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Research Article

An integrated STEM–CBE–ELT framework for engineering education: Bridging theory and practice in resource-constrained contexts

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This study introduces and validates an integrated learning framework that combines Science, Technology, Engineering, and Mathematics education, Competency-Based Education, and Experiential Learning Theory to bridge the gap between theory and practice in electrical–electronic engineering programs in Vietnam. Implemented through a design-based research approach in an Automatic Control Engineering course, the framework was applied across several technical universities using iterative cycles of design, intervention, and reflection. Open-source digital simulations, project-based learning tasks, and ABET-aligned competency assessments were incorporated to ensure feasibility, rigor, and alignment with international standards in resource-constrained environments. Quantitative findings from pre–post surveys (N = 250) and comparative analyses with a control group (N = 247) revealed significant gains in five competency domains—technical problem-solving, systems thinking, teamwork and technical communication, digital simulation, and presentation and technical argumentation—with effect sizes ranging from 1.29 to 1.56, indicating large to very large impacts. Complementary qualitative evidence highlighted stronger theory–practice integration, higher engagement, increased motivation, and greater learner confidence when applying theoretical concepts to authentic engineering tasks. Overall, the results indicate that the integrated Science, Technology, Engineering, and Mathematics-Competency-Based Education- Experiential Learning Theory framework offers a cost-effective, scalable, and pedagogically robust model for strengthening engineering competencies in low-resource settings, providing actionable implications for curriculum designers, instructors, and policymakers seeking to align engineering education with contemporary international quality and accreditation standards.

Keywords: Competency-based education; Digital simulation; Engineering pedagogy; Experiential learning theory; Resource-constrained context; STEM education

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1. Introduction

Amid rapid digital transformation, engineering education is under increasing pressure to reform and equip future engineers with the competencies needed to address complex 21st-century challenges (Kamp, 2016; Organisation for Economic Co-operation and Development [OECD], 2019; United Nations Educational, Scientific and Cultural Organization [UNESCO], 2021). Beyond

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mastering technical expertise, modern engineers are expected to integrate competencies such as critical thinking, problem-solving, teamwork, and adaptability to emerging technologies (National Research Council [NRC], 2011; Stehle & Peters-Burton, 2019). Among recent pedagogical innovations, interdisciplinary Science, Technology, Engineering, and Mathematics [STEM] education has gained prominence for its capacity to connect conceptual knowledge with authentic application, thereby fostering innovation-oriented learning (Bybee, 2010; Eshaq, 2024; Honey et al., 2014).

In Vietnam, Electrical–Electronic Engineering Technology programs continue to face a persistent gap between theoretical instruction and industry expectations. Many students struggle to apply academic knowledge to practical contexts, despite growing employer demand for systems thinking, digital literacy, and hands-on technological competence (Accreditation Board for Engineering and Technology [ABET], 2021; Lattuca et al., 2006; Hashim et al., 2022). While alternative frameworks such as Conceive–Design–Implement–Operate [CDIO], Problem-Based Learning [PBL], and Design-Based Learning [DBL] have been introduced, their impact remains modest due to the lack of standardized competency assessment and reliance on costly digital tools (Passow & Passow, 2017; Zaher & Damaj, 2018). These challenges underscore the need for scalable, resource-efficient pedagogical models that can ensure learning quality under constrained institutional conditions. Recent findings further affirm that STEM-based pedagogies significantly improve conceptual understanding and student performance in technical disciplines (Eshaq, 2024).

Existing research reveals a notable absence of pedagogical frameworks that holistically integrate three essential components. These include: (1) the interdisciplinary mindset of STEM education, (2) the outcome-oriented focus of Competency-Based Education [CBE], and (3) the experiential and reflective learning cycles emphasized in Experiential Learning Theory [ELT]. This gap is particularly evident in developing contexts such as Vietnam, where institutions often contend with limited infrastructure, teaching resources, and access to educational technologies.

Without structured implementation and consistent competency evaluation, even well-intentioned reforms risk fragmented adoption and limited long-term impact, thereby impeding the development of sustainable engineering competence.

Moreover, if such an integrated framework is implemented inconsistently or without systematic evaluation, it may exacerbate the disconnect between learning objectives and actual skill acquisition. This misalignment could lead to superficial compliance with accreditation standards, increased instructional workload, and ineffective resource utilization—ultimately weakening both teaching quality and graduate employability.

This study conceptualizes "concrete implementation" as the systematic translation of theoretical learning outcomes into hands-on engineering practice through standardized assessment and reflection. To respond to these challenges, this study designs, implements, and evaluates an integrated STEM–CBE–ELT learning framework aimed at strengthening the alignment between theoretical instruction and applied engineering performance. The framework was developed collaboratively with multiple technical universities in Vietnam, centered on the core course Automatic Control Engineering. This course was selected for its interdisciplinary nature and practical relevance, encompassing programming, control systems, simulation, and applied mathematics—making it an appropriate setting for testing how theoretical knowledge can be effectively transformed into professional practice.

Unlike studies focusing on high-cost technologies such as virtual or augmented reality (Tene et al., 2024), the present framework emphasizes feasibility and scalability, utilizing open-source digital tools and standardized competency-based assessment. This approach offers a cost-effective and context-sensitive pathway for developing engineering competencies while maintaining alignment with international accreditation standards. For instance, adopting open-source platforms such as Scilab can help minimize cost and reduce faculty workload in resource-limited settings.

Accordingly, this study addresses the following research questions:

RQ 1) Does the integrated STEM–CBE–ELT framework improve the alignment between conceptual understanding and practical competence in electrical–electronic engineering education compared with traditional or CDIO-based approaches?

RQ 2) How do contextual factors such as institutional characteristics, technological readiness, and gender influence the framework's effectiveness?

RQ 3) What strategies support sustainable implementation of the framework in Vietnamese technical institutions operating under resource constraints?

2. Literature Review

2.1. STEM Education in Engineering Training

STEM education integrates science, technology, engineering, and mathematics to cultivate learners' abilities in critical thinking, creativity, and complex problem-solving—skills essential for 21st-century innovation and sustainability (Bybee, 2010; Honey et al., 2014; UNESCO, 2021). In higher-engineering contexts, STEM pedagogy encourages interdisciplinary, inquiry-driven learning that connects theory with authentic practice. Empirical studies consistently show that active STEM approaches outperform traditional instruction in improving academic achievement and conceptual understanding (Freeman et al., 2014; Kelley, 2019; Prince, 2004).

