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Development of STEAM-Based Project-Based Learning (PjBL) Mathematics Learning Tools to Improve Students' Critical Thinking

Lilik Dian[1], Timbul Yuwono[1*], Tatik Retno Murniasih[1]
[1]Mathematics Education, Postgraduate School, PGRI Kanjuruhan University, Malang, Jawa Timur, Indonesia, 65148
*Corresponding author's email: timbulyuwono@unikama.ac.id

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Abstract

This study aims to develop and evaluate the feasibility of STEAM-based mathematics learning tools integrated with Project-Based Learning (PjBL) to enhance students' critical thinking skills in probability learning. This research employed a Research and Development (R&D) design using the 4-D model (Define, Design, Develop, Disseminate). The developed products consisted of lesson plans, student worksheets (LKPD), and critical thinking assessment instruments. The validity of the instruments was evaluated through expert judgment, while practicality and effectiveness were tested through classroom implementation using a pretest–posttest design.The results indicated that the learning tools achieved a high level of validity (mean score = 97%) and demonstrated good reliability (ICC = 0.778). The practicality results showed that all stages of PjBL implementation were conducted optimally. The effectiveness analysis revealed a moderate improvement in students' critical thinking skills (N-Gain = 0.59). Furthermore, a paired sample t-test indicated a statistically significant difference between pretest and posttest scores ($p < 0.05$). These findings confirm that STEAM-based PjBL learning tools are effective in improving students' critical thinking skills.

Keywords: *STEAM education; project-based learning; probability learning; critical thinking; instructional design*

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INTRODUCTION

The growing complexity of global societal, technological, and economic challenges has placed increasing emphasis on the development of twenty-first-century competencies, particularly critical thinking, as foundational outcomes of schooling. Within mathematics education, critical thinking is widely recognized as a core competency that enables students to analyze, evaluate, and reason through novel and uncertain situations, preparing them for adaptive decision-making in real-world contexts (Thornhill-Miller et al., 2023; Vincent-Lancrin, 2023). However, conventional instructional approaches frequently rely on information transmission and emphasize procedural fluency over deep conceptual understanding, leaving students ill-equipped to engage meaningfully with complex mathematical ideas. This is especially evident in probability learning, a domain where misconceptions, intuitive biases, and cognitive limitations often impede conceptual development (Hull et al., 2021). As studies show, students' proportional reasoning, which is central to understanding probabilistic relationships, often underdeveloped, hindering their ability to construct robust probabilistic reasoning (Begolli et al., 2021). Such findings highlight the need for pedagogical models that support deeper engagement, meaningful knowledge construction, and the development of domain-specific critical thinking skills in mathematics.

Parallel concerns have been raised regarding the under-theorization of critical mathematical thinking (CMT) and the persistent difficulty of operationalizing and assessing critical thinking in classroom environments (Monteleone et al., 2023). Students frequently enter secondary schooling with limited foundational CMT, and their epistemological beliefs may further constrain their reasoning processes, as belief justification is strongly tied to the quality of critical thinking (Rott, 2021). Misalignments between students' perceived and actual abilities as illustrated by the Dunning-Kruger effect compound these issues, leading to overconfidence that hinders metacognitive growth and learning (Yousef et al., 2025). Collectively, these findings point to the multifaceted challenges associated with fostering critical thinking in mathematics and, in particular, the urgent need for redesigned learning environments that explicitly cultivate these cognitive skills through authentic, meaningful, and interdisciplinary experiences.

Given these challenges, educators and researchers have increasingly turned to STEAM (Science, Technology, Engineering, Arts, Mathematics) and Project-Based Learning (PjBL) as promising pedagogical approaches for developing higher-order thinking. STEAM-based models promote interdisciplinary engagement, creativity, and problem solving, providing contextualized experiences that mirror real-world knowledge integration (Conde et al., 2021; Diego-Mantecón et al., 2021). PjBL, in turn, foregrounds inquiry, collaboration, and iterative design, creating learning environments in which students must analyze problems, generate evidence-based solutions, and justify decisions all essential components of critical thinking (Loyens et al., 2023). The convergence of STEAM and PjBL thus offers a theoretically grounded instructional alternative to traditional lecture-based learning, which has been shown to inadequately support cognitive engagement and critical thinking (Bates et al., 2025) . In probability learning, where abstract concepts often lack intuitive grounding, STEAM-PjBL approaches hold particular promise for making learning more concrete, meaningful, and conceptually rich.

