. The perception layer is responsible for capturing learner interaction data, such as engagement patterns, assessment performance, and participation metrics, from both physical and digital learning environments. The cognition layer applies artificial intelligence and learning analytics techniques to interpret these data and dynamically update the learner's Digital Twin. This Digital Twin functions as a semantic and behavioral representation of the learner, supporting predictive insights and personalization (Rasheed et al., 2022).

Insights generated by the cognition layer inform the immersion layer, where adaptive learning experiences are delivered through virtual classrooms, simulations, or collaborative digital spaces. Immersive technologies support experiential and skills-based learning, which has been shown to enhance engagement and knowledge retention when properly aligned with instructional goals (Radianti et al., 2020). Oversight is provided by the orchestration layer, which enables human-in-the-loop decision-making. This layer ensures that instructors retain pedagogical control while benefiting from AI-generated insights, addressing ethical and transparency concerns associated with automated educational systems (Mittelstadt et al., 2020; Woolf, 2020).

Methodologically, the framework was established using a conceptual design research methodology rather than empirical hypothesis testing. First, an interdisciplinary literature review was conducted to identify limitations in existing learning management systems, intelligent tutoring systems, and AI-driven educational tools, particularly their fragmented and reactive nature (Al-Fraihat et al., 2018; Holmes et al., 2019). Second, core constructs from Digital Twin and CPS literature were abstracted and mapped to educational processes. Third, iterative refinement was applied to ensure theoretical coherence, scalability, and pedagogical relevance. An illustrative case study was then used to demonstrate operational feasibility and clarify inter-layer interactions, consistent with prior conceptual framework development studies.

Regarding data considerations, the framework is designed to utilize commonly available educational data streams, including time-on-task, assessment outcomes, interaction logs, and collaboration indicators. These data are conceptually modelled to show how they inform learner Digital Twins and adaptive instructional decisions. No empirical data analysis is conducted in this study, as the focus is on architectural design and conceptual validation rather than outcome measurement. This approach aligns with prior conceptual work in AI-enabled learning architectures and Digital Twin-based systems (Rasheed et al., 2021; Tao et al., 2020). Overall, the AIDTC framework provides a theoretically grounded and methodologically structured blueprint for intelligent, adaptive, and human-centered digital classrooms, offering a foundation for future empirical validation and system implementation.

Literature synthesis approach

The development of the AIDTC framework was informed by a structured conceptual synthesis of prior literature rather than a full systematic review. Relevant studies were identified through targeted searches of peer-reviewed journals and conference proceedings focusing on Digital Twin models, cyber-physical systems, artificial intelligence in education, adaptive learning, and immersive learning environments. Seminal and recent works were selected based on their theoretical relevance, citation influence, and contribution to system-level educational design.

The synthesis process followed three analytical stages. First, key theoretical constructs and functional principles were extracted from the selected literature, including learner modelling, feedback loops, intelligent adaptation, immersive interaction, and human-in-the-loop control. Second, these constructs were grouped thematically and analyzed for conceptual overlap and complementarities across domains. Third, the synthesized themes were translated into architectural components and interactions, resulting in the four-layer AIDTC framework comprising perception, cognition, immersion, and orchestration.

This transparent conceptual synthesis approach ensured theoretical coherence and traceability between prior research and the proposed framework, while avoiding the constraints of domain-specific empirical aggregation. Although a PRISMA-style systematic review was not conducted, the synthesis followed a systematic and theory-driven process appropriate for conceptual framework development.

AI-augmented Digital Twin classrooms (AIDTC) framework

The AI-Augmented Digital Twin Classroom (AIDTC) framework conceptualizes the classroom as a layered cyber-physical learning system in which physical learner activity, artificial intelligence, immersive environments, and human instructional oversight are continuously integrated through a closed feedback loop. Rather than treating digital tools as isolated instructional aids, the framework redefines the classroom as an intelligent system that senses learner behavior, reasons over learning states, simulates instructional responses, and orchestrates adaptive interventions in real time. This systems-oriented perspective is grounded in cyber-physical systems theory, Digital Twin modelling, intelligent orchestration, and constructivist learning principles, enabling scalable, personalized, and responsive education.

At the foundation of the framework lies the physical learning environment, where learners interact with instructional content, peers, and tools using digital devices or immersive interfaces. These interactions generate continuous streams of behavioral, cognitive, and contextual data that serve as real-world inputs to the system. Consistent with cyber-physical systems design, the classroom is treated as a tightly coupled physical–digital entity in which sensing, computation, and actuation operate in a continuous loop, enabling real-time responsiveness and adaptive control (Lee, 2008). Similar feedback-driven architectures are widely adopted in industrial Internet of Things ecosystems to support intelligent system behavior and performance optimization (Boyes et al., 2018).

Data originating from the physical learning environment are processed within the system's cognitive intelligence core, where artificial intelligence models analyze learner engagement, progression patterns, and potential learning difficulties. These analyses are used to construct and continuously update a learner Digital Twin, defined as a dynamic semantic and behavioral representation of the learner rather than a static profile. Drawing on Digital Twin theory, this virtual representation evolves through ongoing synchronization with real-world learner activity, enabling predictive analytics, scenario simulation, and proactive instructional decision-making (Tao et al., 2020). The Digital Twin thus functions as the central mechanism through which personalization, adaptation, and learning pathway optimization are achieved.

Insights derived from the learner's Digital Twin are translated into adaptive instructional experiences through immersive learning environments, including virtual classrooms, simulated laboratories, and collaborative three-dimensional spaces. These environments support constructivist learning by enabling exploration, interaction, and experiential knowledge construction within low-risk digital settings. As learners engage within these environments, new interaction data are continuously generated and fed back into the system, ensuring sustained synchronization between the physical learner and the Digital Twin.

Oversight and coordination are provided through an intelligent orchestration layer that bridges human and machine decision-making. This layer delivers real-time dashboards, alerts, and pedagogical recommendations to instructors while preserving human agency through explainable and human-in-the-loop AI mechanisms. Emphasizing transparency, accountability, and ethical alignment, orchestration ensures that artificial intelligence augments rather than replaces educator judgment, addressing key concerns related to explainability and trust in AI-driven systems (Mittelstadt et al., 2020).

The integrated operation of these components forms a closed-loop cyber-physical architecture in which sensing, cognition, immersion, and orchestration continuously inform one another. The overall structure and data flows of the AIDTC framework are illustrated in Figure 1, highlighting how real-time learner interactions drive Digital Twin updates, adaptive immersive learning experiences, and instructor-guided interventions. By framing the classroom as an AI-augmented Digital Twin system, AIDTC advances beyond conventional online and hybrid models, enabling a shift from reactive instruction to proactive, learner-centric pedagogy that evolves dynamically as learning unfolds.

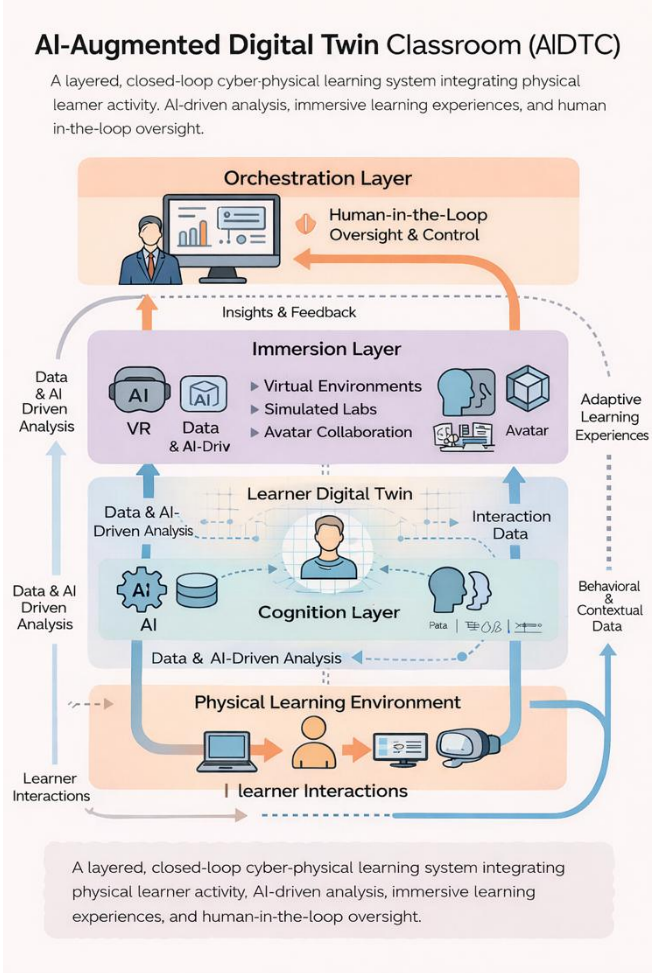

Figure 1. AI-augmented Digital Twin classroom (AIDTC) framework showing a layered cyber-physical learning system with continuous feedback between the physical environment, cognition, immersion, and orchestration layers

Key concepts, variables, and interrelationships in the AIDTC framework

The AIDTC framework is structured around a set of core conceptual constructs that collectively enable adaptive and intelligent learning. At the foundation are learner interaction variables, including engagement behavior, assessment performance, procedural activity, and collaborative participation. These variables represent observable learner actions within the physical and digital learning environment and serve as primary inputs to the system.

These interaction variables are interpreted within the cognition layer through artificial intelligence and learning analytics models, resulting in higher-level learner state variables such as engagement index, concept mastery, procedural competence, collaboration level, and learning risk. These learner state variables form the learner Digital Twin, which functions as an integrated conceptual representation of the learner's cognitive, behavioral, and engagement profile.

The learner Digital Twin acts as a mediating construct linking learner behavior to instructional adaptation. Changes in Digital Twin variables directly influence adaptive instructional decisions within the immersion layer, including task difficulty, scaffolding level, collaboration structure, and feedback intensity. These adaptive decisions are conceptualized as instructional response variables that shape the learner's subsequent learning experience.

The orchestration layer establishes a human–AI governance relationship by enabling instructors to interpret learner Digital Twin states and instructional recommendations. Instructor decisions moderate the influence of AI-generated adaptations, ensuring that pedagogical judgment, ethical considerations, and contextual factors shape the final instructional actions.

The interrelationships among these constructs form a closed feedback loop: learner interactions generate data, data update learner Digital Twins, Digital Twins inform instructional adaptation, and adapted instruction influences subsequent learner interactions. This recursive structure emphasizes conceptual dependency and causality rather than linear process flow.

Case study: Illustrative implementation of the AI-augmented Digital Twin classroom

To demonstrate the practical applicability and internal logic of the proposed AI-Augmented Digital Twin Classroom (AIDTC) framework, this section presents an illustrative case study situated in a higher-education engineering course. The objective of this case is not empirical validation but to operationalize the framework, clarify inter-layer interactions, and show how the conceptual architecture can be instantiated in a realistic instructional context.

The illustrative case considers a blended undergraduate engineering course that combines face-to-face instruction with digital and immersive learning activities. Learners interact with course materials through a learning management system, participate in virtual laboratory simulations, and engage in collaborative problem-solving tasks. Within this setting, the AIDTC framework functions as an integrated cyber-physical system, continuously capturing learner interactions, analyzing learning states, and adapting instructional pathways.

This study adopts a single descriptive case study approach to examine the application of the AI-augmented Digital Twin classroom (AIDTC) framework in a higher-education engineering course. The case was selected to provide a realistic context for observing how learner interaction data can be captured, processed, and interpreted within the proposed framework. Data were drawn from an existing blended course environment and included learning management system logs, assessment records, virtual laboratory activity traces, and participation data generated during regular instructional activities. The analysis was descriptive in nature and focused on deriving learner indicators required for constructing and updating the learner Digital Twin, rather than on inferential statistical testing or generalization beyond the case context.

The operational mapping between the conceptual framework and the case study implementation is summarized in Table 1, which shows how each AIDTC component ranging from the physical learning environment to orchestration performs a distinct yet interconnected role.

To emphasize the applicability of the AIDTC framework for instructional design, the operational mapping is presented as an instructional design representation rather than a purely technical system mapping. Table 1 illustrates how each framework component informs instructional planning, learning activity design, adaptation mechanisms, and instructor decision-making within the case study context.

Table 1. Operational mapping of the AIDTC Framework in the illustrative case study

AIDTC component	Instructional design role	Instructional function in the case study
Physical learning environment	Learning activity context	Provides blended instructional settings (classroom, LMS, virtual labs) where learner interactions are generated
Cognition layer	Learning analytics and diagnosis	Interprets learner activity data to diagnose engagement, mastery, and learning risk
Learner Digital Twin	Learner modelling for design decisions	Represents evolving learner states to support differentiated instructional pathways
Immersion layer	Adaptive learning activity delivery	Delivers simulations, collaborative tasks, and scaffolded activities based on learner state
Orchestration layer	Instructor-guided instructional control	Enables instructors to review AI recommendations and make pedagogically informed decisions

This mapping illustrates how abstract architectural layers are translated into concrete instructional and analytical functions, thereby bridging conceptual design and practical implementation.

As learners engage with instructional activities, the system captures a focused set of behavioral and performance-related data streams, including time-on-task, assessment outcomes, interaction patterns, and collaborative participation. These data are processed within the cognition layer using AI-driven analytics to infer key learner characteristics such as engagement level, conceptual mastery, and potential learning risk.

These inferred attributes collectively form the learner Digital Twin, a dynamic representation that evolves as learning progresses. Rather than storing exhaustive raw data, the Digital Twin maintains a compact set of semantically meaningful variables that support personalization and prediction. The core data streams and corresponding Digital Twin variables used in the illustrative case are presented in Table 2, demonstrating how learner behavior is translated into actionable intelligence without unnecessary system complexity.

The learner indicators reported in Table 2 were derived by normalizing and aggregating the collected case study data using standard learning analytics practices. Engagement index, concept mastery score, collaboration score, and risk probability are represented on a normalized scale between 0 and 1, where higher values indicate stronger presence of the corresponding attribute. Procedural competence is expressed as a percentage based on task completion accuracy in virtual laboratory activities. These values are intended to demonstrate how learner states are quantified and interpreted within the AIDTC framework rather than to report statistically generalizable results.

Table 2. Core learner data streams and Digital Twin variables

Data source	Digital Twin variable	Value
Time-on-task	Engagement index	0.74
Assessment performance	Concept mastery score	0.71
Virtual lab actions	Procedural competence	82%
Discussion participation	Collaboration score	0.63
Interaction patterns	Risk probability	0.19

Insights derived from the learner Digital Twin are used to generate adaptive instructional recommendations, which are delivered through immersive learning environments such as virtual laboratories and collaborative simulations. Based on the learner's current state, the system proposes actions including advanced challenges, scaffolded tasks, or targeted micro-learning support. Crucially, these recommendations are not applied autonomously. Instructors interact with the system through orchestration dashboards that present AI-generated insights alongside contextual information. Educators retain full control to accept, modify, or override system suggestions, ensuring that pedagogical judgment and ethical accountability are preserved. Table 3 illustrates representative learner states, corresponding AI recommendations, instructor decisions, and resulting instructional outcomes, highlighting the role of human–AI collaboration in adaptive teaching.

Table 3. Adaptive instructional actions enabled by AI-Augmented Digital Twin Classroom (AIDTC)

Learner Digital Twin state	Adaptive instructional action (AI-supported)	Expected learning outcome
High mastery, high engagement	Advanced simulations and open-ended challenges	Deeper conceptual understanding and transfer
Moderate mastery, low engagement	Scaffolded virtual labs with guided prompts	Improved engagement and learning persistence
Low mastery, high effort	Targeted micro-learning and formative feedback	Concept clarification and confidence building
Low mastery, low engagement	Instructor-initiated intervention and support	Re-engagement and learning recovery

This illustrative case study demonstrates how the AIDTC framework enables continuous personalization, proactive instructional support, and scalable learning design within a single cyber-physical architecture. By integrating learner data, Digital Twin modeling, immersive environments, and instructor oversight, the framework supports both individual learner needs and class-level instructional optimization.

Although the values and outcomes presented are derived from a single case context, they reflect plausible system behavior grounded in established learning analytics and Digital Twin research. The case thus reinforces the feasibility and conceptual robustness of AIDTC as a future-ready blueprint for intelligent, learner-centric classrooms across disciplines and delivery modes.

Discussion

This discussion focuses on interpreting the proposed AI-augmented Digital Twin classroom (AIDTC) framework and the accompanying case study as the central findings of the study. Rather than reiterating background literature, the section emphasizes how the analyzed learner indicators, Digital Twin representations, and adaptive instructional actions demonstrate the framework's applicability, theoretical grounding, and instructional implications.

The primary objective of this study was to examine how the proposed AI-augmented Digital Twin classroom (AIDTC) framework can be applied and validated within a real higher-education learning context through a case study. The analyzed learner indicators derived from the case study data specifically engagement index, concept mastery score, procedural competence, collaboration score, and learning risk probability as listed in Table 2 demonstrate how learner interaction data are transformed into structured Digital Twin representations. These representations enabled the identification of distinct learner states and informed adaptive instructional actions, as illustrated in Table 3.

The alignment between the analyzed case data and the adaptive instructional responses supports the main purpose of the study by demonstrating the operational feasibility of the AIDTC framework. The results show that the framework can effectively integrate learner data, Digital Twin modeling, and instructor decision-making to support personalized and proactive pedagogy within an authentic educational setting.

This study contributes to the evolving discourse on intelligent digital education by proposing the AI-Augmented Digital Twin Classroom (AIDTC) as an integrated cyber-physical learning framework that unifies artificial intelligence, Digital Twin modeling, immersive learning environments, and human-in-the-loop orchestration. Unlike conventional digital learning systems that emphasize content delivery or isolated adaptive features, AIDTC reframes the classroom as a continuously evolving system capable of sensing learner behavior, reasoning over learning states, simulating instructional responses, and adapting pedagogy in real time. This perspective extends early visions of intelligent tutoring and learner-centered e-learning by embedding them within a system-of-systems architecture grounded in digital engineering principles (Woolf, 2008).

Prior research in artificial intelligence in education has largely focused on standalone intelligent tutoring systems, adaptive assessments, or learning analytics dashboards. Early intelligent tutoring systems demonstrated the effectiveness of individualized feedback and learner modeling but were typically limited to narrowly scoped domains and lacked immersive or collaborative capabilities (Woolf, 2008). More recent scholarship has emphasized the transformative promise of AI for teaching and learning, while also noting the fragmentation of current educational technologies across platforms and pedagogical practices (Holmes et al., 2019).

Immersive learning approaches and virtual apprenticeship models have shown strong potential for experiential and skills-based education, particularly in engineering and professional training contexts (Barr & Johnson, 2020). However, these approaches are often implemented as isolated environments rather than as components of an adaptive, data-driven instructional system. Similarly, learning analytics research has demonstrated the value of real-time monitoring and proactive pedagogical interventions (Zhao & Li, 2021; Taylor & Clark, 2021), yet most implementations remain descriptive or reactive, relying heavily on instructor interpretation rather than automated reasoning.

In contrast, the AIDTC framework integrates these strands by embedding immersive environments and analytics within a Digital Twin-based cyber-physical architecture. This integration enables predictive reasoning, continuous adaptation, and coordinated human–AI decision-making. While prior work has proposed architectures for integrating learning analytics with AI-driven adaptive systems (Zaki et al., 2020), these efforts rarely incorporate immersive learning or Digital Twin synchronization within a single cohesive framework. AIDTC therefore advances existing literature by offering a holistic model that bridges intelligent tutoring, immersive learning, and Digital Twin engineering.

From a pedagogical standpoint, AIDTC supports a shift from reactive instruction toward proactive, learner-centric pedagogy. By continuously updating learner Digital Twins, the framework enables adaptive pacing, differentiated learning pathways, and timely instructional interventions without proportionally increasing instructor workload. This aligns with global calls for human-centered, ethical, and resilient digital education ecosystems (UNESCO, 2019).

Technologically, the framework demonstrates how concepts traditionally applied in smart manufacturing and cyber-physical infrastructure can be meaningfully translated into educational contexts. The orchestration layer plays a critical role by ensuring that AI-generated recommendations remain transparent, interpretable, and subject to human oversight. Such human-AI collaboration is essential for maintaining pedagogical agency and trust in intelligent educational systems (Woolf, 2020).

At an institutional level, AIDTC has implications for curriculum design, digital infrastructure planning, and graduate employability. Exposure to AI-rich, data-driven learning environments fosters systems thinking, adaptability, and digital literacy—competencies increasingly identified as critical for future labor markets (World Economic Forum, 2020).

Despite its potential, the AIDTC framework raises important ethical and equity considerations. Continuous data capture, learner modeling, and predictive analytics necessitate robust governance mechanisms to ensure privacy, informed consent, and responsible data use. Ethical frameworks in learning analytics emphasize transparency, learner agency, and proportionality in the use of educational data (Slade & Prinsloo, 2019).

Moreover, advanced sensing and immersive technologies risk exacerbating existing digital divides if access to devices, bandwidth, or technical support is uneven. Without inclusive design and policy interventions, such systems may reinforce structural inequalities in education (van Dijk, 2020). To address these risks, AIDTC implementations should align with inclusive digital education policies, prioritize accessibility, and adopt open and interoperable standards (UNESCO, 2019; IEEE Standards Association, 2019).

As a conceptual and illustrative contribution, this study does not provide empirical validation of learning outcomes or system performance. The case study and associated tables illustrate plausible operational behavior rather than measured results. Additionally, the framework assumes the availability of reliable digital infrastructure, AI capabilities, and institutional readiness, which may vary significantly across educational contexts.

The learner Digital Twin model is intentionally abstracted to preserve generalizability across disciplines and educational levels. Consequently, specific algorithmic choices, sensing technologies, and data fidelity requirements are not exhaustively specified, representing a trade-off between conceptual clarity and implementation detail.

Future research should focus on empirical validation of the AIDTC framework through pilot deployments across diverse educational settings, including K–12, higher education, and professional training. Longitudinal studies are needed to examine how learner Digital Twins evolve over time and how adaptive interventions influence sustained learning outcomes.

Further work should explore the integration of affective computing and multimodal sensing to capture emotional and social dimensions of learning, which play a critical role in motivation and engagement (Picard, 2021; Kapoor & Picard, 2017). Research is also needed on the design of effective human-AI co-teaching interfaces to ensure transparency, trust, and appropriate division of agency between instructors and intelligent systems (Woolf, 2020).

At the systems level, future studies should investigate interoperability frameworks, ethical governance models, and scalable deployment strategies aligned with AI-driven adaptive architectures and Internet-of-Things standards (Zaki et al., 2020; IEEE Standards Association, 2019). These efforts are essential for transforming AIDTC from a conceptual framework into a deployable, ethically grounded, and scalable educational infrastructure.

Overall, this discussion positions AIDTC as a next-generation educational architecture that synthesizes advances in artificial intelligence, Digital Twins, immersive learning, and cyber-physical systems. By addressing fragmentation in current digital education and emphasizing ethical, human-centered design, the framework offers a coherent pathway toward intelligent, resilient, and future-ready classrooms.

Conclusion

This paper proposed the AI-Augmented Digital Twin Classroom (AIDTC) as a conceptual framework to address key limitations of current digital education systems, including limited personalization, real-time adaptability, scalability, and immersive engagement. By integrating Digital Twin modeling, artificial intelligence, immersive learning environments, and human-in-the-loop orchestration, the framework reconceptualizes the classroom as a dynamic cyber-physical learning system.

The layered AIDTC architecture enables continuous synchronization between learner behavior and digital representations, supporting proactive, data-driven instructional adaptation while preserving educator agency and ethical oversight. The illustrative case study demonstrated how the framework can be operationalized in a realistic higher-education context, reinforcing its internal coherence and practical feasibility.

This study is subject to several limitations. The case study represents a single instructional context and was intended to demonstrate framework applicability rather than to provide empirical generalization of learning outcomes. Additionally, specific algorithmic implementations and sensing technologies were abstracted to maintain conceptual generality. Future research should focus on empirical validation of the AIDTC framework through pilot deployments across diverse educational settings and longitudinal evaluation of learning outcomes.

Although empirical validation remains a direction for future work, this study provides a future-ready blueprint for intelligent, scalable, and learner-centered digital classrooms. The AIDTC framework contributes to ongoing Education 5.0 efforts by bridging educational theory and digital engineering, offering a foundation for the next generation of adaptive and immersive learning ecosystems.

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Cracking Engineering Physics through Crossword Puzzles: A Gamified Active Learning Approach to Enhance Engagement and Concept Retention

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Abstract
This study intends to examine how well gamified active-learning resources, more especially, crossword puzzles, improve student engagement, memory and conceptual understanding of physics topics in first year engineering students. This study offers a scalable, interactive teaching approach intended to close the gap between passive listening and active cognitive involvement in technical subjects, even though standard lecture-based engineering approaches frequently result in shorter attention spans and poor memory. The method uses gamification to turn rote memorizing of technical terms and difficult ideas into a fun, competitive and introspective experience that supports certain learning objectives based on the active learning principle. Crossword puzzles were used as tools for review and pre-assessment of about 300 undergraduate B. Tech students from different branches. A mixed-methods strategy was used to collect the data, measuring both quantitative gains and qualitative involvement through the use of pre- and post-quiz scores, mid-semester examination results, and structured student feedback. As per the results obtained, crossword puzzles are a useful addition to engineering education since they greatly increase conceptual clarity and technical language memory. These findings imply that the drawbacks of conventional physics instruction can be effectively addressed by incorporating gamified components.

Keywords: Active Learning, Crossword Puzzles, Engineering Physics, Concept Retention, Student Engagement.

Introduction

Fostering student enthusiasm for the subject matter and the learning process depends heavily on a teacher's professional skill, especially on their capacity to communicate information efficiently and create an engaging and enjoyable learning environment. In a perfect learning environment, students are motivated to observe and investigate the facts of their surroundings by means of significant and enduring educational experiences. They are persuaded to actively interact with their environment, which fosters awareness and effective utilization of instructional materials. One key strategy for skill development is active learning, which involves students actively participating in the educational process. Students become active learners rather than passive recipients of evaluations as they acquire new abilities, values and attitudes. Active learning facilitates students to consider their own attitudes and values in addition to focusing on skill development (McKeachie 2006; Kasilingam et. al. 2014; Harmann 2011; Hake 2002; Dol et. al. 2017). Active learning methods implemented in the form of lectures, simulations, debates, student presentations, games, role-plays, flip charts and handouts are crucial elements. Active learning comprises three interrelated elements. These include educational tools, learning methodologies and fundamentals (Kintu et. al. 2016; Kumar et. al. 2010; Ritzko 2011; Velaora et. al. 2021; Pivec 2007).

First-year engineering curricula include engineering physics as a core science course that serves as the conceptual and mathematical basis for subsequent discipline-specific courses. Most of the time students perceive this subject as abstract, fast-paced, and substantially content-driven, which results in poor learning, anxiety and disengagement. Traditional teaching methods frequently treat students as passive consumers and make it difficult for them to focus and engage in deep conceptual processing for the duration of a session. Research in scientific and higher education regularly demonstrates that teacher-centred approaches are linked to poor long-term retention, restricted conceptual change and inadequate transfer of knowledge to novel challenges. Gamified methods and active learning have become popular tactics for raising student motivation, engagement and comprehension, making it learner centric. According to numerous experimental research in physics and science education, incorporating game-

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like tasks and challenges improves time on task, participation and frequently, academic performance when compared to non-gamified activities. Compared to traditional settings, gamified environments are typically more immersive and interactive, encouraging deeper processing of complicated topics, active engagement and teamwork. Additionally, analytical data shows that gamification improves learning results overall, with its effects being moderated by user type, discipline, and design principles (Croft 2010; Huynh 2012; Falkner 2010; Franklin 2006; Sannathimmappa 2023; Huang 2014; Maheshwari 2021).

In this context, game-like resources such as puzzles and tests provide a practical means of implementing gamified, active learning in classrooms with lots of students or limited resources. In higher education, crossword puzzles in particular have been utilized as formative evaluation tools to strengthen conceptual links, terminology and definitions. Studies from the field of health and food science demonstrated that the use of crossword puzzles tends to increase learner's engagement and perceived comprehension of the course material (Agarwal 2020; Babayemi 2014; Bryant 2016; Venkata 2023; Veena 2025; Mehta 2025). Evidences from medical and pharmacy education show that crossword based exercises can help with the learning and retention of technical terminology and domain-specific knowledge. These results are in line with more extensive research on game-based and puzzle-based learning, which emphasizes the advantages of activities that are closely matched with learning objectives for motivation, attention, cooperation and information retrieval (Shetgar et al. 2018, Weisskirch et.al. 2010; Zamani et. al. 2021; Udeozor et. al. 2021).

Though there are many evidences showing the implementation of gamification and puzzle based learning methods in various domains, engineering physics remains relatively underexplored. Most of the existing work on gamified physics education focuses on digital games or simulations targeting specific topics like mechanics, motion and trajectories and demonstrates increased engagement and more dynamic learning, sometimes with modest but positive impacts on quiz performance. In higher education, there is also concern that some gamified experiences emphasize extrinsic rewards without adequately fostering autonomy, relatedness and meaningful cognitive challenge, which are critical to intrinsic motivation and deep learning. Within this context, we see that crossword puzzles offer a promising, yet underutilized, form of content gamification for engineering physics. These types of learning activity can embed formulas, core concepts, units and relations directly in the puzzle structure that requires students to recall and apply knowledge (Saran et. al. 2015; Njoroge et. al. 2013; Patrick 2018; Naik 2023; Sargar et. al. 2024; Basakova et. al. 2024). There is a lack of published research on carefully crafted, course outcome mapped crossword puzzles for first-year engineering physics, regardless of the fact that crossword-based interventions have been studied in fields like anatomy, pathology, and food science with positive effects on engagement and perceived understanding. Particularly, there is a dearth of quantitative data relating the usage of crossword puzzles to success on common course tests and idea memory, as well as organized research on students' perspectives in this particular setting.

The purpose of this investigation is to design, implement and evaluate crossword puzzles as a structured active-learning strategy for Engineering Physics and to measure their impact on student engagement, learning outcomes and concept retention; assess the value of crossword puzzles as a cutting-edge teaching and learning tool.

The following are the objectives of the study performed:

(i) To evaluate the how effective crossword puzzles are in improving the understanding and retention of fundamental concepts and technical vocabulary in Engineering Physics.
(ii) To assess student feedback and perception about embedding crossword puzzles within the teaching methodology and to determine the impact of crossword-based learning on academic performance in engineering physics topics.
(iii) To explore the role of crossword puzzles in reducing cognitive load and enhancing long-term memory retention.
(iv) To evaluate how crossword puzzles support the revision and reinforcement of complex theories and formulas in Engineering Physics.

The present study addresses the gap by implementing a gamified active learning that incorporates thoughtfully crafted crossword puzzles into a first-year engineering physics course used to crack the concepts of engineering physics. The puzzles are used as in-class activity and are clearly linked to the course objectives and important conceptual clusters. The study uses a mixed method design that incorporates pre and post-tests, internal examination results, mid- term results and structured student feedback to assess the efficacy of crossword puzzles. The work intends to add empirical evidence to the larger literature on gamification and active learning in engineering physics, as well as useful advice for teachers, by concentrating on a low-cost, readily scalable gamified tool.

Methodology

This concept follows the Bloom's Taxonomy framework which categorizes learning into different cognitive levels like knowledge, comprehension, application, analysis, synthesis and evaluation. Crossword puzzle activities primarily focus on to engage the knowledge and comprehension levels that require students to recall technical terminology, definitions and concepts related to the given physics topics. Additionally, the crossword puzzle solving also supports active learning, where students actively participate in constructing knowledge rather than passively receiving information. These types of mere practice, which has been shown to strengthen memory and conceptual reinforcement in educational settings.

