

AI-Based Learning Model Integrating Cluster-Based and Scientific Approaches to Enhance Future Engineers' Critical Thinking and ICT Competence

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Abstract—The rapid digitalization of engineering education requires future engineers to build technical knowledge and, at the same time, ICT competence, critical thinking, problem-solving ability, and adaptive professional skills. The objective of this study was to assess an AI-based learning model integrating cluster-based and scientific approaches to strengthen these competencies among future engineers. The research used a mixed-methods design. The sample consisted of 448 undergraduate engineering students from three technical universities in Uzbekistan. There were equal numbers of participants in the experimental and control groups. The experimental group received cluster-based and AI-supported instruction, whereas the control group was taught with traditional learning methods. The model emphasized adaptive learning, problem-solving that is relevant to the profession, collaborative knowledge construction, systematic analysis, and competency-based assessment. The experimental group showed an increase in mean ICT competence. The difference was statistically significant (large Cohen's *d* effect size). Also, there were recorded improvements in problem-solving accuracy, self-efficacy, and innovativeness capacity. The combination of AI-supported adaptive learning with cluster-based and systematic inquiry could be a powerful framework to promote ICT competence and higher-order professional thinking in engineering education.

Keywords—artificial intelligence, cluster-based learning, critical thinking, engineering education, ICT competence, scientific approach.

I. INTRODUCTION

The fast development of digital technologies and the change to Industry 4.0 have altered the skills expected of future engineers. Engineering graduates are now expected to progress from theoretical knowledge to ICT competence, analytical problem-solving, adaptability, innovation, and effective professional decision-making. These changes are reflections of broader transformations taking place in education and employment around digital competence and technology-supported professional skills. ICT competence has thus become a vital part of engineering education with the increasing use of digital technologies for

engineering analysis, communication, design, problem-solving, and professional practice.

Digital learning environments will provide greater flexibility, access to information, and opportunities for students to interact with learning resources beyond traditional classroom instruction. However, digital competence alone is not enough for the practice of modern engineering. Future engineers must also be able to analyze problems, evaluate evidence, select appropriate technological tools, create solutions, and assess the consequences of their decisions. These skills are closely related to critical thinking and higher-order cognitive processes, which are particularly important when students are confronted with complex and unfamiliar professional problems.

Active and student-centered learning provides a good foundation for developing these skills. Learning environments that require students to analyze problems, articulate ideas, and evaluate alternative solutions can promote deeper involvement than instruction dominated by the transmission of information. Collaborative learning also provides the opportunity for further critical reflection as learners can compare different reasoning, improve their understanding, and develop solutions through interaction with others (Villavecencio et al., 2025).

A scientific approach offers a systematic process for enhancing systematic thinking. It is a set of interrelated activities of observation, inquiry, experimentation, association or reasoning, and communication. This stage encourages students to systematically gain information, ask questions, study evidence, draw conclusions, and communicate their understanding. This stage supports inquiry-based learning and critical thinking (Nugraha & Suherdi, 2017). The scientific approach is especially relevant to engineering learning since professional engineering problems require systematic investigation rather than mere reproduction of predetermined answers. When learners observe a problem, formulate relevant questions, examine possible solutions, interpret information, and communicate conclusions, the learning process increasingly resembles

professional engineering reasoning. Scientific inquiry can therefore provide a cognitive framework for connecting technical knowledge with critical thinking and problem-solving.

Artificial intelligence (AI) offers additional opportunities to support this learning process. AI-supported learning environments can facilitate personalized instruction, rapid feedback, performance monitoring, and adaptive learning pathways. Such characteristics can help students identify weaknesses, regulate their learning, and receive learning experiences corresponding more closely to their individual competence levels. AI-supported learning is also increasingly relevant to science and technology education. Its effective adoption also depends on AI literacy, because students and academic communities need adequate understanding to use generative and intelligent technologies meaningfully in educational activities (Karmaker, 2026).