Within the broader pedagogical landscape, PjBL has been documented to substantially enhance students' analytical reasoning, problem-solving capabilities, and creativity across STEM domains (Coronado et al., 2021; Vithanage & Nakashima, 2025). Research in engineering, science, and digital-fabrication contexts indicates that PjBL supports systemic thinking, expert-like mechanistic reasoning, and improved performance on complex (Davis et al., 2024; Schneider et al., 2022; Vasconcelos & Zambroni De Souza, 2022). These findings reinforce the viability of PjBL not only as an instructional method but also as a cognitive apprenticeship model that nurtures deep engagement and transferable thinking skills. Despite this evidence, the application of PjBL in mathematics-particularly in probability remains limited, with few studies exploring its combination with STEAM to improve critical thinking outcomes. This gap suggests an opportunity to advance both theoretical and practical knowledge through the design of integrated STEAM-PjBL learning tools tailored specifically for secondary mathematics.

Although previous studies have shown that STEAM and Project-Based Learning (PjBL) can improve students' engagement, creativity, and problem-solving skills, several limitations remain. Most studies focus on general STEM competencies rather than domain-specific critical thinking in probability learning. In addition, previous findings are not always consistent, as some studies report difficulties in connecting mathematical concepts

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with real-world contexts due to limited scaffolding and instructional support. Furthermore, project-based learning may increase students' cognitive load when complex tasks are not accompanied by structured guidance. Therefore, this study addresses these gaps by developing a structured STEAM-based PjBL learning design that explicitly supports students' critical thinking in probability learning through contextual and interdisciplinary activities.

Existing literature also highlights several discipline-specific gaps that impede effective probability learning. Many instructional materials emphasize formulaic computation rather than conceptual understanding, resulting in superficial mastery and persistent misconceptions (Orcos Palma et al., 2022). Vocabulary misalignment between students and expert communities further complicates probabilistic discourse, underscoring the need for instructional designs that support linguistic and conceptual development (Groth et al., 2020). Moreover, students frequently encounter difficulty solving open modelling problems due to inadequate support in identifying unknown quantities, generating assumptions, and applying structured reasoning all essential dimensions of critical thinking (Schukajlow et al., 2023). The absence of materials that incorporate active learning, example-based practice, and domain-specific critical thinking frameworks further exacerbates these challenges (Begolli et al., 2021). Consequently, there is an urgent need for innovative instructional tools that holistically address cognitive, linguistic, and conceptual barriers in probability education.

In response to these pedagogical needs, STEAM-based models offer a holistic and interdisciplinary framework capable of advancing both cognitive and affective dimensions of learning. Research demonstrates that STEAM integrated with hands-on activities, digital making, embodied cognition, and design thinking can enhance creativity, computational thinking, mechanistic reasoning, and other higher-order skills essential to critical thinking (Chang et al., 2023; Hsiao et al., 2022; Weng et al., 2023). Ethnomathematics-oriented STEAM PjBL, for instance, has been shown to promote mathematical creative thinking by situating problems within culturally meaningful contexts (Afifah et al., 2025). Together, these findings indicate that STEAM-based approaches possess the theoretical grounding and empirical support necessary for designing mathematics learning tools that explicitly develop students' critical thinking through interdisciplinary, culturally relevant, and cognitively rich experiences.

Despite the growing body of research on STEAM and Project-Based Learning (PjBL), their integration in mathematics education-particularly in probability learning-remains underdeveloped. Previous studies have demonstrated that STEAM–PjBL has been implemented through interdisciplinary project activities, digital simulations, and design-based tasks that engage students in problem-solving processes (Aini et al., 2023; Purnomo et al., 2025). These studies highlight several advantages of STEAM–PjBL, including the promotion of active learning, enhancement of problem-solving skills, and improvement of students' engagement through real-world contexts.

However, most existing studies focus on general mathematical skills or STEM domains and have not specifically addressed the development of critical thinking in probability learning. In addition, there is still limited research that operationalizes STEAM–PjBL into structured instructional tools that explicitly target critical thinking indicators such as interpretation, analysis, inference, explanation, and evaluation. Furthermore, the rapid expansion of STEAM research has not been accompanied by targeted instructional designs that address common misconceptions in probability, such as proportional reasoning difficulties and uncertainty interpretation (Rosenberg et al., 2022). Therefore, this study addresses this gap by developing a STEAM-based PjBL instructional design that is systematically structured to improve students' critical thinking skills in probability learning.