This study was conducted at a private engineering institute located in Mumbai, Maharashtra. Sample size consisted of 128 respondents who are engineering undergraduate students (first year) from Computer Engineering, Information Technology, Mechanical Engineering, and Electronics & Telecommunication Engineering. Crossword puzzles were designed and curated by the faculty members to ensure alignment with specific physics topics including Semiconductors, Photonics and Engineering Materials. Questions focused on key concepts, definitions, formulas and technical terminology with different difficulty levels (easy, moderate and difficult). Puzzles were created using online tools (Figure 1) and reviewed manually to ensure academic relevance. The crosswords were created using online websites like https://crosswordlabs.com/ and https://puzzlemaker.discoveryeducation.com/.

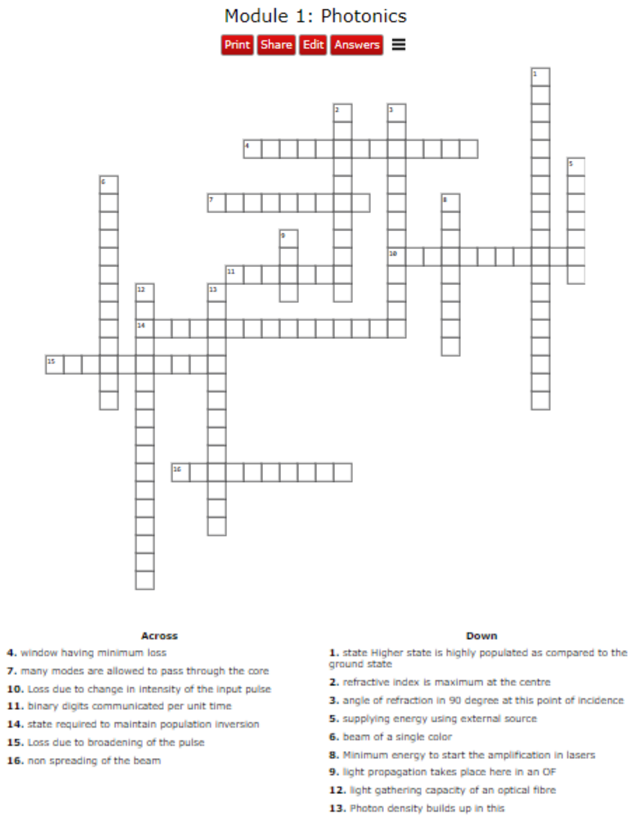

Figure 1. Sample crossword on Photonics

A set of questions with single-word answers was provided to the website, which automatically generated the crossword puzzles. The crossword puzzle was shared with the group of learner's using the Institutes customized LMS Moodle. Students were instructed to work in a team of 2 and solve the puzzle in time duration of 30 minutes. Assessment was conducted using MCQ-based quizzes (pre- and post-activity) as well as internal assessment and mid-semester exam scores. Once they finished, they were instructed to share the PDF version of their completed puzzle on the drive linked shared with them in advance, after which the correct answers were disclosed as is illustrated in Figure 2.

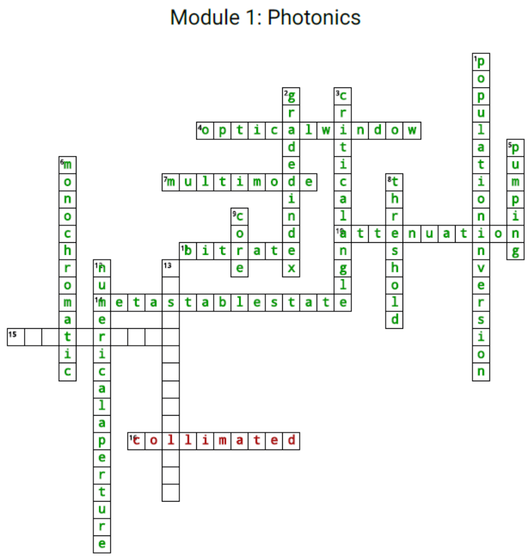

Figure 2. Completed Crossword puzzle attempted by the students

An online student perception survey was conducted using a structured questionnaire administered through Google Forms and based on a 5-point Likert scale. The questionnaire included items designed to capture students' views and experiences regarding the use of crossword puzzles as a learning tool. The collected feedback responses were further analyzed to assess internal consistency.

Results and Discussion

Student's performance analysis

The study was conducted with approximately 300 first-year undergraduate (B. Tech) students enrolled in the Computer Engineering, Information Technology, Mechanical Engineering and Electronics and Telecommunication Engineering branches respectively, at a private engineering institute in Mumbai. Participation in the instructional activity was integrated with regular classroom teaching. Among them, 263 students actively participated in the crossword puzzle activities conducted during the sessions. The statistical analysis was done only for the students who completed both the pre-test and post-test assessments with complete and matched responses. After excluding the incomplete submissions and unmatched responses, 128 students constituted the final matched dataset, which was used for the paired statistical comparison of pre- and post-activity quiz scores. The approach ensured that the analysis was based on paired observations from the same participants, thereby improving the validity of the comparison.

The effectiveness of crossword puzzles as a learning tool was assessed by comparing students' performances for both the modules in the internal assessments (MCQ based quiz) and mid-semester test. A pre-test–post-test design was employed in which an Internal Assessment (IA) was conducted before introducing crossword puzzles and a second Internal Assessment their after implementation to measure impact on student learning outcomes. 128 students actively participated and appeared for both the internal assessments. Students not only thoroughly enjoyed the activity but also completed the crossword independently, without relying on external resources such as books or the internet in the given time.

Student performance in Internal Assessment (IA) and Internal Assessment-2 (IA-2) reveals a clear improvement in overall academic attainment as shown in Figure 3.

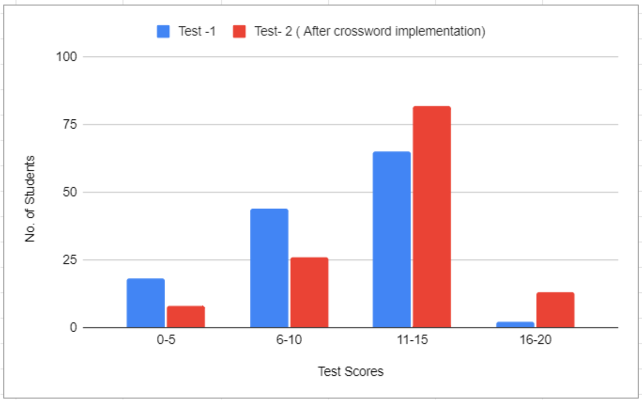

Figure 3. Students' performances in the internal assessments pre and post crossword puzzle activity.

In Category I (0–5 marks) students, number of students dropped markedly from 18 in IA to 8 in IA-2, representing a decline of nearly 59%. This decrease indicates that several students who initially struggled with the subject content were able to improve their performance in the subsequent assessment after crossword practice. A similar kind of pattern was observed in the students of category II (6–10 marks), where the number of students decreased from 44 in IA to 26 in IA-2. The combined decline in the lower performance categories (0–10 marks) clearly indicates that a significant number of students moved into higher score categories in the second assessment. A substantial increase from 65 students in IA to 82 students in IA-2 is seen where the students fall in category III (11–15 marks), indicates that a large portion of students improved their speculative understanding and hence, were able to perform better in the subsequent evaluation. A significant rise in the student from 2 in IA to 13 students in IA-2, reflects a notable rise in high-achieving students in Category IV (16 -20 marks). The decline in Category I & II students combined with the increase in Category III & IV students suggests improved comprehension and retention of course concepts. Such improvement aligns with the principles of Bloom's Taxonomy from a pedagogical viewpoint, where reinforcement of knowledge and comprehension through active learning strategies supports progression toward higher levels of cognitive attainment. Therefore, crossword puzzles can be used as a supplementary tool along with regular lectures for enhancing learning outcomes.

A paired samples ***t***-test was conducted to compare student's performance on the crossword pre-test and post-test to determine the effectiveness of the instructional intervention and the results are displayed in Table 1. The studies performed using paired *t*-test is appropriate because the same group of students (n = 128) participated in both assessments, thus allowing for the evaluation of mean differences within matched observations.

Table 1. Summary of the statistical analysis

Metric	**Pre-Test**	**Post-Test**
Mean Score	11.41	14.03
Standard Deviation	4.27	3.12
Sample Size (n)	128	128
t-statistic	5.772	
p-value	< 0.0001	

Using this statistical method, we ascertain whether the average difference between pre- and post-intervention ratings deviates considerably from zero. The mean score shows an increase from M = 11.41 (SD = 4.27) in the pre-test to M = 14.03 (SD = 3.12) in the post-test, indicating an average gain of 2.62 points following the teaching intervention. The reduction in standard deviation (SD) from 4.27 to 3.12 clearly suggests slightly more consistent performance among students after instruction. A statistically significant difference between pre-test and post-test scores was found using the paired samples t-test (t (127) = 5.772, p <.0001). The obtained p-value 5.67×10^{-8} is significantly less than the standard significance level of $\alpha = 0.05$. The null hypothesis states that there is no significant difference between the mean scores from the pre-test and post-test and is rejected since the computed p-value is significantly below the 0.05 cut-off. The findings show that it is unlikely that the observed mean improvement happened by accident. The observed increase in mean scores from 11.41 to 14.03 reflects a meaningful enhancement in students' understanding of the subject content as measured through the crossword assessment. The large *t*-value and highly significant *p*-value suggest that the teaching strategy employed had a positive and measurable impact on student's learning outcomes. Overall, these findings provide empirical support for the effectiveness of the instructional approach in improving student's conceptual understanding, as evidenced by their enhanced performance in the post-intervention crossword assessment. The findings suggest that incorporating crossword puzzles into physics lectures significantly enhances student performance. Students exposed to crossword-based activities not only retained subject-specific terms better but also demonstrated improved conceptual understanding, which translated into higher exam and assessment scores. The higher gain in internal assessments highlights that crossword puzzles improved continuous engagement and recall, while the greater improvement in mid-semester exams indicates better long-term retention and problem-solving skills.

Feedback Analysis

Overall responses from 128 students show that the students welcomed crossword puzzles as a diversion from the usual lectures and felt they added interest and motivation to the teaching and learning process. In response to the level of difficulty of crossword, varied responses were obtained from the students regarding their experience with the activity as reflected in Figure 4.

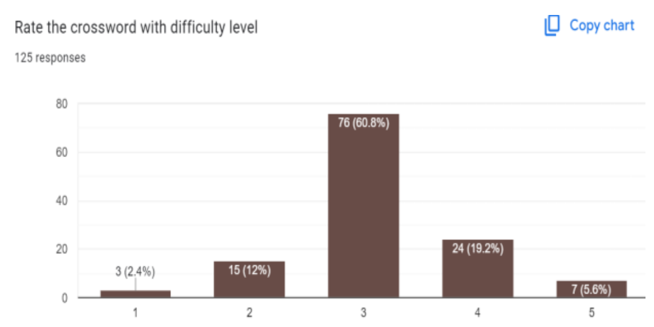

Figure 4. The bar graph showing the difficulty level of the crossword activity received from the students responses

The variation in the answers shows that the students' cognitive ability and the crossword puzzle's difficulty level were suitably matched. Around 60.8 % of the respondents gave the activity a moderate difficulty rating (level 3), indicating that the puzzle activity offered an ideal degree of difficulty thus promoting active participation without placing an undue cognitive burden on participants. Additionally, 24.8% of the students find the puzzles difficult hence, gave it a higher difficulty ratings (4–5) which suggests that some students found the activity to promote deeper cognitive thinking. A relatively smaller proportion of responses lie in the lower difficulty categories (14.4% for levels 1–2) suggests that the activity was not perceived as trivial.

The overall findings demonstrate that crossword puzzles functions as an effective active learning strategy that promotes engagement and conceptual reinforcement among first-year engineering students.

Reponses from the student perception survey, capturing learners' experiences and opinions of the crossword activity, were collected and analysed. As per obtained responses majority of the students had an excellent experience. Table 2 depicts the findings of survey on a 5-grade evaluation scale to assess students' opinions and perception about cross word puzzle activity in classroom (5=strongly agree, 4= agree, 3=neutral, 2=disagree, and 1=strongly disagree).

Table 2. Feedback questionnaire of crossword puzzle activity

Feedback Questions	5 (%)	4 (%)	3 (%)	2 (%)	1 (%)
Did you find solving the crossword puzzle enjoyable?	59.26	37.78	2.96	0	0
Do you believe that thinking is necessary for problem-solving and that this has improved your ability to think?	52.32	43.71	3.97	0	0
Do you think concentration is necessary to solve the puzzle?	53.80	43.67	0.63	1.90	0
Did you remember the subjects as you worked through the puzzle?	53.50	44.59	1.27	0.64	0
Do you think a student can also be evaluated using a crossword puzzle?	47.47	46.84	3.16	0.63	1.90
Solving crossword puzzles in the classroom is a good appraisal of lecture content.	63.57	32.86	1.43	2.14	0

More than 90% of students selected 4 or 5 for most questions, indicating strong agreement. The highest "Strongly Agree" response (63.57%) is for crossword puzzles being a good appraisal of lecture content. Negative responses (2 or 1) are very minimal (<3%), showing overall positive acceptance. Students agreed that crossword puzzles were interesting. They enjoyed it and would surely like to have more such activities in class after a topic is taught which will help students to prepare for the concepts. Crossword puzzles encourage conversation in small groups and foster critical thinking. Hence, it can be inferred that the appropriate implementation of crossword activities has the potential to positively impact student's learning outcomes and significantly enhance their engagement within the classroom environment.

Figure 5 illustrates students' ability to recall theoretical topics while solving the crossword. According to the figure, majority of students (72.2%) said "Yes," indicating that the crossword exercise successfully enhanced their capacity to remember theoretical ideas discussed in the course. 27.8% of respondents chose "moderate," suggesting that although the exercise improved recalling, learners' perceptions of the effect differed based on their level of participation or prior knowledge. Interestingly, no replies expressed a negative opinion, suggesting that students generally thought the activity was beneficial for strengthening conceptual memory.

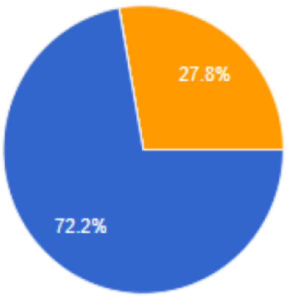

Figure 5. Ability to recall theory topics after attempting crossword puzzle activity

The students' feedback analysis clearly suggests that crossword puzzles are interactive and motivate the students to recall definitions, terms and conceptual connections related to the subject. Learner's feedback response also included the following remarks (i) Crossword puzzles helps creating a relaxing atmosphere as compared to the tedious lectures (ii) increases the interaction, enjoyment of simultaneously learning the subject and (iii) guessing the right spellings helped them solidify their knowledge and thus, they all agreed that more such crossword puzzles ought to be available for all the topics of the physics module in the future.

Moderate claims regarding long-term retention are observed. Long term retention can be correlated with the scores of mid semester examination, as the modules used for crossword activity in class and the modules for mid-semester examination was the same. Figure 6 represents the distribution of mid-semester examination (MSE) scores demonstrating overall student performance. The scores in the mid-semester examination indicate 67.4% of students scored within the 11–15 marks range, 30.2 % scored in the 16–20 marks range, only a small fraction of students (1.6%) scored within the 6–10 marks range, and an almost negligible proportion scored below this range, indicating an overall positive learning outcome across the cohort. This distribution suggests approximately 97.6% of students (11-20 mark range) were able to retain and apply key physics concepts during formal assessment. The improvement in mid-semester exam scores to some extent suggests that the crossword activity may have supported students' retention and recall of theoretical physics concepts, which likely contributed to improved student performance.

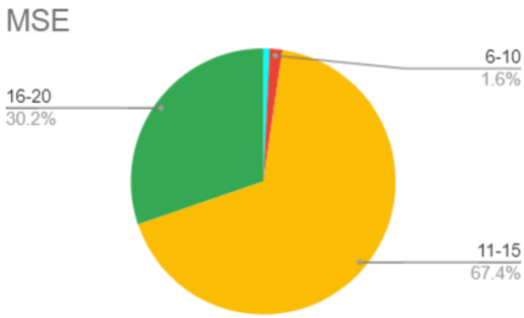

Figure 6. Distribution of Mid-Semester Examination (MSE) scores demonstrating overall student performance following the crossword-based learning activities.

Although improved performance in the mid-semester examination suggests effective reinforcement of course concepts, the study did not include delayed post-tests or standardized cognitive load measurements; therefore, claims regarding long-term retention and cognitive load reduction should be interpreted with caution.

Targeted learning outcomes are positively correlated with gamified instructional methodologies, according to the activity–outcome mapping described in Table 3.

Table 3. Activity–Outcome Mapping of Gamified Learning Intervention in Engineering Physics

Activity	Outcome Achieved
Crossword solving	Improved recall of physics terminology
Peer discussion	Enhanced collaborative learning
Timed puzzles	Increased focus and engagement
Feedback survey	Insight into learner perception

Solving crossword puzzles of engineering physics helped students to recall the terminology. In line with social constructivist ideas, peer conversations encouraged collaborative knowledge building. Timed puzzle exercises improved classroom engagement and student focus. Additionally, the feedback survey showed that students had a favourable opinion of these interactive techniques, pointing to both cognitive and affective advantages. Integrating multiple gamified strategies provides a holistic approach to enhancing both understanding and motivation in an Engineering Physics course.

Conclusions

Crossword puzzles prove to be a creative way to teach and learn. They add concept retention as well as active student participation in class. The study indicates that the crossword puzzles can be an effective supplementary tool in engineering education, as they show to enhance students' speculative and conceptual understanding as well as retention of technical vocabulary. The outcome is supported by the statistical analysis, showing a large t-value and a high significant p-value. When crossword puzzles are used as a teaching strategy, they can have a positive and measurable impact on students' learning outcomes. These studies suggest that the inclusion of gamified activities like crossword puzzles can make learning physics more engaging and interactive. Hence, integrating crossword puzzles with traditional teaching approaches may help address some limitations of conventional physics instruction and enhance the overall learning experience.

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Conflict of interest

The authors declare no conflict of interest.

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Education in the Mirror of Institutions: A Systematic Review of Service Quality and Character

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Abstract
Transformation of higher education services demands the integration of digital services and institutional character in facing the challenges of accessibility, inclusion, and digitalization. This study examines the effectiveness of Service Quality and E-Service Quality models in academic and administrative services, the methodological challenges of using Analytical Hierarchy Process (AHP), Fuzzy Logic, and Importance Performance Analysis (IPA), and the role of institutional characteristics as mediators or moderators of student satisfaction and trust. This study uses a Population, Intervention, Comparator, Outcomes, and Context (PICOC) + Urgency of research and research motivation (UM) -based SLR approach to examine higher education services. Through the synthesis of 26 selected articles (2022–2025), multicriteria analysis such as AHP, Fuzzy, IPA reveals supporting factors, service effectiveness, and institutional contributions to its transformation. This study builds the Framework of Service Quality Impact in Higher Education Institutions (FSQIHEI) model to transform higher education digital services through the integration of AHP, Fuzzy, and IPA. Its contributions include literature mapping 2023–2025, emphasis on Service Quality, and differentiation of service strategies between public and private universities. Institutional characteristics are introduced as important variables in measuring student satisfaction and trust in a sustainable manner. This study includes an institutional characteristics-based FSQIHEI model, strengthening the Service Quality literature, and offering an evaluative approach to digital higher education services that is responsive, measurable, and contextual.

Keywords: E-Service Quality, Higher Education, Institutional Characteristics, Cognitive, Student Trust.

Introduction

The quality and character of higher education services, it is important to place accessibility as a strategic dimension in institutional evaluation (Araujo et al., 2012; Nisar, 2015; Pedrosa et al., 2025; Salazar, 2022). A global interactive map displaying educational institutions based on accessibility-related curricula opens up a discussion about how educational services can be assessed not only from an academic perspective, but also from a commitment to social inclusion (Alhasnawi et al., 2023; Boitier & Rivière, 2013; Hanada, 2013; Jahromi & Jahromi, 2021; Rahman & Nasrin, 2024a; Rhoades, 2016; Soria-barreto et al., 2017). This discourse leads to the understanding that service quality is not only measured by overall student satisfaction, but also by the extent to which educational institutions integrate accessibility values, both in learning design, technological support, and institutional policies (AccessCoVE, 2025).

Various universities in Spain, such as Universidad Complutense and Universidad Autónoma de Barcelona, demonstrate a strong commitment to issues of social integration and disability through their Spanish-language graduate and undergraduate programs, focusing on accessibility, the environment, inclusion, and multidisciplinary social interventions (Liu et al., 2023; Zouine et al., 2024). The need to evaluate higher education services lies not only in fulfilling the aspects of accessibility and inclusion, but also in how institutions respond to the challenges of digital transformation holistically (Ghulam & Mousa, 2019; Kosman et al., 2024; Ponomarenko, 2022). This requires strengthening institutional capacity to manage the dynamics between service quality and institutional character, especially amidst the

Pradana, J. A., Badi'ah, R., Putri, A. I., Salsabilah, V. K., Rowi, S., & Harsito, C. (2026), Education in the Mirror of Institutions: A Systematic Review of Service Quality and Character, *ASEAN Journal of Engineering Education*, 10(1), 70-86. https://doi.org/10.11113/ajee2026.10n1.223

acceleration of digitalization, which has revealed disparities in implementation across universities (Ortagus, 2023; Rahman & Nasrin, 2024a).

The transformation of higher education services in the digital era shows a complex dynamic between service quality and institutional character (Dougherty, 2015; Wider et al., 2024a). Various empirical observations of academic and administrative service practices in higher education institutions, both public and private, have revealed significant variations in the effectiveness of digitalization implementation, which appears to be influenced by factors such as technological support, management flexibility, the need for students to have a business spirit, and stakeholder involvement (Altynbassov et al., 2024; Gaspar Pacheco et al., 2024; Romero-Lora et al., 2024).

Amidst the acceleration of digitalization and the complexity of higher education management, the quality of services—both in person and online (e-service)—is a primary concern for educational institutions (Rahman & Nasrin, 2024a; Wider et al., 2024a). However, in reality, many universities are still unable to optimize the implementation of the Service Quality and E-Service Quality models to support the effectiveness of academic and administrative services as a whole (Maghfiroh & Badi, 2025; Prastyabudi et al., 2024). Although a number of supporting factors such as technological infrastructure, internal quality policies, and human resource competencies are available, strategic integration of digital services is still partial and not yet systematic (Borsatto et al., 2024; Khan Eusafzai, 2024).

This indicates a gap between the potential for a quality service model and the reality of its implementation (Casper & Henry, 2001; Said et al., 2024). Furthermore, analytical approaches such as Analytic Hierarchy Process (AHP), fuzzy logic, and Importance-Performance Analysis (IPA) are starting to be widely used in managerial decision-making related to service quality (Aulia et al., 2024; H. V. Nguyen et al., 2024; P. H. Nguyen, 2021; van der Stap et al., 2024)However, practice in the field shows that many institutions face challenges in terms of limited data, technical understanding of the method users, and doubts about the validity of the analysis results when applied to services that are dynamic and subjective (Guillén Perales et al., 2024; Kotima et al., 2024). This is exacerbated by the lack of analytical capabilities at the managerial level and the absence of applicable standard guidelines (Fakir Mohammad et al., 2024). On the other hand, the differences in characteristics between state and private universities create diverse conditions in terms of challenges and supporting factors for improving the quality of services (Firman, 2024; Pan et al., 2024).

Public institutions tend to have longer bureaucracies, while private institutions face high competitive pressures to maintain student satisfaction as their primary customers. Unfortunately, little research has explored how these institutional characteristics mediate students' cognitive trust and perceptions of service quality. This creates an urgency to explore these differences more deeply and contextually within a coherent conceptual framework. Although the Service Quality and E-Service Quality models have been widely discussed, there is still a lack of research integrating the two to understand the effectiveness of academic and administrative services in the context of higher education digitalization, especially in identifying enabling factors empirically.

This study is closely related to higher education in the field of engineering and STEM disciplines, where the effectiveness of academic and administrative services is crucial for supporting complex learning processes, laboratory management, and digital-based technical education. In technical and STEM programs, students rely heavily on efficient service systems for course registration, access to laboratory resources, guidance in research projects, and timely feedback on assessments. However, inconsistencies in service quality, uneven digital infrastructure, and differences in institutional practices between public and private universities often hinder student satisfaction and reduce cognitive trust in the institution. The research problem addressed in this study is the lack of a comprehensive framework that integrates both service quality and institutional characteristics in evaluating academic and administrative services specifically within the context of STEM-focused higher education. By systematically reviewing literature from 2023 to 2025 and analyzing factors such as digital readiness, human resource competence, and management support, this study identifies the key enablers and barriers affecting service effectiveness. The research also applies quantitative evaluation methods, including AHP, Fuzzy Logic, and the Best-Worst Method, to provide a structured and evidence-based assessment of service quality. This approach ensures that the findings are directly applicable to technical and STEM education programs, guiding universities in designing adaptive, digitalized, and high-quality service systems that enhance student learning experiences, satisfaction, and trust in the institution.

Furthermore, measurement approaches such as AHP, Fuzzy Logic, and Importance-Performance Analysis (IPA) are often used separately, even though methodological challenges and data uncertainty require a combination of approaches to produce precise strategic decisions. Furthermore, research that differentiates between public and private institutions in the context of educational services is also limited, particularly in examining how institutional characteristics can act as mediators or moderators of student satisfaction and cognitive trust. Therefore, further exploration of institutional dynamics and the quality of higher education services is needed. This study draws on literature data collection and observations of phenomena to identify recurring patterns that have not been systematically discussed. From these patterns, the research builds new generalizations about the relationship between digital service quality and educational institution characteristics (Table 1).

The analysis of the three Research Questions provides significant contributions both theoretically and practically. Theoretically, this study broadens the understanding of the integration of Service Quality and E-Service Quality models in the context of digitalization of higher education services, while filling the gap in the literature regarding the influence of institutional characteristics as mediators or moderators on perceived service quality. The methodological approach that combines AHP, Fuzzy Logic, and IPA also provides a more precise evaluation framework in dealing with the complexity of perception data. Practically, these findings can be the basis for strategic decision-making by higher education management in designing adaptive, inclusive, and data-driven academic and administrative services, especially in managing sustainable digital transformation and increasing student satisfaction and trust as key stakeholders.

Research Methods

Research Design

This research design follows a structured and step-by-step Systematic Literature Review (SLR) approach (Oti & Pitt, 2021; Salazar, 2022). The primary objective is to identify trends, methodological contributions, and research gaps in the digitalization of education services. SLR was chosen because it provides a comprehensive synthesis of existing literature with rigorous standards and high replicability, ensuring scientifically sound results (Varghese, 2018).

Quality Standards Research Question

The standard quality approach of Research Question (RQ) using Population, Intervention, Comparator, Outcomes, and Context (PICOC) + Urgency of research and research motivation (UM) is used to compile a literature review systematically and strategically precisely (Wahono, 2015). The framework serves as a sharp focus of the study, starting from who is being studied, the intervention or method used, relevant comparators, and the expected outcomes in the specific context of higher education. By adding elements of urgency and motivation, this approach strengthens the scientific and practical rationale for the research, ensuring its relevance and contribution to gaps in the previous literature, while increasing the accuracy of the literature selection and the validity of the synthesis of findings (Table 2).

Search Strategy

The literature search strategy in this study was systematically designed to ensure relevance, up-to-date coverage, and strong academic contributions to the topic of digital education service quality. The search period focused on 2022 to 2025 to capture the latest developments and current trends in service

Table 1. Research Questions, Motivation and Urgency

ID	Research Question	Motivation	Urgency
RQ1.	How do the Service Quality and E-Service Quality models contribute to improving the effectiveness of academic and administrative services in higher education, and what factors play a significant role as enablers in the service digitalization process?	There is an urgent need to understand the realistic contribution of higher education service quality models in identifying key success factors towards the digital transformation of institutions.	Mapping of supporting factors and the effectiveness of academic services and the role of more efficient administrative activities.
RQ2.	What are the methodological and practical challenges in applying AHP, Fuzzy Logic, and Importance-Performance Analysis (IPA) methods to measure and evaluate perceived quality of educational services, and how does data uncertainty affect the validity of strategic decision-making? and	The complexity of perception data as a challenge to improve accuracy and in-depth validation of methodological limitations and strategic uncertainty solutions for greater precision.	Building strategic decisions on data, facts and a framework to ensure data-based policy evaluation.
RQ3.	To what extent do differences in supporting and inhibiting factors for service quality occur between private and public higher education institutions, and how do institutional characteristics act as mediators or moderators in influencing student satisfaction and cognitive trust?	Educational institutions really need to consider the service quality model, which will enrich institutional factors in mediating or moderating perceptions and expectations empirically.	An in-depth exploration of institutional status in the dynamics of higher education service quality.

Table 2. PICOC + UM Model

ID	Population (P)	Intervention (I)	Comparator (C)	Outcomes (O)	Context (C)	Agency	Motivation
RQ 1	Higher education institutions	Implementation of Service Quality and E-Service Quality models	Institutions without a service digitalization strategy	Effectiveness of academic and administrative services, identification of digitalization enabler factors	Digital transformation of higher education services	Mapping of supporting factors and the effectiveness of academic services and the role of more efficient administrative activities.	There is an urgent need to understand the realistic contribution of higher education service quality models in identifying key success factors towards the digital transformation of institutions.
RQ 2	Users and managers of educational services	Use of the Analytical Hierarchy Process (AHP), Fuzzy Logic, and Importance-Performance Analysis (IPA) methods	Non-multicriteria or intuition-based evaluation methods	Accuracy of service quality perception measurement, validity of strategic decisions	Data-based quality evaluation in educational services	Building strategic decisions on data, facts and a framework to ensure data-based policy evaluation.	The complexity of perception data as a challenge to improve accuracy and in-depth validation of methodological limitations and strategic uncertainty solutions for greater precision.
RQ 3	Private and state universities	Analysis of the role of supporting/inhibiting factors and institutional characteristics	Institutions without considering institutional characteristics	Level of student satisfaction and cognitive trust, the influence of institutional mediation/moderation	Comparison of service quality between types of institutions	An in-depth exploration of institutional status in the dynamics of higher education service quality.	Educational institutions really need to consider the service quality model, which will enrich institutional factors in mediating or moderating perceptions and expectations empirically.

Source: Abusaeed et al., 2023; Vahedi et al., 2023; Wahono, 2015

quality measurement and digitalization in the higher education sector. The search was conducted using Boolean operators combining several key terms, namely:

("Service Quality" OR "E-Service Quality" OR "Servqual Model" OR "Fuzzy Control System" OR "AHP" OR "Fuzzy" OR "Best Worst Method" OR "Importance Performance Analysis") AND ("Higher Education" OR "Private Higher Education Institutions" OR "Public Secondary Schools" OR "Educational Services" OR "In-Service Education" OR "Education Delivery" OR "Education Policy" OR "Quality Education") AND ("Customer Satisfaction" OR "Consumer Satisfaction" OR "Cognitive Trust" OR "Satisfaction" OR "Attitudes") AND ("Cross Border E-Commerce").

This keyword filter was selected to capture quantitative and multi-criteria approaches such as AHP, Fuzzy Logic, BWM, and IPA, as well as the dimensions of user satisfaction and cognitive trust in the digital transformation of education. Furthermore, the incorporation of terms such as Cross-Border E-Commerce aims to explore cross-border digital service models and their adaptability in education. The identified literature comes from various selected journals and is relevant to the topic, including:

1. Acta Psychologica (76th Percentile), access link: https://www.scopus.com/sourceid/29424.
2. Expert Systems with Applications (96th Percentile), access link: https://www.scopus.com/sourceid/24201.
3. Heliyon (82nd Percentile), access link:https://www.scopus.com/sourceid/21100411756.
4. Journal of Cleaner Production (98th Percentile), access link: https://www.scopus.com/sourceid/19167.
5. Plos ONE (89th Percentile), access link: https://www.scopus.com/sourceid/10600153309.
6. Nurse Education Today (96th Percentile), access link: https://www.scopus.com/sourceid/28806.
7. Journal of Management and Innovation (Manova) (SINTA 4), access link: https://sinta.kemdikbud.go.id/journals/profile/8009.