This finding is consistent with a recent meta-analysis demonstrating the positive impact of STEM practices on achievement and process skills (Gürsoy et al., 2023). Recent research also highlights the synergy between STEM and emerging technologies such as AR/VR, 3-D simulation, and online platforms (Li et al., 2020; Tene et al., 2024). Inquiry-based integration of digital tools has further been found to strengthen procedural and conceptual learning in STEM-related contexts (Dereje, 2023).

However, many developing-country institutions face financial and infrastructural barriers to adopting such innovations. Similar constraints are reported in GCC countries, where systemic barriers and resource limitations hinder the implementation of innovative STEM approaches (Ismail et al., 2022). Open-source tools such as Scilab offer a promising and cost-effective alternative for fostering digital-modelling competencies (Couso & Simarro, 2020). Despite its potential, a persistent weakness of STEM implementation lies in the lack of standardized evaluation mechanisms aligned with international accreditation criteria (Passow & Passow, 2017; Prados et al., 2005).

2.2. Competency-Based Education

Competency-Based Education [CBE] provides a middle-level theoretical structure emphasizing measurable learning outcomes and mastery of explicit competencies rather than time-based instruction (Mulder, 2017; Tait & Knight, 2018). In the field of engineering education, CBE enhances alignment between university curricula and professional standards set by bodies such as ABET (2021) and EUR-ACE (Patil & Codner, 2007). CBE focuses on observable performance in domains such as systems thinking, problem-solving, teamwork, communication, and ethical practice. Rubrics, competency maps, and e-portfolios ensure transparency and formative feedback (Besterfield-Sacre et al., 2004; Impagliazzo & Xu, 2024; McGourty et al., 1998; Olds et al., 2005). Recent research in STEM contexts also emphasizes that valid assessment methods are essential for capturing complex learner competencies (Karakaya & Yılmaz, 2022). CBE supports the development of 21st-century competencies—creativity, collaboration, adaptability, and digital literacy—highlighted in global frameworks by OECD (2018) and UNESCO (2021). Recent empirical evidence confirms that competency-oriented STEM interventions can substantially enhance students' scientific achievement and learning motivation (Uzun & Şen, 2023).

2.3. Experiential Learning Theory

Kolb's Experiential Learning Theory [ELT] conceptualizes learning as a four-stage cycle involving concrete experience, reflective observation, abstract conceptualization, and active experimentation

(Kolb & Kolb, 2017). The theory provides an applied foundation that links knowledge construction to authentic, hands-on engagement and reflective practice.

Within engineering contexts, it promotes learning-by-doing through simulation, experimentation, and reflection, connecting cognitive understanding to real-world application (Felder & Brent, 2016). When integrated with STEM and CBE, ELT supports the iterative learning cycle that transforms abstract concepts into professional competence and self-regulated learning. Differentiated experiential strategies have also been shown to improve engagement and performance among STEM learners (Insorio, 2024). Thus, ELT acts as the applied mechanism translating theoretical frameworks into practical behavioral change.

2.4. Critical Review of Existing Engineering Models

Despite numerous pedagogical innovations, traditional frameworks such as Conceive–Design–Implement–Operate, Problem-Based Learning, and Design-Based Learning display structural limitations when applied in resource-constrained contexts. CDIO emphasizes design integration but lacks systematic mechanisms for assessing soft skills and digital simulation (Crawley et al., 2014). In contrast, PBL and DBL encourage collaboration and creativity, yet remain resource-intensive and depend heavily on faculty expertise (Alves et al., 2016; Savery, 2015; Simarro & Couso, 2021). Table 1 provides a comparative analysis of these widely used engineering education models and illustrates how the emerging STEM–CBE–ELT approach addresses persistent gaps through integrated competency assessment and scalable digital simulation.

Table 1
Comparative Analysis of Engineering Education Models

Criteria	*CDIO*	*PBL*	*DBL*	*Emerging STEM–CBE–ELT Approach*
Pedagogical focus	Design cycle	Problem-solving	Iterative design	Integrated STEM competence
Competency assessment	Unstandardized	Product-based	Partial	ABET-aligned rubrics
Digital simulation	Minimal	Absent	Optional	Open-source Scilab integration
21st-century skills	Implicit	Fragmented	Limited	Explicitly embedded
Scalability	Resource-dependent	Low	Moderate	High (cost-effective)

As shown in Table 1, the three legacy frameworks each address valuable aspects of engineering training but do so in fragmented or resource-intensive ways. CDIO improves design orientation yet lacks systematic competency assessment; PBL and DBL foster creativity and collaboration but require substantial faculty capacity and laboratory resources. In contrast, the integrated STEM–CBE–ELT approach combines interdisciplinary inquiry, standardized ABET-aligned rubrics, and low-cost digital tools such as Scilab to provide a more coherent, scalable, and context-appropriate model for engineering programs in low-resource settings.

This synthesis clarifies that none of these legacy frameworks fully integrate interdisciplinary learning, competency-based assessment, and experiential reflection into a single coherent model. Such a pedagogical perspective aligns with recent systems-thinking approaches emphasizing reflective professional practice and the integration of analytical and holistic competencies in engineering education (Goode & MacGillivray, 2023).

2.5. Research Gap and Framework Proposition

Existing studies primarily address K–12 and information technology contexts, leaving a clear void in the application of integrated, outcome-based frameworks to undergraduate electrical-electronic engineering programs in developing countries (Gyasi et al., 2021; Le et al., 2023).

Furthermore, little empirical research examines how low-cost digital tools and competency-based rubrics can be combined to enhance learning outcomes and institutional sustainability. Addressing these gaps, the present study aims to bridge the disconnect between theoretical instruction and practical application through an integrated STEM – CBE – ELT framework tailored for resource-constrained engineering programs. Section 3 builds on this foundation by conceptualizing the proposed framework and formulating the research hypotheses for empirical validation.