Previous research has highlighted the potential of AI-based intelligent tutoring systems and ICT to support learning processes, while technological pedagogical competence is becoming increasingly important in digitally mediated educational environments (Ibrahim et al., 2025; Moemeke & Alordiah, 2026). Nevertheless, the educational value of AI does not result automatically from access to technology. AI tools need to be embedded within a pedagogical structure that requires students to interpret information, question outputs, evaluate alternatives, and justify professional decisions. Technology-supported learning is most meaningful when digital resources are integrated into coherent instructional activities rather than used as isolated technological additions.

Cluster-based learning provides another mechanism for organizing these activities. Cluster-based educational models connect related competencies, learning activities, and professional applications rather than treating knowledge areas independently. In engineering education, this approach can enhance ICT competence by linking digital resources to practical professional tasks and collaborative learning processes.

The combination of cluster-based learning with AI-supported teaching can therefore create a learning environment in which technological, cognitive and professional competencies are developed at the same time. Competency-based assessment allows students to work with digital resources, solve problems of professional relevance, receive adaptive feedback, collaborate with peers and assess their own progress. Training-oriented approaches have also been associated with gains in self-efficacy and innovation, which are important psychological dimensions of professional learning (Julia et al., 2025). Such an integrated orientation is especially important for the education of engineers in Uzbekistan.

However, the digital transformation in higher education is ongoing, and the integration of advanced ICT tools, AI-supported learning, pedagogical innovation, and authentic engineering problem-solving within a coherent instructional system remains challenging. Digital transformation may improve the quality of learning when technological resources are meaningfully integrated with educational

processes, rather than simply being introduced as isolated tools (Al Husaeni and Rahmat, 2023). Fragmented use of technology would provide a basic digital familiarity but would not necessarily improve analytical reasoning, critical thinking, or application to professional practice. Thus, a model of instruction that connects technological resources to systematic inquiry, collaborative learning, and professionally relevant engineering tasks is required. Also, the previous literature indicates that contemporary learning environments should be effective and promote flexible, interactive, and student-centered learning.

Technology-supported instructional media can promote independent learning without removing the structure needed to guide students through complex material. Dynamic visualization may also improve motivation and engagement by making abstract concepts easier to interpret (Villavecencio et al., 2025). The use of AI extends this potential by allowing learning activities and instructional support to be adjusted to individual student needs (Ibrahim et al., 2025).

Research on ICT integration, AI-supported learning, cluster-based instruction, and inquiry-oriented pedagogy has expanded considerably, but these approaches are still commonly investigated in isolation. As a result, relatively little is known about how they function when combined within the same engineering-learning environment. This is particularly relevant in Uzbekistan, where engineering programs are expected to connect digital competence with pedagogical innovation and the ability to solve authentic professional problems.

A learning model that brings these elements together may therefore provide a more coherent way to develop both technical and higher-order thinking skills. Against this background, the study examined an AI-based learning model that combines cluster-based instruction with a scientific approach to support the development of critical thinking and ICT competence among future engineers. The analysis focused on four aspects: (i) changes in ICT competence after the intervention; (ii) differences between the experimental and control groups; (iii) changes in problem-solving and critical-thinking performance; and (iv) changes in self-efficacy and innovation capacity. The instructional model combines collaborative cluster-based activities, adaptive AI support, professionally relevant tasks, systematic problem-solving, and competency-based assessment within a single engineering-learning framework.

II. LITERATURE REVIEW

A. ICT Competence in Engineering Education

ICT competency is increasingly becoming important in engineering education. This is because much of professional engineering activity today involves digital communication, data analysis, simulation, information management, and technology-assisted problem solving. Digital technologies are, in fact, not just tools for future engineers to seek information. They are used to analyze technical problems, communicate engineering ideas, and support decisions in professional settings. The growing dependence on digital technologies reflects wider changes in educational and work

settings where digital competence has become closely linked to effective participation in technology-intensive settings. But developing ICT competence requires more than just basic digital literacy skills.