The seven journals reflect a diverse range of disciplines, from service psychology and intelligent systems to open innovation and higher education policy. These journals were selected to accommodate a multidisciplinary approach and ensure the inclusion of empirical and conceptual research from a variety of global and local perspectives.

Data Extraction and Synthesis

The data extraction and synthesis process was carried out systematically by considering inclusion and exclusion criteria, such as publication year 2022–2025, indexed documents, language, topic relevance, higher education focus, quantitative methodological approach, and relevance to the digitalization of education services (Table 3).

Table 3. Study Inclusion and Exclusion Criteria

No	Selection Category	Inclusion Criteria	Exclusion Criteria
1	Publication Year	Articles published between 2022 and 2025	Articles published before 2022
2	Document Type	Indexed scientific journal articles (Scopus and SINTA)	Opinions, editorials, blogs, proceedings without peer review
3	Language	Written in English or Indonesian	Articles in languages other than English and Indonesian
4	Topic Relevance	Studies that discuss Service Quality, E-Service Quality, AHP, Fuzzy, IPA	Studies outside the context of service quality or not related to education
5	Subject of Study	Focus on higher education, both public and private and the service industry sector.	A study that only discusses service, not physical products.
6	Data & Methods	Using quantitative, multicriteria, or combination methods	Narrative or descriptive studies without a clear methodological approach
7	Digital Context	Discussing aspects of digitalization of services in educational institutions	Does not discuss digital or technology-based services

Source: researcher processing

Systematic Research Flow

The systematic flow of the Systematic Literature Review (SLR) process, based on bibliometrics and visual analysis, focused on the topic of higher education services, specifically related to Service Quality, E-Service Quality, AHP, Fuzzy Logic, and Science. This process began with data collection through two major digital platforms, namely Scopus and SINTA, with a publication year range of 2022 to 2025, and language restrictions of English and Indonesian. All documents were searched using a structured search query, covering the full text of the abstract, introduction, methods, results, and conclusions. From the initial search results, a total of 192 articles were declared eligible. Then, a manual screening process was carried out by the authors in two stages: the first stage involved selection based on title, abstract, future research, and statistical modeling approach, leaving 54 articles. The second stage involved screening based on keyword matching, the presence of a relevant theoretical framework, and a focus on the service industry sector, resulting in 26 final articles as the main sample of the study. Next, the bibliometric mapping and visualization process was carried out with the help of RStudio and VOSviewer, which included analysis of author productivity, number of articles, publisher sources, publication trends, network visualization, and scientific contribution topics. This process was also supported by Excel and SPSS for descriptive data normalization and precise presentation. The final results include data visualization and synthesis used to answer three main research questions (RQ1, RQ2, and RQ3), as well as providing further research directions based on empirical trends and recent scientific contributions in the field of digital transformation of higher education services (Figure 1).

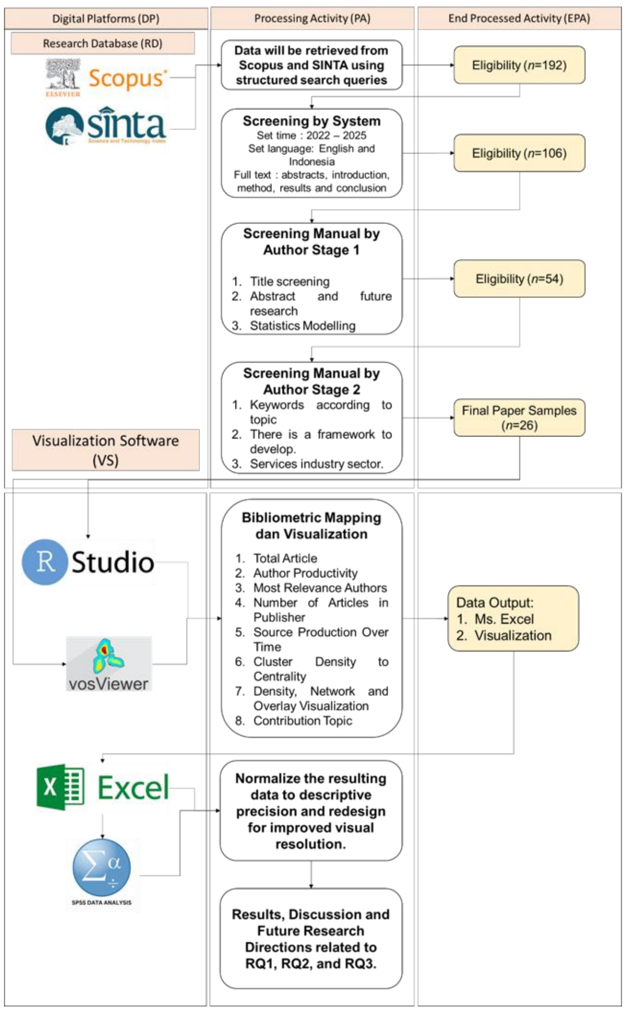


Figure 1. Research methodology (Source: researcher processing)

Result and Discussion

Research Results

RQ1. How do the Service Quality and E-Service Quality models contribute to improving the effectiveness of academic and administrative services in higher education, and what factors significantly act as enablers in the context of service digitalization?

The contribution of Service Quality and E-Service Quality models in improving the effectiveness of academic and administrative services in higher education.

Number of articles from 2022 to 2025, accompanied by predictions up to 2030 using a linear forecasting approach (Fuaddi & Pradana, 2024; Harsito et al., 2024; Idogho et al., 2025). A significant increase from 5 articles in 2022 to 26 articles in 2025, and is expected to stabilize at 7–8 articles per year until 2030. Improving services through digitalization in higher education is a theme that is increasingly attracting the attention of researchers, reflecting the need for a more efficient and adaptive service system. The urgency and potential for sustainable research in the domains of Service Quality and E-Service Quality, especially in digital-based academic and administrative services. This prediction is an indicator that the aspect of service effectiveness through a digitalization approach will be an important topic in the future.

The authors, Nadlifatin R, Ong Aks, Persada SF, and Prasetyo YT, each contributed three articles. These four researchers discuss various strategic aspects, such as the influence of technology support, human resource competency, and student trust in digital campus service systems. Their review of the articles reinforces the understanding that factors such as digital infrastructure readiness and the quality of service interactions are crucial and must be prioritized in developing modern service models.

Author productivity is based on Lotka's principle, where the majority of authors (over 96%) only authored one article. This topic remains open for further exploration and has the potential to become a growing research area. The lack of author dominance also provides an opportunity for new research to offer meaningful contributions, particularly in testing service models that are more relevant to the needs of local institutions.

Distribution of articles by publisher. Heliyon was the most productive journal (34.62%), followed by Social Sciences and Humanities Open (11.54%), while other journals contributed equally. This distribution demonstrates that the themes of digitalization and service quality touch various disciplines, from educational management to information technology, indicating the need for a multidimensional approach to developing a comprehensive service model in higher education.

The sharp increase from 2022 to 2025 suggests that academic attention to technology-based service quality continues to grow, and this topic holds strong appeal for further in-depth study. This fact reinforces the relevance of the research question posed: how service quality, both physical and digital, plays a role in enhancing student satisfaction and institutional effectiveness.

These findings reinforce the importance of examining digitally integrated educational service models. This research not only contributes to the development of modern service theory but also provides an empirical basis for formulating policies to improve campus service quality more clearly and measurably (Figure 2).

The Service Quality and E-Service Quality models have proven to be strategic approaches for measuring, evaluating, and improving the effectiveness of services in higher education, both in academic (registration, assessment, guidance) and administrative (financial services, personnel, IT support). Their contribution is evident in increased student satisfaction, operational efficiency, and increased trust in the campus's digital systems.

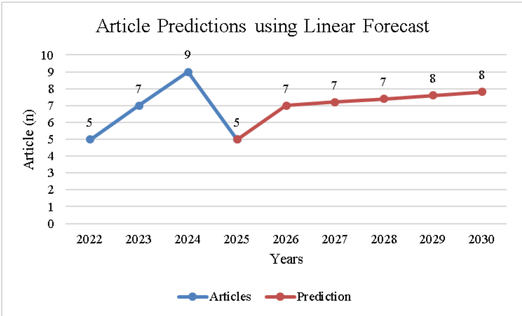
In Service Quality and E-Service Quality, effectiveness is greatly influenced by key enabler factors such as:

a. Availability of information technology and digital systems.
b. Competence of academic staff.
c. Supporting learning infrastructure.
d. Management support for service improvement.
e. Curriculum alignment with industry needs

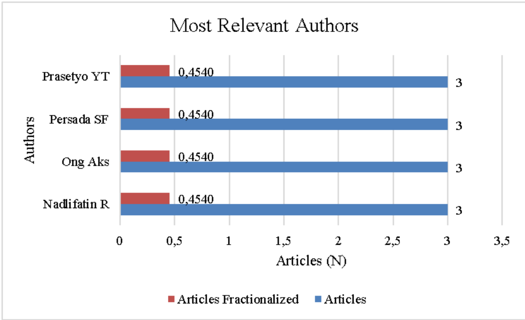
Meanwhile, there are also barriers to the effectiveness of services in higher education, such as:

a. Lack of staff training.
b. Limited operational funding.
c. Resistance to digital transformation.
d. Unclear service procedures (SOPs).
e. Unequal access to services across departments.

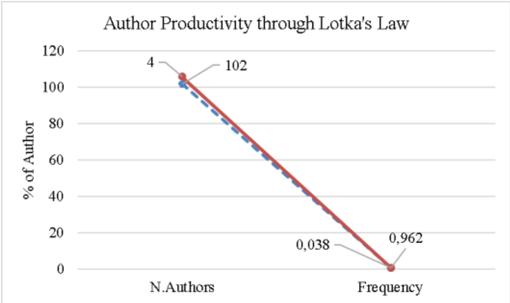
Research by Nadlifatin et al. underscores the importance of technological support, user trust, and a multidimensional approach to service models (Ong et al., 2022, 2023). Furthermore, the wide distribution of publications in journals such as Heliyon and Social Sciences and Humanities Open reflects the interdisciplinary nature of this study, combining service management, information technology, and education policy. Theoretically, this trend strengthens the position of the Service Quality and E-Service Quality models as important frameworks for defining performance indicators for digital-based education services. Practically, this data supports the urgency of campus service reform toward a responsive, inclusive, and standardized digital system. In other words, answering this research question not only explores the contribution of digital service models but also formulates strategies to strengthen institutional capabilities in facing the era of digital transformation in the higher education sector.



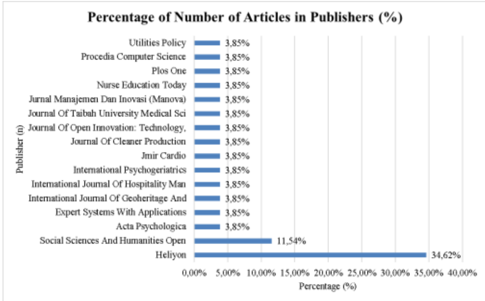
(a) Article Predictions using Linear Forecast



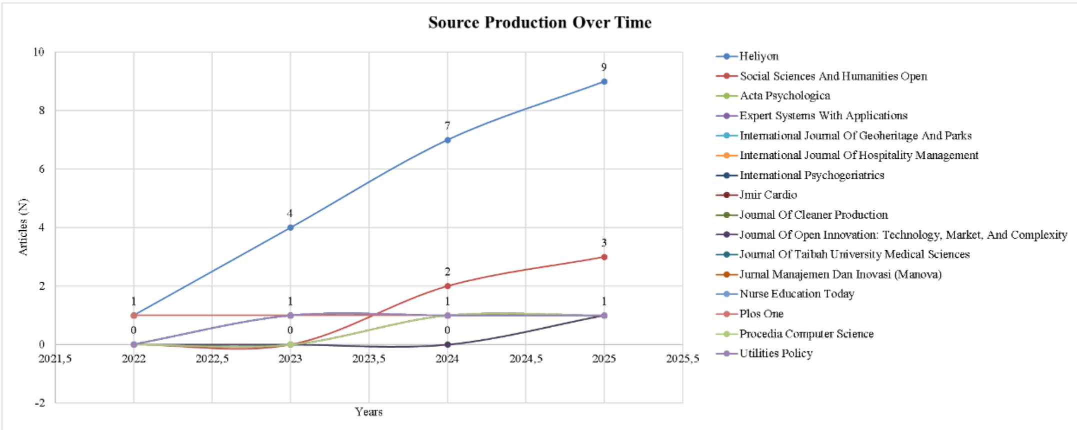
(b) Most Relevant Authors



(c) Author Productivity through Lotka's Law



(d) Percentage of Number of Articles in Publishers (%)



(e) Source Production Over Time

Figure 2. Article Predictions, Key Authors, Productivity, and Publication Trends (Source: Data processing, 2025)

Major Proposition: The Service Quality and E-Service Quality models are strategic foundations for improving the effectiveness of academic and administrative services through adaptive and sustainable digitalization.

Minor Proposition:

a. The surge in publications between 2022–2025 reflects academic urgency regarding the quality of digital services in higher education.
b. The effectiveness of digital services is largely determined by technological readiness, HR competency, and managerial support as key enablers.
c. Barriers such as lack of training, limited funding, and resistance to change are crucial challenges in digital service transformation.

RQ2. What are the methodological and practical challenges faced in applying the AHP, Fuzzy Logic, and IPA methods in measuring and evaluating the perception of the quality of educational services, and how does data uncertainty affect the validity of strategic decisions?

A search of research trends related to service quality shows that this topic is a major focus in the scientific literature, with the highest frequency of occurrence at 24 times. The primary focus is on the measurement and evaluation of service quality applied in various sectors, including digital banking, logistics, tourism, education, and healthcare. The significance of this term is reflected in the Callon Centrality value of 0.1 and Callon Density of 32.6, as well as the cluster frequency of 35.0. This indicates that the issue of service quality has a strong relationship with other topics and also serves as a pivot for various analytical approaches.

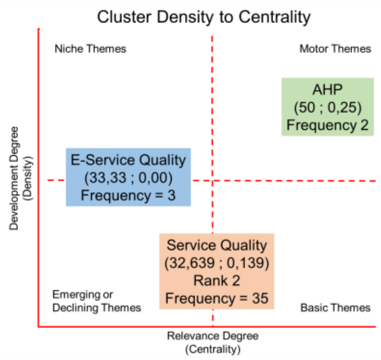
The first group in the mapping shows the dominance of the term "Service Quality," which is examined from both face-to-face and digital service perspectives. It includes terms such as “Higher Education” (appearing six times) and “satisfaction” (three times), indicating the researchers’ focus on user perceptions and their relationship to institutional service quality.

Meanwhile, the digital services category, or "E-Service Quality," emerged as a stand-alone entity with a word density of 33.3, despite its low network centrality. This indicates that this topic has developed relatively independently in the literature, but is not yet closely connected to other domains (Figure 3).

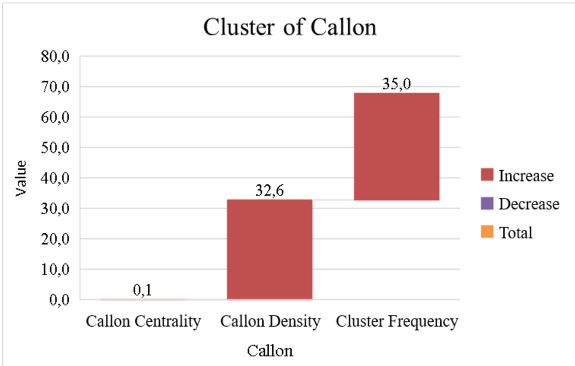
More specific and methodological topics, such as "AHP" (Analytic Hierarchy Process), form their own cluster. Although it only appears twice, its Callon Centrality value of 0.3 and density of 50.0 demonstrate the importance of this approach in systematically structuring and weighting service quality elements.

In several recent publications, the combination of AHP and SERVQUAL methods appears prominently. For example, the study by Bhattacharya et al., with DOI 10.1016/j.ijgeop.2023.04.001 applied AHP-SERVQUAL integration to assess tourism service quality in India, with the highest AHP score (0.92) compared to other dimensions (Bhattacharya et al., 2023). Meanwhile, research by Adiningtyas et al., in the Procedia Computer Science journal shows the strength of e-service quality (0.89) in measuring user sentiment towards mobile banking services (Adiningtyas & Auliani, 2024).

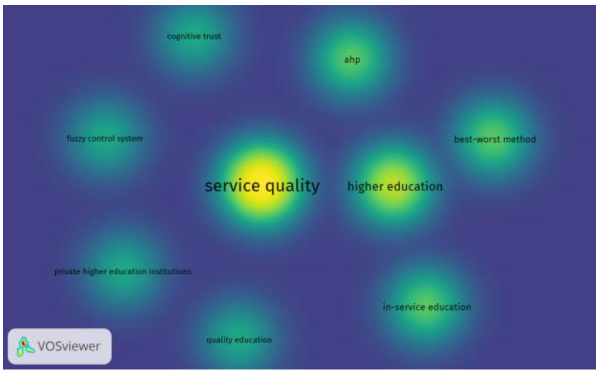
The topic of customer satisfaction, although only recorded three times, still plays a crucial role as a bridge between user perception and service success. In several studies, satisfaction serves as a mediating variable linking service quality and customer loyalty or repurchase intentions, as seen in the research by Hui et al. (Hui et al., 2025) nor Ayvaz-Çavdaroğlu et al (Ayvaz-Çavdaroğlu et al., 2024).



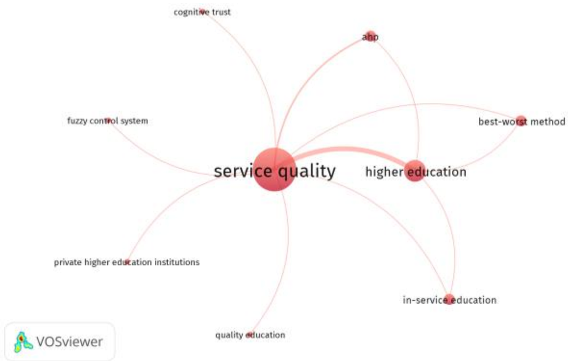
(a) Cluster Density to Centrality



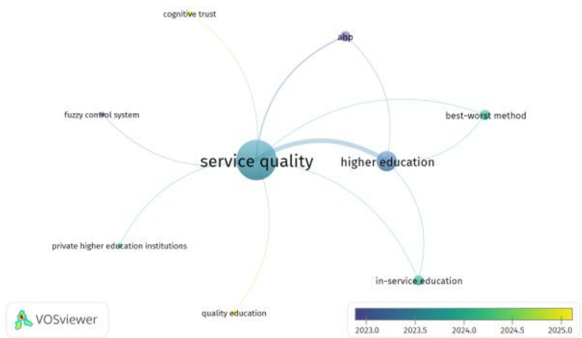
(b) Cluster of Callon



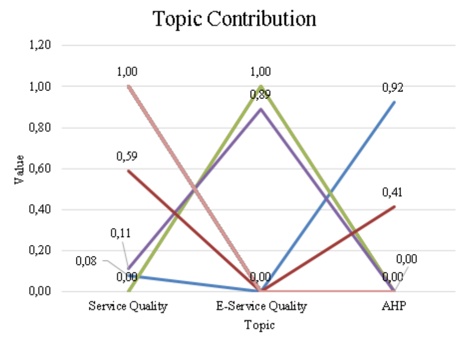
(c) Density Visualization



(d) Network Visualization



(e) Overlay Visualization



(f) Topic Contribution

Figure 3. Visualization of clusters, density, centrality, network, overlay, topic contribution and Callon structure (Source: Data processing, 2025)

Density visualization, where areas with yellow intensity indicate high frequency of occurrence of terms—indicating that “service quality” is the most dominant term. Terms such as “higher education,” “fuzzy control system,” “AHP,” and “best-worst method” appear to spread around the center, but with lower density, indicating interconnectedness but not as strong as the core theme. Network visualization, which depicts relationships between terms based on the strength of their association. “Service quality” is the central node with many connection lines to other terms such as “higher education,” “in-service education,” and “cognitive trust.” The thickness of the lines indicates the strength of the relationship, and this shows that research related to service quality integrates a multi-method approach and includes aspects of educational institutions. Overlay visualization that presents the temporal trend of publications. Blue indicates older terms (2015-2024), while yellow indicates newer terms (2023–2024). The terms “service quality” and “higher education” are in the middle-yellow zone, indicating that they are still highly relevant and continue to be cutting-edge topics. In contrast, “fuzzy control systems” and “cognitive trust” emerged earlier but are still connected to the main theme. Literature mapping shows that service quality is not only a dominant topic but also a center of methodological and interdisciplinary innovation in the context of higher education, involving approaches such as AHP, fuzzy logic, and policy evaluation.

This literature mapping reveals three major axes in the development of service quality research: Exploration and Evaluation of Traditional Service Quality – dominant in the public, education, and health sectors. Transformation Towards Digital Services (E-Service Quality) – developing in the context of e-commerce, fintech, and other online platforms. Integration of Quantitative Approaches such as AHP – used to prioritize service quality attributes structurally.

This study demonstrates that the literature consistently points to the urgency of developing service assessment instruments that are more adaptive to the digital context and personalized to user needs. The emphasis on quantitative methodologies such as AHP, fuzzy logic, and sentiment analysis increasingly marks a shift toward a data-driven approach to strategic decision-making in improving service quality.

The clustering reveals three main areas of focus in the literature. First, Service Quality is the dominant focus with 24 occurrences, supported by the topics "Higher Education," "Satisfaction," and the use of "Fuzzy" methods. This underscores the significant attention paid to service quality evaluation in higher education. Second, the E-Service Quality cluster (3 occurrences) indicates a shift towards service digitalization, such as online administration systems. Third, the AHP cluster (2 occurrences) demonstrates the application of multi-criteria decision-making methods in service assessment (Table 4).

A single cluster (n=1) focuses on Service Quality (Dimension1 = -0.27; Dimension2 = 0.05), encompassing key terms such as Customer Satisfaction (Dimension2 = 2.83), E-Service Quality (Dimension1 = 2.32), and Attitudes (Dimension1 = 3.26). Dominant quantitative methods include AHP (D1 = -0.29) and Fuzzy Logic (D1 = -0.22), as well as the IPA and Best-Worst Method approaches. The application contexts range from Higher Education (D1 = -0.53), Educational Services, to Policy and Delivery, demonstrating a focus on systematic and satisfaction-based evaluation of educational services (Table 5).

Table 4. Occurrence and Cluster Label

Occurrences	Words	Cluster	Cluster_Label
24	Service Quality	1	Service Quality
6	Higher Education	1	Service Quality
3	Satisfaction	1	Service Quality
2	Fuzzy	1	Service Quality
3	E-Service Quality	2	E-Service Quality
2	AHP	3	AHP

Source: Data processing, 2025

Table 5. Term Dimension1 Dimension2 Cluster

Term	Dimension 1	Dimension 2	Cluster
Service Quality	-0.27	0.05	1
Higher Education	-0.53	-0.8	1
E.Service.Quality	2.32	-0.44	1
Satisfaction	-0.17	0.04	1
AHP	-0.29	0.06	1
Fuzzy	-0.22	0	1
Attitudes	3.26	-0.66	1

Best.Worst.Method	-0.31	-0.19	1
Cognitive Trust	-0.29	0.36	1
Consumer Satisfaction	3.26	-0.66	1
Cross-Border E-Commerce	-0.18	0.19	1
Customer Satisfaction	-0.71	2.83	1
Education Delivery	-0.29	0.36	1
Education Policy	-0.1	0.1	1
Educational Services	-0.1	0.1	1
Fuzzy Control System	-0.29	0.36	1
Importance.Performance.Analysis	-0.3	-0.1	1
In.Service.Education	-1.7	-4.01	1
Private.Higher.Education.Institutions	-0.1	0.1	1
Public Secondary Schools	-0.29	0.36	1
Quality Education	-0.29	0.36	1
Servqual.Model	-0.29	0.36	1

Source: Data processing, 2025

Service Quality appears 24 times, with the dominant year distribution being 2024 (Q1 = 2023, Median = 2024, Q3 = 2024), indicating a very strong and recent research trend. This indicates that this topic is at the center of attention in the current literature, reflecting the urgency in evaluating service quality, particularly in digital or educational contexts. Meanwhile, Higher Education appears six times, also with a median of 2024, indicating that service quality issues are now increasingly focused on in the context of higher education. The synergy between these two terms confirms that service quality in higher education is a strategic concern in the current scientific literature.

In recent literature, service quality appears 24 times and higher education 6 times, indicating a high level of attention to the quality of educational services (Figure 4). However, data uncertainty and the heterogeneity of educational institutions pose challenges to measurement validity. Therefore, institutional characteristics indicators are needed as mediators or moderators in evaluation models, including:

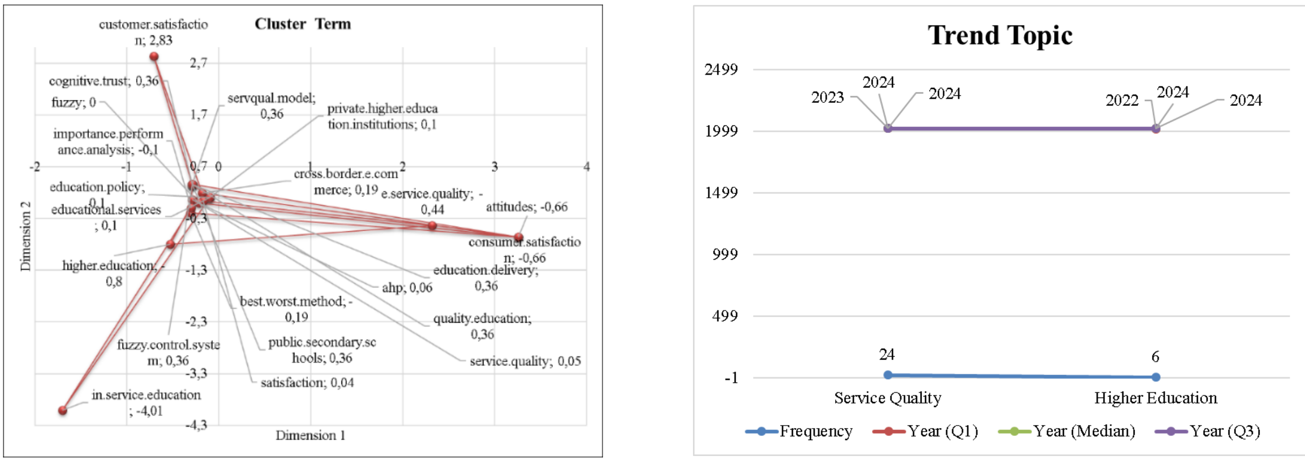
a. Ownership status: private/state.
b. Funding model.
c. Flexibility of managerial policies.
d. Academic autonomy.
e. Relationships with external stakeholders.

The integration of these indicators is important to produce contextual, accurate evaluations, and are able to guide strategic decision-making that is on target, so that an empirical basis is provided in designing more contextual, adaptive, and sustainable educational service policies, both in public and private institutions, in order to increase student satisfaction and institutional competitiveness in the increasingly digital and dynamic higher education ecosystem.

Major Proposition: Evaluation of the quality of educational services faces methodological challenges, due to data complexity and institutional dynamics.

Minor Proposition :

a. Uncertainty in reducing validity and reliability in AHP, Fuzzy and IPA methods has the potential to reduce strategic decision strategies in educational services.
b. AHP, Fuzzy and IPA precision strategies as perceptions of educational service quality.



(a) Cluster Term (b) Trending Topics

Figure 4. Cluster Term and Trend Topic (Source: Data processing, 2025)

RQ2. To what extent do differences in factors supporting and inhibiting service quality occur between private and public higher education institutions, and how do institutional characteristics mediate/moderate their influence on student satisfaction and cognitive trust?

Differences between public and private institutions are evident in their preparedness and strategies for addressing the aforementioned factors. Public institutions tend to be more structured in terms of technology systems and quality management, but often face bureaucratic constraints that hinder innovation and student empowerment. Meanwhile, private institutions, particularly market-oriented ones, tend to be more flexible in adopting technology and responding directly to student needs, but often face limitations in infrastructure and stable human resources. Institutional characteristics such as autonomy, organizational structure, quality culture, and decision-making patterns play a crucial role as mediators or moderators. Adaptive institutions can strengthen the influence of supporting factors on student satisfaction and cognitive trust, while simultaneously mitigating the negative effects of inhibiting factors. Conversely, rigid and centralized institutions can weaken the positive impact of innovation and increase resistance to change. Differences in supporting and inhibiting factors in service quality between public and private institutions are influenced by institutional characteristics, which act as mediators or moderators of the impact of each factor on student satisfaction and cognitive trust (Table 6).

This literature review addresses the need to understand the differences in factors that support and hinder service quality between private and public higher education institutions by examining the role of institutional characteristics as mediating or moderating variables. Using indicators such as ownership status, funding model, managerial policy flexibility, academic autonomy, and relationships with external stakeholders, this study explores how these characteristics shape students' perceptions of service quality. The impact is measured through two main endogenous constructs:

a) Student Satisfaction—which includes administrative services, lecturer-student interactions, access to academic information, campus facilities, and speed and responsiveness of service.
b) Cognitive Trust—which includes trust in the integrity of the institution, perceptions of service reliability, beliefs in quality commitment, expectations of service, and clarity of information.

Table 6. Supporting Factors and Inhibiting Factors

Category	Supporting Factors	Source	Inhibiting Factors	Source
Technology & Digitalization	Adoption of technology in public services (egovernment, AI, digital platforms)	(Aditya et al., 2023; Ayvaz-Çavdaroğlu et al., 2024; Hui et al., 2025; Meng et al., 2024)	Digital inequality and asynchronous technology systems	(Bhattacharya et al., 2023; Hasib & Lukmandono, 2022; Kalibatienė et al., 2023)
HR Interaction & Services	Responsiveness and empathy of service officers	(Meng et al., 2024; Ong et al., 2023; Wong & Chan, 2023)	Lack of training and excessive workload	(Almarhabi et al., 2024; Meng et al., 2024; Oyebode et al., 2023)
Information & Transparency	Accurate and real-time information to customers	(Asawawibul et al., 2025; Han et al., 2025)	User reviews contain noise and subjective bias.	(Adiningtyas & Auliani, 2024; Liang & Liu, 2024)
Environmental Quality & Infrastructure	Attractive and well-maintained destination environment	(Bhattacharya et al., 2023; Wider et al., 2024b)	Inadequate supporting infrastructure (accessibility, WiFi, complaint system)	(Asawawibul et al., 2025; Hui et al., 2025; Kalibatienė et al., 2023)
Management & Organizational Commitment	Commitment to quality management and service sustainability	(Mamun-ur-Rashid, 2023; Rahman & Nasrin, 2024b)	Lack of stakeholder involvement	(Han et al., 2025; Rauf et al., 2024)
Customer Perception & Expectations	Customers feel empowered and empowered (self-efficacy, perceived control)	(Bohórquez et al., 2024; Han et al., 2025)	The gap between expectations and reality creates disappointment.	(Ong et al., 2022, 2023; Rauf et al., 2024)
Data & Evaluation Support Systems	Use of AI & data analytics to analyze customer reviews	(Adiningtyas & Auliani, 2024; Aditya et al., 2023)	Lack of utilization of objective assessment systems and gaps between channels	(Kalibatienė et al., 2023; Liang & Liu, 2024)

Source: Data processing, 2025

The differences between private and public universities necessitate understanding what supports and hinders service quality, and how this impacts student satisfaction and trust in the institution. Factors that support service quality include the availability of information technology, qualified faculty, comprehensive learning facilities, management support for service improvement, and a curriculum that aligns with the needs of the workplace. Meanwhile, barriers include a lack of staff training, limited operational funds, resistance to digital change, unclear service procedures, and unequal access to services across departments.

The characteristics of an institution—such as ownership status (whether private or public), funding methods, policy flexibility, academic management freedom, and relationships with external parties—can influence the influence of these supporting and inhibiting factors. All of this will impact how students assess campus services, from administrative services and relationships with lecturers to ease of access to academic information and campus facilities to the speed and responsiveness of service. Furthermore, student trust in an institution is also shaped by how honestly the institution is assessed, how reliable its services are, how committed it is to quality, how well its services meet student expectations, and the clarity of the information provided. Through this understanding, better ways can be designed to improve educational services, both at private and public universities.