3. Theoretical Framework and Research Hypotheses

3.1. The Integrated STEM–CBE–ELT Learning Framework

This study proposes an integrated learning framework that combines three complementary paradigms: Science, Technology, Engineering, and Mathematics education (Bybee, 2010; Honey et al., 2014), Competency-Based Education (Mulder, 2017; Tait & Knight, 2018), and Kolb's Experiential Learning Theory (Kolb & Kolb, 2017).

This integration provides a cohesive foundation for aligning theoretical knowledge with authentic engineering practice, while remaining adaptable to resource-limited institutional contexts (Couso & Simarro, 2020; Zaher & Damaj, 2018). In this approach, STEM establishes an interdisciplinary basis for inquiry-driven problem-solving; CBE ensures structured, outcome-oriented competency development; and ELT anchors learning in experiential and reflective cycles. Together, they create a synergistic pedagogical model that transforms abstract knowledge into professional competencies—an approach emphasized in contemporary engineering education reforms (Passow & Passow, 2017; Shuman et al., 2005). The framework operates through three interconnected components. Integrated learning activities: students engage in digital simulations using the open-source platform Scilab, collaborate on project-based tasks, and design solutions to real-world engineering problems. Standardized competency assessment: evaluation employs rubrics aligned with ABET standards, incorporating instructor, peer, and self-assessment. This multidimensional approach strengthens reflection, continuous improvement, and accountability in learning outcomes (Impagliazzo & Xu, 2024; Karakaya & Yılmaz, 2022). Expected learning outcomes: the framework targets five competency clusters— technical problem-solving, systems thinking, teamwork and technical communication, digital simulation, and presentation and technical argumentation—representing essential outcomes of modern engineering curricula (Passow & Passow, 2017).

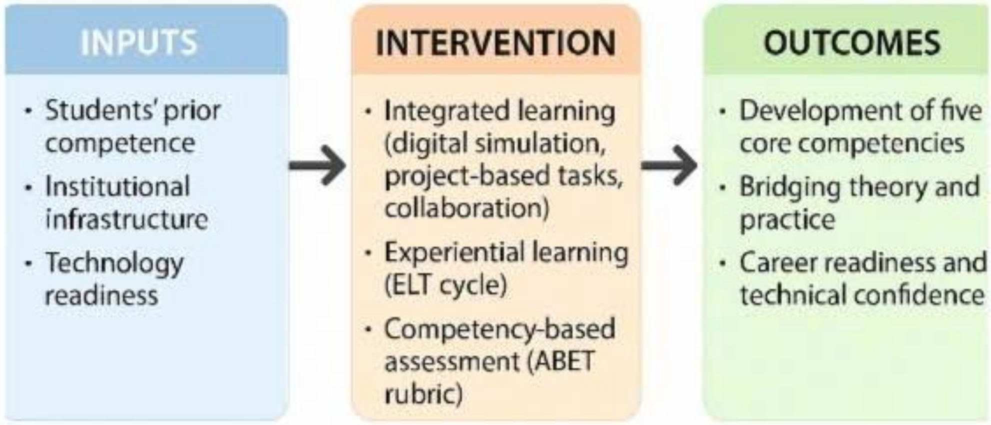
Overall, this framework offers a scalable and evidence-based approach to developing engineering competence through integrated, low-cost, and reflective learning processes (UNESCO, 2021).

3.2. Conceptual Framework

The theoretical foundation of the study is operationalized through an Input–Intervention–Outcome (I–I–O) structure (Anderson & Shattuck, 2012; McKenney & Reeves, 2019), which clarifies how learner and institutional conditions interact with pedagogical interventions to produce targeted learning outcomes. Inputs include foundational competencies (technical knowledge, digital literacy, and motivation), institutional factors (faculty expertise, infrastructure, curriculum design), and technology readiness (ability to use simulation tools and LMS platforms). The intervention comprises integrated learning activities such as digital simulation and project-based teamwork, experiential cycles grounded in Kolb's stages, and standardized assessment using rubrics and reflective feedback. Outcomes emphasize professional competence, reflective practice, and improved theory–practice alignment, leading to enhanced self-directed learning, motivation, and employability (Stehle & Peters-Burton, 2019). This conceptualization illustrates the causal pathway from learner readiness and institutional support to pedagogical design and ultimately, to measurable competency development. The central theoretical assumption is that integrating STEM, CBE, and ELT principles creates a transformative learning pathway that connects disciplinary knowledge with experiential application.

Figure 1 introduces the overarching structure of this theoretical and conceptual model, illustrating how the STEM–CBE–ELT principles interact within the I–I–O process.

Figure 1
Theoretical and Conceptual Framework of the Study



Note. Adapted from Bybee (2010), Mulder (2017), and Kolb and Kolb (2017)

As shown in Figure 1, the framework establishes a coherent progression in which learner characteristics and institutional conditions (Input) shape engagement with simulation-based, project-oriented, and reflective learning activities (Intervention). These activities, in turn, lead to defined competency gains and improved alignment between theory and practice (Outcome). The integrated structure of STEM inquiry, competency-based assessment, and experiential learning cycles ensures that each component reinforces the others, resulting in a holistic and scalable model for engineering education in resource-constrained contexts.

3.3. Research Hypotheses

Drawing from the conceptual model and prior findings, the following hypotheses guide this study:

H1. The integrated STEM–CBE–ELT framework significantly enhances the development of professional competencies—particularly systems thinking, problem-solving, teamwork, communication, and digital simulation—compared to traditional or CDIO-based methods.

H2. The integration of digital simulation, project-based learning, and competency-based assessment enhances learners' motivation and reflective thinking, thereby strengthening the transfer of theory into practice.

H3. Institutional and technological readiness factors (e.g., faculty capacity, infrastructure, and gender) moderate the effectiveness of the integrated framework in developing professional competencies.

H4. The STEM–CBE–ELT framework is feasible and scalable for implementation in resource-constrained institutions by leveraging open-source tools, standardized assessment, and experiential pedagogy. These hypotheses underpin the design-based research methodology adopted in this study, enabling iterative testing, evaluation, and refinement of the proposed model across authentic educational contexts.