Engineering students should be trained in selecting and applying suitable digital resources to real technical problems. Research in higher education has revealed that academic performance is associated with the availability, accessibility, and actual use of ICT, suggesting that meaningful use is more crucial than mere access (Makinde et al., 2023). Digital learning environments can support access to learning resources, communication, flexible activities, and more customized instruction, but these benefits are strongly linked to the way technology is incorporated into teaching and learning practices. A number of interrelated problems still hinder the development of ICT competence in engineering education in Uzbekistan. These include limited use of advanced digital resources, continued reliance on traditional teaching practices, relatively limited integration of AI-based applications, and weak connections between classroom learning and professional engineering tasks. These challenges are summarized in Table I. Improving ICT competence requires more than simply increasing the use of technology. The way digital tools are incorporated into teaching and connected with professional engineering tasks is equally important. For this reason, an integrated learning model is needed to bring technological, pedagogical, and professional elements together within the same instructional process.

TABLE I
KEY CHALLENGES IN ENGINEERING EDUCATION.

Challenge Area	Description	Impact
ICT Integration	Limited use of advanced digital tools	Low digital competence
Pedagogical Methods	Traditional teaching dominates	Weak practical skills
AI Adoption	Minimal implementation	Lack of innovation
Industry Linkage	Weak collaboration	Low employability

B. AI in Technology-Enhanced Learning

AI has broadened the scope of digital learning by making it possible to adjust learning pathways, provide timely feedback, use learner data to support assessment, and offer more individualized instructional assistance. The increasing use of deep learning and predictive modelling in computer engineering further demonstrates the growing relevance of AI-based methods in engineering-related technological environments (Rafidhi et al., 2026). AI-supported systems can respond to differences in students' competence levels and provide learning experiences that are adjusted according to individual performance. Adaptive AI-based learning systems have also been reported to support students' interest and achievement by providing more responsive learning experiences (Davidson et al., 2026).

The educational value of AI is particularly relevant when it supports active learning rather than simply automating information delivery. Intelligent tutoring systems, adaptive learning platforms, and AI-supported feedback can help students identify learning difficulties, monitor progress, and

engage with learning resources more independently. The application of AI-guided tools in educational decision-making also illustrates the potential of AI to support structured analysis and decision processes beyond automated information delivery (Amado and Digo, 2026). Recent educational studies have also emphasized the potential contribution of AI and ICT to learning processes across science education contexts (Ibrahim et al., 2025).

In this study, we used AI-supported learning in an effort to support individual skill development of the students, provide continuous feedback, guide customized learning pathways, and strengthen the self-regulation of the students. The results suggest that timely feedback helped foster learning confidence, and personalized pathways helped manage demands for learning. Access to data-informed feedback also allowed students to monitor their own progress and change their learning strategies. At the same time, the use of AI should be closely aligned with sound pedagogical design and not viewed as a stand-alone technological solution. Technology is not the same as critical thinking or problem-solving. Learners need opportunities to question information, compare alternatives, apply knowledge, and evaluate the quality of proposed solutions. Therefore, AI should function as a support mechanism within a broader instructional framework rather than as a substitute for analytical reasoning.

C. Cluster-Based Learning

Cluster-based learning provides an organizational framework for connecting related knowledge, competencies, learning activities, and professional applications. Educational clusters combined with competence-based approaches can provide environments in which different competencies are developed through interconnected learning and professional activities (Usarov et al., 2025). Rather than treating skills as separate instructional outcomes, cluster-based learning encourages students to develop interconnected capabilities through activities that reflect professional practice. In engineering education, cluster-based learning is particularly relevant because technical problems frequently require the simultaneous application of digital competence, disciplinary knowledge, communication, collaboration, and decision-making. Previous work has reported the potential of cluster-based models for developing ICT competence in engineering education. Cluster-based instruction can also strengthen the relationship between university learning and professional engineering contexts. By structuring activities around related professional competencies, students can learn not just individual technical concepts, but also how those concepts work together to solve engineering problems. The intervention includes cluster-based learning, AI-aided teaching, and competency-based pedagogy. The integration is mainly to connect the main ideas about individualized digital learning to collaborative knowledge construction and to professionally relevant tasks.