This framework (Figure 5) is reinforced by the results of a bibliometric analysis, which shows that Service Quality appears 24 times, becoming the most dominant term. Higher Education appears six times, and Digital Systems four times. Methods such as AHP and Fuzzy Logic each appear twice, but have Callon Centrality values of 0.3 and Density of 50.0, indicating strong methodological weight. Meanwhile, Customer Satisfaction and Cognitive Trust each appear three times, strengthening the endogenous dimension in service evaluation.(Hutabarat et al., 2013; Hutabarat & Sulistyadi, 2024). This framework includes 5 exogenous indicators (enablers), 5 barrier indicators, 5 institutional characteristics indicators, and 5 indicators each for student satisfaction and cognitive trust, making it a reference for precision research based on construct structure.

Discussion

Based on the literature review and bibliometric analysis, the Service Quality and E-Service Quality models have proven to be strategic frameworks for enhancing the effectiveness of academic and administrative services in higher education, improving student satisfaction, operational efficiency, and trust in campus digital systems (Adiningtyas & Auliani, 2024; Aditya et al., 2023). The significant increase in publications from 5 articles in 2022 to 26 articles in 2025, with a predicted stabilization at 7–8 articles per year until 2030, reflects growing academic attention to the digitalization of educational services (Asawawibul et al., 2025; Hui et al., 2025; Kalibatienė et al., 2023).

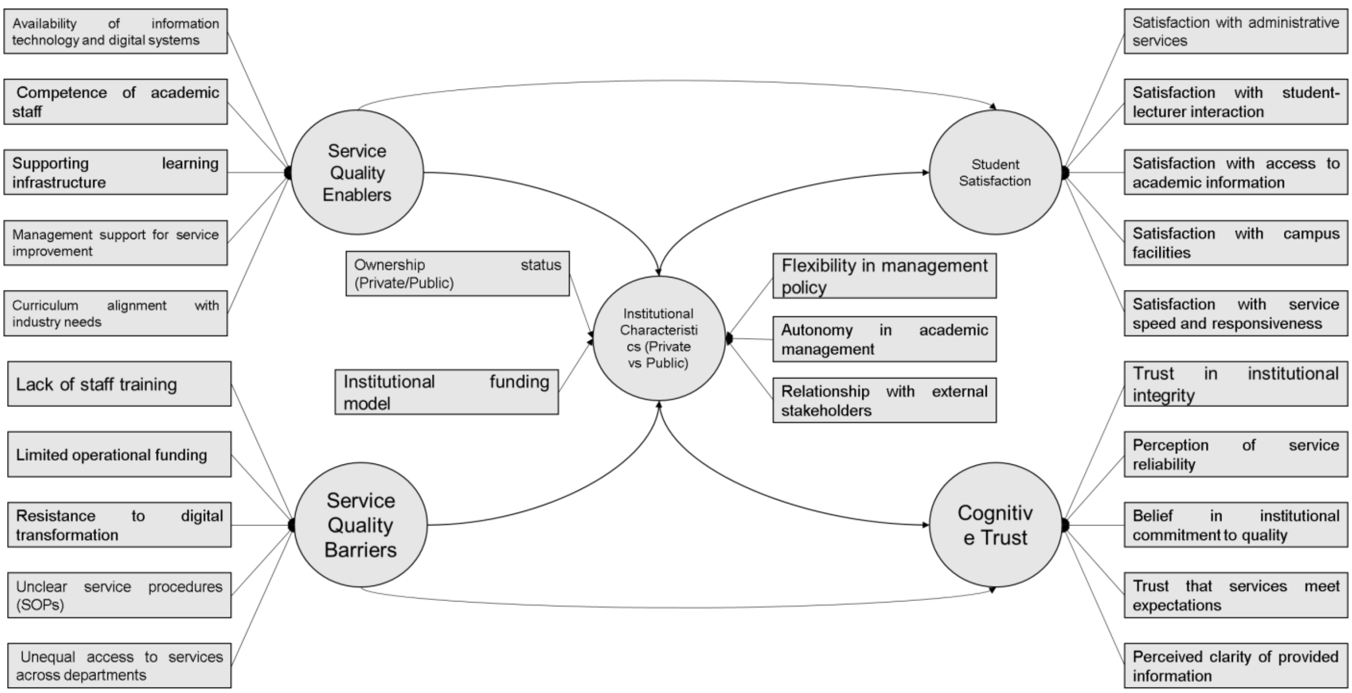


Figure 5. Framework of Service Quality Impact in Higher Education Institutions (FSQIHEI) (Source: Researcher Processing

Key enabler factors include digital infrastructure readiness, academic staff competence, managerial support, learning facilities, and curriculum alignment with industry needs, while major barriers involve insufficient staff training, limited funding, resistance to digital transformation, unclear service procedures, and unequal access across departments. Differences between public and private institutions further highlight the mediating/moderating role of institutional characteristics, where flexibility, academic autonomy, and external stakeholder relationships can strengthen supporting factors and mitigate inhibiting ones (Aditya et al., 2023; Ayvaz-Çavdaroğlu et al., 2024; Hui et al., 2025; Meng et al., 2024). The use of quantitative methods such as AHP, Fuzzy Logic, and IPA demonstrates methodological challenges due to data uncertainty and institutional complexity but also emphasizes the need for adaptive, contextual, and sustainable service evaluation instruments. Overall, this study provides empirical and practical justification for reforming higher education services toward responsive, inclusive, and standardized digital systems.

The FSQIHEI framework explains how supporting and inhibiting factors of service quality affect student satisfaction and cognitive trust, with institutional characteristics (private vs. public) acting as mediators/ moderators. The model systematically maps five key indicators for each variable, covering technology, human resources, management policies, and the psychological dimensions of students.

The findings show that institutional characteristics influence the relationship between service factors and student outcomes. Private universities are more adaptive in digitalization and responding to student needs, although they are constrained by limited resources. Characteristics such as autonomy, quality culture, and policy flexibility act to strengthen or weaken the influence of external factors on student perceptions (Assab, 2011; Kristiyanti & Sugiharto, 2007; Martilla & James, 1977; Parasuraman et al., 1985).

The model measures satisfaction as a short-term indicator and cognitive trust as a long-term indicator, providing an empirical basis for improving higher education service policies. With five structured indicators per variable, the model is ready for quantitative testing using SEM-PLS, enabling validation based on field data (Figure 6).

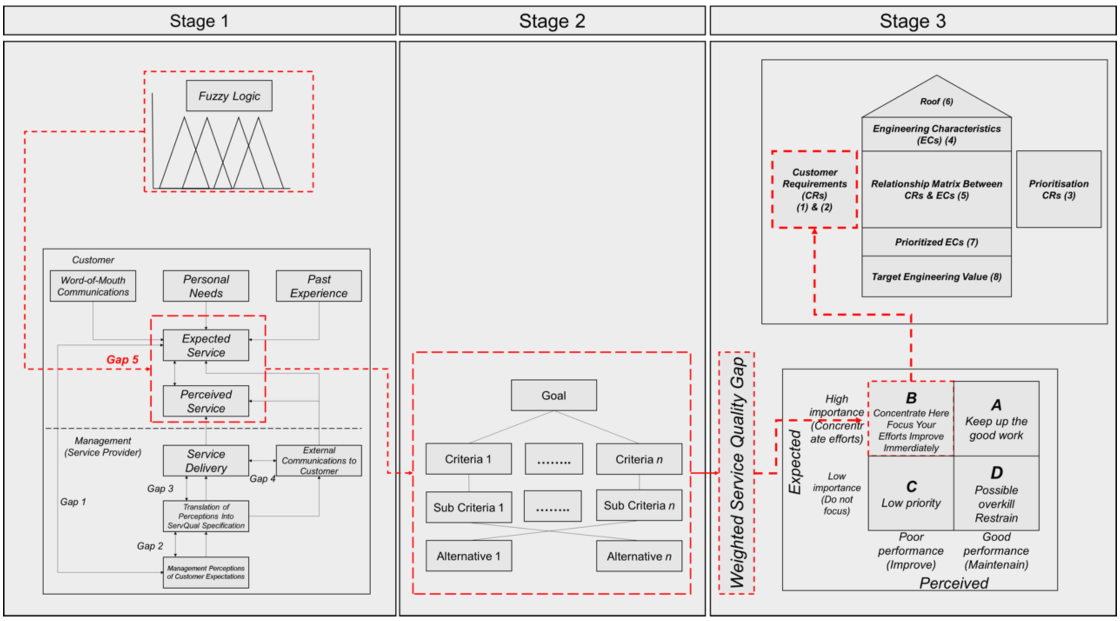
Conclusion

Main Contributions of the Study

This study contributes to the Service Quality model in improving academic and administrative digital services in higher education.

This study provides a mapping of the current literature (2023–2025) related to service quality, with a primary focus on the term "Service Quality" as a thematic axis in the literature.

This study fills the literature gap regarding the differences in service strategies between public and private universities by adding the dimension of institutional characteristics as a key variable that has previously been underexplored empirically and conceptually.



Note: = Focus Future Research Directions

Figure 6. Future Research Directions (Source: adopted from Assab, 2011; Kristiyanti & Sugiharto, 2007; Martilla & James, 1977; Parasuraman et al., 1985)

Key Findings

This study found an increase in articles from 5 (2022) to 26 (2025), predicted to remain stable at 7–8 articles/year until 2030. Heliyon is the most productive (34.62%), the majority of authors have only one article, the topics are multidisciplinary and open to study.

Integration of Multicriteria Methodology: Demonstrates the significant role of quantitative methods such as AHP, Fuzzy Logic, and Best-Worst Method in evaluating service quality, especially in the higher education and digital sectors. Contributes to the literature by highlighting the need for institutional characteristics indicators in assessing service quality in the education sector, as a form of strengthening the one-dimensional approach currently used.

This study develops the Framework of Service Quality Impact in Higher Education Institutions (FSQIHEI) which integrates supporting factors (enablers), inhibiting factors (barriers), and institutional characteristics as mediators or moderators in influencing student customer satisfaction and cognitive trust.

Practical Implications

The Service Quality and E-Service Quality models serve as important frameworks for assessing the performance of digital education services. They support the formulation of a digital campus strategy that is efficient, responsive, and standardized, and enhances student satisfaction.

The need for digitization and user personalization. The use of AHP and Fuzzy Logistics approaches helps universities design more systematic and data-driven service systems. Variables such as ownership status, funding model, managerial flexibility, and academic autonomy should be included in service quality evaluations.

The use of digital technology, human resource training, and data analytics-based evaluation systems such as AI are crucial steps in increasing responsiveness and student trust. The FSQIHEI model also serves as a reference for developing data-driven quality policies and institutional characteristics, both in the public and private sectors.

Research Limitations

The lack of author dominance, the theme is still wide open, requires local research and a strategy to strengthen digital institutions.

AHP and E-Service Quality only appear two or three times, indicating that this quantitative study is still developing and needs to be expanded. The dominant focus remains on education and digital services, with other sectors such as transportation, energy, or manufacturing underexplored. It does not include temporal co-word analysis or topic evolution analysis.

This research is still conceptual and has not been supported by direct empirical testing at higher education institutions. Furthermore, external factors such as national policies, local culture, and financing systems have not been fully integrated into the model. Another limitation lies in the scope of the literature, which still focuses on general contexts without in-depth comparisons between regions or countries. Further recommendations include empirical validation of the FSQIHEI model through quantitative approaches (SEM/PLS) and a deeper exploration of the cognitive trust dimension in the context of digital transformation in education.

Recommendations and Future Research Agenda

The Future Research Directions framework is built from a bibliometric analysis that shows the dominance of service quality topics, then developed through the integration of Fuzzy Logic to capture perceptual ambiguity, Gap 5 to measure service gaps, AHP for the hierarchy of quality attributes, and IPA for strategic priorities, resulting in a multidimensional model that is responsive to the real needs and institutional context of higher education.

General Conclusion

This study enriches the literature by integrating a Service Quality model based on institutional characteristics, highlighting the importance of differentiating service strategies between public and private universities. Bibliometric findings and literature mapping for 2023–2025 reinforce the urgency of developing responsive, measurable, and personalized digital services, and point to future research directions based on a multidimensional and data-driven approach to sustainably improve student satisfaction and trust.

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Conflict of Interest

No conflict of interest.

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On augmenting students' learning in beam structures using numerical simulations

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Abstract
Virtual laboratories are seen as an alternative to the delivery of traditional laboratory activities. Additionally, it can be used to supplement or complement traditional teaching practices, especially for engineering topics that are typically assumed by students to be difficult to grasp. In this paper, the use of numerical simulations for a laboratory exercise on a major course in aerospace engineering will be discussed. Moreover, the influence of finite element analysis (FEA) on the learning process of students regarding beam profile and bending performance will be highlighted. SolidWorks program was used for the modeling and structural analysis of beam profiles under predetermined conditions. Numerical model verification and validation were made using established formulae and theories from engineering mechanics. This method was later implemented under the aerospace laboratory course for aerospace engineering students. Fourteen (14) students were asked to report the results of their simulations as well as observations on the structural performance of the beams through a laboratory report. Students' consent to perform content analysis of their reports was secured through Google survey. Applying FEA, students were able to establish connections between beam profile, moment of inertia and bending stiffness, which are often hard to explain in traditional teaching methods. Further, students better appreciate theories associated with beams and their application to aircraft structures. As we navigate a VUCA environment and rapid advancements in computing, numerical simulation programs can supplement or provide alternative avenues where students can learn topics that are conventionally perceived to be challenging.

Keywords: Aerospace engineering, Beams, Computer-aided design, Remote laboratory, Simulation.

Introduction

In engineering education, laboratories are critical as they enhance learning of students in specific topics or fields of expertise. Over the years, the finite element analysis (FEA) has been frequently used in various industries to hasten product development and increase the reliability of machine parts. Rapid advancements in the semi-conductor industry enabled the generation of high-performance computers, enabling the FEA to be more reliable than ever. As educators are challenged to deliver lessons effectively to students, this paper will delve into the use of FEA in teaching, specifically on an I-beam section commonly utilized in aircraft structures. The use of numerical simulations in teaching is not new. Plass et al. (2012) said that computer-based simulations helped improve the learning of students in Chemistry. This is also supported by Pucholt (2020), citing that simulations enhance the performance of students in Physics, and he claimed that computer-based simulations can be an alternative to traditional teaching strategies utilized in Physics. Fluid dynamics and transport phenomena are some of the complex topics in fluid mechanics. Gajbhiye (2020) suggested the use of computer-based simulations in teaching the said topics and later found improvements in the learning process of chemical engineering students. Bishay (2020) found a statistical increase in the performance of engineering students who have acquired the FEA intervention as compared to those coming from traditional approaches.

Moment of inertia is one of the concepts introduced in engineering mechanics when dealing with beams. Yet, according to a survey conducted by Streveler et al. (2006), it is one of the least understood topics in engineering mechanics. In particular, the good bending performance of I-beam structures can be linked to its moment of inertia. Inertia is defined as the object's tendency to resist motion. Meanwhile, moment can be described as the turning effect of a force acting

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on the body. Thus, we can define moment of inertia as a characteristic of a body to resist a turning motion as an effect of a force acting on a body. Contrary to the typical moment of inertia utilized in rotating bodies, the area moment of inertia or second moment of the area describes the ability of a body to resist deformation due to loading (Weisstein, 2012).

The second moment of area can also be referred to as planar or polar moment of inertia, which describes how a body can resist loading by virtue at which the areas are distributed from an axis (Collins, 2018). Polar moment of inertia, which is often used interchangeably with planar moment of inertia, defines the resistance of a body to torsion. Unlike planar moment of inertia, in which the moment is taken at a distance normal to its cross section, the distance utilized for calculation for polar moment of inertia is taken parallel to its cross section. Mass moment of inertia differs from second moment of area by virtue of its units. Collins (2018) noted that the mass moment of inertia is of great importance to angular acceleration and describes how the distribution of mass goes along in an axis, not the areas only.

The behavior of a homogenous material subjected to pure bending can be depicted in Figure 1. The Euler-Bernoulli theory, widely known as the classical or simple beam theory, sets forth the fundamental principles associated with slender and long beams (Bauchau & Craig, 2009), typical of aircraft wings. It can be realized that the highest strains can be located at the top and bottom parts of the beam. Whereas the portion of the beam near the neutral axis, the line that intersects the longitudinal plane of symmetry and neutral surface, experiences little to no stresses. This is further supported by Sun (2006), saying that much of the segments of a beam with rectangular cross section are not utilized for carrying stress, and the use of an I cross section is well justified. The area moment of inertia of an I cross section is also greater than of a rectangular one, enhancing the bending resistance of the beam, which is well clarified from the Flexure formula.

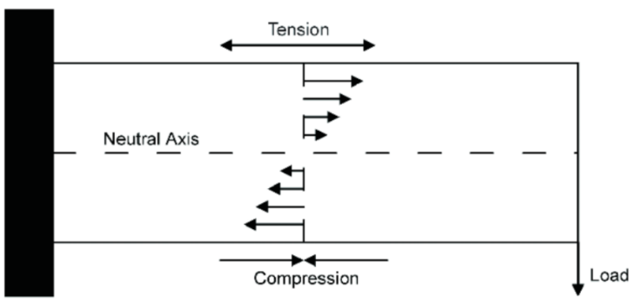


Figure 1. Stress distribution for a simple beam under loading. Adapted from "Feeding Mechanics in Spinosaurid Theropods and Extant Crocodilians" by A. Cuff and E.J. Rayfield, 2013, PloS one, 8(5). Copyright 2013 by PloS one.

A cantilever wing is a wing construction with no external bracing as shown in Figure 2. The design is typically introduced in aircraft to reduce drag and is often employed in high-speed aircraft. Though, the implication of the design is more on the structure. Wing construction requires sound selection of spar length, size, and profile, which can address issues with cantilever wing design. An aircraft wing can be viewed as a long beam fixed in one end that needs to withstand bending as well as torsional loads during flight. The wing structure essentially gets its high bending stiffness from the spar configuration, typically of an I-beam cross section. According to engineering mechanics, the good bending stiffness of the I shaped cross-section can be found from the high magnitude of moment of inertia, specifically, the area moment of inertia, which is dependent on how far the concentrated area is from the neutral axis. The more distant the concentrated area from the neutral axis, the lesser the bending. Sun (2006) told that aircraft wings are typically constructed with high span to depth ratio. Thus, bending stress is more critical than transverse shear. Nonetheless, the latter is generated when bending is induced to a body.

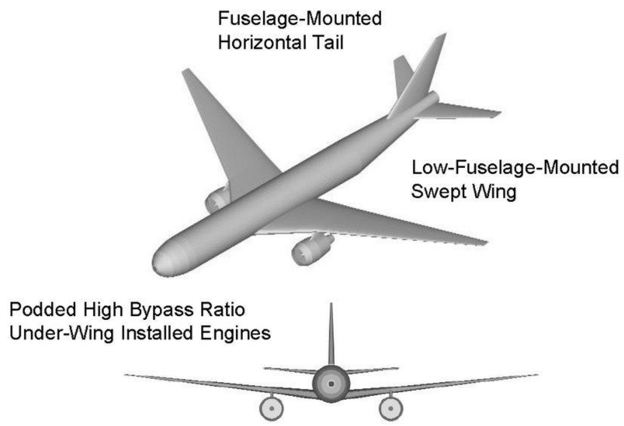


Figure 2. Cantilever wing design utilized in aircraft. Reprinted from "Multidisciplinary Design Optimization of low-noise transport aircraft [Doctoral dissertation]" by L.T. Leifsson, 2005. Copyright 2005 by L.T. Leifsson.

The finite element method (FEM) is one of the utilized algorithms by most numerical simulation programs. The FEM concept can be likened to how we solve an area or perimeter of an irregular shape. Typically, we aim for an exact solution, which is associated with higher degree equations. Meanwhile, an irregular shape can be broken down to a composite of regular shapes, where equations are of lower degree. Therefore, the solution is simpler. Solutions to engineering problems are accompanied by complex differential equations and if the composite shape idea is applied, it can simplify the approach and get an approximation of a problem, regardless of how complex it is. The FEM process starts in pre-processing.

Pre-processing includes setting the boundary conditions (inputs for the simulation), and importantly the size and number of elements (mesh). As FEM is an approximation technique, the accuracy of the solution lies in how we select the elements. A delicate balance between solution accuracy and computational time is desired. In the solution phase, this is where the software resolves the problem defined in the pre-processing. To verify and validate the solution, post-processing is undertaken. This is where the user interrogates the model and qualifies whether the result is acceptable or not. Inputs for the calibration of the model came from post-processing. Until a desired model is obtained, the process is repeated.

Computational software not only offers solutions to complex physics problems of a model being simulated. It can also provide insights into the behavior and response of a model when subjected to a certain input (force, temperature, velocity). This can be done through generation of visual plots that further enhance the understanding of the user. Literatures on student learning have already established the relevance of visual demonstrations and improved learning. Visual demonstrations enable problem analysis to be more operational rather than superficial (Bassok & Holyoak, 1989; Butcher, 2006; Goldstone & Son, 2005; Joseph & Dwyer, 1984; Moreno et al., 2011; Sloutsky et al., 2005). Moreover, Moreno et al. (2011) & Scheiter et al. (2009) said that student learning is at its best when both abstract and concrete visual demonstrations are present. Further, visualizations allow learning to be centered on establishing connections between students' prior knowledge and the information at hand instead of the typical knowledge transfer which is often one way (Bransford et al., 2000; Collins et al., 2018; Donovan & Bransford, 2005; Moreno et al., 2011). With this, it can be noted that one of the scientific foundations for the positive effect of numerical simulations on student learning can be linked to visual representations.

Most of the literature available on the use of numerical simulations for teaching centers on CFD, Mathematics, Material Science, and Magnetism. FEA has been mentioned as well in various sources. However, most of them focus on its implementation as a precursor to a formal FEA course or a tool to check a design or proof of concept. Meanwhile, sources concerning the FEA of beams revolve around its design and development, its industrial applications, and optimization techniques for solving related problems. Little to none was directly conducted on the use of numerical simulations to aid in teaching beam structures among students. It is the objective of this paper to demonstrate how FEA can be utilized to aid in teaching beam structures among aerospace engineering students enrolled in aerospace laboratory 1.

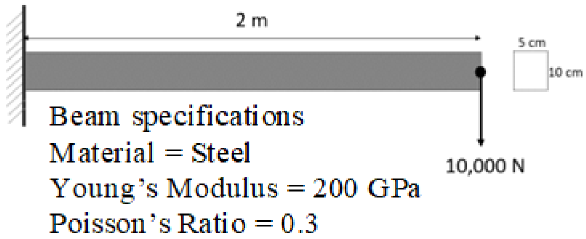


Figure 3. Simulation constraints in relation to the cantilever beam construction

Figure 4. Conceptual framework of the study

Several studies have investigated the use of simulations in teaching engineering concepts. Zapalska (2021) utilized simulations and gamification to teach undergraduate engineering students the essence of business within a manufacturing setting. Anchored in the principles of experiential learning, Zapalska (2021) found that students found the experience both enjoyable and educational. Additionally, students learned to work in teams, which is a primary graduate outcome for engineering programs. Taher and Khan (2014) studied the influence of simulation-based methods in teaching circuit construction within an engineering technology program. The authors found that the simulation-based strategy had a slight effect on student learning compared to a hands-on approach. However, they noted that students still found simulation-based programs lacking in terms of mimicking real-world situations and suggested that a hybrid teaching approach (simulation + hands-on) should be implemented. They argued that simulation-based strategies can complement traditional instruction in undergraduate engineering courses. Negahban (2024) reviewed the literature on the impact of simulations in engineering education, finding that simulation-based learning is often less costly than traditional physical experiments. Moreover, Negahban (2024) noted that simulation-based teaching can enhance student engagement and motivation. Finally, the author argued that future research must address existing gaps in linking simulation-based teaching to learning theories and concretizing simulation-based assessments.

The Aerospace Laboratory 1 subject aims to provide laboratory activities that will reinforce the learning of students on some major courses in the aerospace engineering program, including aircraft structures. Wing structure is one of the topics being discussed in aircraft structures and several subtopics discussed on the subject include beams, wing bending and torsional performance, and stiffeners. This paper determines whether FEA can help achieve the intended learning outcomes for the laboratory activities in the Aerospace Laboratory 1 subject and improve the student learning process. Specifically, this study addresses the following objectives:

1. Collect data on student output regarding the accomplishment of laboratory activity objectives.
2. Gather insights into how students navigate laboratory activities in relation to achieving objectives and reinforcing specific topics.
3. Verify whether students benefited from using numerical modeling to achieve laboratory objectives and the overarching course outcomes.

Reinforced by literature regarding the positive effects of simulation-based activities on the student learning process, this study is anchored in the concepts of simulation-based learning for teaching challenging engineering topics, as illustrated in Figure 4. Beyond simply using simulation programs for laboratory activities, this undertaking aims to enhance student comprehension of complex engineering concepts. To improve the implementation of these interventions, reflection is integrated into the framework represented by the bidirectional arrows connecting each element. This design addresses identified gaps in simulation-based learning strategies, specifically regarding their connection to learning theories and the concretization of associated assessments. These arrows also emphasize the importance of a feedback mechanism that ties simulation-based strategies directly to teaching and learning outcomes.

Method

Prior to the implementation of the FEA based strategy as a laboratory activity in aerospace laboratory 1, modeling and FEA of beams with rectangular and I shaped cross sections were conducted. Results of the numerical simulations were verified using established engineering mechanics formulae. Cantilever wing construction was implemented in the simulations, with one end fixed and the other end applied with a force parallel to the cross section of the beam. The details provided as boundary conditions (see Figure 3) were taken to typical problems encountered by students in engineering mechanics. Principles and concepts associated with beams were utilized to verify and validate the results acquired from the simulations. SolidWorks utilizes a library of materials based on Metals Handbook Desk Edition, ASM International by Davis (1998), ensuring the accuracy of the simulations. This, in a way, ensures that the results of the simulations are with high degree of consistency with experimental results (Genouvrier, 2014). Though, controlling the properties of steel is difficult and the usual characteristics of steel utilized in textbooks reflect the average (Mahendran, 1996). The elastic modulus and Poisson's ratio utilized in this paper are commonly reflected in sources, which often reflect that of mild steel (Mahendran, 1996).

Table 1 shows that the value for maximum deflection acquired by numerical simulation is in good agreement with the result of a mathematical equation. Aside from the deflection value, the shape of the beam deflection generated in the simulations is similar to that of a typical response of an actual beam from a load when Physics validation is made as displayed in Figure 5. This is supported by (Skotny, 2017), noting that the deformation shape is as equally important to the performance values acquired during simulations.

Table 1. A comparison of cantilever rectangular beam performance values from numerical simulations and code verification

Performance value	Mathematical calculation	Numerical simulation
Maximum deflection (mm)	32	32
Maximum bending stress (MPa)	240	245

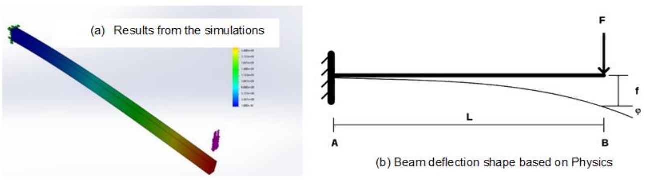


Figure 5. The beam deflection shape acquired in the simulation by students is similar to the deformation shape as prescribed by Physics. The image at the right is created by Pekaje (public domain).

Model validation can be performed by utilizing established simple beam problems with known loadings and boundary conditions as reference (McCaslin, 2021). The output obtained from this undertaking was later used to check the submissions of students. Most students have received lectures on wing structure before the lab activity was given to them. All of them finished engineering mechanics prior to their enrolment in Aerospace Laboratory 1. Prior to the lab exercise, most students find the I-beam topic puzzling or difficult to grasp, consistent with the findings of Streveler et al. (2006). It can be further attested when a recitation on I-beam performance has been asked and none of them convey a clear response and have utilized moments of inertia in their answers. Students were first introduced to the basic principles of FEA, the software SolidWorks and how to do modeling in the program. Students enrolled in the course have little to no previous experience with the use of SolidWorks and a full day session has been dedicated to the matter.

Student permission was obtained to conduct a content analysis of laboratory reports for this study. Each report consists of five sections. The first section contains administrative details, including the student's name and the report title. In the second section, students generate the required plots and perform simulation verifications to assess the soundness of their models using concepts learned prior to the laboratory course. Beyond verification, students must validate their results, an essential step in any simulation activity. While verification confirms the theoretical accuracy of the simulation (the mathematical "correctness"), validation evaluates its physical realism (the "real-world" accuracy). This process instills the importance of post-processing and interrogating simulations to ensure they reflect real-world models accurately. The third section requires students to summarize their learning by connecting prior knowledge with insights gained during the activity. This serves as the reflective component of the assessment, allowing students to narrate their learning process and realizations. Finally, students provide a conclusion based on their findings (Section 4) and offer recommendations for the further enhancement of the intervention (Section 5). Collectively, these sections were designed to concretize learning while enabling students to contribute to the continuous improvement of the laboratory activity.

Students were asked for their consent to include their laboratory reports in this study via a Google Form. This form sought the permission of students enrolled in the laboratory course to use their work for research purposes. Out of 19 students enrolled in the course, 16 responded to no objections and out of 16, 14 managed to submit on time. Only a few universities in the Philippines offer aerospace engineering. Compared to the other engineering and technology programs offered at the university, aerospace engineering is an up-and-coming program. On Mindanao, which is one of the major islands in the Philippines, only Ateneo de Davao University offers aerospace engineering. This can explain the modest size of students in the program. With the establishment of the space agency, the exposure space research is gaining through small satellite development and scholarships made available to the program and the Philippine government and several key industries initiating activities towards the establishment of the aerospace sector (Asian Development Bank, 2021), Aerospace engineering enrolment is estimated to increase in the years to come.

Content analysis has been selected in this paper for the reason of non-rigidity of the approach. Content analysis seeks “messages” on various types of data, visual, aural or textual in nature, to comprehend the information the material tries to convey (Krippendorff, 2018). Also, students' answers come in various forms (textual and pictorial) and the use of highly structured strategies may not capture the needed information from the students. The specifications of beams utilized in the undertaking were pre-determined and were based on usual structures utilized in the aircraft, such as long, slender beams typical of simple beams (Bauchau & Craig, 2009; Sun, 2006).

The first objective of the study was addressed through an analysis of the first and second sections of the students' laboratory reports. These sections were designed to assess student comprehension of the simulation-based intervention introduced prior to the assignment. The second objective was addressed by examining the third and fourth sections, where students narrated their process for handling results and the specific insights they acquired during the activity. Finally, the third objective was met through the analysis of the final section of the report, which gathered student recommendations for enhancing the simulation-based learning intervention.

Results and Discussion

This section discusses the major themes extracted from the analysis of students' work in Aerospace Laboratory 1. Testimonies highlighting the enhanced learning of students regarding beam profile and structure concepts and principles were included. Students’ insights on using numerical simulation for enhanced learning not only of aerospace engineering concepts but also of engineering in general, were captured.

All the student laboratory reports analyzed in this study were able to explain the influence of beam profiles on bending performance when using numerical simulations. Most students were able to show in detail how they did the simulations. Some even managed to do more aspects beyond the expectations for the laboratory report, such as the study of deformation scales (Figure 6) in the post-processing and the influence of the meshing strategy (Figure 7) on the results of the simulations. The activity also makes the learning more participatory, since the students voluntarily explore other aspects necessary for a better understanding of the topics involved. Students were able to connect learning that they acquired from courses they took prior to taking the subject by performing code verification (McCaslin, 2021; Thacker et al., 2004), which is an important step in ensuring that the results generated by the numerical model are consistent and valid. Table 2 presents some of the notable remarks made by students on the positive influence of numerical simulations on their learning of the subject.