4. Methodology

4.1. Research Design

This study employed a design-based research methodology to guide the systematic development, implementation, and refinement of the integrated STEM–CBE–ELT learning framework. DBR is particularly suitable for engineering education because it strengthens the connection between pedagogical theory and real classroom practice through iterative cycles of design, enactment, analysis, and revision (Anderson & Shattuck, 2012; McKenney & Reeves, 2019). Within this study, DBR was combined with a convergent mixed-methods design. Quantitative and qualitative data were collected in parallel and integrated during interpretation. This design made it possible to obtain a robust, multi-layered understanding of how the framework operated across different institutional contexts and how it influenced students' competency development.

4.2. Research Context and Participants

The study was conducted during the 2024–2025 academic year across accredited technical universities in Vietnam that represented differing institutional missions and resource levels. The sample was drawn from three accredited technical universities in Vietnam, including Ho Chi Minh City University of Technology and Education [HCMUTE] and two partner institutions with comparable program structures. A total of 497 undergraduate students enrolled in Automatic Control Engineering participated in the study. In addition, 28 instructors were involved in implementing the framework and maintaining reflective journals, which contributed to data triangulation.

To document the distribution of students, Table 2 reports the allocation of participants across the experimental and control groups.

Table 2
Experimental and Control Group Allocation

Group	*Sample Size (n)*	*Instructional Approach*
Experimental	250	STEM–CBE–ELT Integrated Framework
Control	247	Traditional / CDIO-Based Instruction

Note. Quasi-random assignment at the class-section level was used to maintain demographic and academic balance between the two groups (total N = 497).

As shown in Table 2, 250 students participated in the experimental group, which received instruction through the integrated STEM–CBE–ELT framework, while 247 students formed the control group, which followed traditional or CDIO-based instruction. The quasi-random assignment ensured that class sections with comparable academic backgrounds were distributed evenly between the two conditions, minimizing selection bias and supporting internal validity.

Baseline equivalence was further assessed using demographic and academic indicators. Table 3 presents these characteristics for both groups.

Table 3
Demographic Characteristics

Variable	*Experimental*	*Control*	*Test*	*df*	*Statistic*	*p*
Gender (M/F)	72% / 28%	70% / 30%	χ^2	1	0.43	.65
GPA (4.0 scale)	3.28 ± 0.42	3.25 ± 0.45	T	495	0.70	.48
Internship (Yes %)	34%	32%	χ^2	1	0.14	.71

The results in Table 3 show no statistically significant differences between the experimental and control groups in terms of gender distribution, grade point average (GPA), or prior internship experience ($p > .05$). This confirmed that the two groups were initially comparable and that subsequent differences in outcomes could more confidently be attributed to the instructional intervention rather than pre-existing disparities.

4.3. Data Collection Tools and Procedures

Data collection followed a convergent mixed-methods design in which quantitative and qualitative evidence were gathered simultaneously and later integrated.

Quantitatively, a 25-item survey was administered at the beginning and end of the course to measure perceived competence in five domains: technical problem-solving, systems thinking, teamwork and technical communication, digital simulation, and presentation and technical argumentation. Responses were recorded on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Reliability analysis yielded a Cronbach's alpha of .87, indicating strong internal consistency.

Qualitatively, semi-structured interviews were conducted with a purposive subsample of 60 students and 12 instructors drawn from the participating universities. These interviews explored participants' learning experiences, perceptions of the integrated framework, perceived benefits and challenges, and suggestions for improvement (Braun & Clarke, 2006). Additional qualitative data were obtained from student artifacts, including Scilab simulation models, laboratory outputs, project reports, reflection journals, and oral presentations.

Technological support was provided primarily through Scilab, an open-source simulation platform that supports digital modeling and collaborative analysis in resource-constrained environments (Couso & Simarro, 2020; Zaher & Damaj, 2018). To enhance validity, data triangulation was employed by comparing patterns across surveys, rubric-based assessments, interviews, and student artifacts (Creswell & Plano Clark, 2018). Convergent and divergent findings were examined systematically to strengthen the trustworthiness of interpretations.

4.4. DBR Implementation Process

The development of the instructional model followed a four-phase DBR cycle. To clarify this developmental logic, Table 4 presents the phases used to construct, implement, and refine the integrated STEM–CBE–ELT framework. The table summarizes the objective and key activities of each phase.

Table 4
DBR Implementation Process

Phase	*Objective*	*Key Activities*
Needs Analysis	Identify core competencies for development	Conduct surveys and interviews; benchmark against ABET standards
Model Design	Construct the integrated learning framework	Develop course content, simulation materials, project, and rubrics
Implementation	Test the framework in authentic settings	Apply in three technical universities; monitor implementation; collect feedback
Evaluation & Refinement	Improve the framework using empirical evidence	Analyze data; revise model accordingly

Note. Developed by the author based on Anderson and Shattuck (2012), and McKenney and Reeves (2019).

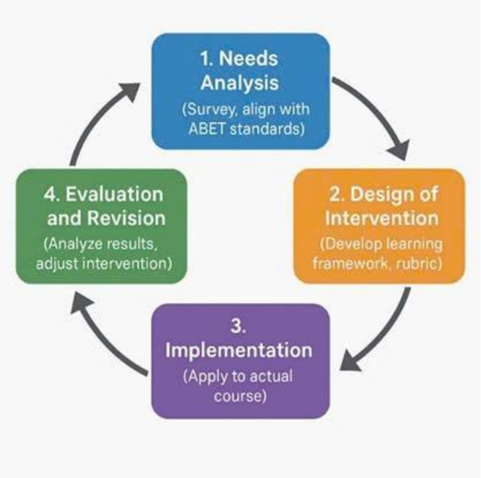
As shown in Table 4, the DBR process began with a needs analysis phase in which core competencies were identified based on ABET criteria and national engineering standards. In the model-design phase, integrated course content, digital simulation tasks, and competency rubrics were developed in alignment with the intended learning outcomes. The implementation phase involved testing the framework in authentic classroom settings across three technical universities, under real institutional and resource constraints. In the evaluation and refinement phase, quantitative and qualitative data were analyzed and used to revise the framework, ensuring that the final model reflected both empirical evidence and contextual feasibility.