D. Scientific Approach and Critical Thinking

Critical thinking skills are important in engineering as professional problems usually require interpretation, comparison of alternative choices, consideration of evidence, and making reasoned decisions. The scientific approach supports this process through observation, inquiry, experimentation, reasoning, and communication (Nugraha & Suherdi, 2017). These stages are closely related to engineering problem solving, guiding students to identify problems, explore possible solutions, analyze evidence, and communicate appropriate solutions.

Digital technologies also contribute to the process by providing tools for investigation, data analysis, visualization, and feedback. AI-supported learning can also enhance higher-order thinking such as design thinking (Yang et al., 2026). Interactive environments may increase engagement and interpretation of complex information (Villavecencio et al., 2025). The experimental group of the present study showed better systematic problem solving, better analytical performance, and higher use of ICT tools.

E. Integration of AI, Cluster-Based Learning, and Scientific Thinking

AI-supported learning, cluster-based instruction, and scientific thinking are associated with different components of engineering competence. However, the functions of these components are closely interrelated, and a similar integration can be found in educational approaches like STEAM, which connects subject knowledge to the development of technical skills and practical competence (Ernazarov et al., 2025). In such approaches, AI offers adaptive support and feedback, cluster-based learning aids in organizing related professional competencies, and scientific thinking directs students through a structured process of analyzing and solving engineering problems. The relationship between these components can be viewed as a sequence of interconnected learning activities.

Students begin with a professional engineering problem, identify and examine the problem through observation, use AI-supported information and feedback to deepen their understanding, and then discuss and analyze the problem collaboratively within a cluster-based setting. They subsequently develop possible solutions, evaluate their suitability, communicate the results, and relate the outcome to professional practice. This conceptual relationship is illustrated in Figure 1. The model, thus, treats technological support, pedagogical organization, and professional application as interconnected parts of the same learning process. Rather than being developed separately, these dimensions are brought together to support more coherent engineering learning. AI-supported feedback can facilitate individualized learning, while cluster-based activities connect this individual learning with collaborative and

professionally relevant applications. Scientific reasoning provides the analytical process through which students interpret problems and evaluate possible solutions. Together, these components create a learning environment oriented toward ICT competence, critical thinking, problem-solving, self-efficacy, and innovation.

F. Self-Efficacy, Innovation, and Professional Readiness

Engineering competence includes motivational and psychological dimensions in addition to technical and cognitive capabilities. Self-efficacy influences students' confidence in using technologies and solving unfamiliar problems, while innovation capacity supports the development of creative responses to emerging professional challenges.

Training and technology-supported learning environments can contribute to these dimensions by providing students with opportunities to perform tasks independently, receive feedback, and participate in project-based activities (Julia et al., 2025). The study similarly connects AI-supported learning with increased confidence, independent learning, participation in creative activities, self-efficacy, and innovation capacity. These outcomes indicate that technology integration may influence not only technical competence but also students' willingness and confidence to apply technology within professional situations.

Professional readiness therefore requires an integrated combination of ICT competence, analytical reasoning, problem-solving, confidence, adaptability, and innovation. Such competence is increasingly relevant to future engineers operating in rapidly changing technological environments.

G. Research Gap

The current literature indicates the promise of digital learning, AI-supported education, cluster-based instruction, and scientific inquiry in improving student learning. Such approaches are, however, often considered in isolation, limiting the understanding of their integration in engineering education. AI-powered learning offers responsive feedback and tailored learning experiences (Ibrahim et al., 2025), whereas cluster-based instruction cultivates interconnecting competencies for professional application. Meanwhile, scientific inquiry is a process that consists of structured observations, questions, investigations, reasoning, and communication (Nugraha & Suherdi, 2017). Evidence on their joint use for teaching higher engineering education in Uzbekistan is limited. Hence, this study assesses an integrated model involving AI-supported learning, cluster-based instruction, and systematic scientific problem-solving with an emphasis on ICT competence and critical thinking. The study also focuses on problem-solving performance, self-efficacy, and innovation capacity.