Despite the growing implementation of STEAM and Project-Based Learning (PjBL) in mathematics education, limited studies have specifically developed structured learning tools for probability learning that explicitly target students' critical thinking skills. Previous studies also provide inconsistent findings regarding the effectiveness of interdisciplinary and project-based approaches due to limited scaffolding and contextual support. Therefore, this study addresses these gaps by developing and evaluating STEAM-based PjBL mathematics learning tools designed to improve senior high school students' critical thinking in probability learning. The study specifically examines the validity, practicality, and effectiveness of the developed learning tools.

METHODS

This study employed a Research and Development (R&D) approach using the Four-D (4-D) instructional development model proposed by Thiagarajan, Semmel, and Semmel (1974). The model comprises four sequential phases: Define, Design, Develop, and Disseminate. The 4-D model was selected because it provides a systematic framework for developing valid, practical, and effective learning tools.The participants of this study consisted of 33 twelfth-grade students from a senior high school in East Java, Indonesia, aged between 16 and 17 years. The participants were selected using purposive sampling based on their prior exposure to probability learning and the school's readiness to implement STEAM-based Project-Based Learning (PjBL). The intervention was conducted over three classroom meetings during the probability learning unit.

In the *Define* stage, the researcher conducted several analyses to identify learning needs and challenges in probability learning. The initial–final analysis examined existing classroom conditions and students' difficulties in understanding probability concepts. The curriculum analysis reviewed the alignment between probability materials and curriculum learning outcomes. The student characteristics analysis identified students' prior knowledge, learning preferences, and difficulties in higher-order thinking tasks. The material analysis focused on key probability concepts, misconceptions, and proportional reasoning difficulties. Meanwhile, the learning objectives analysis formulated learning goals integrating STEAM elements, Project-Based Learning (PjBL), and critical thinking indicators.

The *Design* stage focused on developing the structure of the STEAM-based PjBL learning tools, including lesson plans, LKPD design, learning activities, assessment instruments, and technology-supported learning resources. The learning activities were designed to facilitate students' interpretation, analysis, inference, explanation, and evaluation skills during probability learning. In the *Develop* stage, LKPD prototypes and instructional materials were validated by experts in mathematics education and revised based on validator feedback. The validation process covered content, construct, language, and design aspects. The *Disseminate* stage involved limited classroom implementation to evaluate the practicality and effectiveness of the developed learning tools. Practicality data were collected through classroom observation sheets, while effectiveness data were obtained using pretest and posttest assessments. To assess students' critical thinking skills, the study used open-ended probability problems based on five indicators adapted from Facione: interpretation, analysis, inference, explanation, and evaluation. Student responses were assessed using an analytic scoring rubric ranging from 1 to 4, where higher scores indicated stronger reasoning and conceptual understanding. Data were analyzed using descriptive statistics, N-Gain analysis, and paired sample t-test to determine the significance of students' improvement after the intervention. The overall research procedure is presented in Figure 1