Table 2. Numerical simulations enhance the learning of students with beam profiles and structures

Respondent	Remarks
1	*"This activity helped add more skills in analyzing the scenarios involving different materials."*
3	*"The values for maximum deformation between the simulation and the manual computation are more or less identical, with only a small error."*
4	*"This lab experiment highlights how much of a difference just the shape of a material makes in how it counters forces being acted on it"*

Table 3 posits that students have improved their learning about the influence of beam profile on its bending performance after they took the laboratory activity. Due to the interactive nature of the program, it enables students to be more involved with the learning process. Students were able to establish the effects of varying the cross-section of the beam on its bending performance. Numerical simulations reinforced the results acquired by students in performing manual calculations of beams' stress, displacement, and strain. The approach of students was no longer confined to the variables of the equations alone, instead, they questioned them together with the results of the simulations. This confirmed the findings by Moreno et al., 2011 and Scheiter et al., 2009, noting that students learn best when abstract activities (in this case, manual calculations, and theoretical lectures in the classroom) are complemented by visual representations. The activity also enabled them to relate the moment of inertia with the beams' performance, where most of them find the topic difficult when a lecture about it is delivered on a separate course.

Table 3. FEA improves students' comprehension regarding the relation between beam profile and bending performance

Respondent	Remarks
6	*"Comparing the 2 beams, the I-beam when introduced by a load, experiences less bending. This is because of how the area of the beam is shaped thus leading it to be distributed in a way that maximizes its capacity to withstand bending stress."*
8	*"We were able to understand that given the beam dimensions from the exercise, the I-beam indeed performed better. Moreover, another advantage that the I beam has is that it is relatively lighter and much more appropriate to use if drilling holes is necessary."*
9	*"The stress on the rectangular beam has a greater value between the two (rectangular and I profiles) as well. This trend also follows for the strain between the two beams."*
10	*"The I-beam has shown to have a lower amount of stress compared to the reference beam (rectangular beam)"*
14	*"In the straight beam (rectangular) there is a lot of bending stress while the I beam has lesser bending stress. This is due to the different shapes of both beams."*

Streveler et al. (2006) reported that some theories associated with solid mechanics, particularly with a moment of inertia, are taken by students to be difficult to grasp during lectures. With the aid of numerical simulations, students not only relate the moment of inertia with beam profile and bending performance, but also explain the physical meaning of the parameters as exhibited in Table 4. This can be supported by the fact that visual plots generated by numerical simulations can be used for post-processing of data as shown in Figure 8. Also, students have employed the typical method to solve for the maximum deflection of the beam and compare it with the results of the simulation. Even if they have yet to take a formal FEM class, it can be inferred that students have learned to verify and validate the results of their simulations. Students employed the post-processing step, which is critical in any numerical simulation. In the absence of actual lab activity to check the bending performance of the beam through a bending test, they were able to verify and validate their work by interrogating the results of the simulations. Model verification and validation are paramount to identify whether the simulation's results are accurate and conform to the real beam performance (McCaslin, 2021; Skotny, 2017). According to Bishay (2020), the use of FEM in teaching can induce critical thinking and an increased interest in the topic taught to students. Gajbhiye, et al. (2020) also noted that understanding of complex topics/ subjects in engineering can be enhanced with the use of simulations. The explanations made by students on the better performance of I cross section in bending are consistent with those of (Bauchau & Craig, 2009) and (Sun, 2006). The findings by the respondents support the definition made by Collins (2016) and were able to demonstrate comprehension of the concept through the analysis of simulation results.

Table 4. Students learn and appreciate better theories associated with beams and structures through FEA

Respondent	Remarks
1	*"Since both beams have the same cross-sectional area, the advantage of the I beam extends to the force distribution around the area of the I beam, which spreads out more with larger outer dimensions than the more compact rectangular beam, which makes the I beam stiffer."*
2	*"The wide flanges on top and the bottom of the I-beam are located farthest from the neutral axis."*
11	*"A beam's resistance to bending is measured by its moment of inertia"*
13	*"By having more material (planar moment of inertia) further from the neutral axis, the greater the moment of inertia. The I-beam is designed to maximize the bending stress it can withstand while minimizing the weight.".*

Students also reported that the activity can be extended to other courses in the program and can supplement or be an alternative to the delivery of these lessons as displayed in Table 5. Young et al. (2012) mentioned that the FEA allows civil engineering students to comprehend and perform analysis of structures through three dimensional (3D) visualizations. Coyle and Keel (2001) argued that FEA should be introduced early to engineering students to reinforce their learning in basic engineering principles. The visual plots generated by FEA software enable students to have a physical understanding of the model they're studying (Coyle & Keel, 2001; Young et al., 2012).

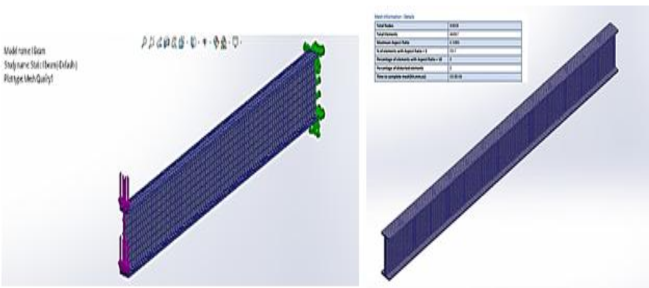


Figure 6. Students inputting the boundary conditions and trying different mesh settings to verify the FEA model

It is also interesting to note that most students have inquired with other sources how the cross section would perform in other conditions such as buckling. This enables them to appreciate the presence of lateral stiffeners and ribs, which is a common subject in aircraft structures. This has affirmed the literature on the effect of visual demonstrations in enabling students to be more operational in their analysis rather than fixed and superficial (Bassok & Holyoak, 1989; Butcher, 2006; Goldstone & Son, 2005; Joseph & Dwyer, 1984; Moreno et al., 2011; Sloutsky et al., 2005).

Table 5. The use of FEA software can be an alternative or supplement to traditional teaching approaches in complex engineering subjects

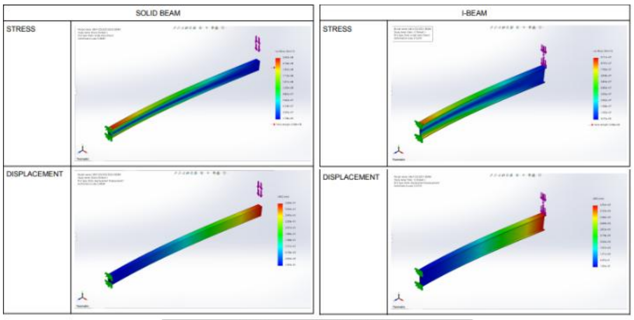
Respondent	Remarks
1	*"I learned that utilizing this tool would generate more clarity when studying the strength of materials necessary for building and plane construction. I was also able to review the effects of the shape of a material on its structural integrity."*
2	*"This simulation activity taught me the principle between yield strength and stress, the relationship between stress and strain, and the effect of changing cross-section shape to the deflection and bending experienced by a beam."*
12	*"I highly recommend doing this activity while learning about Statics of Rigid Bodies. This is to help learners visualize what really is happening on a body with a given external loads."*

Part of a student's laboratory report is for him/her to provide a summary of his/her learning from the concerned activity. Students must also include recommendations for the improvement of the activity if they find any. Several remarks made by students to improve laboratory exercise can be seen in Table 6. Common responses include the extension of the activity to pre-requisite courses such as Statics of Rigid Bodies and Strength of Materials and the improvement of virtual laboratory access to computers with SolidWorks. Moreover, some students gain more confidence in using numerical simulations and would want to engage in trying other complicated engineering problems to simulate.

Table 6. Students recommendations for the improvement of the laboratory exercise

Respondent	Remarks
5	*"Analyze more complex systems and models to further our understanding on the different forces in play"*
7	*"I recommend simulating models and meshes related to the aerospace field"*

The activity was given in an online setting, and most students do not have the software (SW) in their computers. Remote access has been the option for others, and most of the students that did remote access share the same sentiments when it comes to poor access due to internet connectivity among others. Much of the improvements should be made in remote access to lab software, not only with access to software in lab computers in the university. It is advised that the virtual laboratory is enhanced such as the use of 3D experience and high performance computing (HPC) on demand features of SolidWorks.



	$STRESS_{MAX}$	$DISPLACEMENT_{MAX}$	$STRAIN_{MAX}$
SOLID BEAM	2.440e+08	3.369e+01	9.814e-04
I-BEAM	9.711e+07	6.355	3.878e-04

Figure 7. Students generated the goal plots to show the differences in performance between rectangular and I-shaped beam profiles at a certain deformation scale

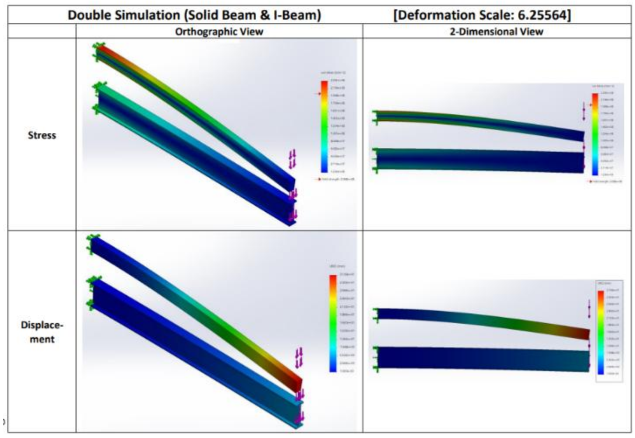


Figure 8. Students have utilized and compared the stress and displacement plots to determine the influence of profile on beam structural performance

There must be a constant and conscious effort to teach not only what and how of numerical simulations. Most importantly, to teach students to interpret the results of numerical simulations through verification and whether it reflects actual results (validation). The exercise not only made the students better appreciate concepts in mechanics and aircraft structures, but as well to recognize the advantages and limitations of the simulations, by interrogating the results of the simulations, which is crucial in engineering, in generating sound and ethical decisions and actions.

Conclusion

The use of numerical simulations can help improve the learning of students in I-beam construction for aircraft structures. Teaching beam profile, moment of inertia and bending stiffness, and how these concepts are related to each other can be augmented with the use of FEA. Moreover, students' appreciation of theories with regards to I-beam structure and its application to aircraft structures is enhanced using numerical simulations. As we navigate a VUCA environment and rapid advancements in computing, numerical simulation programs can supplement or provide alternative avenues where students can learn topics that are conventionally perceived to be challenging.

Suggestions

This study can be extended to other engineering related disciplines to further verify the findings reported in the paper. Despite the advantages of numerical simulations for teaching and learning, educators and school administrators must be cognizant of the financial, technological, and training requirements associated with the use of technology.

Co-Author Contribution

Rodolfo S. Treyes: Validation, Writing – Review & Editing, Supervision
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Conflict of Interest

No conflict of interest.

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Exploring Student Learning Experiences in a PowerPoint-Based Open-Ended Virtual Laboratory for Environmental Engineering Education

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Abstract
Virtual laboratory technology can provide students with the same learning outcome through a simulated experiment without accessing a physical laboratory. It can also be designed to be open-ended, allowing students to develop the methodology to solve a given problem. This is in-line with Outcomes-Based Education as required by the Engineering Accreditation Council of Malaysia. Therefore, the development of an open-ended virtual laboratory and understanding of how it impacts learning outcomes and student engagement are important. This study developed an interactive, animated, open-ended virtual laboratory for an undergraduate environmental engineering water treatment course using the PowerPoint platform, and its effectiveness in delivering hands-on laboratory instruction was measured from students' perspectives. Students' attainment of the learning outcome was analysed through their laboratory assessment, and their engagement with the virtual laboratory was measured using a survey. The results showed that students successfully navigated the open-ended laboratory assessment and achieved the intended learning outcome. In terms of learning engagement, 90% of students agreed that the virtual laboratory was easy to operate and understand, flexible, stimulating, satisfying, and good for distance learning. However, only 20% of students agreed that they learned and understood more in a virtual laboratory than in a physical one, and only 10% reported gaining hands-on skills through the virtual laboratory.

Keywords: virtual laboratory, open-ended laboratory, learning engagement, open distance learning, engineering education

Introduction

The educational landscape has changed significantly due to the COVID-19 pandemic, with a dramatic increase in the adoption of educational technology by institutions worldwide. It has necessitated adapting teaching methods, including laboratory-based exercises, by developing ways for students to perform experiments (Vasiliadou, 2020). As such, virtual laboratories provide an interactive platform for students to learn from simulated experiments and are a viable alternative to physical experiments from the perspectives of both students and instructors (Hanine et al., 2025). It allows students to practice in a risk-free environment and provides a more flexible learning opportunity (Formella-Zimmermann et al., 2022) and greater inclusivity (Zhou et al., 2024). Moreover, these features enable repeated experimentation, encouraging active learning among students prioritising hands-on engagement and investigation, thereby fostering a so-called Exploratory Learning Environment (ELE) (Papalazarou et al., 2024). Váraljai (2016) indicated that an ELE supported by virtual laboratories enhances learning effectiveness by improving preparedness and reducing anxiety, enabling well-supported self-exploration of conceptual understanding. In this context, virtual laboratories can also work in tandem with physical laboratories to cater to the needs and experiences of a broad range of learners (Reeves et al., 2021). In general, studies involving virtual laboratories strongly align with learner-centred and activity-oriented pedagogical frameworks (Yindeemak, et al. 2026), alongside experiential and inquiry-based learning approaches, which emphasise active engagement, exploration and problem-solving in the context of the virtual laboratory environment.

Further, the pedagogical approach of constructivism, which describes learners actively constructing knowledge through interaction with their environment, engaging in experimentation, inquiry and problem-solving applies to the implementation of

Tan, Y. Y., Ho, C. L. I., & Tang, F. E. (2026), Exploring Student Learning Experiences in a PowerPoint-Based Open-Ended Virtual Laboratory for Environmental Engineering Education, *ASEAN Journal of Engineering Education*, 10(1), 96-102. https://doi.org/10.11113/ajee2026.10n1.227

virtual laboratories; as virtual laboratories are part of online engineering education (Sertu, et al. 2025). Eliza, et al. (2024) state that constructivist thinking is relevant in the context of virtual laboratories, as it provides a platform to allow students to experience engineering practice interactively and independently, where they can construct their own knowledge about the phenomenon they are studying. Sertu et al. (2025) go on to describe that constructivism addresses the loss of active experiential learning in virtual laboratories by designing simulations that enable students to manipulate and study the sensitivity of certain parameters to the outcomes.

In Malaysia, the implementation of Outcome-Based Education (OBE) in engineering education requires pedagogical approaches that prioritise the determination and measurement of student learning outcomes across cognitive, affective, and psychomotor domains, moving beyond content delivery to promote active student engagement in the learning activities (Mistamiruddin et al., 2024). An essential component in the curriculum of engineering courses with OBE implementation is open-ended laboratory (OEL) assignments (Roslia and Sadikinb, 2025). In conventional laboratory approaches, students are guided to attain the expected results. In contrast, students are only given the project purpose or problem in OELs, and are free to develop their own experiments to develop solutions (Hamid and Sakdun, 2024). Through the OEL approach, students are encouraged to think critically and to incorporate theory and logical justification in formulating objectives, procedures, and analytical methods, thereby requiring higher-order critical thinking and complex problem-solving skills (Zaini et al., 2026). In particular, OEL may help increase independent learning by fostering the development of these skills and moulding students to exercise their creativity and innovation (Hamid and Sakdun, 2024). As a result, it allows the students to not only apply theories in laboratory assessments but also to work practically as professionals (Persano Adorno et al., 2023). Due to the complexity of implementing an OEL, students typically work in groups to complete the assigned tasks. Persano Adorno et al. (2023) also suggested that an OEL project enhances communication skills among students, as the exploratory activity of formulating the experimental objectives and methodology encourages comprehensive discussion and active sharing. However, several challenges remain in implementing OEL and ensuring learning outcome attainment, including the limited availability of consumables and restricted access to the laboratory, which constrain students' ability to fully engage in exploratory experimentation and iterative experimental design refinement (Roslia and Sadikinb, 2025). Therefore, it is worthwhile to explore whether the OEL can be effectively delivered in a virtual environment without compromising the attainment of learning outcomes.

Although cloud-based virtual laboratory platforms are recognised for extensive simulations and high pedagogical values in converting OELs into a virtual mode for remote learning, the implementation is constrained by the need for institution-wide subscription, limited user accounts, and high computational and stable internet requirements for students' devices (Narwal, R., & Joyti, 2024). Moreover, most virtual laboratories are designed as virtual versions of conventional laboratories with fixed objectives, variables, and procedures, and thus their application to the OEL is limited (Hanine et al., 2025). Therefore, a degree of flexibility needs to be embedded in virtual laboratories to create an effective ELE for students (Gal et al., 2015). It is beneficial to design appropriate open-ended virtual laboratories (OEVL) using a universally available platform for engineering programmes in Malaysia to meet the Engineering Accreditation Council's requirements as well as to enhance students' learning experience. Microsoft PowerPoint is one of the most commonly used presentation and content-authoring tools in higher education, as it is easy to use and integrates flexibly with institutional learning management systems, while requiring no additional licensing (Wanner, 2015). The development of an interactive OEVL using PowerPoint is a practical and inclusive alternative, owing to its pedagogical flexibility when the priority is learning outcome attainment rather than visually rich simulation.

There are two research questions in this study, namely (1) What are the design considerations in developing a PowerPoint-based OEVL to support students' attainment of the intended learning outcomes in an undergraduate environmental engineering course? and (2) What are the perceptions of students on the PowerPoint-based OEVL in terms of flexibility and engagement? This paper presents a case study of an interactive, animated virtual laboratory developed for an undergraduate environmental engineering water treatment course using PowerPoint, providing students with an opportunity to achieve the same learning outcome through a simulated experiment without accessing the physical laboratory. In addition, the effectiveness of technology adoption in delivering a hands-on laboratory exercise was measured through students' attainment of the intended learning outcome and gauged from the students' perspective.

Methodology

An OEVL was developed for an undergraduate water treatment course, where the students were in their third year of study in an undergraduate environmental engineering course. This class consisted of 10 students. Due to its potential for facilitating students' investigation, the Jar Test experiment was selected as the experiment to be simulated as an OEVL.

Within the water treatment process, the jar test is an important experiment to investigate the effectiveness of the coagulation and flocculation process with respect to variation in some parameters, including coagulation type, pH, coagulant dosage and others (Joo et al., 2000). For instance, variation in the pH with a constant dosage of coagulant will result in variation in the coagulation effectiveness, denoted by the water turbidity levels. The key learning outcome from the jar test experiment is understanding the coagulation and flocculation process and how parameters such as pH and coagulant dosage affect the water turbidity, and therefore could be designed for optimisation of the process.

To create an OEL, the students were given a real-world scenario related to water quality issues. The students were asked to complete a report to optimise the water treatment process with the data collected from the virtual laboratory. The OEVL addresses the learning outcome "Apply principles of environmental engineering to water resources management" within the course, which emphasises the application of theory in a practical setting to optimise the water treatment process.

This study was divided into two stages, namely the development and application of the OEVL (Stage 1) and the evaluation of the effectiveness of the OEVL (Stage 2).

Stage 1: Development and application of the OEVL

The interactive virtual laboratory was developed using the PowerPoint platform to simulate the jar test experiment according to the ASTM D2035-19 Standard Practice for Coagulation-Flocculation Jar Test of Water (ASTM International, 2019). Developing the virtual laboratory using PowerPoint is both pragmatic and achievable with relatively little coding expertise. Moreover, it can be easily used or manipulated by students with little or no prior training.

The virtual laboratory was designed with an introduction and videos, which were made available to students, to demonstrate the operation of measurement instruments. Users were able to manipulate parameters in the simulated experiment to collect data. To achieve this, a database of experimental data consisting of water turbidity levels was created based on a combination of several variables for the jar test simulation. These variables consisted of types of coagulants, the dosage of the coagulant, and the pH of the mixture. Figure 1 shows an example of the pH adjustment in the virtual laboratory. Students were able to select the type of coagulant they wanted to use, the coagulant dose, and adjust the pH of the mixture to obtain the experimental result. In this study, the experimental result database was established from previous experiments carried out in the same laboratory, as well as from published data from the literature. The OEVL, which was created on the PowerPoint software, was made available as a file to students through their Learning Management System.

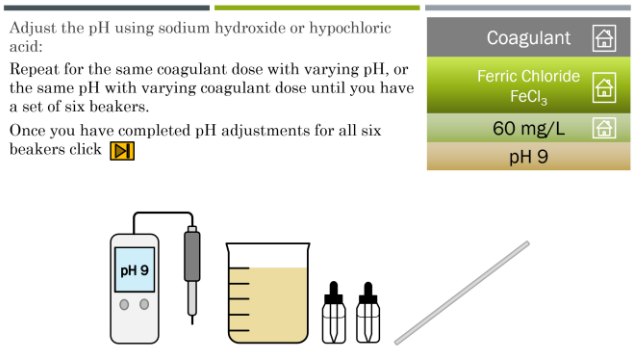

Figure 1. Screenshot of pH adjustment in the PowerPoint-based OEVL

The workflow for this laboratory assessment is as follows. In this OEL, the students conducted a literature review on optimising the coagulation and flocculation process for water treatment, and based on their literature review, developed the objectives and methodology (i.e. designing for different combinations of variables to test) as part of the pre-laboratory preparation.

In the virtual laboratory, the students selected the appropriate variables based on their pre-laboratory preparation and performed a simulated jar test to collect data virtually, as shown in Figure 2. The result was the final turbidity of the water, which varied according to the combination of variables they selected. The data was then analysed and discussed to complete the tasks of the OEL assessment. Students were grouped into groups of two to three students and given 4 weeks to complete the assessment.

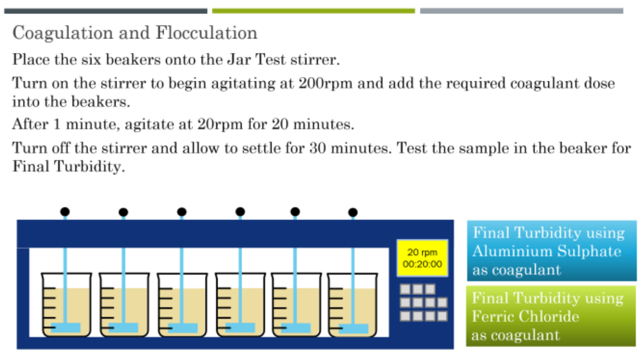

Figure 2. Example of Jar Test in OEVL

Stage 2: Evaluation of the effectiveness of the OEVL

The OEVL addresses the learning outcome "Apply principles of environmental engineering to water resources management" within the course, which emphasises the application of theory in a practical setting to optimise the water treatment process. In the assessment, students are required to evaluate the coagulation and flocculation process and to recommend optimum conditions (coagulant and pH dosage) for turbidity removal through a jar test experiment. Students are assessed based on their experimental design, analysis and evaluation of the lab results and their understanding and insight into the coagulation and flocculation process. Students are also expected to validate the values obtained from the lab against appropriately sourced references and demonstrate that the data obtained is reliable. These items form the basis of the assessment rubric. Students' attainment of the learning outcome addressed by this assessment was measured through their submission of a lab report marked against performance criteria differentiating "Below standard", "Meet standard" and "Excellent standard". Where students are able to present their analysis and evaluation of the laboratory results in sufficient detail, recommend optimum conditions and validate their data successfully, they either meet or exceed the standard.

The effectiveness of the OEVL as a learning tool was evaluated through students' attainment of the learning outcome as described above, as well as a survey. A set of survey questionnaires was distributed to the students to collect feedback regarding the suitability of the virtual laboratory, which was developed based on Naidoo and Govender's framework (Naidoo and Govender, 2014) to assess productive online learning through three key components, namely suitability of online technology, self-regulated learning, and learner-centred activity.

Table 1 summarises the questionnaire items, and students were asked to rate their agreement on a 5-point Likert scale, ranging from 1 (Strongly Agree) to 5 (Strongly Disagree) for 10 questionnaire items, and an additional 4 questionnaire items that were open-ended were also included. The students' perception of the effectiveness of the OEVL is assessed based on ease of operation and understanding, flexibility in terms of time and location, its ability to stimulate effective engagement in the learning activities, and the overall learning satisfaction. These evaluations provided fundamental insights into the feasibility of using a virtual laboratory as an alternative to hands-on laboratory exercises from the students' perspective, with particular emphasis on its suitability for learners. The survey also explored whether the OEVL is more suitable for more advanced students, in their second year and above, given concerns that first-year students may lack the fundamental knowledge and skills required for in-depth investigation to complete the tasks. In addition, the survey covered students' perceptions of virtual and physical laboratories by comparing their level of understanding, opportunities for extended learning, suitability of distance learning, and impact on hands-on skills. The open-ended questions in the survey invite the students to reflect on their perceptions of learning outcome attainment and understanding of the experiment, as well as identifying the strengths and weaknesses of the PowerPoint-based OEVL. Ethical approval for conducting the student survey was granted by the Curtin Human Research Ethics Office (HRE2020-0674).

Table 1. Questionnaire items to evaluate the effectiveness of the OEVL

I found the virtual laboratory easy to operate.
I found the virtual laboratory easy to understand.
I found the virtual laboratory flexible to use in relation to time and place.
I found the virtual laboratory stimulating.
I found the virtual laboratory satisfying.
I think the virtual laboratory is more suitable for senior students (2nd-year students and above).
I think that I learn and understand more in a virtual laboratory environment than in a conventional laboratory.
The virtual laboratory is good because I can perform the laboratory exercise outside the laboratory operating hours.
The virtual laboratory is good because it can be used for distance learning, i.e. by students who are away from campus.
I gain hands-on skills through the virtual laboratory.
Learning outcomes are the outcomes (skills or experience) you will achieve upon completion of this laboratory. Do you think you have achieved the relevant learning outcomes for this laboratory exercise? (For your information, the learning outcomes for this lab are stated in the marking rubrics/assignment brief)
After completing this virtual laboratory, do you think you fully understand the coagulation process, and how turbidity varies with pH and coagulant dosage?
Which aspects of this virtual laboratory work well?
Which aspects of this virtual laboratory needs improvement?

Results and Discussions

This study is conducted as an exploratory study to explore the possibility of implementing OEVLs in engineering programmes. As such, Stage 2 of the study is focused on determining students' perceptions of the suitability of the OEVL for learners, which would inform the development and refinement of the OEVL tool moving forward. Then, the tool may be implemented with a larger sample of students taking the course. Nonetheless, in the present study, all students taking the water treatment course (n = 10) participated in the study.

The assessment rubric associated with the OEVL is mapped against the learning outcome "Apply principles of environmental engineering to water resources management". Students' successful achievement of the learning outcome is dependent on whether their laboratory report achieves the "Meet standard" performance criteria in the marking rubric. Meanwhile, the overall learning outcome attainment for this student cohort is determined by calculating the percentage of students who successfully achieve this learning outcome.

Assessment result showed that attainment for the learning outcome was 96%, indicating that students were able to attain the intended learning outcome by successfully navigating the OEL assessment. Students were able to design appropriate parameter values to obtain experimental results from the virtual laboratory and analyse the results to arrive at a reasonable solution to the problem.

The administered survey achieved a 100% response rate (n=10), with all students in the class providing feedback on the implementation of the OEVL for the jar test experiment. Table 2 presents the results of the statements appraised on a Likert scale by the students, which evaluate students' perception of the effectiveness of the OEVL carried out.

Based on the survey outcomes, 90% (or 9 students) agreed that the virtual laboratory was easy to operate and good for distance learning, while all ten (10) students (or 100%) agreed that the virtual laboratory was easy to understand and was flexible. A total of 80% (or 8 students) agreed that they found the virtual laboratory stimulating and that the virtual laboratory was good because they could perform the laboratory exercise outside the laboratory operating times. Further, 70% (or 7 students) were satisfied with the virtual laboratory. From the open-ended survey question, a student emphasised that there were no safety issues with conducting a virtual laboratory, and the wastage of chemicals was also avoided. These outcomes aligned with the findings in Van den Beemt et al. (2023), where the remote laboratory, incorporating active learning pedagogy, allowed flexibility for the students to plan and organise their learning activities, subsequently achieving the goal of self-regulated learning. In terms of improvement, five (5) students commented that the OEVL did not need improvement, but two (2) students suggested that more explanation should be given as to the operation of the virtual laboratory. In contrast, one (1) student suggested that the virtual laboratory could be simplified. Six (6) students found that the presentation of the virtual laboratory was very detailed, interactive, and easy to use, and they could easily understand the concept of the jar test.

However, only 20% (or 2 students) agreed that they learned and understood more in a virtual laboratory than in a physical laboratory. Additionally, from the open-ended survey question, six (6) students believe that they understood the theory of the coagulation process through the OEVL. However, only 10% (or 1 student) perceived that they gained hands-on skills through the virtual laboratory. A student also reflected in the open-ended survey question that the virtual laboratory could not replace actual participation in a physical laboratory environment. The findings aligned with the literature, where Poo et al. (2023) highlighted that a virtual laboratory is less effective in providing hands-on and haptic experience essential for embodied learning and developing practical skills compared to physical labs.

Despite a 96% attainment in their learning outcome, only four (4) of the students perceived that they had achieved the learning outcomes through the OEVL. This perception can be explained by the challenges that are posed by self-regulated learning to their motivation, commitment, and desire to learn (Reginald, 2023). The OEVL in this study supports self-regulated learning, as the assessment requires students to construct their learning environment through designing the experiment, carrying out the analysis and verifying their findings independently.

Table 2. Estimate on Likert scale on how many respondents agreed with the statements (N = 10)

Statement	1 = Strongly agree	2 = Agree	3 = Neutral	4 = Disagree	5 = Strongly Disagree
I found the virtual laboratory easy to operate.	40%	50%	0%	10%	0%
I found the virtual laboratory easy to understand.	30%	70%	0%	0%	0%
I found the virtual laboratory flexible to use in relation to time and place.	60%	40%	0%	0%	0%
I found the virtual laboratory stimulating.	20%	60%	20%	0%	0%
I found the virtual laboratory satisfying.	20%	50%	20%	10%	0%
I think the virtual laboratory is more suitable for senior students (2nd year students and above).	10%	50%	20%	20%	0%
I think that I learn and understand more in a virtual laboratory environment than a conventional laboratory.	10%	10%	40%	30%	10%
The virtual laboratory is good because I can perform the laboratory exercise outside the laboratory operating hours.	20%	60%	20%	0%	0%
The virtual laboratory is good because it can be used for distance learning, i.e. by students who are away from campus.	50%	40%	10%	0%	0%
I gain hands-on skills through the virtual laboratory.	0%	10%	40%	30%	20%

This is consistent with Reginald (2023), which proposed that virtual labs have the ability to initiate self-regulation and promote meaningful learning. To improve the learning experience and ensure better navigation and understanding of lab procedures, the design of online learning activities should incorporate scaffolded support through video demonstrations and a built-in help system. Additional modules could be developed to specifically focus on imparting practical skills that students might otherwise miss in a virtual environment by including virtual demonstrations of hands-on techniques or interactive modules that simulate practical skill application.

Conclusions

This study developed a virtual laboratory for the jar test using the PowerPoint platform in an undergraduate environmental engineering water treatment course. The effectiveness of the OEVL was evaluated through the attainment of learning outcomes and students' satisfaction. The high attainment of the learning outcome implies that the students were able to achieve the intended learning outcomes. As for the students' satisfaction, majority of students agreed that the virtual laboratory was easy to operate and understand, flexible, stimulating, satisfying, and good for distance learning. However, only 20% of students agreed that they learned and understood more in a virtual laboratory than in a physical laboratory, and only 10% of students perceived that they had gained hands-on skills through the virtual laboratory. This suggests that further development is required to address the hands-on skills gap, such as the use of augmented reality (AR) to improve students' learning experience.

This study shows that environmental engineering students do not think that this type of virtual laboratory could replace physical laboratory exercises. However, the students showed a very positive response towards the virtual learning experience.