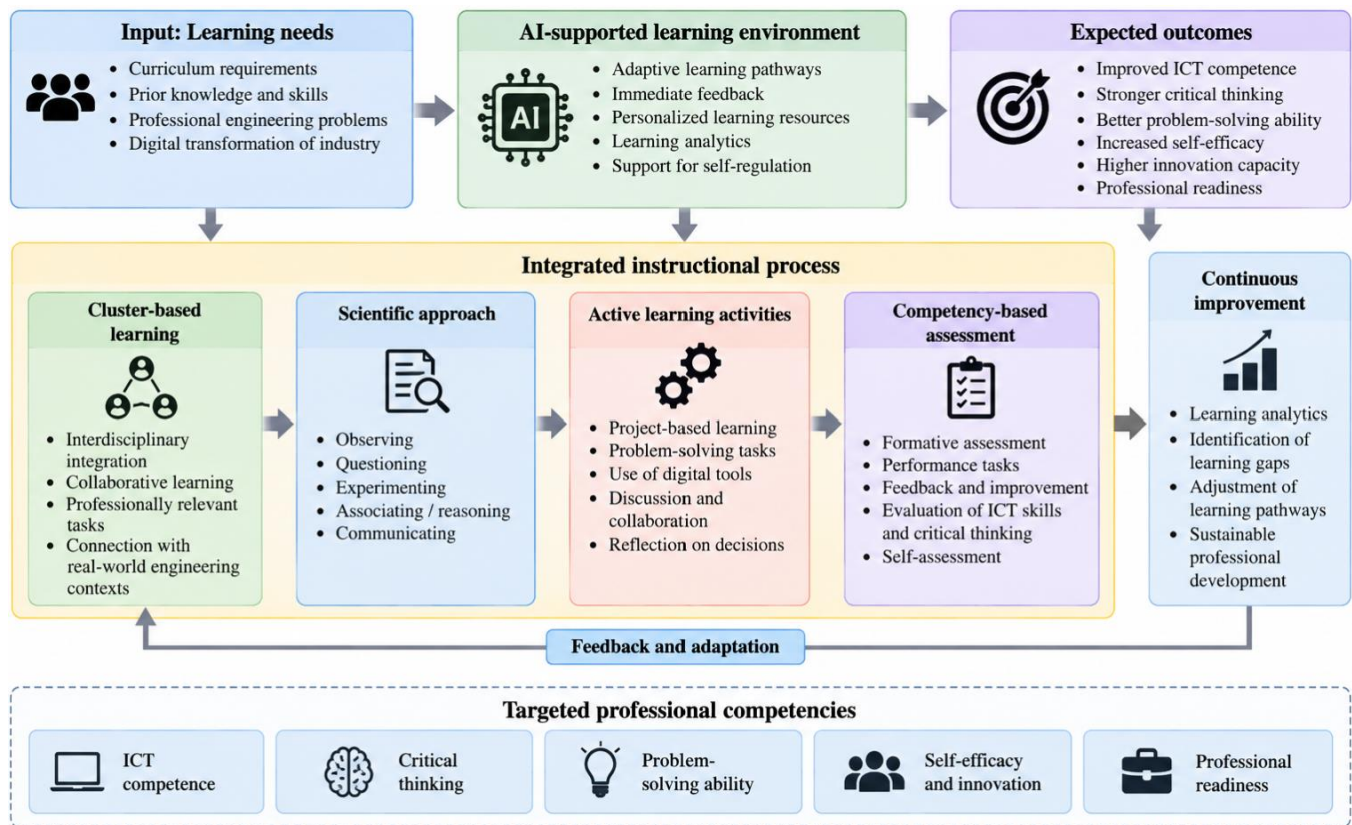


Fig. 1. Conceptual model of technology-enhanced engineering education integrating ICT, pedagogy, and professional competence.

III. METHODOLOGY

A. Research Design

The present research used a mixed-method experimental design to test the AI-supported cluster-based learning model. Quantitative data compared changes in ICT competence between experimental and control groups. Qualitative observations explored problem-solving, digital-tool use, self-efficacy, and innovation-related behaviors. The study comprised diagnostic assessment, intervention, and outcome comparison. The experimental group was exposed to AI-supported adaptive learning, cluster-based activities, competency-oriented instruction, and professional engineering tasks, and the control group received conventional instruction.

