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Research article

The development of learning and innovation skill by using integration STEM education with robotics and automation for lower secondary school students

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Abstract: Developing 21st-century skills such as creative thinking and problem-solving is a critical goal in modern education. In this study, we investigated the effectiveness of an integrated learning approach combining STEM education with robotics to foster these key competencies in lower secondary students. Our objective was to compare students' creative thinking and problem-solving abilities before and after the intervention. A one-group pretest-posttest design was employed with a sample of 30 lower secondary school students selected via purposive sampling. The intervention consisted of four lesson plans integrating STEM concepts with hands-on robotics and automation activities. Data were collected using validated creative thinking and problem-solving assessment tests and were analyzed using paired-samples t-tests. The results revealed statistically significant improvements in both skills. The mean score for creative thinking increased from 28.29 to 44.85, while the mean score for problem-solving rose from 26.46 to 36.27 ($p < 0.05$ for both). The findings demonstrated that this integrated pedagogical approach is an effective strategy for enhancing students' learning and innovation skills, providing practical implications for curriculum design aimed at fostering tangible 21st-century competencies.

Keywords: learning and innovation skill, STEM education, robotics and automation, lower secondary school students

1. Introduction

Thailand is actively developing an innovation-driven economy, referred to as a Value-Based Economy. This strategic initiative aims to overcome the middle-income trap, elevate the nation to high-income status, and simultaneously alleviate socioeconomic inequality. It also seeks to foster economic and social balance within the country. Consequently, educational management in this innovation-driven era should adopt approaches that encourage learners to integrate innovation into driving economic development within their communities and society. This aligns with the evolution of Thailand's education system from the 4.0 era into the 21st century, which emphasizes teaching and learning that enables students to creatively synthesize knowledge to develop innovations that meet societal needs [1]. Furthermore, it promotes crucial skills such as analytical thinking, problem-solving, and creativity, which are considered foundational competencies for developing innovations and technologies that enhance the quality of human life.

However, there has been a notable decline in student interest in science disciplines, primarily due to their perceived difficulty. This has resulted in the scientific and technological knowledge and capabilities of Thai youth lagging behind international benchmarks. This disparity is clearly evidenced by the results of international assessments of science and mathematics literacy, such as the Program for International Student Assessment (PISA) and Trends in International Mathematics and Science Study (TIMSS) [2]. These initiatives, conducted by the International Association for the Evaluation of Educational Achievement (IEA), consistently demonstrate that Thai youth's performance is surpassed by that of their counterparts in other countries. Moreover, the workforce in science and technology remains insufficient to support future competitive demands [3].

Recognizing these challenges, the Institute for the Promotion of Teaching Science and Technology [4] acknowledges the need to establish clear educational directions to align with future societal changes and demands. The goal is to prepare learners to adapt to evolving technology, society, and the economy, while equipping them for life and work in an increasingly dynamic global landscape. To this end, IPST has developed the concept centered on Robotics and Automation, leveraging this crucial national industry to inspire student learning. This initiative focuses on fostering knowledge and skill development among students and provides teachers with a framework for designing learning activities tailored to their educational context. These activities align with the indicators and core learning standards for science and technology (Revised Edition 2017) as outlined in the Basic Education Core Curriculum B.E. 2551 [5]. This approach is further integrated with STEM Education, a pedagogical method that promotes 21st-century skills, by emphasizing interdisciplinary teaching and learning across science, technology, engineering, and mathematics. STEM leverages scientific and mathematical knowledge and applies engineering principles to create practical applications and innovations for daily life. It encourages students to use knowledge domains, including factual understanding, critical thinking, and other essential skills, for problem-solving, research, and the creation of novel ideas. The important keys of this approach include fostering deep understanding, promoting active student engagement with technological information and tools, and cultivating an environment that encourages challenge, innovation, and effective problem-solving [4]. Consequently, integrated STEM learning management serves as a highly responsive approach to educational reform, enabling the adaptation and evolution of educational practices to meet the demands of a changing society and global landscape.

Schools in Phakdi Chumphon District, under the Chaiyaphum Primary Educational Service Area Office 1, are in the western part of Chaiyaphum Province. This region is characterized by highlands and mountain ranges that extend from east to west, and some areas share borders with Lopburi and Phetchabun provinces. Because the district lies far from the provincial center, local schools face several pressing challenges. One of the most significant issues is the shortage of science teachers combined with a heavy academic workload. Students are often required to participate in academic skill competitions, which reduces the time available for classroom-based science learning. In addition, the scarcity of suitable science and technology instructional media limits students' learning opportunities and weakens their motivation to engage with science. To address these challenges, we propose the development of learning and innovation skills through an integrated STEM education approach, combined with robotics and automation, for lower secondary school students. In this research, we aim to enhance learning opportunities and inspiration for students in remote areas, while fostering crucial contemporary skills. These skills will help prepare students to learn and work effectively, utilizing new competencies that align with societal demands and can accommodate future changes.

2. Theoretical framework

The 21st Century Learning Skill, or Knowledge and Skills Rainbow, is considered a foundational skill set, emphasizing that learners should integrate their core subject knowledge with skills: Learning and Innovation Skills, Life and Career Skills, Information, Media, and Technology Skills. These competencies are considered essential knowledge and skills that learners require in their lives, careers, and economic and social development [6]. Learning and Innovation Skills, as one of these components, constitute critical competencies in the 21st-century enabling individuals to adapt and thrive in our rapidly changing and increasingly complex world, such as creative thinking, which is the ability to generate new ideas, brainstorm solutions, and generate new knowledge that can be applied or developed into valuable products, services, processes, or business models. Moreover, problem-solving skills are crucial. This involves the ability to analyze, evaluate evidence, reason, and distinguish information, as well as to identify problems, ask appropriate questions, organize information, and assess options. These skills will equip learners with solving complex problems.