The findings of this project would support the implementation of virtual laboratories in Malaysia, and around the region, should remote/online learning become a necessity due to resource limitations, or where access to a physical laboratory is not possible. In addition, developing the virtual laboratory using PowerPoint is both pragmatic and achievable with relatively little coding expertise, hence it can be implemented with ease to meet the Outcomes-Based Education expectations for engineering programmes.

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Conflict of Interest

The authors declare no conflict of interest regarding this paper.

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From STEM Identity to Engineering Identity: A Critical Review of Theoretical Development and Emerging Research Directions

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Abstract
Engineering identity has become an important construct in engineering education research because of its influence on student engagement, persistence, belonging, and professional development. However, its theoretical foundations remain dispersed across psychology, sociology, science education, STEM education, and engineering education. This paper presents a structured critical review of engineering identity research by tracing its development from foundational identity theories through science and STEM identity frameworks to contemporary engineering identity models. Drawing on 49 core publications published primarily between 2000 and 2026, the review shows that engineering identity has gradually consolidated around three core dimensions: interest, performance and competence, and recognition. Contemporary scholarship, however, has expanded beyond this tripartite structure to include agency, belonging, emotional experience, developmental perspectives, contextual variation, and professional readiness. The review identifies key challenges in the literature, including conceptual fragmentation, methodological concentration, Western-centred evidence, and limited longitudinal understanding. Based on these findings, the paper proposes future research directions that emphasise contextualisation, ASEAN and Global South perspectives, industry readiness and employability, longitudinal inquiry, and more integrated identity frameworks. This review contributes by consolidating the theoretical evolution of engineering identity and clarifying opportunities for future conceptual and empirical development.

Keywords: Engineering Identity; STEM Identity; Science Identity; Engineering Education; Identity Development.

1. Introduction

Engineering identity has become an important concept in engineering education research because it helps explain how students develop a sense of belonging, confidence, and professional self-understanding within engineering. Beyond acquiring technical knowledge, students need to see themselves, and be recognised by others, as legitimate members of the engineering community. This identity formation process is important because it influences students' motivation, persistence, engagement, and long-term commitment to engineering pathways (Tonso, 2006a; Carlone & Johnson, 2007; Godwin, 2016; Patrick et al., 2018).

The growing interest in engineering identity reflects a broader shift in engineering education research. Earlier work in STEM education often focused on achievement, participation, and retention, but more recent scholarship has increasingly examined how students construct disciplinary and professional identities over time. Identity is no longer viewed only as an internal psychological trait. Instead, it is understood as a socially situated and relational process shaped by participation, recognition, belonging, and interaction within educational and professional communities (Gee, 2000; Wenger, 1998). From this perspective, becoming an engineer involves more than completing an engineering programme. It also involves gradually internalising the values, practices, expectations, and social meanings associated with engineering.

The theoretical roots of engineering identity research can be traced to broader scholarship on identity development, science identity, and STEM identity. Foundational work by Carlone and Johnson (2007) conceptualised science identity through the dimensions of competence, performance, and recognition. Their model was significant because it showed that disciplinary identity depends not only on what individuals know, but also on how they perform that knowledge and how they are recognised by others. Hazari et al. (2010) later extended this discussion within physics education by incorporating interest as a central motivational dimension linked to persistence. These models provided an important foundation for later engineering identity research because they established identity as a multidimensional construct shaped by both internal self-perception and external validation.

Building on this foundation, Godwin (2016) adapted the identity framework to engineering

Abdul Lahtif, A.I. & Zakaria, Z.Y. (2026), From STEM Identity to Engineering Identity: A Critical Review of Theoretical Development and Emerging Research Directions, *ASEAN Journal of Engineering Education*, 10(1), 103-123. https://doi.org/10.11113/ajee2026.10n1.237

education by conceptualising engineering identity through three key dimensions: interest, performance and competence, and recognition. This model has become one of the most widely used approaches in engineering identity scholarship because it offers clear constructs for examining how students identify with engineering. Subsequent studies have continued to support the importance of these dimensions, particularly the roles of interest and recognition in shaping students' engineering self-identification and persistence (Godwin et al., 2016; Patrick et al., 2018; Verdín, 2021). However, while this model has provided important conceptual and empirical clarity, engineering identity research has also expanded beyond these original dimensions to include agency, belonging, emotional experience, gendered experience, and developmental progression.

Despite these advances, the literature remains theoretically and methodologically fragmented. Engineering identity has been examined through multiple lenses, including social constructivism, communities of practice, social cognitive career theory, possible selves theory, identity-based motivation, and social identity theory. Each of these perspectives contributes useful insight, but they are not always integrated into a coherent explanation of how engineering identity develops. Some studies emphasise motivation and self-efficacy, while others focus on recognition, belonging, participation, or sociocultural positioning. As a result, the field has developed a rich but uneven body of knowledge, where theoretical models and empirical findings sometimes operate in parallel rather than being critically synthesised.

Another important limitation is the strong concentration of engineering identity research within Western educational contexts. Many influential models and empirical studies have been developed and validated in North American or Western higher education systems. These studies have generated valuable insights, but their direct applicability to non-Western, collectivist, and policy-driven education systems remains underexamined. This is important because engineering identity does not develop in a cultural vacuum. Students' decisions, motivations, and professional self-understanding may be shaped by family expectations, institutional structures, national policy priorities, accreditation systems, labour market conditions, and broader societal perceptions of engineering. Therefore, models developed in individualistic educational settings may not fully explain engineering identity formation in contexts where collective expectations and structural conditions play a stronger role.

The current literature also shows methodological imbalance. Many engineering identity studies rely heavily on quantitative survey-based approaches, particularly because identity dimensions such as interest, performance and competence, and recognition can be operationalised through validated instruments. While this has strengthened measurement precision and allowed large-scale analysis, it may also reduce identity to measurable constructs and underrepresent lived experience, contextual meaning-making, and sociocultural negotiation. Earlier sociocultural and ethnographic studies showed that engineering identity is deeply shaped by institutional culture, peer norms, participation, and recognition. Therefore, future engineering identity research needs to balance measurement-based approaches with interpretive, contextual, and qualitative perspectives that can capture how identity is experienced and negotiated in specific educational settings.

In addition, engineering identity research has increasingly recognised that identity development is not static. Students' sense of becoming engineers evolves across educational and professional stages, from early STEM exposure to undergraduate participation, industrial training, postgraduate development, and professional practice. However, many existing studies examine identity at isolated stages rather than as a developmental continuum. This creates a gap in understanding how early interest, university experiences, social recognition, and professional exposure interact over time to support or weaken engineering identity. A more integrated understanding is needed to explain how identity develops across transitions from school to university and from university to the engineering profession.

Although several reviews have examined aspects of engineering identity, STEM identity, and engineering education, including definitions, measurement approaches, development factors, and higher education contexts (Patrick & Borrego, 2016; Morelock, 2017; Rodriguez et al., 2018; Co & Chen, 2025), limited attention has been given to synthesising the theoretical progression from STEM identity to engineering identity while critically examining the conceptual, methodological, and contextual challenges that continue to shape the field. This review addresses that gap by providing an integrated analysis of the development, consolidation, and future directions of engineering identity scholarship.

Given these gaps, this paper presents a critical review of the theoretical development of engineering identity research. The purpose of the review is to trace the conceptual progression from general identity theories and STEM identity frameworks to engineering-specific identity models, while critically examining how the field has evolved, consolidated, and expanded. Specifically, the paper aims to: (1) review the theoretical foundations informing STEM and engineering identity research; (2) examine the development of major engineering identity models and dimensions; (3) critically analyse conceptual, methodological, and contextual limitations in existing scholarship; and (4) propose future research directions for more contextually responsive engineering identity research.

This review contributes to engineering education scholarship in three ways. First, it synthesises the theoretical progression from STEM identity to engineering identity, clarifying how key constructs such as interest, performance and competence, and recognition became central to the field. Second, it critically examines the expansion of engineering identity research beyond the tripartite model by considering agency, belonging, emotion, gender, and developmental perspectives. Third, it highlights the need for more contextually responsive identity research, particularly in non-Western and Global South settings where sociocultural, institutional, and professional conditions may shape identity formation differently.

The paper is structured as follows. Section 2 explains the review methodology. Section 3 discusses the theoretical foundations of identity development relevant to engineering education. Section 4 traces the movement from STEM identity to engineering identity. Section 5 reviews major engineering identity models and dimensions. Section 6 critically analyses key limitations in existing scholarship. Section 7 outlines emerging research directions. The final section concludes by emphasising the need for more integrated, developmental, and contextually grounded approaches to engineering identity research.

2. Review Methodology

2.1 Review Design

This study employed a structured critical review approach to examine the theoretical development, conceptual evolution, and emerging directions of engineering identity research. Unlike systematic literature reviews that primarily focus on exhaustive identification and quantitative synthesis of studies, a structured critical review aims to critically analyse, interpret, and integrate theoretical and empirical scholarship to generate deeper conceptual understanding and identify research gaps. This approach was considered appropriate because the objective of the present review was not merely to catalogue existing studies, but to examine how engineering identity has evolved from broader identity traditions and to evaluate the strengths, limitations, and future directions of the field.

The review was guided by principles of transparency, relevance, and conceptual synthesis. Particular attention was given to studies that contributed significantly to the development of identity theory, STEM identity, science identity, and engineering identity scholarship. The review also considered contemporary studies that expanded or challenged existing understandings of engineering identity through new theoretical, methodological, or contextual perspectives.

2.2 Literature Search Strategy

The literature search was conducted using major academic databases commonly used in engineering education and educational research, including Scopus, Web of Science, ERIC, and Google Scholar. These databases were selected because they provide broad coverage of engineering education, STEM education, identity research, and higher education scholarship.

The search process utilised combinations of the following keywords and search terms:

- "engineering identity"
- "engineering student identity"
- "professional identity in engineering"
- "STEM identity"
- "science identity"
- "engineering education"
- "identity development"
- "engineering persistence"
- "engineering belonging"
- "engineering recognition"
- "engineering self-concept"

Additional studies were identified through backward and forward citation tracking of highly influential publications, particularly foundational works by Carlone and Johnson (2007), Hazari et al. (2010), Godwin (2016), Wenger (1998), and Gee (2000). This process enabled the identification of seminal studies that have significantly influenced the development of engineering identity scholarship.

2.3 Inclusion and Exclusion Criteria

To ensure relevance and quality, studies were selected based on several inclusion criteria. Included studies were:

1. Published in peer-reviewed journals, conference proceedings, academic books, or recognised research reports.
2. Focused on identity development within STEM, science, engineering, or related educational contexts.
3. Published primarily between 2000 and 2026, while allowing inclusion of earlier seminal theoretical works that informed contemporary identity scholarship.
4. Relevant to theoretical, conceptual, empirical, or methodological discussions of identity development.
5. Written in English.

Studies were excluded if they:

1. Focused exclusively on technical engineering content without discussion of identity-related constructs.
2. Addressed professional identity outside STEM or engineering contexts without clear conceptual relevance.

3. Were duplicate publications or non-scholarly sources.
4. Provided insufficient theoretical or empirical contribution to the objectives of the review.

The inclusion of both foundational and contemporary studies ensured that the review captured the historical development of engineering identity while also reflecting recent advances in the field.

2.4 Data Analysis and Synthesis

The selected literature was analysed through an iterative process of reading, comparison, categorisation, and thematic synthesis. Rather than treating studies as isolated sources of information, the review sought to identify patterns, theoretical continuities, conceptual shifts, and emerging trends across the literature.

The analysis proceeded through four stages. First, foundational theories relevant to identity development were identified and examined. These included Identity Theory, Social Identity Theory, Communities of Practice, Social Cognitive Career Theory, Identity-Based Motivation Theory, and related perspectives. Second, the evolution of STEM and science identity scholarship was analysed to understand how engineering identity emerged from earlier disciplinary identity research. Third, major engineering identity models and dimensions were compared and synthesised. Finally, recurring conceptual, methodological, and contextual limitations were identified to establish future research directions. Following the screening, selection, and synthesis process, 49 core publications were retained for detailed thematic analysis. These publications comprised foundational theoretical works, influential engineering identity frameworks, and recent empirical studies that collectively informed the critical synthesis presented in this review.

Throughout the analysis, emphasis was placed on identifying areas of convergence and divergence across studies, examining the contexts in which theories were developed and validated, and evaluating the extent to which existing frameworks addressed diverse educational and sociocultural settings.

2.5 Scope and Limitations of the Review

Although the review adopted a structured and transparent search strategy, it does not claim to represent an exhaustive systematic review of all engineering identity literature. Instead, the review prioritised influential, highly cited, and conceptually significant studies that contributed directly to the development of engineering identity scholarship. Consequently, some relevant studies may not have been included.

Nevertheless, the review provides a comprehensive synthesis of the major theoretical traditions, empirical developments, and emerging research directions that have shaped contemporary understanding of engineering identity. By integrating foundational theories, established models, and recent scholarship, the review offers a critical perspective on the evolution of engineering identity research and highlights opportunities for future conceptual and contextual advancement. The next section therefore examines the theoretical foundations that informed this development.

3. Theoretical Foundations of Engineering Identity Research

Engineering identity research is grounded in a broad theoretical tradition that spans psychology, sociology, science education, STEM education, and engineering education. Although contemporary engineering identity studies often focus on specific constructs such as interest, performance and competence, and recognition, these constructs did not emerge in isolation. They developed from earlier theories that explain how individuals form self-understandings, participate in social groups, imagine future selves, and gain recognition within communities of practice.

This section reviews the major theoretical perspectives that have shaped engineering identity scholarship. The discussion is organised thematically so that closely related theories can be examined together according to their shared assumptions about identity development. Identity Theory and Social Identity Theory are first discussed together because both explain identity through role internalisation, group membership, and social belonging. Communities of Practice and Situated Learning are then discussed together because both emphasise learning, participation, legitimacy, and identity formation within social contexts. The section then turns to motivational and developmental perspectives, including Social Cognitive Career Theory, Identity-Based Motivation Theory, and Possible Selves Theory, before discussing science and STEM identity foundations and the emergence of engineering identity as a discipline-specific construct.

To provide a structured overview of these theoretical perspectives, Table 1 summarises the major theories and frameworks informing engineering identity scholarship, including their core concepts, contributions, and key limitations. The key limitation column is included to highlight the conceptual boundaries, contextual constraints, and explanatory gaps within existing theories. These limitations help explain why engineering identity scholarship has continued to evolve and provide an important foundation for the critical analysis and future research agenda presented in this review.

Table 1. Summary of Major Identity Theories Relevant to Engineering Education

Theory / Framework	Key Authors	Core Concepts	Contribution to Engineering Identity Research	Key Limitation
Identity Theory	Burke & Stets (2009); Stryker (1980)	Identity meanings, role expectations, self-verification	Explains how individuals internalise and enact professional roles such as becoming an engineer. Highlights the relationship between role performance and self-concept.	Focuses primarily on individual role identities and provides limited attention to broader sociocultural influences.
Social Identity Theory	Tajfel & Turner (1979)	Social categorisation, group membership, social belonging	Explains how engineering students develop a sense of belonging through identification with engineering communities and peer groups.	Not specifically designed to explain professional identity formation within educational settings.
Communities of Practice and Situated Learning	Wenger (1998); Lave & Wenger (1991)	Participation, belonging, legitimate peripheral participation, community membership	Conceptualises engineering identity as developing through participation in engineering practices and communities. Widely used to explain learning and identity formation in engineering education.	Difficult to operationalise and measure quantitatively.
Science Identity Framework	Carlone & Johnson (2007)	Competence, performance, recognition	Provides the foundational disciplinary identity model from which engineering identity frameworks emerged. Emphasises recognition as a critical component of identity formation.	Developed within science education rather than engineering-specific contexts.
Physics Identity Framework	Hazari et al. (2010)	Interest, performance and competence, recognition	Introduces interest as a central motivational dimension and demonstrates the relationship between identity and persistence in STEM pathways.	Developed specifically within physics education and may not fully capture engineering-specific experiences.
Social Cognitive Career Theory (SCCT)	Lent, Brown, & Hackett (1994)	Self-efficacy, outcome expectations, goals	Explains how confidence, career expectations, and goal orientation influence engineering persistence and career decisions.	Emphasises individual cognitive processes and provides limited attention to social recognition and belonging.
Identity-Based Motivation Theory	Oyserman (2015)	Future selves, identity congruence, action readiness	Explains how students' perceptions of their future professional selves influence motivation, engagement, and persistence.	Less discipline-specific and relatively abstract when applied to engineering education.
Possible Selves Theory	Markus & Nurius (1986)	Future self-concept, aspirations, anticipated identities	Provides insight into how engineering students envision future professional identities and align current behaviour with future goals.	Focuses primarily on future-oriented cognition rather than social identity processes.
Engineering Identity Model	Godwin (2016)	Interest, performance and competence, recognition	Provides the most widely adopted engineering-specific identity model. Offers conceptual clarity and strong empirical support across engineering education studies.	Predominantly validated in Western higher education contexts and relies heavily on survey-based measurement approaches.
Critical Engineering Agency Framework	Godwin et al. (2016)	Agency, sociopolitical awareness, recognition, interest	Extends engineering identity beyond competence and recognition by incorporating societal contribution and empowerment.	Empirical applications remain relatively limited and concentrated within specific populations.
Gendered Engineering Identity Perspective	Wang et al. (2022)	Gender identity, emotional experience, resilience, engineering identity	Highlights emotional, psychological, and gender-related influences on engineering identity development.	Context-specific and not yet widely integrated into mainstream engineering identity frameworks.

3.1 Identity Theory and Social Identity Theory

Identity Theory, as articulated by Stryker (1980) and further developed by Burke and Stets (2009), provides one of the foundational perspectives for understanding how individuals internalise roles and attach meaning to who they are within social structures. From this perspective, identity is connected to role expectations, self-meanings, and the ways individuals verify their sense of self through action and interaction. In engineering education, this theory is useful because students do not simply learn engineering knowledge; they gradually negotiate whether the role of "engineer" becomes part of their self-concept. Becoming an engineer therefore involves more than academic achievement. It also involves adopting the values, expectations, and practices associated with the engineering profession.

Social Identity Theory (Tajfel & Turner, 1979) complements this role-based view by emphasising group membership and belonging. It explains how individuals define themselves in relation to social groups and how identification with a group can shape confidence, motivation, and participation. In engineering education, this is especially relevant because students often develop identity through their perceived membership in engineering communities. When students feel accepted by peers, lecturers, mentors, and professional communities, their sense of belonging to engineering may be strengthened. Conversely, weak recognition or exclusionary environments may weaken identification with the discipline.

Together, Identity Theory and Social Identity Theory show that engineering identity is both personal and social. It involves internal self-understanding, but it is also shaped by external recognition and group affiliation. This dual emphasis is important because engineering identity cannot be reduced to technical competence alone. A student may perform well academically but still fail to see themselves as an engineer if they lack recognition, belonging, or meaningful participation within the engineering community.

3.2 Communities of Practice and Situated Learning

Communities of Practice Theory and Situated Learning (Lave & Wenger, 1991; Wenger, 1998) provide another important foundation for engineering identity research. Lave and Wenger's theory of situated learning explains that learning occurs through participation in social practices rather than through knowledge acquisition alone. Wenger later extended this idea by arguing that identity develops through participation, mutual engagement, and alignment within communities of practice.

In engineering education, this perspective is highly relevant because students become engineers through participation in engineering-related practices. These practices may include design projects, laboratory work, teamwork, problem-solving, internships, capstone projects, professional communication, and engagement with industry expectations. Through these experiences, students learn not only technical content but also what it means to think, act, and communicate as engineers.

This perspective shifts engineering identity from a static personal trait to a socially mediated process. Identity develops when students are given opportunities to participate meaningfully in engineering practices and when their participation is recognised as legitimate. This explains why authentic learning environments, collaborative projects, industrial exposure, and mentorship are often associated with stronger engineering identity. Students are more likely to internalise an engineering identity when they experience themselves as active contributors rather than passive recipients of technical knowledge.

However, Communities of Practice Theory also has limitations. While it provides strong sociocultural insight, it is less easily operationalised into measurable dimensions. This makes it more suitable as an interpretive lens than as a direct measurement framework. Nevertheless, its contribution remains important because it reminds engineering education researchers that identity development is embedded in practice, interaction, and community membership.

3.3 Motivational and Developmental Perspectives

Engineering identity research has also been influenced by motivational and developmental theories, including Social Cognitive Career Theory (Lent et al., 1994), Identity-Based Motivation Theory (Oyserman, 2015), and Possible Selves Theory (Markus & Nurius, 1986). In engineering education, this theory helps explain why students persist or disengage from engineering pathways. Students who believe they can succeed in engineering and who perceive engineering as leading to meaningful future outcomes are more likely to sustain motivation and career commitment.

Identity-Based Motivation Theory and Possible Selves Theory further extend this discussion by focusing on future-oriented self-concepts. These perspectives suggest that students' current actions are influenced by how they imagine their future selves. If students can imagine themselves as future engineers, they may be more likely to engage in behaviours that support engineering persistence, such as participating in projects, seeking feedback, improving technical skills, and building professional networks.

These motivational theories are useful because they connect engineering identity to persistence, aspiration, and career direction. They explain why identity is not only a reflection of present experience but also a projection of future possibility. Students' sense of becoming engineers is shaped by whether they see engineering as attainable, meaningful, and aligned with their future goals.

However, motivational theories are often more individualistic in orientation. They tend to emphasise self-efficacy, goals, and personal motivation, but may give less attention to broader social, cultural, institutional, and structural influences. This limitation is important because engineering identity is not formed only through individual confidence or aspiration. It is also shaped by recognition, family expectations, institutional culture, professional pathways, and sociocultural meanings attached to engineering.

3.4 STEM Identity and Science Identity Foundations

The movement from general identity theories to engineering identity was strongly shaped by science and STEM identity research. One of the most influential models is Carlone and Johnson's Science Identity Framework, which conceptualised science identity through competence, performance, and recognition. This framework was important because it showed that disciplinary identity requires more than knowledge. Individuals must be able to demonstrate competence and be recognised by themselves and others as legitimate members of the discipline.

Recognition is especially important in this framework. A student may be competent in science or engineering, but without recognition from teachers, peers, family, or professional communities, identity may remain weak. This insight became central to later engineering identity research because it highlighted the social nature of identity formation.

Hazari and colleagues extended this discussion in physics education by incorporating interest as an additional dimension. Their work linked identity to students' persistence intentions and showed that interest, performance and competence, and recognition were important predictors of STEM-related persistence. This development marked an important shift because it connected identity not only to social recognition but also to motivation and future participation.

Together, the science identity and physics identity frameworks provided the conceptual foundation for engineering identity research. They established identity as a multidimensional construct involving internal motivation, demonstrated ability, and social recognition. However, these frameworks were developed within science and physics contexts. Engineering differs from these fields because it is closely tied to design, problem-solving, professional practice, accreditation, teamwork, industry expectations, and societal application. Therefore, engineering identity required a more discipline-specific conceptualisation.

3.5 Emergence of Engineering Identity

Engineering identity emerged as a distinct construct when scholars began adapting STEM and science identity models to engineering education. Godwin's engineering identity model became one of the most widely adopted frameworks in the field. Building on earlier identity frameworks, Godwin conceptualised engineering identity through interest, performance and competence, and recognition.

Interest refers to students' personal engagement with engineering. It captures the extent to which students find engineering meaningful, enjoyable, and relevant. Performance and competence refer to students' confidence in understanding and performing engineering-related tasks. Recognition refers to whether students see themselves, and are seen by others, as engineering people. These three dimensions provide a clear and useful structure for examining how students develop identification with engineering.

The strength of Godwin's model lies in its operational clarity. It allows researchers to study engineering identity empirically and to examine how identity relates to persistence, belonging, motivation, and career intention. Subsequent studies have reinforced the importance of these dimensions, particularly recognition and interest. Many studies suggest that students' sense of being recognised as engineers can be as important as, or even more important than, technical ability alone.

Nevertheless, the model also has limitations. Much of the empirical validation has occurred within Western higher education contexts, and many studies have relied on survey-based measurement. While this has strengthened quantitative analysis, it may not fully capture how engineering identity is shaped in different cultural, institutional, and professional contexts. In collectivist or policy-driven education systems, for example, engineering identity may also be shaped by family expectations, national development priorities, accreditation structures, and industry readiness. These influences may not be fully explained by the original tripartite dimensions.

3.6 Synthesis of Theoretical Foundations

The theoretical foundations reviewed in this section indicate that engineering identity is a multidimensional, socially situated, and developmental construct. Identity Theory and Social Identity Theory explain the importance of role internalisation and group belonging. Communities of Practice and Situated Learning show that identity develops through participation in meaningful disciplinary practices. Motivational and developmental perspectives explain how self-efficacy, future goals, and possible selves influence persistence and career orientation. Science and STEM identity frameworks provide the conceptual bridge toward engineering identity by foregrounding competence, performance, recognition, and interest.

Taken together, these theories suggest that engineering identity cannot be understood through a single lens. It is not only a psychological construct, a social construct, or a motivational construct. Rather, it is formed through the interaction of personal interest, perceived competence, social recognition, disciplinary participation, future aspiration, and contextual influence. This explains why engineering identity research has become theoretically rich but also conceptually fragmented.

A key implication is that future engineering identity research must move beyond simply measuring identity dimensions. It must also examine how those dimensions are experienced, negotiated, and shaped within specific educational, cultural, and professional contexts. This is especially important in non-Western and Global South settings, where engineering identity may be influenced by sociocultural expectations, institutional systems, and labour market realities that differ from the contexts in which many dominant models were originally developed.

The next section builds on this theoretical foundation by tracing the progression from STEM identity to engineering identity and examining how major models have shaped the development of the field.

4. From STEM Identity to Engineering Identity

4.1 Origins of STEM Identity Research

The emergence of engineering identity research cannot be understood independently of broader developments within STEM identity scholarship. Before engineering identity became established as a distinct area of inquiry, researchers in science and STEM education had already begun investigating how learners developed a sense of belonging, participation, and identification within disciplinary communities. These studies shifted attention away from achievement alone and toward understanding how students came to see themselves as members of particular academic and professional domains.

Early identity research within STEM fields was influenced by sociocultural perspectives that viewed learning as a process of participation rather than simple knowledge acquisition. Within this tradition, identity became an important explanatory construct because it helped explain why some students persisted in STEM pathways while others disengaged despite comparable academic ability. Researchers increasingly recognised that academic performance alone could not fully explain participation patterns, particularly among underrepresented groups. Studies on STEM pathways, early engineering identity development, and STEM career aspirations further show that identity-related factors may emerge before university and are shaped by early exposure, self-concept, and perceptions of STEM professionals (Cannady et al., 2014; Capobianco et al., 2012; Capobianco et al., 2015; Chen et al., 2024). Instead, students' perceptions of themselves and their experiences of recognition within disciplinary communities appeared equally important.

This shift laid the foundation for disciplinary identity research, particularly within science education, where identity began to be examined as a multidimensional construct influenced by competence, participation, and social recognition. These developments ultimately provided the conceptual basis from which engineering identity scholarship emerged.

4.2 Science Identity as a Foundational Framework

A major milestone in disciplinary identity research was the work of Carlone and Johnson (2007), who proposed one of the most influential science identity frameworks. Their model conceptualised science identity through three interconnected dimensions: competence, performance, and recognition. Competence referred to an individual's understanding of disciplinary knowledge, performance reflected the ability to demonstrate that knowledge in socially meaningful ways, and recognition captured the extent to which individuals were acknowledged by themselves and others as legitimate participants within the discipline.

The significance of this framework extended beyond science education. By demonstrating that disciplinary identity depends not only on knowledge but also on social validation, Carlone and Johnson fundamentally changed how researchers conceptualised identity development. Their work showed that students may possess competence but still fail to develop a strong disciplinary identity if they are not recognised as legitimate members of the community.

Another important contribution of the framework was its emphasis on sociocultural context. Identity was not viewed as an internal psychological characteristic but as a socially negotiated construct shaped through interaction and recognition. This perspective later became highly influential in STEM and engineering identity research because it highlighted the importance of belonging, legitimacy, and community participation.

Despite its influence, the framework was developed within science education and focused primarily on women of colour in scientific settings. Consequently, questions remained regarding its applicability to engineering, where professional practice, design activities, teamwork, and industry engagement play a more prominent role.

4.3 Expansion Through Physics and STEM Identity Research

Building upon the science identity tradition, Hazari et al. (2010) extended identity research within physics education by introducing interest as a central component of disciplinary identity. Their work retained the dimensions of performance and competence, and recognition, while emphasising the motivational role of interest in shaping persistence intentions.

This extension represented an important theoretical advancement because it linked identity directly to future educational and career decisions. Interest was shown to function not merely as an outcome of positive educational experiences but as an active driver of continued engagement with STEM pathways. Students who reported stronger interest, greater recognition, and higher confidence in their abilities were more likely to persist in STEM-related fields.

Hazari's framework therefore contributed two important developments. First, it strengthened the predictive capacity of identity research by linking identity to persistence and career intentions. Second, it introduced a more explicit motivational dimension that would later become central to engineering identity scholarship.

Nevertheless, the framework remained rooted in physics education. While many of its insights were transferable, engineering education presents unique characteristics that extend beyond those typically associated with science and physics disciplines. Engineering programmes place stronger emphasis on design, problem-solving, teamwork, innovation, professional practice, and interaction with industry. Consequently, scholars increasingly recognised the need for a discipline-specific identity framework capable of capturing these distinctive features.

4.4 Emergence of Engineering Identity as a Distinct Construct

The transition from STEM identity to engineering identity reflected broader developments within engineering education research. During the early 2000s, scholars began examining why some students remained committed to engineering while others left the discipline despite demonstrating adequate academic performance. Traditional explanations based on grades, retention statistics, and technical ability proved insufficient for explaining these patterns.

At the same time, sociocultural studies of engineering education highlighted the importance of participation, belonging, and professional socialisation. Research by Tonso (2006a, 2006b) and Stevens et al. (2008) demonstrated that students developed engineering identities through interaction with peers, engagement in engineering practices, and negotiation of professional roles within engineering communities. These studies suggested that engineering identity was shaped by both technical competence and social participation.

Consequently, engineering identity gradually emerged as a distinct construct that combined elements of STEM identity research with insights from engineering education. Scholars increasingly recognised that becoming an engineer involved not only acquiring technical knowledge but also developing a sense of professional legitimacy, belonging, and identification with engineering culture and practice.

4.5 Godwin's Engineering Identity Model

A major breakthrough occurred when Godwin (2016) adapted earlier STEM identity frameworks specifically for engineering education. Building upon Carlone and Johnson (2007) and Hazari et al. (2010), Godwin conceptualised engineering identity through three dimensions: interest, performance and competence, and recognition.

This model offered several important advantages. First, it provided conceptual clarity by translating identity constructs into an engineering-specific context. Second, it enabled empirical investigation through validated measurement instruments. Third, it established a common language that allowed engineering identity research to develop greater theoretical coherence.

Subsequent studies consistently demonstrated the importance of these dimensions. Interest was associated with motivation and engagement, performance and competence reflected students' confidence in their engineering abilities, and recognition functioned as a mechanism through which students gained legitimacy within engineering communities. Research also suggested that recognition and interest often exerted stronger influence on identity development than technical competence alone.

Despite its widespread adoption, the model is not without limitations. Most empirical validation has occurred within Western higher education environments, and much of the research relies on survey-based methodologies. Consequently, questions remain regarding how these dimensions operate within different sociocultural contexts and how broader influences such as family expectations, institutional structures, and professional systems interact with identity development.

4.6 Evolutionary Synthesis

The progression from science identity to engineering identity reflects a process of theoretical adaptation and disciplinary refinement. Science identity research established the importance of competence, performance, and recognition. Physics identity research expanded this structure by introducing interest as a motivational dimension linked to persistence. Engineering identity scholarship subsequently adapted these dimensions to engineering education while incorporating insights from professional socialisation, participation, and disciplinary practice.

This evolution demonstrates that engineering identity did not emerge as an entirely new construct. Rather, it represents the culmination of several decades of theoretical development across identity research, STEM education, and engineering education. At the same time, the progression reveals important limitations within existing scholarship. Most dominant frameworks have been developed within Western contexts and validated through quantitative approaches, creating potential gaps in understanding how identity develops within diverse cultural, institutional, and professional environments.