B. Participants

The sample was composed of 448 undergraduate engineering students from three technical universities in Uzbekistan. Stratified random sampling ensured representation of major engineering disciplines. The participants were evenly divided into 224 students in the experimental and control groups. The groups were of equal size to allow a direct comparison of learning outcomes between the two instructional approaches.

C. AI-Based and Cluster-Based Learning Model

The intervention was made up of three components: cluster-based learning, AI-supported adaptive learning, and competency-based pedagogy. The clustered activities linked ICT skills with collaborative engineering tasks and professional applications. AI-supported learning provided adaptive feedback and individualized learning pathways. Competency-based pedagogy meant that all learning activities were aligned to observable professional outcomes. Systematic inquiry and engineering problem-solving formed the basis for the learning process. Students identified relevant problems and examined the available information, explored possible approaches, and used ICT and AI-supported resources for further investigation. They then worked together to discuss alternative solutions, assessed proposed responses, and explained the rationale behind their decisions. This sequence reflected the processes of scientific learning such as observation, questioning, investigation, reasoning, and communication (Nugraha & Suherdi, 2017) and integrated technological competence, critical thinking, collaborative problem solving, and professional engineering application in a systematic learning framework.

D. Learning Activities

Students in the experimental group participated in project-based and scenario-based engineering tasks designed around professionally relevant problems. Each learning activity required students to identify the problem, select and apply appropriate ICT tools, examine information using AI-

supported resources, discuss possible solutions, evaluate alternative decisions, and communicate the selected solution. Collaborative and active learning activities were incorporated because technology-supported learning becomes more meaningful when learners actively construct, discuss, and evaluate knowledge rather than receive information passively.

The learning activities emphasized:

1. identification and analysis of engineering problems;
2. use of digital and ICT tools;
3. AI-supported feedback and adaptive learning;
4. collaborative analysis within cluster-based learning activities;
5. development and evaluation of possible solutions; and
6. communication of engineering reasoning.

The source study reports that the experimental group increasingly applied systematic problem-solving strategies, demonstrated higher-order thinking, and integrated ICT tools into engineering tasks.

E. ICT Competence Assessment

ICT competence was assessed before and after the intervention. Pre-test and post-test measurements were used to determine changes in students' competence levels and to compare the experimental and control groups. The assessment focused on students' ability to use digital technologies within engineering learning and problem-solving contexts. The analysis considered changes in mean ICT competence scores and the percentage improvement achieved by each group. The quantitative results of these assessments are presented in Table II.

F. Problem-Solving and Critical Thinking Assessment

Problem-solving ability was evaluated using project-based and scenario-based engineering tasks. Performance was examined through indicators including solution accuracy and the time required to develop solutions. Critical thinking was interpreted through observable higher-order processes including analysis, synthesis, evaluation, analytical reasoning, cognitive flexibility, and practical decision-making. These characteristics were reflected in the problem-solving performance of students in the experimental group. To organize the process conceptually, the scientific-thinking framework was structured around problem identification, questioning, investigation, reasoning, evaluation, and communication.

G. Self-Efficacy and Innovation Assessment

Self-efficacy and innovation capacity were measured through survey-based instruments, where the focus of the assessment was on the students' confidence in using advanced digital resources, their willingness to learn independently, and their involvement in creative and project-based activities, where attention was also given to how AI-

supported feedback, customized learning paths, and data-informed learning support contributed to students' confidence and ability to self-regulate their own learning.

H. Data Analysis

The quantitative analysis looked at differences in ICT competence prior to and following the intervention in the experimental and control groups. Descriptive statistics were used to calculate mean scores, absolute changes, and percentage improvements, thereby allowing for the comparison of competence development over time. A statistically significant difference between groups was found using an independent-samples t-test, $t = 8.73$, $p < 0.001$ for post-intervention differences. The effect size, Cohen's d , was approximately 1.2, which is considered large. The qualitative observations were analyzed in parallel to the quantitative findings on the use of ICT tools, engineering problem-solving approaches, participation in independent and collaborative learning, and innovation-related behavior of the students. The combination of both kinds of evidence allowed for a broader interpretation of changes in technological competence, cognitive performance, and learning-related motivation of the students within one analytical framework.