The design of a learning management approach to foster 21st-century learner skills involves creating targeted enrichment activities designed to enhance learners' potential. These learning activities are characterized by several key features: 1) Defining the objectives of the learning management that are consistent with the content and indicators of the curriculum, and that specify the behaviors that the learners are to demonstrate in two skills: problem-solving skills and creative thinking. 2) Determining the content of the activities according to the learning standards and indicators according to the Basic Education Core Curriculum B.E. 2551, A.D. 2008, and the Robotics and

Automation curriculum [4]. 3) Organizing learning activities according to the STEM education learning approach [4] and the engineering design process [7]. 4) Reflecting on learning outcomes from activities, critique work, analysis of efficiency, and analysis of advantages and limitations. This framework is operationalized through a five-stage model based on the engineering design process: 1) Problem Identification, 2) Related Information Search, 3) Solution Design, 4) Testing, Evaluation, and Design Improvement, and 5) Presentation (Figure 1).

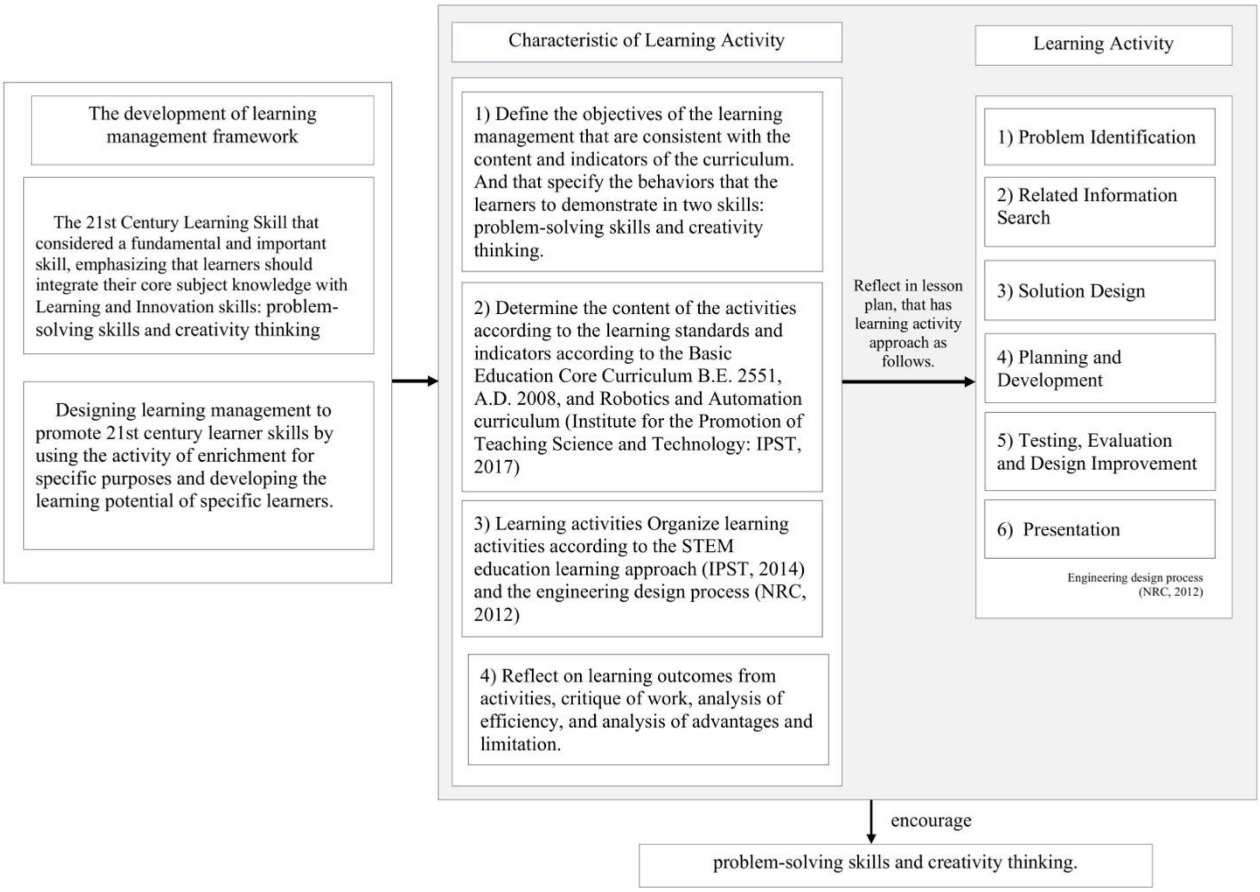

Figure 1. The characteristics of learning activities.

Jamnianpol [8] conducted a study entitled Guidelines for Promoting Student Development Activities toward Robot Coding Excellence for Lower Secondary School, with the objectives of examining the characteristics of student development activities in robot construction and identifying guidelines to support lower secondary school students in achieving proficiency in robot coding and construction. The findings revealed three critical dimensions characterizing learner development activities in robot coding construction: First, learners must acquire a foundational understanding of core STEM principles; second, instructors must facilitate the practical integration of conceptual knowledge and hands-on practice; and third, integrated learning activities must be designed primarily to enhance students' potential in robot construction.