To further illustrate the cyclical nature of DBR, Figure 2 provides a visual representation of the feedback loops that connected these phases and supported continuous improvement. Figure 2 depicts how insights from each cycle—particularly from classroom implementation and evaluation—fed back into subsequent design decisions. Adjustments to learning activities, project tasks, and assessment instruments were guided by this iterative process, helping the framework remain closely aligned with learner needs, instructor feedback, and institutional realities.

4.5. Implementation of the STEM–CBE–ELT Framework

The integrated STEM–CBE–ELT framework was enacted over a 15-week semester in the Automatic Control Engineering course. The implementation was structured according to Kolb's four-stage

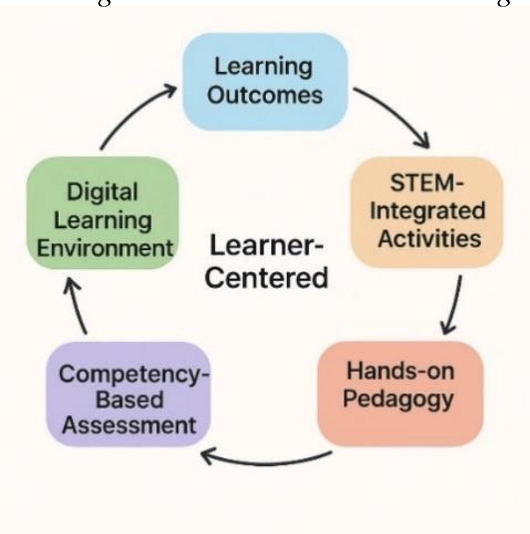
Figure 2
Iterative DBR Cycle for Model Development and Validation



Experiential Learning Theory cycle. Each instructional unit engaged students in concrete experience (through laboratory demonstrations or Scilab/Scicos simulations), reflective observation (via guided peer-group discussion), abstract conceptualization (supported by instructor-led synthesis and explanation), and active experimentation (through project-based problem-solving).

Figure 3 presents the overall structure of the integrated framework as applied in this study.

Figure 3
The Integrated STEM–CBE–ELT Learning Framework

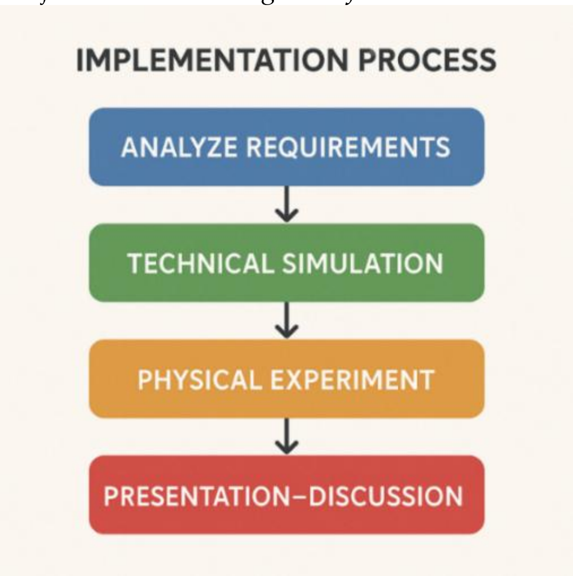


Note. Adapted from Biggs (2003), Kolb (1984), and Mulder (2017).

As illustrated in Figure 3, the framework connects STEM-based inquiry with competency-oriented assessment and cyclical experiential learning. Constructive alignment (Biggs, 2003) was used to ensure coherence among intended learning outcomes, learning activities, and assessment strategies. Five competency domains—technical problem-solving, systems thinking, teamwork and technical communication, digital simulation, and presentation and technical argumentation—served as the central focus of instructional design and evaluation.

To clarify how the framework was operationalized at the course level, Figure 4 displays the project-based workflow used in the Automatic Control Engineering course. Figure 4 shows how students progressed through four iterative stages: (1) analyzing technical requirements and problem constraints, (2) developing simulation models using Scilab, (3) conducting experiments and validating control strategies using simulated or available laboratory devices, and (4) presenting and defending their design solutions. Each stage corresponded to one or more phases of the ELT cycle and was supported by ABET-aligned rubrics, structured feedback, and reflective journaling. This implementation design enabled the study to isolate the effects of the integrated framework by contrasting it with a control group that followed traditional or CDIO-based instruction without systematic ELT cycles or rubric-based feedback.

Figure 4
Project-Based Learning Workflow under the STEM–CBE–ELT Framework



Note. Developed by the author based on Kolb (1984), Felder and Brent (2016), and Zaher and Damaj (2018).

4.6. Competency Assessment Rubrics

Student performance was evaluated using an ABET-aligned competency rubric that covered five targeted domains, each defined across four mastery levels. Table 5 summarizes the structure of this rubric and the description of the highest proficiency level in each domain.

Table 5
ABET-Aligned Competency Rubric

Competency Domain	*Level 4 – Description (Highest Proficiency)*
Technical Problem-Solving	Effectively analyzes and solves complex engineering problems using creative, evidence-based approaches.
Systems Thinking	Models engineering systems and integrates interdisciplinary perspectives.
Teamwork and Technical Communication	Collaborates proactively and communicates technical content with clarity.
Digital Simulation	Accurately designs and applies adaptable digital simulation models.
Presentation and Technical Argumentation	Constructs logical, evidence-supported arguments and communicates them effectively.

As shown in Table 5, the rubric provided explicit and observable descriptors for technical problem-solving, systems thinking, teamwork and technical communication, digital simulation, and presentation and technical argumentation. Before full implementation, the rubric was pilot-tested with 12 instructors to ensure contextual appropriateness and shared understanding of performance criteria. Inter-rater reliability was high (Krippendorff's α = .87), and the Content Validity Index reached .89, both of which are acceptable according to educational research standards (Hayes & Krippendorff, 2007; Polit & Beck, 2006).

Three complementary assessment modes were employed: instructor evaluation, peer assessment, and self-assessment. This combination supported reflective learning, allowed multiple perspectives on students' performance, and generated richer data on competency development.

4.7. Intervention Management and Group Equivalence

To preserve internal validity, the experimental and control groups received the same course content and were taught by the same instructors over 45 contact sessions. The main difference lay in the pedagogical approach and assessment strategy.