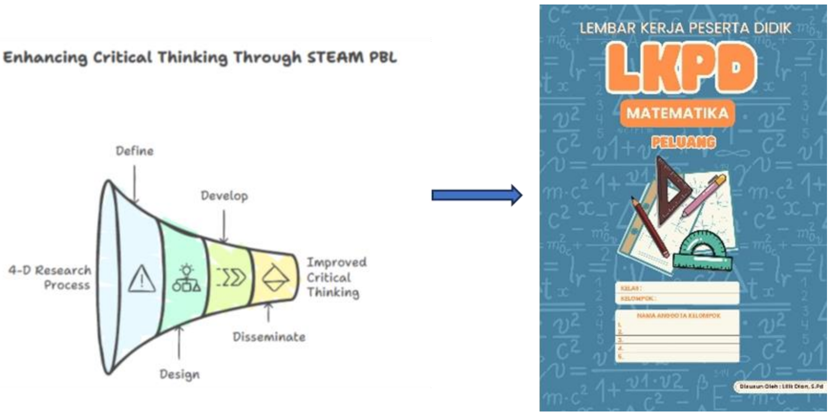


Figure 1. Research Procedures

To ensure the quality of the developed learning tools, three types of evaluation were conducted: validity, practicality, and effectiveness tests.**Validity Test**: The validity of the learning tools was assessed by three experts consisting of two mathematics education lecturers and one experienced mathematics teacher. The validation covered aspects of content, construct, language, and design. Each aspect was evaluated using a Likert scale, and the results were analyzed using percentage scores. Inter-rater reliability was calculated using the Intraclass Correlation Coefficient (ICC) to determine the consistency among validators. **Practicality Test**: The practicality of the learning tools was evaluated through classroom implementation. Observations were conducted during three learning sessions to assess the implementation of the PjBL syntax and the usability of the LKPD. The observation data were analyzed using percentage-based descriptive analysis, indicating the level of implementation in each learning phase. **Effectiveness Test**: The effectiveness of the learning tools was measured using a pretest–posttest design. Students' critical thinking skills were assessed before and after the intervention using a test based on five indicators: interpretation, analysis, inference, explanation, and evaluation. The improvement in students' scores was analyzed using N-Gain, and inferential statistical analysis (paired sample t-test) was conducted to determine the significance of the improvement.

RESULTS AND DISCUSSION

Stages of Analysis

This development research employed the 4D model, which consists of four stages: Define, Design, Develop, and Disseminate. The Define stage served as the primary foundation for determining the needs, objectives, and direction of developing Project-Based Learning (PjBL) and STEAM-based learning tools aimed at improving students' critical thinking skills. At this stage, several systematic analyses were conducted, including preliminary analysis, needs analysis, curriculum analysis, student characteristics analysis, material analysis, and task analysis. These analyses were carried out to ensure that the developed learning tools were relevant, applicable, and aligned with the learning context at Maarif NU Pandaan Senior High School.

First, the initial and final analysis was carried out to review the factual conditions of the mathematics learning process, especially in the Probability material. Based on the results of observations and interviews with teachers, it was found that learning is still teacher-centered and has not provided space for students to think critically, analyze, and find solutions through project activities. Students tend to be passive and rely only on memorizing formulas. In fact, the Independent Curriculum requires learning that facilitates the 4Cs (critical thinking, creativity, collaboration, communication), especially in analytical materials such as opportunities. These findings reinforce the need for more innovative, contextual, and collaborative learning tools.

Second, needs analysis is directed to identify gaps between ideal conditions and learning practices in the field. The main need that arises is the importance of learning tools that are able to integrate project activities with STEAM elements so that students not only understand the concept of opportunities, but also can solve problems based on real contexts. In addition, the school has adequate facilities such as LCDs and technology devices, but it has not been optimally utilized. This is the basis for choosing a STEAM-based PjBL strategy in the development of LKPD and other learning tools.

Third, curriculum analysis is carried out to ensure alignment with the Learning Outcomes (CP) phase F and Learning Objectives (TP) in accordance with BSKAP 2024. Probability material includes enumeration rules, permutations, combinations, event chances, conditional chances, and interpretation of probabilistic data. All of these competencies are highly relevant to the STEAM approach that demands the integration of data, technology, creativity, and mathematical logic. Therefore, the device is compiled with the PjBL syntax to direct students to research, develop solutions, and present project results.

Furthermore, the analysis of student characteristics showed that students had a high interest in the use of visual media and technology but were poorly trained in high-level problem-solving. They can work well together but require structured guidance in developing mathematical arguments and reasoning. Therefore, the LKPD is designed with scaffolding for each critical thinking indicator (interpretation, analysis, evaluation, inference, explanation).

Finally, material analysis and assignment analysis are conducted to map the depth of the concept, determine the context of the relevant project, and design activities that allow students to build on the concept of probability through exploration. The tasks are designed in stages, ranging from observation of probability phenomena, structured problem solving, to designing STEAM-based projects in daily life.

Overall, the analysis stage provides a comprehensive overview of learning needs, device development directions, and student profiles so that the products developed are targeted, measurable, and have the potential to improve critical thinking skills. This stage ensures that the STEAM-based PjBL device is not only theoretically valid, but also practical and relevant to real learning conditions.

Design Stage

The design stage aims to produce an initial design of a learning tool in the form of STEAM-based Project Based Learning (PjBL) LKPD which will be validated in the next stage. At this stage, the process of selecting device formats, visual design, preparation of project activity flows, and development of evaluation instruments is carried out. The structure of the LKPD is designed systematically to support the active involvement of students and encourage critical thinking skills. The initial part of the LKPD consists of a cover and identity that contains titles, thematic images, learning competencies, and STEAM elements as characteristics of the approach used. Furthermore, the introduction section displays introductory activities, learning objectives, and project orientations to build learners' readiness. LKPD also contains context-based perceptions that present real situations related to opportunities so that students can connect mathematical concepts with daily life. The core activities are designed to follow the stages of STEAM-based PjBL, including the observation of random phenomena (Science), the use of simple simulations

(Technology), the design of probability experiment models (Engineering), data visualization through diagrams (Art), and the calculation and interpretation of opportunities (Mathematics). All activities are arranged in stages through practice questions that increase in complexity, until finally students reflect on critical thinking based on five Facione indicators, namely interpretation, analysis, evaluation, inference, and explanation.