Furthermore, Kaewkraison and Kaewkraison [9] conducted a study on the development of creative thinking skills among students in a robotics club through STEM Education-based learning activities under the theme Robots: The Alternative of the Future. The findings demonstrated that students who participated in STEM Education-based learning activities showed statistically significantly higher post-instruction creative thinking scores than their pre-instruction scores at the .01 level of significance. These results suggest that STEM-based learning integrated with robotics and automation constitutes an effective approach to developing 21st-century learner competencies, including creative thinking, computational thinking, and creative problem-solving skills, by enabling learners to understand scientific and technological principles through experimentation and hands-on construction, engage with engineering design processes, develop systematic thinking skills, and synthesize knowledge across disciplines, all of which are essential competencies for future professional practice.

3. Method

3.1. Participants

The study sample comprised 30 lower secondary school students at Banladchumpol School, Chaiyaphum Primary Education Service Area Office 1 during the first semester of 2024, who were selected via purposive sampling.

3.2. Research instrument

Three major instruments were utilized in this study: (1) Lesson plans for Robots and Mechanics, Robotics and Automation, Sensors, and Drive Systems. The plans were validated by a panel of experts to determine their Index of Item-Objective Congruence (IOC); yielding IOC values ranging from 0.67 to 1.00, indicating a high degree of appropriateness. (2) A Creative Thinking Assessment Test, developed in accordance with the guidelines of Supannee Chanprasert [10] and Guilford [11,12], comprising the following components of creative thinking: Using Principles of STEM, Originality, Fluency, Flexibility, Elaboration, and the success of the work piece (Table 1). This was reviewed by experts to evaluate its IOC (Index of Item-Objective Congruence); results were 1.00, which is considered appropriate. The reliability analysis of the try-out test evidenced by a Cronbach's Alpha coefficient of 0.81. (3) A Problem-Solving Assessment Test, which consists of assessment items applied according to the guidelines of Weir [13]. The components are as follows: Statement of the Problem, Defining the Problem, Searching for and Formulating a Hypothesis, Verifying the Solution, and Elaboration and Application (Table 2). This was reviewed by experts to evaluate its IOC (Index of Item-Objective Congruence); results were 1.00, which is considered appropriate. A try-out of the test yielded a Cronbach's Alpha coefficient of 0.81, indicating high reliability.

Supanni Chanprasert [10], Director of the Chemistry Division at the Institute for the Promotion of Teaching Science and Technology (IPST), examined the design of STEM-based instructional frameworks in the context of 21st-century skill development, proposing a structured approach to rubric construction for STEM activities that incorporates explicit assessment criteria and corresponding performance indicators. She further introduced a design-and-construction rubric for the Battery Charging with Clean Energy activity, evaluating six dimensions: integration of scientific, mathematical, technological, and engineering design principles; task completion; equipment efficiency; planning and collaboration; creative thinking; and critical thinking. This rubric was subsequently adopted in the STEM Education Activity Book for Secondary School Students (Grades 7–12) published by IPST, underscoring the imperative that assessment instruments for STEM activities must be congruent with the pedagogical objectives of the tasks and the 21st-century competency development of learners.

Consistent with this principle, Poolbun [14] investigated the development of creative thinking skills in the context of natural disasters and the greenhouse effect among Grade 6 students, employing a modeling-based instructional approach grounded in STEM Education. A purpose-built creative thinking assessment instrument was constructed around five dimensions derived from the modeling process: fluency, flexibility, originality, elaboration, and artifact design and construction. The instrument adopted a five-point rating scale (5 = highest to 1 = lowest), with content validity established through an Index of Item-Objective Congruence (IOC) of 0.87, indicating satisfactory alignment between items and intended constructs.

In a related study, Plaingam, Saksuparb, and Hemaprasit [15] (2021) examined the effects of a STEM Education approach on the creative problem-solving abilities of Mathayom Suksa 5 students (Grade 11). Their assessment instrument comprised three hierarchically structured components: (1) Problem Identification, including problem exploration, causal analysis, and problem prioritization; (2) Ideation, encompassing fluency, flexibility, originality, and logical reasoning; and (3) Solution Planning, evaluated on the basis of procedural clarity and coherence. Performance was rated on a five-point scale (excellent, good, moderate, fair, and needs improvement), and an IOC value of 0.97 confirmed strong content validity.

Informed by these frameworks, we developed a creative thinking skills assessment instrument synthesizing the rubric guidelines of Supannee Chanprasert [10] with Guilford's [12] multidimensional model of creative thinking. The instrument encompasses six components: Using principles of STEM, Originality, Fluency, Flexibility, Elaboration, and the success of the work piece. Additionally, a problem-solving skills assessment instrument was constructed in accordance with Weir's framework, incorporating five foundational components: Statement of the Problem, Defining the Problem, Verifying the Solution, Searching for and Formulating a Hypothesis, and Elaboration and Application.

Table 1. Creative thinking assessment between before and after learning with an integrated learning approach based on STEM education combined with the concepts of robotics and automation.