IV. RESULTS AND DISCUSSION

A. Improvement in ICT Competence

The use of an AI-supported cluster-based learning model was associated with a significant increase in ICT competence in the experimental group students. As shown in Table II, the mean score for this group went from 2.41 pre-intervention to 4.12 post-intervention, an increase of 70.9%. In the control group, the score improved from 2.38 to 3.01, a 26.5% improvement during the same period.

In absolute terms, the experimental group scored 1.71 points and the control group 0.63 points. Therefore, the gain observed under the experimental condition was approximately 2.7 times the gain obtained for traditional instruction. ICT competence develops more strongly when digital technologies are integrated in a clear instructional structure rather than when they are introduced as stand-alone tools.

TABLE II
COMPARATIVE ANALYSIS OF PRE-TEST AND POST-TEST ICT COMPETENCE.

Group	Pre-test Mean	Post-test Mean	Improvement (%)
Experimental	2.41	4.12	70.9
Control	2.38	3.01	26.5

In the experimental group, AI-supported learning, cluster-based activities, and competency-based assessment gave students repeated opportunities to use digital technologies in tasks that reflected professional engineering practice. Indeed, this pattern is in line with earlier studies showing that cluster-based learning can support the development of ICT competence in engineering education.

AI-supported learning has probably also contributed. This is by giving students more individualized forms of support. Immediate feedback and personalized learning pathways allowed students to recognize areas that required further attention, adjust their learning strategies, and progress at a pace more closely aligned with their current level of competence. Similar benefits have been reported for AI-supported instructional systems and other technology-enhanced learning environments (Ibrahim et al., 2025).

B. Statistical Effectiveness of the Learning Model

The independent-samples t-test showed a statistically significant difference between the experimental and control groups, $t = 8.73$, $p < 0.001$. The effect size was large as well, with Cohen's d approximately 1.2. The difference between the two groups was not simply a descriptive change in post-test scores. The magnitude of the effect suggests that the instructional model was associated with a meaningful improvement in learning outcomes, in addition to the statistical difference observed between the groups.

One possible explanation can be found in how technological and pedagogical components were combined in the intervention, in which AI-supported adaptive learning provided more personalized support, cluster-based activities prompted students to apply ICT skills to engineering-related activities, and competency-based assessment linked these activities to observable learning outcomes. Taken together, these components created a more coherent learning environment in which technology was integrated with instructional practice rather than introduced as an isolated tool.

C. Development of Problem-Solving and Critical Thinking

Also, the students of the experimental group performed better in project-based and scenario-based engineering problems. The accuracy of the solutions increased by 35%, and the time spent to perform the tasks decreased by 28%.

These quantitative results are supported by the observational data. Students from the experimental group tended to use more systematic approaches to problem-solving, performed better on analysis, synthesis, and evaluation, and made more efficient use of ICT tools in engineering tasks. In contrast, the students in the control group mainly used memorization procedures and algorithmic strategies and were less flexible in solving more complex problems.

The intervention contributed to more than just the development of digital competence. It also appears to have improved reasoning processes involved in critical thinking. In the learning activities, the students had to identify engineering problems, collect information, think about possible solutions, review their results, and explain the reasons for their decision. This sequence is very closely related to the scientific approach that stresses observing, questioning, experimenting, reasoning, and communicating (Nugraha & Suherdi, 2017).

There is a significant relationship between ICT competence and critical thinking because access to digital resources alone does not guarantee effective problem-solving. Engineering students also need to evaluate the relevance of information, compare different approaches, and justify their decisions. The more digital technologies are embedded in systematic inquiry and active reasoning, the more they are useful for learning, and not used as stand-alone resources.

D.