In addition to designing the content of the LKPD, at this stage the necessary assessment instruments are also prepared to test the quality of the learning tools. The instruments include validation sheets for material experts and media experts, observation sheets for learning implementation, questionnaires for student and teacher responses, and critical thinking tests carried out through pre-tests and post-tests. The critical thinking skill indicators used refer to Septiningrum et al. (2021), including interpretation, analysis, evaluation, inferences, and explanation. This set of designs ensures that learning tools are not only engaging and contextual, but also measurable in terms of validity, practicality, and effectiveness.

Development Stage

At the development stage, the learning tools that had been designed in the previous phase were realized into real products in the form of STEAM-based Project Based Learning (PjBL) LKPD. The initial product then went through a validation process by three validators, two mathematics education lecturers and one mathematics teacher each. In addition, the reliability of the critical thinking test instrument was examined before classroom implementation using Cronbach's Alpha to measure the internal consistency of the test items. The results showed a Cronbach's Alpha coefficient of 0.82, indicating high reliability and demonstrating that the instrument was sufficiently consistent for assessing students' critical thinking skills in probability learning.

Validation includes aspects of material, construction, language, and design feasibility as shown in Table 1 and consistency testing between assessors using the Intraclass Correlation Coefficient (ICC) presented in Table 2.

Table 1. Validity of Learning Tools (LKPD

No	Indicator	Validity	Remarks
1	Content	95%	Valid
2	Construct	100%	Highly Valid
3	Language	95%	Highly Valid
4	Design	97%	Highly Valid

Table 2. Results of the Intraclass Correlation Coefficients LKPD Statistical Test

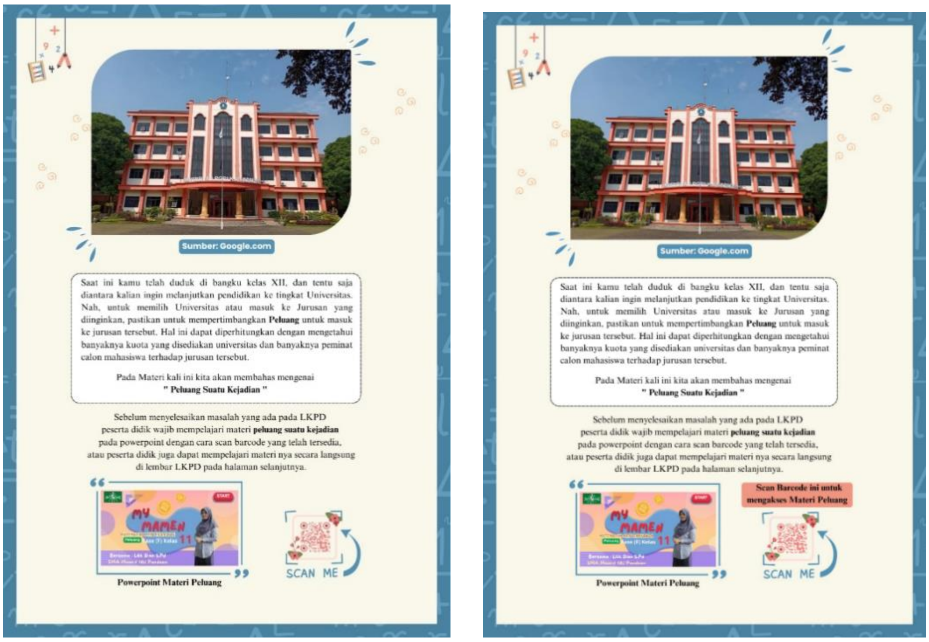
Intraclass Correlation	Category
0,778	*Good Agreement*

The results of the assessment showed that the device obtained a *valid–highly valid* category and the ICC value was in the *range of good agreement*, indicating adequate consistency of assessment between validators. Thus, the LKPD is declared suitable for use after minor repairs are made according to the validator's direction.

Feedback from validators is then analyzed to determine the parts that need improvement. In the content aspect, the validator noted that several examples of probability problems need to be made more contextual and concise to facilitate students' critical thinking processes. In the language aspect, it was found that some sentences were too long or had the potential to cause ambiguity so they had to be simplified. In terms of design, the arrangement of illustrations and certain tables is considered disproportionate so it is revised to be more communicative and easy to read.