Assessment items	Description and Score				
	20	15	10	5	0
Using principles of STEM	Using principles of science, mathematics, technology, and engineering design processes are applied to key aspects of	Using principles of science, mathematics, technology, and engineering design processes is applied to key aspects of workpiece	Using principles of science, mathematics, technology, and engineering design processes is applied to key aspects of workpiece	Using principles of science, mathematics, technology, and engineering design processes are applied partially.	There’s no mention or indication of it in the document, assignment, or presentation.

Assessment items	Description and Score				
	20	15	10	5	0
	workpiece development, with a correct understanding and detailed consideration.	development, with a correct understanding but detailed consideration partially.	development, but there is a misconception.		
Originality	Create a workpiece with innovative ideas based on correct and complete STEM principles.	Create a work piece with innovative ideas based on correct STEM principles.	Create a work piece with innovative ideas based on STEM principles partially.	Create a work piece based on STEM principles	Create a work piece inconsistent with STEM principles
Fluency	Create a work piece based on correct and complete STEM principles, and complete the work on time.	Create a work piece based on correct STEM principles, and complete the work on time.	Create a work piece based on STEM principles, and completed the work on time.	Create a work piece based on STEM principles partially, and incomplete the work on time.	Create a work piece inconsistent with STEM principles, and incomplete the work on time.
Flexibility	Modified or adapted workpiece based on STEM principles, correctly and completely.	Modified or adapted work piece based on STEM principles, correctly and completely.	Modified or adapted work piece based on STEM principles, correctly partially.	Modified or adapted work piece based on STEM principles, partially.	Modified or adapted workpiece inconsistent with STEM principles
Elaboration	The workpiece based on STEM principles, correctly and completely, suitable for practical use, durable, and safe.	The workpiece based on STEM principles, suitable for practical use, durable, and safe.	The work piece based on STEM principles, suitable for practical use.	The work piece based on STEM principles partially, suitable for practical use.	The workpiece inconsistent with STEM principles is inappropriate, and suitable for practical use.
The success of the work piece	Create a workpiece based on STEM principles, correctly and completely, that can be tested for efficiency at least twice, with improvements made while maintaining its original condition.	Create a work piece based on STEM principles, correctly, that can be tested for efficiency at least twice, with improvements made while maintaining its original condition partially.	Create a work piece based on STEM principles, correctly, that can be tested for efficiency at least twice, with partial defects.	Create a work piece based on STEM principles, correctly, that can be tested for efficiency at least once, with partial defects.	The work piece is defective or tested for efficiency at wear-out.

Table 2. Problem-solving assessment between before and after learning with an integrated learning approach based on STEM education combined with the concepts of robotics and automation.

Assessment items	Description and Score				
	5	4	3	2	0
Statement of the Problem	Defining the Problem according with the situation, correctly and completely.	Defining the Problem according with the situation partially, correctly and completely.	Defining the Problem according with the situation partially, correctly.	Defining the Problem according with the situation partially.	Cannot define the Problem.
Defining the Problem	Analyze and identify the problems that accord with the situation, correctly and completely.	Analyze and identify the problems that accord with the situation partially, correctly and completely.	Analyze and identify the problems that accord with the situation partially, correctly.	Analyze and identify the problems that accord with situation partially.	Cannot analyze and identify the problems.
Verifying the Solution	Present solutions that are consistent with the analysis process and the given situation, covering all relevant issues correctly and completely	Present solutions that are consistent with the analysis process and the given situation partially, covering all relevant issues correctly and completely	Present solutions that are consistent with the analysis process and the given situation partially, covering relevant issues correctly.	Present solutions that are consistent with the analysis process and the given situation partially.	Cannot present solutions
Searching for and Formulating a Hypothesis	Apply problem-solving approaches to solve problems that accord with the situation, correctly and completely.	Apply problem-solving approaches to solve problems that accord with the situation, correctly.	Apply problem-solving approaches to solve problems that accord with the situation partially, correctly.	Apply problem-solving approaches to solve problems that accord with the situation partially.	Cannot apply problem-solving approaches to solve problems
Elaboration and Application	Apply knowledge in given situations and reapply it in other situations correctly and completely.	Apply knowledge in given situations and reapply it in other situations correctly.	Apply knowledge in given situations partially and reapply it in other situations correctly.	Apply knowledge in given situations partially correctly.	Cannot apply knowledge in given situations.

3.3. Data collection

Our purpose of the study was to compare students' creative thinking and problem-solving abilities before and after the intervention. A one-group pretest–posttest design was employed with a sample of 30 lower secondary school students selected using purposive sampling. The intervention consisted of four lesson plans integrating STEM concepts with hands-on robotics and automation activities. Data were collected using validated assessments of creative thinking and problem-solving abilities and analyzed using paired-samples t-tests. The sample participated in four lesson plans, each lasting three hours, for a total of 12 hours of instruction (Table 3).