These observations provide the foundation for the next section, which examines the major dimensions of engineering identity and evaluates how contemporary scholarship has expanded beyond the traditional tripartite structure. By reviewing these dimensions in greater detail, it becomes possible to understand how engineering identity has evolved from a relatively focused framework into a broader and increasingly multidimensional construct.

To illustrate the theoretical progression discussed in this section, Table 2 summarises the major identity frameworks that have influenced the development of engineering identity scholarship. In addition to highlighting the evolution of key dimensions and contributions, the table identifies important limitations associated with each framework. These limitations provide the basis for the critical evaluation presented throughout this review and help justify the need for broader conceptual, methodological, and contextual development within future engineering identity research.

Table 2. Evolution of Identity Frameworks from Science to Engineering

Framework	Key Authors	Core Dimensions	Major Contribution	Key Limitation
Science Identity Framework	Carlone & Johnson (2007)	Competence, Performance, Recognition	Established disciplinary identity as a multidimensional construct and highlighted recognition as a critical component of identity formation. Provided the theoretical foundation for later STEM and engineering identity models.	Developed within science education and focused primarily on women of colour in science contexts. Limited engineering-specific applicability.
Physics Identity Framework	Hazari et al. (2010)	Interest, Performance and Competence, Recognition	Extended science identity by incorporating interest as a motivational dimension. Demonstrated the relationship between identity and STEM persistence intentions.	Developed within physics education and may not fully capture engineering-specific learning experiences and professional practices.
Engineering Identity Model	Godwin (2016)	Interest, Performance and Competence, Recognition	Adapted STEM identity dimensions to engineering education. Provided a discipline-specific framework and enabled large-scale empirical investigation of engineering identity.	Predominantly validated in Western higher education settings and heavily dependent on survey-based measurement approaches.
Critical Engineering Agency Framework	Godwin et al. (2016)	Agency, Recognition, Interest, Sociopolitical Awareness	Expanded engineering identity by integrating agency, empowerment, and societal contribution. Emphasised engineering as a vehicle for social impact.	Limited empirical application across diverse cultural and educational contexts.
Belonging-Oriented Engineering Identity Research	Rohde et al. (2019); Kajfez et al. (2019); Ortiz et al. (2019)	Identity, Belonging, Community Participation	Highlighted the importance of belonging, peer relationships, and participation in shaping engineering identity development.	Belonging is often treated as a related construct rather than a fully integrated component of engineering identity frameworks.
Gendered and Emotional Engineering Identity Perspectives	Hoch et al. (2020); Wang et al. (2022)	Identity, Emotional Experience, Resilience, Gender Identity	Extended engineering identity research beyond cognitive and social dimensions by incorporating emotional and gender-related experiences.	Empirical evidence remains concentrated in specific populations and Western university contexts.
Contemporary Developmental and Contextual Perspectives	Lockhart & Rambo-Hernandez (2024); Liquete et al. (2025); Treadway et al. (2025)	Developmental Identity, Contextual Experience, Affective Engagement	Conceptualises engineering identity as a dynamic process evolving across educational and professional stages. Highlights contextual and affective influences on identity formation.	Longitudinal and cross-cultural evidence remains limited, particularly outside North America and Europe.

5. Major Engineering Identity Models and Dimensions

5.1 Introduction

As engineering identity scholarship has matured, several dimensions have emerged consistently across theoretical and empirical studies. While early research focused primarily on participation and belonging within engineering communities, subsequent scholarship increasingly sought to identify the specific constructs that explain how individuals come to see themselves as engineers. This effort resulted in the stabilisation of several core identity dimensions, particularly interest, performance and competence, and recognition. These dimensions have become central to contemporary engineering identity research and have been repeatedly validated across different educational settings and student populations.

At the same time, more recent scholarship has expanded beyond these foundational constructs by incorporating agency, belonging, emotional experience, and developmental progression. These developments reflect growing recognition that engineering identity is not a static attribute but a dynamic process shaped by motivational, social, emotional, and contextual influences. This section reviews the major dimensions that currently define engineering identity scholarship and examines how they contribute to understanding identity formation within engineering education.

5.2 Interest

Interest is widely recognised as one of the most influential dimensions of engineering identity. It refers to an individual's intrinsic attraction toward engineering activities, concepts, and career pathways. Interest influences how students engage with engineering-related experiences and often serves as an entry point into identity development. Students who find engineering personally meaningful are more likely to participate actively in learning activities, pursue engineering opportunities, and persist despite academic challenges.

The importance of interest became particularly evident through the work of Hazari et al. (2010), who identified interest as a significant predictor of persistence within STEM pathways. Godwin (2016) subsequently incorporated interest into the engineering identity framework, where it became one of the three foundational dimensions. Subsequent studies consistently demonstrated that students with stronger interest in engineering tend to report higher levels of identity salience, motivation, and persistence. Related studies also show that engineering identity is associated with students' career interests, professional expectations, and confidence in pursuing engineering-related pathways (Choe & Borrego, 2020; Choe et al., 2019; Godwin & Kirn, 2020).

Interest also interacts closely with other identity dimensions. Recognition from peers, lecturers, and family members may strengthen interest by reinforcing students' perceptions that engineering is an appropriate and attainable pathway. Similarly, successful performance experiences often increase interest by enhancing confidence and enjoyment. Consequently, interest functions not only as a motivational factor but also as a mechanism through which students begin to internalise engineering as part of their developing self-concept.

However, interest should not be viewed as a stable trait. Research suggests that interest evolves through exposure, participation, and meaningful educational experiences. Design projects, industry engagement, authentic engineering tasks, and mentorship opportunities may all contribute to strengthening students' engineering interest over time.

5.3 Performance and Competence

Performance and competence represent students' perceptions of their ability to understand, apply, and demonstrate engineering knowledge and skills. Although these concepts were originally treated separately within science identity research, they are commonly combined within engineering identity scholarship because both relate to students' confidence in performing engineering-related tasks.

Competence refers to students' understanding of engineering concepts and their belief that they possess the knowledge necessary to succeed within the discipline. Performance refers to the ability to demonstrate that knowledge through engineering activities, problem-solving tasks, design projects, communication, and professional practice. Together, these constructs contribute to students' perceptions that they are capable of functioning effectively as engineers.

Empirical studies consistently indicate that performance and competence play a significant role in engineering identity development. Students who experience success in engineering coursework, laboratory activities, and project-based learning environments often develop stronger engineering self-concepts. Positive performance experiences reinforce beliefs about capability and strengthen identification with engineering.

Nevertheless, research also suggests that performance and competence alone are insufficient for sustaining a strong engineering identity. Students may achieve high levels of academic success while still failing to identify strongly with engineering if they do not experience recognition or belonging. This observation highlights an important distinction between academic achievement and identity formation. Competence contributes to identity development, but it does not automatically produce identity.

Recent scholarship further suggests that students' interpretations of competence may be shaped by contextual factors such as institutional culture, assessment practices, peer comparison, and educational expectations. Consequently, performance and competence should be understood not only as individual capabilities but also as socially interpreted experiences that contribute to identity construction.

5.4 Recognition

Recognition is widely regarded as the most distinctive and influential dimension within engineering identity scholarship. Recognition refers to the extent to which individuals perceive themselves, and are perceived by others, as legitimate members of the engineering community. It captures the social validation necessary for identity internalisation and reflects the relational nature of identity development.

The importance of recognition was first highlighted by Carlone and Johnson (2007), who argued that competence and performance become meaningful only when recognised by others. This insight has been repeatedly supported within engineering identity research. Studies consistently demonstrate that recognition from family members, peers, lecturers, mentors, and industry professionals significantly influences whether students come to view themselves as engineers. Recent work has further shown that recognition experiences vary across race, gender, and first-generation student backgrounds, indicating that recognition is not experienced uniformly across student groups (McIntyre et al., 2024; Verdín et al., 2024).

Recognition operates at multiple levels. Self-recognition reflects students' internal acceptance of an engineering identity, whereas external recognition reflects affirmation from social and professional communities. Both forms of recognition are important because identity development involves ongoing interaction between personal self-understanding and social validation.

Research further suggests that recognition often exerts stronger influence on engineering identity than technical competence alone. Students who receive encouragement, affirmation, and validation are more likely to persist within engineering pathways and develop stronger professional identification. Conversely, environments characterised by exclusion, limited feedback, or weak support structures may hinder identity development even among academically capable students.

These findings reinforce the view that engineering identity is fundamentally social. Becoming an engineer requires more than acquiring knowledge; it also requires being recognised as an engineer by oneself and by others.

5.5 Agency and Societal Contribution

The Critical Engineering Agency framework proposed by Godwin et al. (2016) expanded engineering identity scholarship beyond the traditional tripartite structure by incorporating concepts related to agency and societal contribution. Agency refers to students' perceptions that they can use engineering knowledge and skills to influence society, solve meaningful problems, and contribute to positive change.

The Critical Engineering Agency framework introduced this perspective by emphasising the relationship between engineering identity and sociopolitical awareness. From this perspective, engineering identity is not limited to technical competence or professional recognition. It also involves beliefs about purpose, impact, and responsibility.

The incorporation of agency represents an important conceptual expansion because it acknowledges that students often develop stronger identification with engineering when they perceive engineering as meaningful and socially relevant. Students who believe their work can improve communities, address societal challenges, or contribute to sustainable development may experience stronger motivation and deeper professional commitment.

Although agency has not yet achieved the same empirical stability as interest, performance and competence, and recognition, it provides valuable insight into how identity intersects with purpose, values, and social responsibility. As engineering increasingly addresses global challenges such as sustainability, climate change, and technological transformation, agency may become an increasingly important component of engineering identity development.

5.6 Belonging and Community Participation

Belonging has emerged as another important extension of engineering identity research. While closely related to recognition, belonging refers specifically to students' feelings of acceptance, inclusion, and connection within engineering communities. It captures the emotional and relational aspects of participation that influence whether students perceive themselves as legitimate members of the discipline.

Studies examining design teams, project-based learning environments, mentoring relationships, and learning communities consistently demonstrate that belonging contributes positively to engineering identity development. Belonging has also been shown to interact with social relationships, design experiences, peer support, and persistence-related constructs, particularly among students from underrepresented backgrounds (Rohde et al., 2019; Kajfez et al., 2019; Ortiz et al., 2019; Polmear et al., 2024; Verdín et al., 2018; Earle et al., 2024). Students who feel connected to peers, lecturers, and professional communities are more likely to participate actively and persist within engineering programmes.

Communities of Practice Theory provides an important explanation for this relationship. Identity develops through participation, and participation is more likely when individuals feel accepted within the community. Consequently, belonging functions as both a psychological outcome and a mechanism that supports identity formation.

Belonging may be particularly important for students from underrepresented groups, who often face additional challenges related to legitimacy, inclusion, and representation. In such contexts, supportive communities and inclusive learning environments may play a critical role in strengthening engineering identity.

5.7 Emotional and Developmental Dimensions

Recent research increasingly recognises that engineering identity is influenced by emotional experiences and developmental processes. Recent studies have examined these issues through gendered, affective, developmental, and context-sensitive perspectives, showing that engineering identity may be shaped by emotional experience, resilience, gender, stability, and educational transition (Hoch et al., 2020; Wang et al., 2022; Lockhart & Rambo-Hernandez, 2024; Lockhart et al., 2025; Liquete et al., 2025; Treadway et al., 2025). Earlier models tended to emphasise cognitive, motivational, and social dimensions, but contemporary scholarship highlights the importance of affective experiences such as confidence, anxiety, resilience, stress, and emotional engagement.

Engineering students continuously interpret successes, failures, feedback, and challenges. These interpretations shape how they understand their competence, belonging, and future potential within engineering. Positive emotional experiences may reinforce identity development, whereas repeated negative experiences may weaken confidence and increase disengagement.

At the same time, engineering identity is increasingly viewed as developmental rather than static. Identity evolves across educational stages, beginning with early STEM exposure and continuing through undergraduate study, postgraduate development, industrial experience, and professional practice. Different dimensions may become more or less important at different stages. For example, interest may dominate early identity formation, while recognition, belonging, and professional validation become increasingly significant as students progress toward professional practice.

This developmental perspective highlights that engineering identity should not be understood as a fixed outcome. Rather, it is an evolving process shaped by accumulated experiences, opportunities for participation, and ongoing negotiation of professional self-understanding.

5.8 Synthesis of Engineering Identity Dimensions

The literature reviewed in this section demonstrates that engineering identity has evolved from a relatively narrow focus on interest, performance and competence, and recognition toward a broader multidimensional construct. While the traditional tripartite structure remains the most widely adopted framework, contemporary scholarship increasingly recognises the importance of agency, belonging, emotional experience, and developmental progression.

Taken together, these dimensions suggest that engineering identity is best understood as a dynamic process involving motivation, capability, recognition, participation, purpose, and professional self-understanding. No single dimension is sufficient on its own. Rather, engineering identity emerges through the interaction of multiple factors that collectively shape how individuals perceive themselves and are perceived by others as engineers.

This multidimensional understanding provides a more comprehensive foundation for examining engineering identity development. However, the expansion of engineering identity dimensions has also introduced new theoretical, methodological, and contextual challenges. As the field continues to grow, critical examination is needed to determine how these dimensions relate to one another and whether existing frameworks adequately capture the complexity of identity development across diverse educational settings. These issues are examined critically in the following section.

6. Critical Analysis of Current Engineering Identity Scholarship

6.1 Introduction

Engineering identity research has expanded significantly over the past two decades. The field has progressed from small-scale sociocultural investigations toward more structured theoretical models and large-scale empirical validation studies. Core dimensions such as interest, performance and competence, and recognition have become relatively stabilised, and engineering identity is now widely recognised as an important construct for understanding student engagement, persistence, belonging, and professional development.

Despite these advances, important challenges remain. A critical examination of the literature reveals several recurring limitations that constrain theoretical development and practical application. These challenges include conceptual fragmentation across competing theoretical perspectives, methodological concentration around survey-based approaches, strong dependence on Western educational contexts, limited understanding of identity development over time, and ongoing difficulties in integrating contextual influences into existing frameworks. Collectively, these issues suggest that engineering identity scholarship has reached a stage where further advancement requires greater theoretical integration, methodological diversification, and contextual sensitivity.

6.2 Conceptual Fragmentation

One of the most significant challenges within engineering identity research is conceptual fragmentation. Although engineering identity is frequently discussed as a unified construct, the literature reveals considerable variation in how identity is defined, operationalised, and interpreted.

Some scholars conceptualise engineering identity primarily through the dimensions of interest, performance and competence, and recognition. Others emphasise belonging, agency, motivation, participation, professional identity, emotional experience, or career aspirations. While these perspectives provide valuable insights, they often operate independently rather than being integrated into a coherent conceptual framework.

This fragmentation partly reflects the interdisciplinary nature of engineering identity scholarship. The field draws from psychology, sociology, STEM education, science education, and engineering education, each of which contributes different assumptions about how identity develops. As a result, engineering identity is sometimes treated as a psychological construct, sometimes as a sociocultural process, and sometimes as a motivational mechanism. These different perspectives are not necessarily contradictory, but they are not always theoretically integrated.

The consequence is that researchers may use the same term, "engineering identity," to describe substantially different phenomena. This creates challenges for theory building, comparison across studies, and cumulative knowledge development. Future research therefore requires greater conceptual clarity regarding the relationships between identity dimensions, identity processes, and contextual influences.

6.3 Methodological Concentration

A second limitation concerns the methodological concentration of engineering identity research. Since the widespread adoption of Godwin’s (2016) engineering identity model, much of the literature has relied heavily on survey-based methodologies and quantitative measurement approaches.

The popularity of these approaches is understandable. Survey instruments allow researchers to examine large populations, compare institutions, and test statistical relationships between identity and outcomes such as persistence, academic performance, and career intentions. Several studies have contributed to this measurement tradition by developing or validating instruments for examining engineering identity among undergraduate and postgraduate students (Borrego et al., 2018; Lockhart et al., 2025). These studies have contributed significantly to the empirical validation of engineering identity dimensions and have strengthened the reliability of measurement practices.

However, the dominance of survey-based research also introduces limitations. Identity is fundamentally a meaning-making process shaped by lived experience, social interaction, and contextual interpretation. Survey instruments may capture patterns and relationships, but they cannot fully explain how students interpret recognition experiences, negotiate belonging, respond to institutional expectations, or construct professional self-understandings.

Consequently, important aspects of identity development may remain underexplored. Qualitative approaches, including interviews, focus groups, ethnography, narrative inquiry, and longitudinal case studies, offer opportunities to examine the complexity of identity formation in greater depth. Greater methodological diversity would therefore strengthen the field by providing richer understanding of how identity develops across different educational and professional contexts.

6.4 Western Dominance and Contextual Limitations

A third challenge concerns the geographical and cultural concentration of engineering identity scholarship. Many of the most influential theories, frameworks, and empirical studies have been developed within North American or Western higher education systems.

This concentration has generated valuable knowledge and contributed substantially to the development of the field. However, it also raises questions regarding contextual applicability. Educational systems differ in their institutional structures, cultural expectations, professional pathways, and relationships between education and employment. Consequently, identity dimensions that function effectively within one context may operate differently in another.

The issue is particularly important in collectivist societies where family expectations, community obligations, and social relationships may exert stronger influence on educational and career decisions. Similarly, policy-driven education systems may shape engineering identity through accreditation requirements, national development priorities, and labour market expectations. These contextual influences are often discussed as background variables rather than being incorporated directly into engineering identity frameworks.

Recent scholarship has begun to acknowledge these limitations, yet empirical evidence from non-Western settings remains relatively limited. Emerging studies from Asian, Malaysian, and other culturally diverse contexts indicate that engineering identity may be shaped by gender, ethnicity, family, professional practice, and local educational structures in ways that require further contextual investigation (DeBoer et al., 2019; Espino et al., 2024; Mastam et al., 2025; Koul, 2018). Engineering identity research therefore risks presenting theoretically robust but contextually incomplete explanations of identity development. Expanding research beyond dominant Western contexts is essential for establishing whether existing models possess broader explanatory relevance or require contextual adaptation.

6.5 Limited Understanding of Identity Development Across Time

Although engineering identity is frequently described as developmental, much of the literature examines identity at a single point in time. Cross-sectional studies dominate the field, providing valuable snapshots of students' identity perceptions but offering limited insight into how identity evolves across educational and professional transitions.

Identity development is unlikely to occur as a linear or stable process. Students encounter multiple experiences that may strengthen, weaken, or transform identity over time. Early STEM exposure, university entry, design experiences, internships, industrial training, postgraduate study, and workplace transition may each contribute differently to identity formation. Yet relatively few studies examine these transitions longitudinally.

The lack of longitudinal evidence creates important gaps in understanding. It remains unclear how identity trajectories develop, which experiences are most influential at different stages, and whether identity dimensions change in importance across educational pathways. Addressing these questions would significantly strengthen theoretical explanations of engineering identity development.

Future research should therefore move beyond isolated educational stages and examine identity as a developmental continuum extending from early education to professional practice.

6.6 Future Conceptual Challenges

Beyond the limitations discussed above, several broader conceptual challenges remain unresolved. First, existing frameworks continue to prioritise individual-level dimensions while providing limited explanation of how institutional, cultural, and structural influences shape identity development. Second, the relationship between engineering identity and related constructs such as belonging, professional identity, agency, and employability remains insufficiently clarified. Third, the increasing expansion of identity dimensions raises questions regarding conceptual boundaries and theoretical coherence.

As the field continues to evolve, researchers must balance conceptual expansion with theoretical clarity. The addition of new dimensions may enrich understanding, but excessive expansion risks creating fragmented frameworks that lack explanatory coherence. Future scholarship should therefore focus not only on identifying additional identity influences but also on explaining how these influences interact within broader identity development processes.

Ultimately, the future of engineering identity research depends on its ability to integrate individual, social, cultural, institutional, and professional influences into more comprehensive explanatory frameworks. Such integration would allow engineering identity scholarship to move beyond isolated dimensions toward a more holistic understanding of how engineers come to see themselves, and are recognised by others, as members of the engineering profession.

6.7 Synthesis of Critical Challenges

The critical analysis presented in this section suggests that engineering identity scholarship has achieved considerable theoretical and empirical maturity, yet several important limitations continue to constrain the field. The issues discussed in this section, including theoretical inconsistency, methodological concentration, geographical imbalance, limited longitudinal evidence, and unresolved conceptual challenges, indicate that engineering identity research remains an evolving area of inquiry.

These observations do not diminish the contributions of existing scholarship. Rather, they highlight opportunities for future advancement. The next section builds upon these insights by proposing emerging research directions that may contribute to more integrated, contextually responsive, and theoretically robust approaches to engineering identity research.

7. Emerging Research Directions

7.1 Introduction

The critical analysis in the previous section indicates that engineering identity research has reached an important point of development. The field has established strong foundational dimensions, particularly interest, performance and competence, and recognition. It has also expanded to include agency, belonging, emotional experience, and developmental progression. However, several limitations remain, especially in relation to contextual applicability, methodological diversity, longitudinal understanding, and theoretical integration.

This section outlines emerging research directions that can strengthen future engineering identity scholarship. Rather than proposing a completely new model, the section identifies areas where existing models can be extended, refined, and contextualised. These directions are particularly important for advancing engineering identity research beyond dominant Western contexts and toward more inclusive, developmental, and globally relevant understandings of identity formation.

7.2 Contextualising Engineering Identity

Future engineering identity research should give greater attention to contextual influences. Existing models have contributed significantly to understanding identity dimensions, but they often give limited attention to how cultural, institutional, and professional environments shape identity development. This is important because engineering identity does not develop in isolation from the educational systems and social structures within which students learn.

Contextualising engineering identity means examining how identity is shaped by family expectations, institutional culture, accreditation systems, national development priorities, labour market conditions, and professional pathways. In some contexts, students may enter engineering because of personal interest. In others, their decisions may be shaped strongly by family encouragement, social mobility aspirations, or national workforce demands. These differences suggest that engineering identity frameworks should not assume a universal pathway of identity development.

Future studies should therefore examine how established dimensions such as interest, performance and competence, and recognition operate within specific cultural and institutional settings. Rather than simply applying existing instruments across contexts, researchers should investigate whether the meanings of these dimensions vary across educational systems. For example, recognition may come not only from lecturers and peers, but also from family members, community expectations, industry mentors, or professional bodies. Similarly, competence may be interpreted not only through academic performance, but also through employability, communication, teamwork, and readiness for professional practice.

7.3 Expanding Global South Perspectives

A second important direction is the expansion of engineering identity research within Global South contexts. Much of the existing literature has been developed within North American and Western European settings. While these studies are valuable, they do not fully represent the diversity of engineering education systems worldwide.

Engineering education in Global South contexts may be shaped by different economic priorities, cultural values, institutional capacities, and professional expectations. In many developing or rapidly industrialising countries, engineering is closely linked to national development, infrastructure growth, technological modernisation, and social mobility. These conditions may influence how students understand the meaning and value of becoming engineers.

Expanding Global South perspectives would help determine whether dominant engineering identity models are universally applicable or require contextual adaptation. Such research could also reveal new identity influences that are less visible in Western-centred studies. These may include collectivist family expectations, community responsibility, religious or moral values, national development narratives, and industry readiness concerns.

Importantly, expanding Global South scholarship should not be treated merely as adding more geographical cases. It should involve theoretical contribution. Studies from Asia, Africa, Latin America, and other underrepresented regions can challenge existing assumptions and help develop more globally responsive engineering identity frameworks.

Within this broader Global South agenda, ASEAN countries represent a particularly important context for future engineering identity research. Although ASEAN nations differ in their educational systems, economic development, and industrial priorities, many share common characteristics, including policy-driven higher education reforms, rapid industrialisation, strong emphasis on graduate employability, and collectivist cultural values. These characteristics may influence how engineering students develop professional identities, experience recognition, and perceive their future roles as engineers. Regional initiatives related to engineering mobility, accreditation, and workforce development also provide opportunities to examine how engineering identity develops across diverse yet interconnected educational environments. Consequently, ASEAN countries offer a valuable setting for extending and testing engineering identity frameworks beyond the Western contexts in which most dominant models were originally developed.

7.4 Industry Readiness and Employability

Another important research direction concerns the relationship between engineering identity, industry readiness, and employability. Existing engineering identity literature often focuses on students' experiences within educational institutions, but identity development is also shaped by students' understanding of professional practice and workplace expectations.

Engineering is a practice-oriented profession. Engineering outreach, industry-academia engagement, and employability-oriented learning experiences may therefore contribute to identity development by connecting students' academic learning with professional expectations and workplace realities (Balakrishnan & Azman, 2017; DeBoer et al., 2019). Therefore, students' identity development may be strengthened when they experience authentic engineering work through internships, industrial training, capstone projects, site visits, industry mentoring, and professional engagement. These experiences allow students to connect academic learning with real-world engineering practice and may help them see themselves more clearly as future engineers.

Future research should examine how employability-related experiences contribute to engineering identity development. This includes not only technical competence, but also communication, teamwork, ethical judgment, leadership, problem-solving, adaptability, and professional confidence. Industry readiness may function as a bridge between academic identity and professional identity, helping students move from "studying engineering" to "becoming engineers."

Regional accreditation and professional registration systems may also shape engineering identity by defining what counts as legitimate engineering competence and performance. For example, in Malaysia, the Board of Engineers Malaysia and Washington Accord-aligned accreditation expectations emphasise outcome-based competencies such as problem analysis, design ability, ethical responsibility, communication, teamwork, and lifelong learning. These requirements can influence how students understand the performance and competence dimensions of engineering identity by connecting academic learning with externally recognised professional standards. In practical terms, accreditation expectations may shape curriculum design, capstone assessment, industrial training requirements, and graduate attribute evaluation, thereby making competence and performance visible through both academic and professional benchmarks. In this sense, accreditation and professional bodies do not merely regulate engineering programmes; they also help define the qualities through which students learn to recognise themselves, and be recognised by others, as future engineers.

Greater attention should also be given to the role of industry professionals, professional bodies, and accreditation systems in shaping engineering identity. Recognition from lecturers and peers remains important, but recognition from industry mentors and workplace supervisors may carry particular significance as students approach graduation and professional practice.

7.5 Identity Across Educational and Professional Stages

Future research should also examine engineering identity as a developmental continuum rather than a fixed outcome. Current studies often focus on specific educational stages, such as first-year students, undergraduate students, or postgraduate students. While these studies provide useful insights, they do not fully explain how identity develops across transitions.

Engineering identity may begin before university through early STEM exposure, school experiences, family encouragement, and informal learning. It may then be strengthened or weakened during undergraduate education through coursework, projects, peer interaction, assessment, and industrial exposure. Later, it may continue to develop during postgraduate study, professional training, and workplace practice.

Longitudinal research is needed to understand how engineering identity changes across these stages. Such research could examine which experiences are most influential at different points, how recognition changes over time, and how students respond to challenges, failure, or uncertainty. It could also explore how students move from aspirational interest to academic participation and eventually to professional self-identification.

Understanding engineering identity development across stages would help educators design more effective interventions. Early exposure may support interest, undergraduate experiences may strengthen competence and belonging, while industry engagement may reinforce professional recognition and employability confidence.

7.6 Toward Integrated Engineering Identity Frameworks

The future of engineering identity research also requires more integrated frameworks. Existing studies have identified many important dimensions, including interest, performance and competence, recognition, agency, belonging, emotion, motivation, and professional readiness. However, these constructs are not always clearly connected.

An integrated framework should explain how these dimensions interact rather than treating them as separate variables. For example, interest may motivate participation, participation may produce competence, competence may invite recognition, recognition may strengthen belonging, and belonging may reinforce long-term professional identification. Similarly, industry exposure may transform academic identity into professional identity by providing authentic recognition and practice-based confidence.

Integrated frameworks should also connect individual, social, institutional, and professional levels of identity development. At the individual level, students develop interest, confidence, motivation, and future self-concepts. At the social level, they experience recognition, belonging, mentorship, and peer validation. At the institutional level, curricula, assessment, pedagogy, and university culture shape opportunities for identity practice. At the professional level, industry exposure, accreditation expectations, and employability demands influence how students understand engineering as a future career.

Such integration would help move engineering identity research beyond isolated constructs and toward a more holistic explanation of how engineering identity develops.

7.7 Methodological Directions

Future engineering identity research should also adopt more diverse methodological approaches. Quantitative studies have provided valuable evidence regarding identity dimensions and their relationships with persistence, belonging, and career intention. However, qualitative and mixed-methods approaches are needed to understand how students interpret identity-related experiences.

Qualitative studies can capture the meanings students attach to recognition, belonging, competence, and professional expectations. Longitudinal qualitative work can reveal how identity develops across time and transitions. Mixed-methods studies can combine the strength of measurement with the depth of lived experience. Comparative cross-cultural studies can also examine whether engineering identity dimensions operate similarly or differently across educational systems.

Greater methodological diversity would strengthen the field by allowing researchers to examine both patterns and processes. This is especially important for understanding identity development in contexts where existing instruments may not fully capture local meanings.

7.8 Synthesis of Future Directions

The future of engineering identity research lies in moving from established dimensional models toward more contextual, developmental, and integrated understandings of identity formation. Existing models remain valuable, but they should be extended through research that examines cultural context, Global South perspectives, industry readiness, educational transitions, and methodological diversity.

These directions do not reject existing engineering identity frameworks. Rather, they build upon them by asking how identity dimensions operate across different settings, stages, and systems. Such work can help develop more inclusive and globally relevant understandings of what it means to become an engineer. The concluding section synthesises these contributions and reiterates the importance of more integrated and contextually responsive engineering identity research.

8. Conclusion

Engineering identity has emerged as one of the most influential constructs in engineering education research because of its ability to explain students' engagement, persistence, sense of belonging, and professional development. As engineering education increasingly seeks to prepare graduates who are not only technically competent but also professionally committed and socially responsive, understanding how engineering identity develops has become an important area of scholarly inquiry.

This review traced the theoretical progression of engineering identity research from broader identity theories through science identity and STEM identity scholarship to contemporary engineering identity frameworks. The review demonstrated that engineering identity is grounded in a diverse set of theoretical traditions, including Identity Theory, Social Identity Theory, Communities of Practice, Social Cognitive Career Theory, Identity-Based Motivation Theory, and Possible Selves Theory. These perspectives collectively contributed to the development of engineering identity as a multidimensional construct shaped by individual, social, and contextual influences.

The review further highlighted the significant contributions of Carlone and Johnson's (2007) Science Identity Framework, Hazari et al.'s (2010) Physics Identity Framework, and Godwin's (2016) Engineering Identity Model. Together, these frameworks established the dimensions of interest, performance and competence, and recognition as central components of engineering identity development. Over time, however, engineering identity scholarship has expanded beyond this traditional tripartite structure to include agency, belonging, emotional experience, and developmental perspectives, reflecting a growing appreciation of the complexity of identity formation.

Despite substantial progress, several challenges continue to constrain the field. The review identified conceptual fragmentation, methodological concentration, contextual limitations, and limited longitudinal understanding as recurring issues within the literature. Engineering identity is often examined through different theoretical lenses and research approaches, creating difficulties in integrating findings across studies. Furthermore, much of the existing evidence remains concentrated within Western educational contexts, raising important questions regarding the broader applicability of dominant frameworks across diverse cultural, institutional, and professional environments.

In response to these challenges, this review proposed several future directions for engineering identity research. These include greater attention to contextual influences, increased representation of Global South perspectives, stronger integration of industry readiness and employability considerations, expanded longitudinal research, and the development of more holistic and integrated identity frameworks. Collectively, these directions can help advance engineering identity scholarship toward more comprehensive and contextually responsive understandings of identity development.