Product Revision Results

The evaluation provided by the validator in the Initial LKPD draft that has been made includes, among others. It is necessary to add detailed readings and studies related to probability materials. Teaching materials are prepared to present reading topics that are relevant to the learning context, adjustments to teaching materials are made based on learning indicators and objectives. Revision A more complete probability material is compiled in *a powerpoint slide* that can be accessed by scanning the barcode contained in the LKPD introduction page. The barcode listed in the previous LKPD must be given information so that students know the steps that must be taken to get more complete probability materials. A revised LKPD snippet is presented in Figure 2. Before and After LKPD Introduction Page Revision

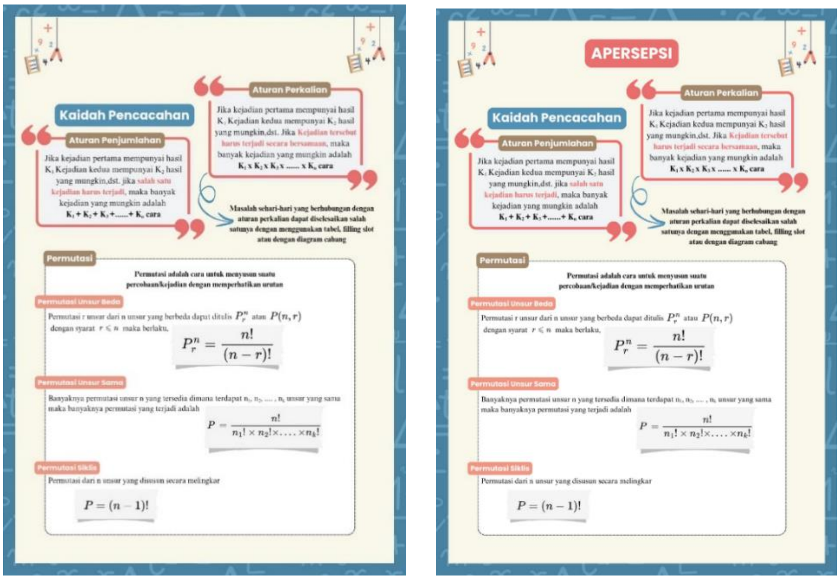


(a) Before Revision (b) After Revision

Figure 2. Before and After LKPD Introduction Page Revision

The revision in Figure 2 focuses on improving the clarity and usability of the LKPD introduction page. Specifically, the revised version includes: (1) the addition of clear instructions for accessing supplementary learning materials through the QR code; (2) improved labeling and visual emphasis on the "SCAN ME" section to guide students more effectively; and (3) refinement of layout and text organization to enhance readability and reduce ambiguity.

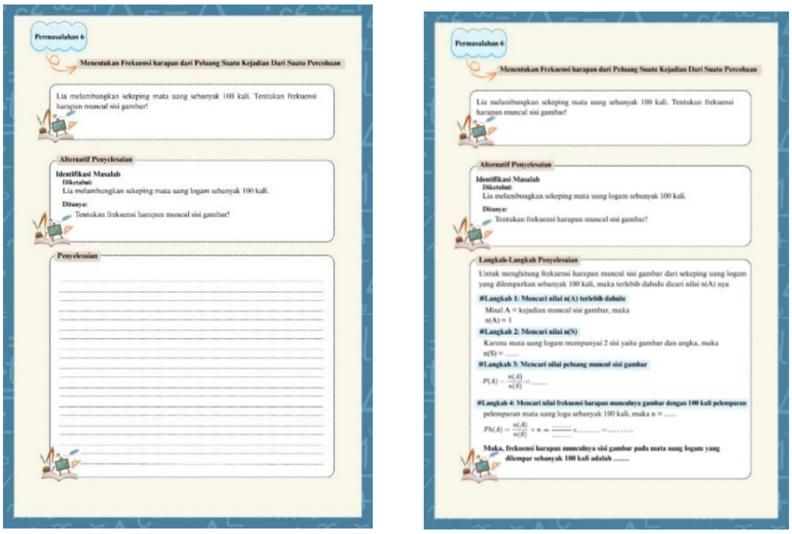
In the probability concept material, it is necessary to add the caption "Perception" to make it easier for students to recognize the part of the material that must be studied first to be able to understand the concept of probability material. The probability material page contained in the previous LKPD draft was revised to the LKPD page shown in Figure 3.