Table 3. Detailed lesson plan**.**

Week	Lesson plans	Description	Time	Evaluation	Instrument / Tools
1	Introduction	Lesson overview	1 hours	Ask and Answer questions	-
2	Robots and Mechanics	Pretest	15 minutes	Pretest	Creative Thinking Assessment
					Problem-Solving Assessment
		- Work shop on Robots and Mechanics - Reflective activities (3 hours)	3 hours	Creative Thinking Assessment of student work pieces	Creative Thinking Assessment
				Problem-Solving Assessment across divided into five stages of student work pieces	Problem-Solving Assessment
3	Robotics and Automation	- Work shop on Robotics and Automation - Reflective activities	3 hours	Creative Thinking Assessment of student work pieces	Creative Thinking Assessment
				Problem-Solving Assessment across divided into five stages of student work pieces	Problem-Solving Assessment
4	Sensors	- Work shop on Sensors - Reflective activities	3 hours	Creative Thinking Assessment of student work pieces	Creative Thinking Assessment
				Problem-Solving Assessment across divided into five stages of student work pieces	Problem-Solving Assessment
5	Drive Systems	- Work shop on Drive Systems - Reflective activities	3 hours	Creative Thinking Assessment of student work pieces	Creative Thinking Assessment
				Problem-Solving Assessment across divided into five stages of student work pieces	Problem-Solving Assessment
		Posttest	15 minutes	Posttest	Creative Thinking Assessment
					Problem-Solving Assessment

The data collection process commenced with 1) an orientation session conducted prior to the learning management to establish agreements and clarify the procedures and learning activities with the students. 2) The administration of a pre-test was conducted. Thirty students were given the 5-item Creative Thinking Assessment Test and 5-item Problem-Solving Assessment Test; the tests had a total duration of 15 minutes. 3) The learning management was implemented using four lesson plans, each lasting three hours, resulting in a total of 12 hours of instruction. The researcher personally conducted the learning activities. For each lesson plan, students were given learning and skills assessment tests on creative thinking and problem-solving skills. 4) The next part was the administration of the Post-Test to the students. They were given the 5-item Creative Thinking Assessment Test and 5-item Problem-Solving Assessment Test; the tests had a total duration of 15 minutes, which were the same tests as the pre-test.

3.4. Data analysis

The data collected from the pretest and posttest assessments for creative thinking and problem-solving were analyzed using descriptive and inferential statistics. Descriptive statistics, including the mean and standard deviation, were calculated to summarize the general performance of the students. To address our research objectives, a paired-samples t-test was employed to compare the mean scores of the students before (pretest) and after (posttest) the instructional intervention. Results were evaluated at $p < 0.05$ with a 95% confidence level, and effect sizes were calculated using Cohen's d [16].

4. Results

As presented in Table 4, the analysis revealed a statistically significant improvement in students' creative thinking scores. There was a significant difference between the pre-test and post-test in the experimental group. The mean score increased from the pretest ($\bar{x}$ = 28.29) to the posttest ($\bar{x}$ = 44.85), which showed a statistically significant difference (p <.001). The score increase was significantly higher in the post-test than in the pre-test, and effect sizes were calculated using Cohen's d (Cohen's d = 1.42). Furthermore, the results of the Creative Thinking Assessment from the students' projects showed that the highest score of creativity was elaboration thinking at 115, whereas the lowest score was flexibility thinking at 60 (Figure 2).

The analysis of the Problem-Solving Assessment, detailed in Table 5, also indicated a statistically significant increase in student performance. The mean score increased from the pretest ($\bar{x}$ = 26.46) to the posttest ($\bar{x}$ = 36.27), which showed a statistically significant difference (p <.001). The score increase was significantly higher in the posttest than in the pretest, and effect sizes were calculated using Cohen's d (Cohen's d = 0.75). Furthermore, an evaluation of the students' projects highlighted varying levels of proficiency across the problem-solving process. The highest scores were attained in the Statement of the Problem phase (Score = 30), whereas the lowest were in Elaboration and Reapplication (Score = 18) (Figure 3).

Table 4. Students' test on creative thinking assessment between before and after learning with an integrated learning approach based on STEM education combined with the concepts of robotics and automation.

Assessment	n	$\bar{x}$	$\boldsymbol{S.D}$	df	t	p	95% CI of Difference	Cohen's d
Pretest	30	28.29	2.218	29	45.317	<.001	15.82, 17.31	1.42
Posttest	30	44.85	1.302					

Table 5. Students' test on the problem-solving assessment between before and after learning with an integrated learning approach based on STEM education combined with the concepts of robotics and automation.

Assessment	n	$\bar{x}$	$\boldsymbol{S.D}$	df	t	p	95% CI of Difference	Cohen's d
Pretest	30	26.46	2.432	29	16.431	<.001	8.59, 11.03	0.75
Posttest	30	36.27	2.723					