The main contribution of this review is that it consolidates the theoretical development of engineering identity into a clearer and more integrated scholarly narrative. Specifically, the review shows how engineering identity evolved from broader identity theories, science identity, and STEM identity research before becoming established around the dimensions of interest, performance and competence, and recognition. It also demonstrates that contemporary engineering identity scholarship has moved beyond this tripartite structure by incorporating agency, belonging, emotional experience, developmental progression, contextual variation, and professional readiness. By synthesising these developments, the paper provides a clearer foundation for future engineering identity research, particularly in non-Western, ASEAN, and Global South contexts where sociocultural, institutional, accreditation, and employability conditions may shape identity formation differently.

Ultimately, engineering identity should not be viewed as a fixed characteristic possessed by students. Rather, it is a dynamic and evolving process through which individuals develop interest, confidence, recognition, belonging, and professional self-understanding within engineering communities. As engineering education continues to respond to changing societal, technological, and workforce demands, a deeper understanding of engineering identity will remain essential for supporting the development of future engineers who are capable, committed, and prepared to contribute meaningfully to society.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Between ABET and EUR-ACE Accreditation: A Decision-Oriented Framework for Engineering Programs Outside the U.S. and Europe

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Abstract
Engineering program accreditation plays a critical role in assuring educational quality, supporting graduate mobility, and enhancing institutional credibility in an increasingly globalized higher education landscape. Among the most influential accreditation systems worldwide, ABET and the EUR-ACE® label represent distinct accreditation paradigms shaped by different professional, academic, and governance traditions. While both frameworks are widely adopted beyond their regions of origin, institutions outside the United States and Europe face limited guidance in selecting the accreditation pathway that best aligns with their mission, graduate trajectories, and external environment. This study addresses this gap through a qualitative, document-based comparative analysis of ABET and EUR-ACE accreditation frameworks. Official accreditation criteria, policy documents, and peer-reviewed literature are systematically analyzed to examine differences in accreditation philosophy, student outcome structures, recognition mechanisms, and mobility pathways. Rather than ranking the two systems, the study develops a decision-oriented analytical framework that supports strategic accreditation choice based on institutional objectives, labor-market orientation, and academic mobility considerations. The analysis shows that while ABET is strongly aligned with professional practice and industry recognition, EUR-ACE is more closely embedded in academic mobility and qualification transparency within the European Higher Education Area. The proposed framework provides institutional leaders and policymakers with a structured tool to align accreditation decisions with regional context and long-term strategic goals.

Keywords: Engineering accreditation; ABET; EUR-ACE®; decision-oriented framework; international engineering programs; graduate mobility; quality assurance; accreditation strategy.

List of Abbreviations

- **ABET** – Accreditation Board for Engineering and Technology
- **EUR-ACE** – European Accredited Engineer
- **ENAEE** – European Network for Accreditation of Engineering Education
- **ENQA** – European Association for Quality Assurance in Higher Education
- **EHEA** – European Higher Education Area
- **EQF** – European Qualifications Framework
- **ECTS** – European Credit Transfer and Accumulation System
- **ESG** – Standards and Guidelines for Quality Assurance in the European Higher Education Area
- **IEA** – International Engineering Alliance
- **WA** or **Washington Accord** – Washington Accord (spell out first, then acronym if used)
- **SO** – Student Outcomes
- **CQI** – Continuous Quality Improvement
- **GCC** – Gulf Cooperation Council
- **MENA** – Middle East and North Africa

Introduction

Engineering education is widely recognized as a strategic driver of national development, industrial productivity, and technological innovation. As economies transition toward knowledge-intensive and digitally interconnected models, the demand for engineers capable of working across borders, collaborating in heterogeneous teams, and solving complex, real-world problems has increased significantly (UNESCO, 2021; OECD, 2019). In this context, ensuring that engineering graduates possess the required competencies is not only a matter of institutional accountability but also a structural requirement for national competitiveness. Accreditation frameworks function as formal assurance mechanisms that verify the quality, relevance, and consistency of engineering programs. They assess whether programs achieve expected learning outcomes, maintain academic rigor, provide adequate laboratory and design experiences, and

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operate under effective internal quality systems (Dill & Beerkens, 2010; ENQA, 2015).

Among the various accreditation models that have gained international prominence, ABET (formerly the Accreditation Board for Engineering and Technology) and EUR-ACE® (administered by the European Network for Accreditation of Engineering Education, ENAEE) stand as the two most influential and widely recognized frameworks. While ABET originated in the United States and EUR-ACE emerged within the European Higher Education Area (EHEA), both now operate transnationally and are increasingly sought by engineering programs outside their regions of origin (Augusti, 2008; Campbell & Wolfenden, 2016). Their influence extends across Asia, Africa, Latin America, and the Middle East, where institutions pursue accreditation both to strengthen internal quality practices and to enhance graduate mobility in an increasingly competitive global labor market (Knight, 2013; Al-Yahya & Barrage, 2010).

Despite shared objectives, ABET and EUR-ACE are grounded in distinct policy environments, educational traditions, and strategic orientations. ABET accreditation reflects the North American emphasis on outcomes-based assessment, program-level continuous improvement, and alignment with professional engineering practice (Lattuca et al., 2006; Rogers, 2006). It is closely linked to professional licensure pathways, industry expectations, and longstanding relationships between academia and professional engineering societies. The ABET framework defines student competencies in terms of problem-solving ability, design capacity, ethical awareness, teamwork, communication skills, lifelong learning, and contemporary technical knowledge (ABET, 2024). Its global recognition is reinforced by alignment with multinational engineering employers and with international agreements such as the Washington Accord, which promotes mutual recognition of accredited engineering qualifications (International Engineering Alliance, 2021).

In contrast, EUR-ACE is situated within the Bologna Process, which seeks to harmonize higher education structures across Europe through comparable degree cycles, qualification frameworks, and credit transfer mechanisms (Clarke, 2021; European Commission, 2020). The EUR-ACE label emphasizes academic transparency, mobility, and compatibility across national education systems rather than professional licensure alone. The framework specifies program requirements at both Bachelor and Master levels and aligns expected learning outcomes with the European Qualifications Framework (EQF) and the Standards and Guidelines for Quality Assurance in the European Higher Education Area (ESG) (ENAEE, 2023; ENQA, 2015). As such, EUR-ACE situates engineering programs within a broader governance architecture designed to promote student mobility, mutual recognition of academic credentials, and structured progression to advanced studies across Europe (Maffioli & Augusti, 2003; Augusti, 2008).

For engineering programs outside Europe and the United States, the choice between ABET and EUR-ACE is not merely technical. It represents a strategic institutional decision shaped by national policy priorities, graduate mobility patterns, labor market orientation, industry partnerships, and aspirations for international visibility. Institutions in the Gulf region and parts of Asia, for example, have adopted ABET accreditation to strengthen recognition among international employers and align curricula with global industry standards (Al-Yahya & Barrage, 2010). In contrast, universities in North Africa, Turkey, and parts of Eastern Europe have increasingly turned to EUR-ACE to support student mobility into European master's and doctoral programs and to align with regional higher education convergence policies (Campbell & Wolfenden, 2016; Clarke, 2021).

Despite the growing importance of this strategic choice, comparative studies of ABET and EUR-ACE remain limited in analytical depth. Existing discussions tend to focus on procedural characteristics, surface-level criteria, or isolated institutional experiences. What is largely missing is a structured analysis that situates both accreditation systems within their broader governance logics, accreditation philosophies, and graduate mobility frameworks. This gap is significant, as accreditation decisions influence not only curriculum design and assessment practices but also institutional identity, international partnerships, recognition pathways, and long-term strategic positioning (Hazelkorn, 2015; Marginson, 2016).

At the same time, the global shift toward competency-based engineering education has further increased the strategic importance of accreditation. As engineering programs place greater emphasis on problem solving, interdisciplinary collaboration, and real-world design, accreditation frameworks function not only as compliance instruments but also as drivers of curricular reform and organizational change (Jesiek et al., 2010). In this context, accreditation choice shapes how institutions define learning outcomes, engage with industry, and support graduate trajectories (Crawley et al., 2014; Walther & Radcliffe, 2007).

Against this background, this paper examines ABET and EUR-ACE as global models of engineering accreditation through a comparative and decision-oriented lens. The analysis focuses on their philosophical and policy foundations, student outcome structures, approaches to recognition and mobility, and the implications of these differences for engineering programs operating outside the United States and Europe. Rather than ranking the two systems or proposing their integration, the study aims to clarify how their distinct orientations align with different institutional missions and external environments.

Methodologically, the study adopts a qualitative, document-based comparative approach, drawing on official accreditation frameworks and peer-reviewed literature. The contribution of the paper lies in conceptualizing accreditation choice as a form of institutional positioning and in proposing a decision-oriented analytical framework to support universities, accreditation committees, and policymakers in aligning accreditation pathways with institutional objectives and regional contexts.

Accreditation Philosophies: Foundations and Governance Logics

This study adopts a qualitative, document-based comparative approach. The analysis draws on official accreditation criteria, policy documents, and peer-reviewed literature to examine the philosophical foundations, governance logics, and outcome structures of ABET and EUR-ACE. The comparison proceeds through thematic identification of key accreditation dimensions, followed by cross-framework mapping and interpretive synthesis. The objective is not to evaluate or rank accreditation systems, but to support strategic accreditation decision-making for engineering programs operating outside the United States and Europe.

Although ABET and EUR-ACE are both designed to assure the quality of engineering education, they are grounded in distinct historical trajectories and policy environments. These differences shape how each framework defines engineering competence, professional identity, and institutional accountability. Understanding these underlying philosophies is important because accreditation is not merely a technical procedure. It reflects broader assumptions about the role of engineers in society and the relationship between universities, professional practice, and governance systems.

The ABET Model: Professional Competence and Continuous Improvement

ABET emerged in the early twentieth century in parallel with industrial expansion and the professionalization of engineering in the United States. Its foundational logic is rooted in engineering as a regulated profession, where competence is demonstrated through standardized preparation, ethical responsibility, and alignment with professional practice (Lattuca et al., 2006).

Within this model, accreditation emphasizes professional readiness, problem solving and design capability, outcomes-based assessment, and continuous quality improvement. Graduates are expected to enter engineering practice with the technical, analytical, and professional skills required for immediate contribution. Continuous improvement is treated as an institutional obligation, supported by systematic assessment and evidence-based decision making (Rogers, 2006).

This orientation positions the university as responsible for producing engineers who are technically proficient, ethically grounded, communicatively effective, and capable of sustained professional growth. Accordingly, ABET student outcomes foreground analytical reasoning, engineering design under realistic constraints, experimentation and data interpretation, teamwork, communication, professional responsibility, and lifelong learning. Quality, in this framework, is demonstrated when measurable learning outcomes align with professional competencies and are reinforced through documented cycles of assessment and improvement.

The EUR-ACE Model: Academic Mobility, Transparency, and Harmonization

EUR-ACE emerged from a different historical and policy context, namely the Bologna Process and the development of the European Higher Education Area. Its primary objective is to harmonize diverse national higher education systems in order to promote transparency, comparability of qualifications, and academic mobility across borders (Clarke, 2021; ENQA, 2015).

Rather than being anchored in professional licensure systems, EUR-ACE is grounded in qualifications frameworks and degree-cycle compatibility at the Bachelor and Master levels. Emphasis is placed on clarity of intended learning outcomes, coherence of curricula within degree structures, and alignment with European mechanisms such as the European Credit Transfer and Accumulation System and the European Qualifications Framework.

Within this perspective, the engineer is conceived as a knowledge professional operating within a transnational academic space. Professional and design competencies are included, but they are embedded within a broader educational architecture oriented toward intellectual development, transparency of qualifications, and structured academic progression, particularly toward graduate studies.

Philosophical Contrast Between ABET and EUR-ACE

Although both accreditation systems aim to ensure high-quality engineering education, they reflect different governance logics and educational rationalities. ABET is closely aligned with professional practice and labour market signalling, while EUR-ACE is embedded in a framework of academic harmonization and mobility. These contrasts influence curriculum design, assessment practices, and the professional identity of graduates.

Table 1 summarizes the main philosophical differences between the two frameworks and highlights how their distinct orientations translate into different strategic values for institutions.

Table1: Philosophical Foundations of ABET and EUR-ACE Accreditation Frameworks

Dimension	ABET	EUR-ACE
Historical Root	Professional engineering practice in the U.S.	Harmonization of European higher education systems
Primary Orientation	Professional readiness and competency demonstration	Academic transparency and international mobility
Methodology	Outcomes-based assessment + continuous improvement cycles	Qualification descriptors + alignment with Bologna and EQF
Identity of Engineer	Practice-ready professional capable of immediate engineering work	Knowledge professional progressing through structured academic and professional pathways
Strategic Value	Strong recognition by global employers and licensing bodies	Strong recognition for academic mobility and degree equivalence

The choice between the two systems is therefore not one of superiority, but of alignment. Each framework serves institutions differently depending on mission, graduate trajectories, and regional priorities.

Implications for Institutions Outside the United States and Europe

For institutions operating outside the United States and Europe, the philosophical differences between ABET and EUR-ACE take on strategic significance. Accreditation functions as a signalling mechanism through which institutions align themselves with particular academic or industrial ecosystems and shape the professional and educational trajectories of their graduates. In practice, this choice affects curriculum priorities, industry engagement strategies, student career pathways, and international collaboration networks.

Student Outcomes and Graduate Formation

Although both ABET and EUR-ACE adopt outcomes-based approaches, the structure, emphasis, and interpretation of outcomes differ. ABET articulates outcomes at the program level, while EUR-ACE defines outcomes at the qualification level, linked to the European Qualifications Framework (EQF) Level 6, which corresponds to the first cycle (Bachelor) in the Bologna structure. The comparison below clarifies how each framework conceptualizes the graduate engineer. The comparison below clarifies how each framework conceptualizes the graduate engineer.

ABET Student Outcomes (EAC, 2024)

A core element of comparison between ABET and EUR-ACE lies in how each framework defines the learning outcomes that engineering graduates must achieve. These outcomes reflect deeper assumptions about the formation of the engineer, the balance between theory and practice, and the role of the university in preparing graduates for professional and academic trajectories.

Graduates of an ABET-accredited engineering program must demonstrate the ability to achieve the following outcomes as detailed in Table 2, which presents the seven student outcomes (SO1–SO7) that structure outcomes-based assessment in ABET-accredited engineering programs.

Table 2: ABET Student Outcomes (SO1–SO7): Core Competencies in Engineering Education

Code	ABET Student Outcome
SO1	Identify, formulate, and solve complex engineering problems using principles of engineering, science, and mathematics.
SO2	Apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, welfare, and global, cultural, social, environmental, and economic factors.
SO3	Communicate effectively with a range of audiences.
SO4	Recognize ethical and professional responsibilities and make informed judgments considering global, economic, environmental, and societal impacts.
SO5	Function effectively on teams to establish goals, plan tasks, and create a collaborative environment.
SO6	Develop and conduct experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.
SO7	Acquire and apply new knowledge as needed, using appropriate learning strategies.

These outcomes foreground analytical reasoning, engineering design under realistic constraints, experimentation and data interpretation, teamwork, communication, professional responsibility, and lifelong learning. Within the ABET framework, quality is demonstrated when these outcomes are measurably achieved and reinforced through documented cycles of assessment and continuous improvement.

EUR-ACE Bachelor (First Cycle) Expected Learning Outcomes

Graduates awarded the EUR-ACE Bachelor label must demonstrate outcomes in six domains (ENAEE, 2023):

1. Knowledge and Understanding
2. Engineering Analysis
3. Engineering Design
4. Investigations
5. Engineering Practice
6. Transferable Skills

These domains collectively define the expected profile of the first-cycle engineering graduate within the Bologna architecture. They emphasize analytical reasoning, structured design practice, investigative capacity, and transferable skills that support both academic progression and entry into professional environments. Unlike ABET, where outcomes are expressed as program-level capabilities, EUR-ACE outcomes are embedded in a broader qualifications framework that links degrees, learning levels, and mobility pathways across national higher education systems. This structural positioning enables the EUR-ACE label to function not only as an indicator of program quality, but also as a mechanism of academic transparency and portability across the European Higher Education Area.

Comparative Mapping (Bachelor Level)

To clarify how these two frameworks align in practice, the following comparison maps ABET's seven student outcomes to the six EUR-ACE outcome domains at the Bachelor (first-cycle) level, highlighting points of convergence as well as differences in emphasis and interpretation. Table 3 provides a comparative mapping between ABET student outcomes and the EUR-ACE Bachelor-level outcome domains, illustrating areas of convergence as well as differences in framing and educational emphasis.

Table 3: Comparative Mapping Between ABET Student Outcomes and EUR-ACE Bachelor Domains

ABET Outcome	Corresponding EUR-ACE Outcome Domain(s)	Interpretation
SO1: Solve complex engineering problems using math, science, and engineering principles.	Knowledge and Understanding + Engineering Analysis	Strong alignment. Both frameworks require analytical competence rooted in scientific and mathematical foundations.
SO2: Apply engineering design considering constraints and broader impacts.	Engineering Design + Engineering Practice	Equivalent emphasis on design as an iterative process; EUR-ACE more explicitly links design to context of professional practice.
SO3: Communicate effectively.	Transferable Skills	Identical intent; EUR-ACE frames communication as part of transversal professional skills.
SO4: Recognize ethical and professional responsibilities; consider impacts.	Engineering Practice + Transferable Skills	ABET articulates ethics explicitly; in EUR-ACE ethics is embedded within responsible practice and professional conduct.
SO5: Function effectively on teams.	Transferable Skills	Full convergence; teamwork and collaboration are core transferable skills in both systems.
SO6: Conduct experiments and interpret data.	Investigations	Perfect one-to-one alignment; EUR-ACE explicitly defines investigative skills as experimental, analytical, and data-driven inquiry.
SO7: Acquire new knowledge using appropriate learning strategies.	**Transferable Skills** (lifelong learning capacity)	Both frameworks emphasize self-directed learning; EUR-ACE ties it to mobility and academic progression.

Overall, the two frameworks exhibit substantial conceptual convergence in analytical capability, design practice, experimentation, communication, teamwork, and lifelong learning. The primary difference lies not in the competencies themselves, but in how they are framed and situated within broader educational architectures. ABET positions outcomes in relation to professional readiness and a practice-oriented engineering identity, whereas EUR-ACE embeds outcomes within the qualification and mobility logic of the Bologna Process.

This difference reflects distinct strategic orientations. ABET outcomes are aligned with professional employability and practice-readiness, supporting transitions from university to industrial and professional environments. EUR-ACE outcomes, by contrast, support academic mobility and degree comparability, ensuring that first-cycle graduates are positioned to progress into Master's and doctoral programs within the Bologna framework. Structurally, ABET defines a fixed set of student outcomes applicable across engineering programs, while EUR-ACE integrates outcomes into a qualifications framework that allows alignment with national and institutional contexts.

For institutions operating outside the United States and Europe, these differences translate into distinct forms of graduate positioning and program governance. ABET's standardized outcomes require sustained internal assessment cycles, documentation practices, and evidence-driven continuous improvement processes. EUR-ACE, while also outcomes-based, allows alignment with national qualification descriptors, offering greater flexibility in mapping curricula to expected graduate profiles. The choice between frameworks therefore influences not only graduate trajectories, but also institutional planning, assessment culture, and the organization of academic quality management.

Recognition, Mobility and International Positioning

While the previous sections examined the philosophical and pedagogical foundations of ABET and EUR-ACE, this section focuses on how accreditation choices translate into international recognition, graduate mobility, and institutional positioning. For many institutions outside the United States and Europe, these considerations play a decisive role in selecting an accreditation pathway. Accreditation functions not only as an internal quality assurance mechanism, but also as a signal interpreted by employers, regulators, universities, and professional bodies in global academic and labour markets.

Global Recognition Pathways

ABET and the Washington Accord: ABET accreditation is formally recognized within the framework of the Washington Accord, an international agreement that establishes substantial equivalence of accredited engineering degrees across its signatory countries (IEA, 2021). Current signatories include major engineering economies such as the United States, Canada, Australia, the United Kingdom, Japan, South Korea, and Singapore. This recognition implies that graduates of ABET-accredited programs are generally considered to have met the academic requirements for professional engineering licensure in these jurisdictions, often without the need for additional credential evaluation.

As a result, ABET accreditation holds particular relevance in contexts where graduates seek employment in multinational firms, where engineering practice is regulated, or where national professional bodies align their standards with internationally recognized industrial frameworks.

EUR-ACE and the European Higher Education Area: EUR-ACE operates within the Bologna Process and the European Higher Education Area (EHEA), which harmonizes degree structures and quality standards across 49 countries (European Commission, 2020). The EUR-ACE label ensures that accredited programs are aligned with EQF Level 6 at the Bachelor level and are compatible with Bologna degree cycles. Consequently, EUR-ACE-accredited degrees are readily recognized for admission into Master's and doctoral programs across Europe, support academic mobility through ECTS compatibility, and facilitate entry into professional qualification pathways linked to European frameworks.

In this sense, EUR-ACE is particularly advantageous for institutions seeking integration into Bologna-aligned academic networks and collaborative higher education initiatives.

Employer and Industry Perception

Where ABET's recognition is driven primarily by professional practice and licensure pathways, EUR-ACE's visibility is more closely associated with academic comparability and mobility within Europe. Table 4 compares how ABET and EUR-ACE accreditation are perceived by employers and professional environments, particularly with respect to industry visibility, practice-readiness, and alignment with licensure systems.

Table 4: Recognition and Professional Alignment of ABET and EUR-ACE Accreditation Systems

Aspect	ABET	EUR-ACE
Recognition by Multinational Engineering Firms	High (strong industry visibility, especially in GCC/Asia/Africa)	Moderate to High (stronger in Europe, less universal outside)

Signalling of Practice-Ready Skills	Strong emphasis	Present but embedded within broader academic outcomes
Alignment with Engineering Licensure and Professional Registration	Direct (ABET criteria often referenced by licensing bodies)	Indirect (depends on national professional regulations)

In many regions outside Europe, ABET carries stronger employer recognition due to its long-standing association with global industry hiring practices. EUR-ACE, while well regarded academically, has more limited industrial branding outside European contexts.

Mobility and Institutional Positioning Outside the United States and Europe

The recognition logics of ABET and EUR-ACE shape not only how degrees are perceived, but also the types of mobility they enable. To distinguish the types of graduate mobility enabled by each accreditation framework, Table 5 contrasts professional and academic mobility pathways associated with ABET and EUR-ACE.

Table 5: Mobility Pathways Enabled by ABET and EUR-ACE Accreditation

Mobility Type	ABET	EUR-ACE
Professional Mobility (cross-border work as an engineer)	Supported via Washington Accord	Indirect — depends on country and professional engineering council recognition
Academic Mobility (admissions to graduate programs)	Recognized, but not embedded in a system-wide degree framework	Strongly supported via Bologna / EQF / ECTS

For institutions outside the United States and Europe, these mobility patterns translate into strategic positioning choices. ABET tends to support professional mobility by facilitating transitions into regulated engineering practice and multinational industrial environments. EUR-ACE, by contrast, strengthens academic mobility by embedding degrees within a harmonized European qualifications structure that supports progression into graduate studies across the EHEA. Table 6 aligns common institutional strategies with the accreditation framework most likely to support them, emphasizing how ABET and EUR-ACE function as signals within different professional and academic ecosystems.

Table 6: Alignment of Institutional Strategies with ABET and EUR-ACE Accreditation Pathways

Institutional Strategy	Best Fit	Reason
Becoming an internationally competitive engineering school with strong industry pipelines	ABET	Reflects global industry expectations and practice-ready emphasis
Integrating with European research networks, student exchange alliances, and double-degree programs	EUR-ACE	Aligns with Bologna mobility systems and academic recognition
Serving domestic or regional markets with limited outbound mobility	Either	Decision depends on regulator preference and employer culture

Accreditation thus functions as a signalling mechanism through which institutions align themselves with particular professional or academic ecosystems. The selected framework shapes how graduates are positioned within labour markets or academic systems and influences institutional identity in international higher education landscapes.

Cost, Duration, Visibility, and Market Acceptance

Beyond recognition and mobility, institutions must consider the operational implications of accreditation. ABET accreditation typically involves higher direct costs, extensive documentation requirements, and sustained continuous improvement processes that require dedicated internal capacity. These demands are often justified by the strong global visibility of the ABET label and its recognition in international engineering labour markets.

EUR-ACE accreditation is frequently administered through national or regional quality assurance agencies authorized by ENAEE, which can reduce cost and procedural complexity, particularly in systems already aligned with the Bologna framework. Table 7 outlines key operational characteristics of ABET and EUR-ACE accreditation, including accreditation cycles, cost structure, visibility, and links to professional regulation.

Table 7: Operational Frameworks of ABET and EUR-ACE Accreditation

Dimension	ABET	EUR-ACE	Comparative Implication
Accreditation Cycle Length	6 years (typical), with interim visits possible	5 years (most agencies), aligned to EQF cycles	EUR-ACE cycles are slightly shorter due to Bologna harmonization
Time to First Accreditation (process duration)	18–36 months depending on readiness	12–24 months depending on agency and regional alignment	ABET tends to be more exhaustive and slower
Cost Structure	Generally higher: evaluation fees + team travel + documentation preparation + sustained CQI system costs	Generally lower, particularly when conducted by national or regional agencies authorized by ENAEE	ABET is a financial investment, EUR-ACE is relatively cost-efficient
Visibility in Global Industry & Multinational Firms	Very High, especially in GCC, Asia, Africa, and Anglo-influenced markets	High within Europe, moderate outside Europe	ABET has stronger hiring signal power in global industrial economies
Visibility in Academic Mobility Networks	Recognized, but not structurally embedded in multi-country academic exchange frameworks	Very High in EHEA through Bologna / ECTS / EQF	EUR-ACE is stronger for academic progression, ABET is stronger for workforce entry
Association with Professional Licensure	Direct via Washington Accord	Indirect – varies by national engineering bodies	ABET is the clearer route where engineering is a regulated profession
Perception in Emerging Economic Hubs (GCC, Turkey, India, SE Asia)	Extremely High – ABET is seen as the "global mark of engineering quality"	Growing but not equal in brand strength outside Europe	Brand-value favours ABET in non-European markets

Strategic Decision Framework for International Engineering Programs

For institutions outside the United States and Europe, the selection between ABET and EUR-ACE is a strategic positioning decision rather than a purely procedural one. Accreditation functions as a signal in international academic and labour markets, communicating how an engineering program aligns with professional practice, academic mobility, and institutional identity. The decision must therefore account for graduate destination profiles, institutional mission, regional economic context, and the financial and administrative capacity of the institution.

Key Decision Dimensions

The first decision dimension concerns graduate destination profiles. Institutions whose graduates predominantly enter professional engineering practice, particularly in regions integrated into global industrial and multinational labour markets, tend to benefit from the professional signalling power of ABET. In contrast, institutions whose graduates frequently pursue postgraduate studies, especially within Europe, may derive greater benefit from EUR-ACE due to its embedding within the Bologna architecture of academic recognition and mobility.

A second dimension is institutional identity and strategic orientation. Universities positioning themselves as practice-oriented engineering schools focused on applied problem solving, design competence, and industry engagement often find ABET aligned with their educational mission. Institutions emphasizing academic formation, research integration, and participation in European knowledge networks may find EUR-ACE more coherent with their long-term strategy.

A third dimension relates to regional economic and industrial geography. In regions where professional standards and labour markets are influenced by U.S. or Anglo-Saxon engineering norms, ABET generally carries stronger recognition among employers and professional bodies. In regions with strong cultural, academic, or regulatory ties to Europe, EUR-ACE aligns more naturally with prevailing qualification and mobility systems.

Financial and administrative capacity constitutes a fourth dimension. ABET typically requires higher investment in documentation, assessment infrastructure, and continuous improvement processes. EUR-ACE is often less costly and procedurally lighter, particularly when administered through ENAEE-authorized national agencies, making it more accessible for institutions at earlier stages of quality assurance development.

Decision Matrix for Accreditation Selection

Synthesizing the preceding analysis, Table 8 presents a decision-oriented framework that supports institutions in selecting an accreditation pathway aligned with graduate trajectories, institutional mission, and regional context.

Table 8. Decision-Oriented Framework for Selecting ABET or EUR-ACE

Decision Criterion	ABET	EUR-ACE
Primary graduate destination	Professional engineering practice	Graduate studies and academic mobility
Institutional identity	Practice-oriented, industry-facing	Academically oriented, research-integrated
Recognition geography	Global industry and licensure markets	European Higher Education Area
Alignment with labour markets	Strong in multinational and regulated environments	Indirect, varies by national regulation
Academic mobility support	Present but not systemically embedded	Strong via Bologna, EQF, and ECTS
Administrative and financial demand	High	Moderate to low
Suitability for emerging QA systems	Demanding	More accessible

How Institutions Can Use the Framework

Institutions may apply this framework by assessing their position along each decision dimension and identifying where alignment is strongest. Where indicators consistently favour one framework, the accreditation choice becomes clear. In cases where institutional objectives and graduate trajectories are mixed, a phased or dual-alignment strategy may be appropriate, provided that regulatory and resource constraints permit such an approach.

Taken together, the framework emphasizes that the decision is not about accreditation superiority, but about coherence between accreditation logic, institutional mission, and the environments in which graduates will operate. ABET is generally advantageous for institutions prioritizing professional readiness and industrial recognition, while EUR-ACE is more coherent for institutions emphasizing academic mobility and integration into European higher education

Conclusion and Policy Recommendations

Engineering accreditation frameworks increasingly shape how institutions define their educational purposes, articulate institutional identity, and position graduates within global professional and academic landscapes. The comparison between ABET and EUR-ACE demonstrates that accreditation is not merely a quality assurance exercise, but a strategic decision that aligns universities with specific networks of recognition, mobility, and influence. ABET reflects a tradition of engineering as a regulated profession, emphasizing competence, ethical responsibility, problem-solving capability, and preparedness for industrial practice. EUR-ACE, by contrast, is rooted in the Bologna Process and focuses on transparency, comparability, and portability of engineering degrees within a harmonized academic space.

For universities outside the United States and Europe, the central question is therefore not which framework is intrinsically superior, but which more coherently aligns with institutional mission, graduate aspirations, regional economic structures, and patterns of international collaboration. Institutions operating in labour markets that prioritize applied engineering practice, multinational corporate employment, or professional licensure are likely to derive greater benefit from ABET, which enjoys strong global industry visibility and recognition through the Washington Accord. Conversely, institutions that are academically oriented, research-intensive, or integrated into European mobility and knowledge networks may find EUR-ACE more strategically appropriate, as it facilitates academic progression and situates degrees clearly within the European Qualifications Framework.

Accreditation selection should not be understood as a static or one-time choice. Institutional missions, graduate trajectories, and international partnerships evolve over time in response to national policy shifts and global mobility trends. Effective accreditation strategies are therefore dynamic and adaptive. In some contexts, EUR-ACE may serve as a foundational step toward strengthening internal quality assurance systems and regional recognition, with ABET pursued later once outcomes assessment cultures and continuous improvement mechanisms are fully established. In other cases, dual or sequential accreditation strategies may be appropriate, particularly where institutions seek to support diverse graduate destinations while enhancing both industrial relevance and academic portability.

Clear policy implications follow from this analysis. National higher education authorities should avoid prescribing a single accreditation pathway as universally optimal. Instead, they should enable institutions to conduct structured self-assessments that consider graduate trajectories, industry demand, research integration, and international partnership ecosystems. Governments can support this process by funding accreditation readiness initiatives, investing in faculty development related to outcomes-based education, and strengthening national quality assurance frameworks that minimize duplication of evaluation efforts. Regional cooperation initiatives, particularly across MENA, African, and Asian higher education systems, can further enhance institutional capacity to engage with international accreditation systems in ways that align with national development priorities.

In conclusion, ABET and EUR-ACE each provide rigorous and internationally recognized frameworks for engineering education, yet they embody distinct philosophies and serve different strategic functions. The value of accreditation lies not in the label itself, but in the clarity of institutional purpose that emerges from the process of selecting, preparing for, and engaging with an accreditation system. Institutions that treat accreditation as a strategic instrument rather than a compliance obligation are better positioned to advance their educational mission, enhance graduate capability, and establish a coherent presence within the global landscape of engineering education and practice.

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Conflict of Interest

The author declares no conflict of interest.

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