(a) Before Revision (b) After Revision

Figure 3. Before and After Revision of the Probability Concept Material Page

It is necessary to add examples of material problems and opportunities that occur in daily life with the guidance of the steps to solve them. Students are given the probability to understand the concept of probability by solving the given problems in a structured manner through the help of the steps provided in the revised LKPD. If in the initial LKPD draft, only examples of problems and their solutions were given. In the revision of the LKPD draft, examples of problems have been added along with assistance in steps to solve these problems. The assistance of these completion steps is in the form of points that must be filled in by students, the LKPD page examples of problems of probability materials that have been revised are shown in Figure 4.



(a) Before Revision (b) After Revision

Figure 4. Revision of the Example of Probability Problems Page

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Dissemination Stage

The dissemination stage was conducted to evaluate the practicality and effectiveness of the STEAM-based PjBL LKPD after the validation and revision processes had been completed. The limited field trial involved students of class XII-6 at Maarif NU Pandaan Senior High School, with mathematics teachers acting as facilitators during the implementation process.

Practicality data were collected using structured observation sheets completed by observers during three learning meetings. The observation instrument assessed the implementation of each phase of the Project-Based Learning (PjBL) syntax, including introductory activities, project planning, project scheduling, project monitoring, assessment, and reflection activities. Each observed aspect was rated using an implementation checklist based on whether the learning activities were carried out according to the designed procedures. The percentage score was calculated using the formula:

$$Implementation\ Percentage = \frac{Number\ of\ Implemented\ Activities}{Total\ Planned\ Activities} x100\%$$

The results showed that all planned learning activities were implemented during the classroom sessions, resulting in an implementation percentage of 100% for each observed phase. This finding indicates that the developed learning tools were highly practical and could be implemented consistently according to the designed learning procedures.

The dissemination stage was carried out to test the practicality and effectiveness of STEAM-based LKPD PjBL which has gone through a validation and revision process. The limited field trial was carried out in grades XII-6 of Maarif NU Pandaan High School by involving mathematics teachers as facilitators and students as direct users of the device. During implementation, observations were made to ensure the implementation of the PjBL learning syntax, the suitability of the use of LKPD with the flow of activities, and the response of students to project-based learning activities. Practicality data were obtained through the observation sheets presented in Table 3.

Table 3. Observation Results of Learning Implementation in Meeting 1 Field Trial

Aspects observed	Average Mode (%)	Remarks
Introduction	100%	Positive
Core Activities		
Phase 1: Defining the Fundamental Questions	100%	Positive
Phase 2 : Planning the Project	100%	Positive
Phase 3 : Preparation of Project Schedule	100%	Positive
Closing	100%	Positive

The results of the field trial showed that all aspects from the introduction, each phase of the PjBL's core activities, to the conclusion obtained a 100% mode with a positive category. These findings indicate that LKPD has been rated very well by users because it is able to guide the learning process clearly, concisely, and easily followed. With very high acceptability in all indicators, the LKPD was declared highly feasible to use without requiring substantial revision

The results of the observation of Meeting 2, as seen in Table 4, show that all aspects of learning at the second meeting starting from the introduction, core activities, project monitoring phase, to the closing obtained a 100% mode with a positive category. This indicates that the learning process is carried out very well and according to plan, and all instructions in the LKPD can be followed optimally by the participants. With maximum achievement on all indicators, the learning tool was declared highly feasible and effective to implement without requiring substantial improvement.

Table 4. Observations of the Implementation of Learning Meeting 2 Field Trials

Aspects observed	Average Mode	Remarks
Introduction	100%	Positive
Core Activities		
Phase 4 : *Project monitoring*	100%	Positive
Closing	100%	Positive

The results of the observation of Meeting 3 as shown in Table 5 show that all aspects of learning at the second meeting reached 100% mode with a positive category. These findings confirm that the learning process is going very well and all LKPD instructions can be followed optimally. With these achievements, the learning tools are declared feasible and effective

Table 3. Observations of the Implementation of Learning Meeting 3 Field Trials

Aspects observed	Average Mode (%)	Remarks
Introduction	100%	Positive
Core Activities		
Phase 5 : *Assessment*	100%	Positive
Phase 6 : *Evaluating the experience*	100%	Positive
Closing	100%	Positive

The results in Table 5. show that all aspects of learning at the third meeting were carried out 100% and were in the positive category. This indicates that teachers and students are able to follow the entire PjBL syntax without obstacles, with consistent involvement in each learning phase.