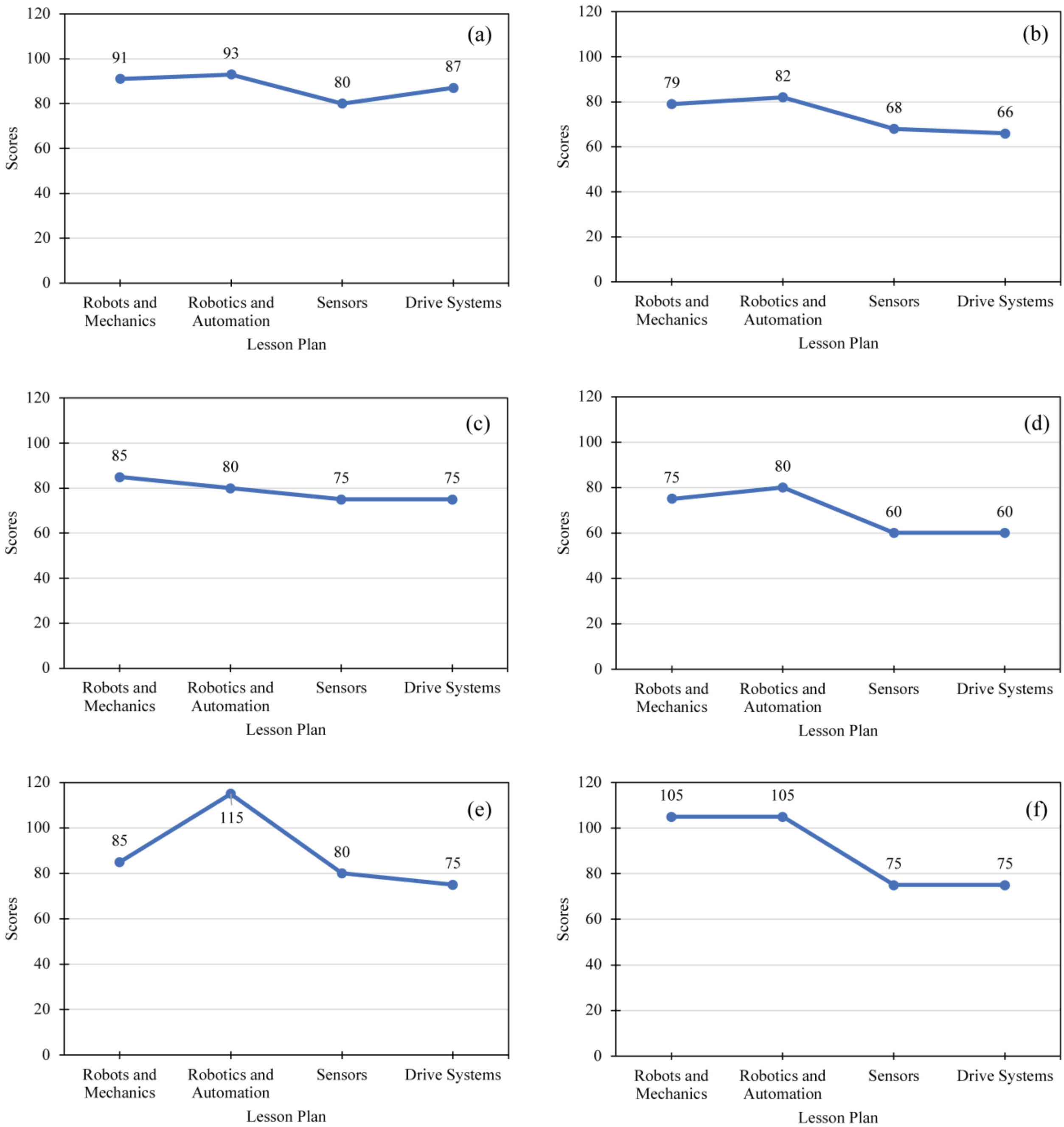

Figure 2. Overall scores from the Creative Thinking Assessment of student work pieces across four learning units. The assessment evaluates six criteria: (a) Using principles of STEM, (b) Originality, (c) Fluency, (d) Flexibility, (e) Elaboration, and (f) Success of the work piece. The maximum score for each criterion is 120 points.