The experimental group was taught using the integrated STEM–CBE–ELT framework, which emphasized digital simulations, project-based learning, structured reflection, and ABET-aligned rubrics. The control group followed traditional or CDIO-based instruction, where theory and practice were delivered as separate components and performance was primarily assessed through written examinations and conventional project reports. To clarify the nature of the comparison condition, the control group followed a traditional lecture–lab format with selected CDIO-inspired activities (e.g., conceive–design tasks). This approach did not include systematic digital simulation, competency-based assessment rubrics, or structured ELT reflective cycles. Therefore, the control group represented a conventional instruction model commonly used in Vietnamese engineering programs, lacking the integrated and iterative design features of the STEM–CBE–ELT framework.

Weekly coordination meetings were held with instructors throughout the DBR cycle to discuss implementation, resolve emerging issues, and ensure that the instructional design was applied consistently across institutions. This monitoring process also generated qualitative insights into feasibility and scalability.

4.8. Research Ethics

All procedures adhered to institutional and international ethical guidelines for research involving human participants. Participation was voluntary, and students and instructors were informed about the purpose of the study, the confidentiality of their responses, and their right to withdraw at any time without penalty. Data were anonymized, securely stored, and used exclusively for academic research. Ethical approval was obtained from the research ethics committees of the participating universities prior to data collection.

4.9. Data Analysis

Quantitative datasets were first screened for completeness, normality, and outliers. Normality was assessed using skewness and kurtosis, with all competency variables falling within the acceptable range ($-1 < Sk < 1$; $-1 < Ku < 1$). Descriptive statistics were computed to summarize central tendencies and variability.

To examine changes in competencies within the experimental group, paired-samples t-tests were conducted on pre–post scores. Independent-samples t-tests and one-way ANOVA were used to compare competency gains between the experimental and control groups. Multiple linear regression (Enter method) was employed to identify predictors of competency growth, including instructional model, institutional context, technology readiness, and gender.

All analyses were conducted using IBM SPSS Statistics 26.0, with the significance level set at $p < .05$. Effect sizes were calculated using Cohen's d and interpreted according to conventional thresholds.

Qualitative interview data were analyzed thematically following Braun and Clarke's (2006) six-step procedure: familiarization with the data, generation of initial codes, search for themes, review of themes, definition and naming of themes, and final reporting. Thematic findings were then triangulated with quantitative results and artifact analysis to produce an integrated interpretation of the framework's impact on competency development.

5. Results

5.1. Quantitative Results

5.1.1. Pre–post analysis in the experimental group

Table 6 presents the pre- and post-course competency scores for the experimental group across the five targeted domains.

Table 6
Pre–Post Competency Gains in the Experimental Group

Competency	*Pre (M ± SD)*	*Post (M ± SD)*	*Change (%)*	*95% CI for Mean Difference*	*p-value*	*Cohen's d*	*Effect Size*
Technical Problem-Solving	3.12 ± 0.61	3.98 ± 0.52	27.60%	[0.78, 0.94]	< .001	1.42	Very Large
Systems Thinking	2.85 ± 0.68	3.83 ± 0.55	34.40%	[0.89, 1.07]	< .001	1.56	Very Large
Teamwork and Technical Communication	3.41 ± 0.53	4.18 ± 0.44	22.60%	[0.69, 0.85]	< .001	1.38	Very Large
Digital Simulation	3.25 ± 0.59	4.02 ± 0.48	23.70%	[0.69, 0.85]	< .001	1.29	Large
Presentation and Technical Argumentation	3.18 ± 0.57	4.00 ± 0.50	25.80%	[0.74, 0.90]	< .001	1.31	Large

The results indicate statistically significant improvements in all five competencies (p < .001). Systems thinking and technical problem-solving showed the largest percentage gains, followed by teamwork and technical communication, digital simulation, and presentation and technical argumentation. All effect sizes were large to very large (Cohen's d > 1.2), suggesting that the integrated framework had a substantial impact on students' perceived competencies.

To make these changes more visible, Figures 5 and 6 provide graphical representations of the quantitative findings.

Figure 5
Pre- and Post-Course Competency Comparison (Bar Chart)

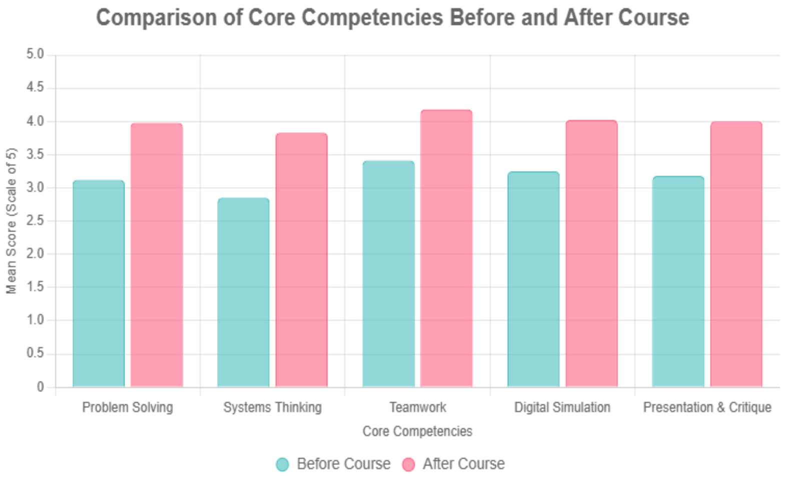
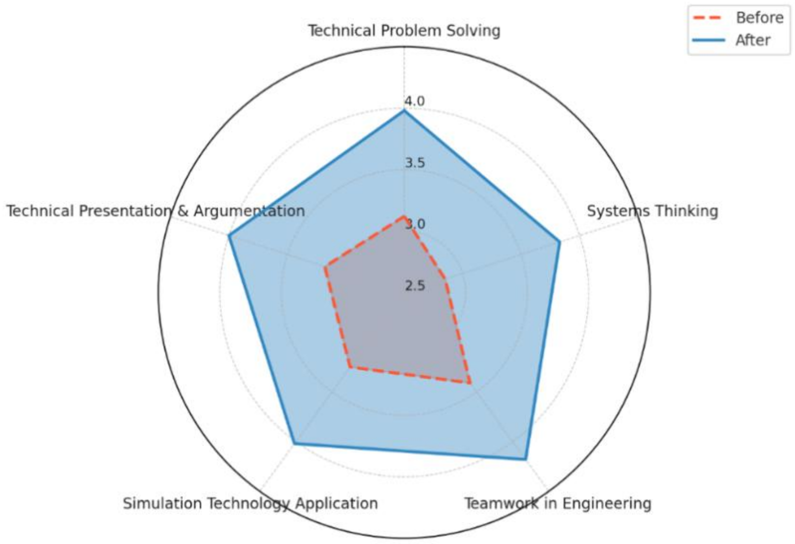


Figure 5 shows clear upward shifts in mean scores across all domains from pre- to post-test, while Figure 6 illustrates balanced growth in the overall competency profile. Together, these figures reinforce the conclusion that the STEM–CBE–ELT framework effectively strengthened multiple dimensions of engineering competence rather than improving only isolated skills.