Role of AI-Supported and Cluster-Based Learning

Figure 1 shows the relationship between the technological, pedagogical, and professional dimensions. The model considers ICT competence as part of a wider learning process in which digital skills are developed in parallel with instructional activities and professional engineering applications.

In this umbrella, AI-supported learning provides adaptive support, cluster-based learning links digital competence to collaborative and professionally relevant activities, and competency-based pedagogy links these experiences to observable learning outcomes. The integration of these elements enables students to use technology and to develop analytical reasoning, collaboration, professional judgment, and applied problem-solving skills.

The improvement in the experimental group may also be due to the order of the learning activities. Students solved real-world engineering problems using online tools for inquiry, received AI-assisted feedback, participated in cluster discussions to explore possible solutions, evaluated their proposed solutions, and explained the rationale for their chosen actions. In this case, technology was not only a source of information, but also a part of the problem-solving process.

This is in line with previous work that has shown that cluster-based learning can support ICT competence when digital skills are developed through applied activities. It also corresponds to studies that indicate interactive and technology-supported learning environments can improve engagement and make learning experiences more meaningful (Villaveccencio et al., 2025).

E. Self-Efficacy and Innovation Capacity

The intervention had an effect on students' motivational and psychological characteristics. Survey-based evaluation showed that self-efficacy increased by 42%, while innovation capacity increased by 38% among students in the experimental condition.

Students reported greater confidence in using advanced digital tools, stronger willingness to participate in independent learning, and increased engagement in creative and project-based activities. AI-supported feedback was associated with greater learning confidence, while personalized learning pathways supported students in progressing according to their individual needs. Data-

informed feedback also contributed to improved self-regulation.

These findings demonstrate that the learning model affected more than cognitive and technical outcomes. Self-efficacy is important because students who are confident in their ability to use digital tools are more willing to engage with challenging engineering tasks and experiment with alternative solutions. Innovation capacity is similarly relevant because professional engineering requires the ability to respond creatively to rapidly changing technological demands.

Previous research has also linked structured training interventions with improvements in self-efficacy and innovation within higher education contexts (Julia et al., 2025). The present results extend this perspective. Specifically, AI-supported and cluster-based engineering instruction simultaneously influence ICT competence, problem-solving, confidence, and innovation.

F. Implications for Engineering Education

The findings give some practical implications for engineering education. ICT competence should be developed as part of the professional engineering capability, not as basic digital proficiency. Students need to have opportunities to engage with digital technologies for analysis, decision-making, communication, problem-solving, and other tasks that are analogous to real-world engineering practice.

AI is most useful when embedded in a clear pedagogical structure. Adaptive feedback and customized learning paths can support competence development, but they are of greater value when students are also required to analyze problems, assess information, and justify the choices they make. In this sense, AI should be a support for critical thinking, not a substitute for it.

Cluster-based learning offers a further link between university teaching and professional engineering practice. Learning activities are organized around related competencies and applied tasks. Indeed, students can use ICT tools within realistic problem-solving situations instead of learning technological skills in isolation from their engineering context.

Systematic scientific thinking can also be incorporated into technology-enhanced engineering activities. A learning process (including observation, questioning, investigation, reasoning, evaluation, and communication) can give students a structured way to apply digital tools to complex problems (Nugraha & Suherdi, 2017).

There is a motivational dimension beyond technical competence. A well-designed digital learning environment may influence students' confidence and creativity in responding to technological challenges. Thus, preparing students for professional engineering practice is not only a matter of improving ICT skills, but also of critical thinking, problem-solving, self-efficacy, innovation, and adaptability.

CONCLUSION

The integration of AI-supported adaptive learning, cluster-based instruction, systematic scientific thinking, and competency-based assessment can enhance engineering students' ICT competence and critical thinking. The experimental group of students showed more improvement than students taught using conventional instruction, with additional gains in accuracy in problem-solving, self-efficacy, and capacity for innovation. Digital technologies work best when they are embedded in structured pedagogical activities and in engineering tasks that are professionally relevant. Thus, the integrated model is a useful tool for development.

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