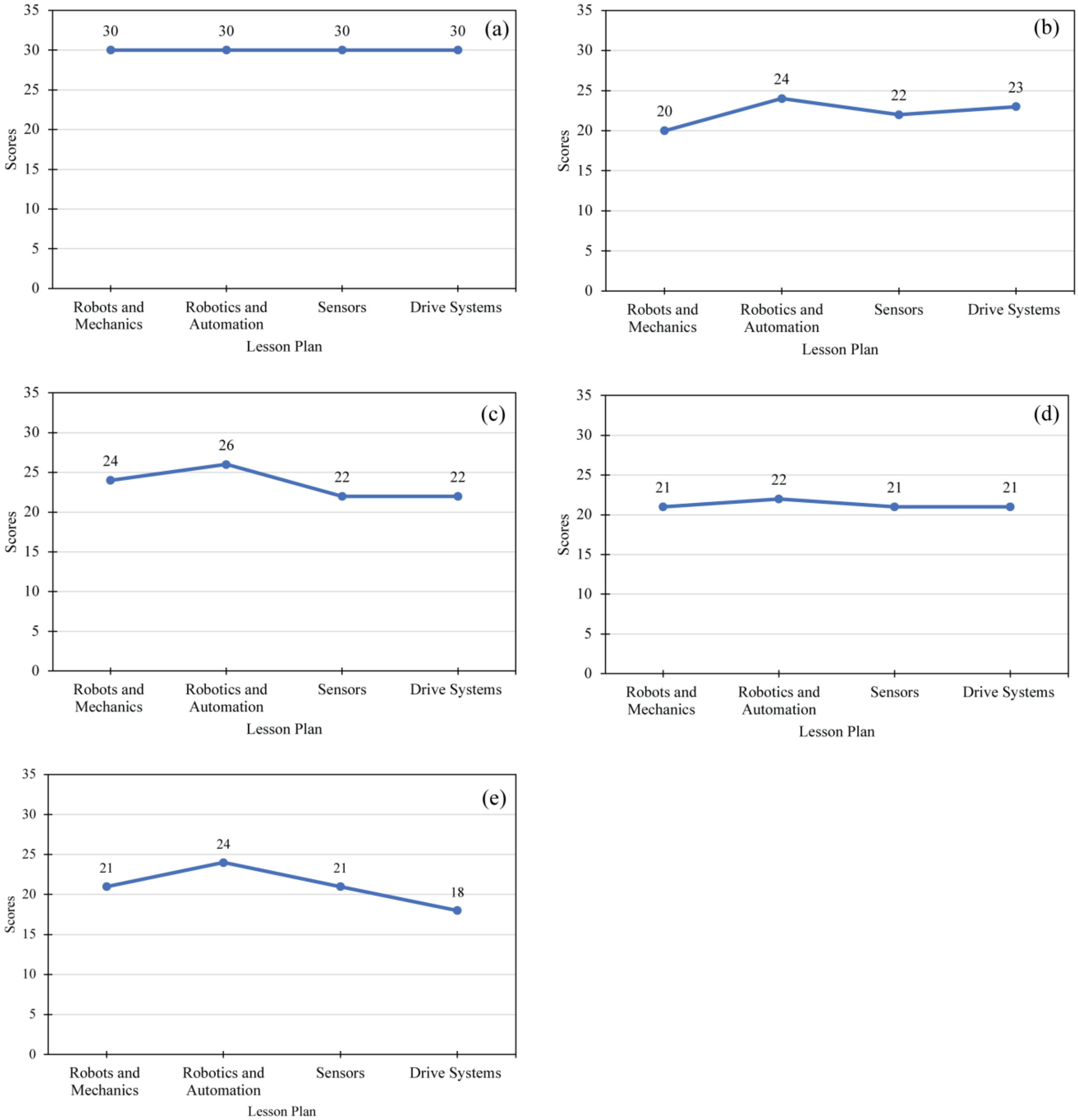

Figure 3. Scores from the Problem-Solving Assessment across four learning units. The assessment is divided into five stages: (a) Statement of the Problem, (b) Defining the Problem, (c) Verifying the Solution, (d) Formulating a Hypothesis, and (e) Elaboration and Application. The maximum score for each stage is 30 points.

5. Conclusions

The objectives of this research were (1) to compare the learning and innovation skill in creative thinking before and after learning with an integrated learning approach based on STEM education combined with the concepts of robotics and automation; and (2) to compare the learning and innovation skill in problem-solving before and after learning with an integrated learning approach based on STEM education combined with the concepts of robotics and automation. The research samples were thirty lower secondary school students at Banladchumpol School, Chaiyaphum Primary Education Service Area Office 1, during the first semester of 2024, selected by purposive sampling.

Student performance on the Creative Thinking Assessment was evaluated before and after the integrated STEM intervention. This approach combined robotics and automation concepts through four sequential lesson plans: Robots and Mechanics, Robotics and Automation, Sensors, and Drive Systems. Posttest mean scores (44.85) were significantly higher than pretest scores (28.29), demonstrating a statistically significant improvement in students' creative thinking ($p < .001$). The calculated effect size (Cohen's $d = 1.42$) indicates a large effect that significantly exceeds conventional thresholds. This value suggests a substantial increase in scores; however, the practical implications should be interpreted within the context of hands-on creative thinking skills. Figures 2(a–f) illustrate the assessment results for workpieces across the four learning units. Evaluations were conducted after each session using a rubric that assessed STEM principles, originality, fluency, flexibility, elaboration, and workpiece success. The highest creativity score was observed for the "elaboration" dimension (115) within the Robotics and Automation unit. This result may be attributed to students' prior interest in robotics, which enabled them to articulate their group's design and mechanical components clearly. Such conceptual understanding supports effective workpiece development. Furthermore, while elaboration is typically a complex dimension of creativity to assess, the high scores likely resulted from the collaborative learning approach, where students engaged in collective brainstorming and shared decision-making. These findings align with Paramathikul [17], who noted that robotics-based STEM education encourages hands-on knowledge construction and fosters creativity. This is further evidenced by the consistently high scores observed in creativity and design assessments across the curriculum.

In this study, we examined student performance on the Problem-Solving Assessment before and after an integrated STEM intervention. This approach combined robotics and automation concepts across four sequential lesson plans: Robots and Mechanics, Robotics and Automation, Sensors, and Drive Systems. Results indicated that posttest mean scores (36.27) were significantly higher than pretest scores (26.46, $p < .001$). The calculated effect size (Cohen's $d = 0.75$) suggests a medium-to-large effect, indicating that the instructional method effectively enhanced students' problem-solving skills. Figures 3(a–e) illustrate the assessment results for the workpieces across the four learning units. Evaluations were conducted after each session using a rubric that assessed five stages: (a) Statement of the Problem, (b) Defining the Problem, (c) Verifying the Solution, (d) Formulating a Hypothesis, and (e) Elaboration and Application. The highest problem-solving score (30) was observed in the "Statement of the Problem" stage across all units. This success may be attributed to the STEM approach's emphasis on scenario-based problem-solving and the integration of the engineering design process, which focused on enabling students to develop innovative solutions for specific problems. These findings align with Sararit and Nasaree [18], who observed that STEM-based learning management progressively develops problem-solving skills by helping students understand the underlying causes of and solutions to challenges. Overall, the results demonstrate that integrated STEM education, combined with robotics and automation, enhances the problem-solving capabilities of lower secondary students. This improvement is further reflected in the learners' ability to identify scientific problems correctly within their workpiece presentations.