Figure 6
Holistic Competency Development (Radar Chart)



5.1.2. Regression and ANOVA analyses

To identify the main predictors of competency growth, a multiple linear regression analysis was conducted with competency gain scores as the dependent variable and instructional model, institutional context, technology readiness, and gender as predictors.

Table 7
Multiple Linear Regression Predicting Competency Growth (Enter Method)

Predictor Variable	*β*	*t*	*p-value*	*Interpretation*
STEM–CBE–ELT Group	0.42	6.11	< .001	Strong positive effect
Institution (HCMUTE)	0.21	2.89	.004	Moderate effect
Technology Readiness	0.18	2.37	.019	Moderate effect
Gender (Male)	–0.05	–0.91	.362	Not significant

As summarized in Table 7, participation in the STEM–CBE–ELT framework emerged as the strongest and statistically significant predictor of competency growth ($\beta = 0.42$, $p < .001$). Institutional context and technology readiness also showed moderate positive effects, whereas gender did not reach statistical significance. The model as a whole was significant, explaining a substantial proportion of variance in competency gains.

To compare overall competency gains between the experimental and control groups, a one-way ANOVA was conducted.

Table 8
One-Way ANOVA Comparing Instructional Models

Source of Variation	*Sum of Squares*	*df*	*MS*	*F*	*p-value*
Between Groups	15.28	1	15.28	24.64	< .001
Within Groups	307.42	495	0.62		

The ANOVA results reported in Table 8 indicate a statistically significant difference between instructional models, $F(1, 495) = 24.64$, $p < .001$. Students in the experimental group achieved higher competency gains than those in the control group, confirming the superior effectiveness of the integrated STEM–CBE–ELT framework over traditional or CDIO-based instruction.

5.2. Qualitative Results

Thematic analysis of interview transcripts yielded three major themes that aligned closely with the quantitative findings: theory–practice integration, collaboration and peer review, and motivation and confidence. These themes, along with representative student quotes, are summarized in Table 9.

Table 9
Thematic Categories and Representative Quotes

Theme	*Description*	*Student Quote*
Theory–Practice Integration	Enhanced retention through applied projects	"Applying theory to projects helped me remember better." (ST012)
Collaboration and Peer Review	Improved error detection and solution quality through team critique	"Debating with classmates helped me realize my mistakes." (ST076)
Motivation and Confidence	Increased engagement through interaction with real equipment	"I felt more confident after interacting with real devices." (ST091)

These three themes collectively illustrate how the integrated STEM–CBE–ELT framework shaped students' learning behaviors and reasoning processes. They highlight shifts in how students applied concepts, interacted with peers, and approached engineering challenges. The following sections elaborate on each theme in depth.

5.2.1. Theme 1: Theory–practice integration

Students consistently described how the framework helped them bridge theoretical concepts with practical engineering tasks. Rather than relying on rote memorization, they engaged in hands-on simulations and iterative project cycles that required applying, testing, and refining theoretical ideas. One student reflected, "Applying theory to projects helped me remember better" (ST012), while another explained how troubleshooting deepened conceptual clarity: "When the simulation didn't behave as expected, I had to retrace the equations and check every block connection. After several revisions, I finally understood how each parameter shaped the system response and controller performance." (ST045). These reflections point to genuine conceptual restructuring, consistent with the strong quantitative gains in systems thinking and technical problem-solving.

5.2.2. Theme 2: Collaboration and peer review

Students emphasized the critical role of peer critique in sharpening their analytical reasoning. Group discussions functioned as intellectual checkpoints where assumptions were challenged and alternative solutions emerged. One student noted, "Debating with classmates helped me realize my mistakes" (ST076). Another described how collaborative troubleshooting broadened their understanding: "Our group spent nearly an hour debating the cause of a persistent oscillation… that exchange helped me see not only where my own reasoning was incomplete, but also how others approached the problem differently." (ST088). These accounts show that teamwork operated not merely as a course requirement but as a cognitive amplifier, reinforcing the gains observed quantitatively in teamwork, communication, and technical argumentation.

5.2.3. Theme 3: Motivation and Confidence

Experiential engagement—through simulations, real equipment, and project completion—played a central role in increasing learners' motivation and confidence. Many students described becoming more willing to experiment, revise, and persist through challenges. One student explained, "I felt more confident after interacting with real devices" (ST091), while another linked confidence to mastery: "Completing the project gave me confidence that I could handle real industry problems, not just exams." (ST023). These accounts suggest that rising confidence strengthened both emotional readiness and cognitive persistence, supporting the improvements observed in digital simulation and presentation competencies.

Across all themes, students described how iterative experimentation, feedback, and revision prompted them to identify gaps in understanding and gradually refine their engineering judgment. These qualitative findings align closely with the quantitative results, particularly the large effect sizes recorded in systems thinking, technical problem-solving, teamwork, and communication. Together, they demonstrate that the integrated STEM–CBE–ELT framework not only enhanced measurable competencies but also nurtured deeper habits of mind essential for engineering practice, including iterative reasoning, analytical persistence, and reflective problem-solving.

5.3. Integrated Interpretation of Findings

The combined evidence provides a coherent and compelling account of the framework's effectiveness. Quantitative analyses showed substantial pre–post improvement, strong predictive influence of the instructional model, and clear advantages over traditional approaches. Qualitative findings deepened this understanding by illustrating how students internalized engineering concepts, refined their problem-solving strategies, and developed greater confidence through authentic learning experiences.