Moreover, the results suggest that an integrated STEM approach, combined with robotics and automation concepts, can enhance the learning and innovation skills of lower secondary students, particularly in creativity. Through hands-on experiences, collaborative knowledge exchange, and idea sharing, students acquired a coherent understanding of scientific principles, technology, engineering, and mathematics. This knowledge was successfully integrated to develop workpieces that were conceptually grounded in STEM principles and relevant to the assigned scenarios. Furthermore, this study contributed to the field through the development of two instruments: The Creative Thinking Assessment and the Problem-Solving Assessment. However, as we employed a one-group pretest–posttest design, these findings should be interpreted as preliminary evidence of effectiveness.

The creative thinking assessment of student work pieces across four learning units revealed that Lesson Plan 2 (Robotics and Automation) and Lesson Plan 3 (Sensors) exhibited a declining trend in scores, particularly in the criteria of originality and flexibility. This decline may be attributed to the novelty and complexity of the content, which introduced challenging concepts related to automation principles and the application of mechanisms in everyday life. Specifically, these units required learners to engage with fundamental types of mechanical mechanisms, configurations of barrier gate systems (e.g., barrier gates and car park systems), and the application of scientific principles concerning voltage, electric current, and resistance. Furthermore, students were expected to construct graphs illustrating the relationship between resistance and conductor length, calculate voltage drops across resistors, and utilize multimeters to measure voltage drop values, leading to the practical assembly of circuits and programming for automated control.

Given that these learning units were designed with progressive difficulty, the increasing complexity of the content and the task demands may have constrained learners' ability to fully apply creative thinking skills. This limitation was particularly evident in the dimensions of originality, which requires novel and divergent ideation, and flexibility, which requires the capacity to generate solution pathways. Moreover, when learners were required to apply foundational scientific principles in the construction of their work pieces, a greater proportion of cognitive effort may have been directed toward comprehending and executing technical procedures rather than generating innovative ideas. Consequently, learners' capacity for multi-perspective thinking, conceptual adaptation, and situational responsiveness was likely diminished, resulting in lower scores in the dimensions associated with deeper creative thinking.

To address these challenges, the design of future learning activities should consider the following recommendations. First, task difficulty should be calibrated appropriately through task segmentation or scaffolding strategies, enabling learners to develop foundational understanding progressively before advancing to creative production tasks. Second, a balanced sequencing of foundational knowledge, scientific principles, and learning activities should be established to prevent excessive cognitive overload from content complexity. Third, open-ended tasks that permit multiple solution pathways should be incorporated, even within engineering or science-based contexts, to foster originality and flexibility in thinking. These recommendations represent important directions for enhancing the effectiveness of STEM education instructional design in future implementations.

Additionally, the notably high effect size reported for creative thinking skills (Cohen's $d = 1.42$) warrants careful interpretation. First, the relatively small sample size may have contributed to inflated and unstable effect size estimates, particularly within a one-group design that inherently presents constraints on internal validity. The absence of a control group makes it difficult to determine whether the observed changes resulted directly from the instructional intervention or were attributable to confounding variables such as history effects. Second, the lack of a comparison group further limits the interpretation of the effect size, as it cannot be confirmed whether the magnitude of the observed gains was a specific consequence of the implemented pedagogical innovation or merely reflected a natural developmental trajectory that would have occurred among learners over the same period regardless of the intervention. Accordingly, future research employing experimental designs with control groups and larger sample sizes is essential to substantiate the robustness and replicability of these findings across educational contexts.

Although the findings indicate positive trends in learners' skill development, these improvements cannot be conclusively attributed solely to the designed STEM activities. This limitation arises from the adoption of a one-group pretest-posttest design, which presents significant constraints on internal validity and, consequently, undermines the capacity for robust causal inference. Therefore, the developmental outcomes observed following the implementation of STEM activities integrated with robotics and automation may have been influenced by extraneous confounding factors, including: maturation effects (natural developmental changes occurring in learners over the course of the study period); testing effects (increased familiarity with assessment instruments resulting from prior exposure to the pretest, which may have artificially inflated posttest scores); and history effects (external events or experiences encountered by participants during the intervention period that may have independently contributed to observed changes). Furthermore, we employed a relatively small sample size ($N = 30$), selected through purposive sampling from a single school representing a specific target population. Consequently, the generalizability of the findings is limited to the studied sample context, namely lower secondary school students in a school with insufficient technological resources and infrastructure. Researchers should therefore consider increasing the sample size, adopting probability sampling methods, and expanding the study to multiple schools or diverse educational contexts to enhance the external validity and broader generalizability of the findings. Future research should adopt designs that include a control or comparison group to enhance the credibility of the findings. Such an approach would more clearly determine whether the observed improvements are directly attributable to the intervention or to external factors.

Author contributions

Wichuta Auansrimuang: Conceptualization, Methodology, Formal Analysis, Project Administration, Writing – Original Draft; Waraporn Chanwiang: Writing – Original Draft, Data Curation, Validation; Teerawat Piwkom: Writing – Original Draft, Validation. All authors contributed to Writing – Review & Editing. All authors have read and agreed to the published version of the manuscript.

Use of Generative-AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare that there is no conflict of interest in this manuscript.

Ethics declaration

Official permission to conduct this study and collect data on the school premises was formally requested and granted by the school director. Prior to the commencement of the activities, all participating students were fully informed of the research objectives, procedures, and their rights as participants. Throughout the entire research process, all data containing personally identifiable information were kept strictly confidential, and the anonymity of the participants was ensured through the use of coded identifiers in all data records and reporting.

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