Together, these results indicate that the integrated STEM–CBE–ELT framework successfully strengthened multiple dimensions of engineering competence and offered a viable pathway for bridging long-standing gaps between theory and practice in resource-constrained engineering programs.

6. Discussion

The findings of this study indicate that the integrated STEM–CBE–ELT framework substantially strengthened students' engineering competencies by linking theoretical concepts with authentic, practice-oriented learning activities. The notably large effect sizes may be attributed to the multi-component structure of the intervention, which combined simulation-based exercises, project-oriented tasks, iterative formative feedback, and structured reflection across a 15-week learning cycle. Previous research has shown that multi-modal instructional designs—particularly those grounded in experiential and competency-based principles—tend to produce deeper and more durable learning gains than single-method approaches (Borrego & Henderson, 2014; Mulder, 2017). The significant improvements in systems thinking and technical problem-solving identified in this study align with recent evidence demonstrating that structured, iterative modeling activities enhance students' abilities to interpret system behavior and make informed engineering decisions (Goode & MacGillivray, 2023).

The qualitative findings further illuminate these quantitative gains. Students' descriptions of cognitive restructuring during simulation debugging are consistent with recent studies showing that digital simulation, guided inquiry, and structured reflective feedback support deeper conceptual understanding and the transferability of problem-solving skills (Cubacub & Jimenez, 2025; Eshaq, 2024). Similarly, the importance of collaboration and peer critique identified in this study aligns with evidence that shared reasoning and structured peer evaluation strengthen analytical judgment and increase engagement in STEM learning environments (Dereje, 2023; Gürsoy et al., 2023). Together, these insights suggest that the integrated framework reinforces not only individual cognitive development but also the social and communicative dimensions of engineering practice.

When compared with established pedagogical models such as CDIO, PBL, and DBL, the STEM–CBE–ELT model demonstrated a clear comparative advantage. Previous research has frequently reported moderate competency gains under these models (Ismail et al., 2022; Tsai et al., 2022), whereas the present study documented substantially stronger improvements across multiple domains. This difference likely stems from the tighter alignment between learning activities, competency standards, and assessment processes in the integrated model. Broader international analyses similarly emphasize that digitally supported, competency-driven instructional frameworks enhance scalability, flexibility, and inclusiveness in engineering education (OECD, 2019; UNESCO, 2021). Additional support comes from studies showing that well-structured STEM-based interventions can significantly enhance students' motivation and academic performance (Uzun & Şen, 2023), which resonates with students' increased confidence and persistence in this study.

Further evidence from resource-conscious educational settings reinforces the value of experiential and differentiated learning approaches. Studies have demonstrated that hands-on, technology-supported tasks improve engagement and academic performance, particularly in under-resourced contexts (Insorio, 2024). This finding aligns closely with the third qualitative theme in this study, where students reported heightened motivation and a greater readiness to tackle complex engineering tasks following interaction with real or simulated equipment. Collectively, these results demonstrate that accessible digital tools, reflective practice, and competency-focused assessment can produce meaningful learning gains even in environments with limited laboratory infrastructure.

The findings also carry important pedagogical and institutional implications. Effective implementation of the framework requires instructors to shift from content transmission toward intentional learning design supported by strengthened Technological Pedagogical Content Knowledge (Mishra & Koehler, 2006). This direction is consistent with broader transformations in engineering education, where blended and digitally supported environments increasingly shape instructional practice. At the institutional level, the results provide evidence supporting the adoption of competency-based frameworks as a means of enhancing program relevance and strengthening alignment with industry expectations. For institutions with limited financial resources, the successful use of open-source tools such as Scilab highlights a viable pathway for modernizing laboratory instruction without imposing prohibitive costs.

The moderate institutional effect observed for HCMUTE suggests that contextual factors—such as stronger digital infrastructure and prior exposure to simulation tools—may amplify the effectiveness of the integrated model. This underscores the need for differentiated support strategies when scaling the framework across institutions, particularly in areas related to technological readiness and faculty development.

Despite the promising outcomes, several challenges remain. Limited digital infrastructure, uneven instructor expertise, and variation in students' prior competencies may hinder systematic implementation. Sustainable scaling will require coordinated investment in professional development, shared instructional resources, and integration of competency-based assessment tools within institutional quality assurance systems.

Future research should examine the framework across a broader range of institutions to explore how contextual characteristics shape implementation and outcomes. Longitudinal studies are needed to determine whether competency gains persist into advanced coursework or professional practice. Additionally, analytical approaches such as learning analytics and structural modeling may provide deeper insights into the interaction of experiential, digital, and competency-based components within complex learning systems. As emerging technologies—such as AI-driven tutoring, virtual laboratories, and augmented simulation environments—continue to advance, future studies should also explore their potential to enhance personalization, accessibility, and long-term engagement in engineering education.

7. Conclusion

This study proposed and validated an integrated STEM–CBE–ELT framework that effectively enhances engineering competencies by strengthening the connection between theoretical understanding and practical application. The framework's coherent combination of digital simulation, project-based learning, and competency-based assessment contributed to substantial improvements across core engineering skills, confirming its strong impact on student learning outcomes in resource-constrained contexts.

The results extend existing evidence on competency-based and experiential learning by demonstrating that systematic integration of instructional components can yield higher gains than conventional approaches such as CDIO, PBL, and DBL. The model also proved feasible and cost-effective through the use of open-source tools, supporting scalability for institutions with limited infrastructure. These findings highlight the framework's value both as a pedagogical contribution and as a practical solution for modernizing engineering programs.

Beyond technical proficiency, the framework fostered students' reflective thinking, collaboration, and confidence—attributes increasingly essential in digitally mediated learning environments. The study therefore offers a viable roadmap for institutions seeking to align curricula with contemporary competency standards and industry expectations.

Future research may expand implementation across more diverse institutional settings and employ longitudinal or advanced analytical methods to examine long-term competency development. Exploring the integration of emerging technologies such as AI-supported assessment, virtual laboratories, and adaptive learning systems may further enhance personalization and sustainability within engineering education.

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