These findings reinforce that STEAM-based PjBL LKPD is very practical and suitable for use in learning. Where each meeting shows a 100% implementation percentage in all aspects observed. These findings indicate that the device is practical used by teachers and is easy for learners to follow without requiring complex additional explanations. Teachers also responded positively to the availability of clear project steps, an attractive LKPD display, and an activity flow that facilitated group discussions and investigation of probability concepts.

In addition to practicality, the dissemination stage also tests the effectiveness of the device in improving students' critical thinking skills. Data were obtained through critical thinking tests given before and after learning (posttest), then analyzed using N-Gain as shown in Figure 5.

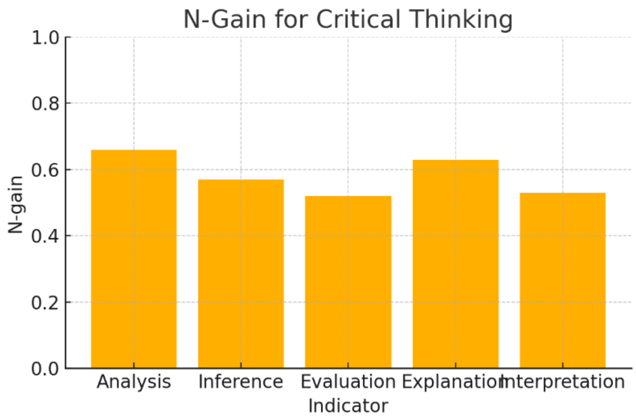

Figure 5. N-Gain Chart For Critical Thinking

The analysis results showed an average N-Gain score of 0.59, which was categorized as moderate improvement. To further examine the significance of the improvement, a paired sample t-test was conducted, revealing a statistically significant difference between pretest and posttest scores ($p < 0.05$). In addition, the effect size analysis indicated a moderate-to-high intervention effect, suggesting that the STEAM-based PjBL learning tools had a meaningful impact on students' critical thinking skills. The visualization of this improvement is presented in the Critical Thinking Ability N-Gain Graph included in the appendix. These findings are consistent with the characteristics of STEAM-based PjBL learning, which encourages students to observe phenomena, analyze data, formulate arguments, and explain their reasoning systematically The results of the analysis showed an average N-Gain of 0.59 which was included in the medium category, with significant improvements occurring in the indicators of interpretation, inference, and explanation. The visualization of this improvement is shown through the Critical Thinking Ability N-Gain Graph included in the appendix of the development results. This increase is in line with the characteristics of the PjBL-STEAM-based LKPD which requires students to observe phenomena, analyze data, formulate arguments, and explain their thinking processes systematically.

The effectiveness of the device was strengthened by the results of the student response questionnaire presented in Table 6. Analysis of Students' Responses to STEAM-Based LKPD PjBL. Most of the students gave a positive response – very positive to the attractiveness of the display, the ease of understanding the work steps, the usefulness of the project activities, and the relevance of the LKPD to their learning experience. Learners reported that project activities made the concept of opportunities easier to understand, increased motivation to learn, and helped them work together more actively in groups. This positive response shows that the device is not only effective in improving learning outcomes, but also in creating meaningful learning experiences.

Overall, the dissemination stage demonstrates that the developed STEAM-based PjBL LKPD has a high level of practicality and good effectiveness in improving students' critical thinking skills. These findings confirm that the learning tools are feasible for broader implementation in mathematics learning, particularly in probability topics, and can contribute to the achievement of students' competencies in accordance with curriculum demands.

The results of students' responses in the field trial indicate that the developed learning materials received highly positive evaluations as shown in Table 6.

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Table 4. Data on the Results of Student Responses to Field Trials

No	Statement	Response Category	Percentage (%)
I	What is your opinion about the learning materials?	Very interesting	33.33
		Interesting	65.15
		Not interesting	1.52
		Very uninteresting	0.00
II	Do you feel that the learning materials presented are new to you?	Very new	16.36
		New	80.00
		Not new	3.64
		Very not new	0.00
III	Are the learning activities you participated in beneficial in helping improve your critical thinking skills?	Very beneficial	31.82
		Beneficial	68.18
		Not beneficial	0.00
		Very not beneficial	0.00
IV	After the learning session ended, how do you perceive the questions presented in the final test?	Very easy	13.64
		Easy	81.82
		Difficult	4.55
		Very difficult	0.00

Most students perceived the learning materials as interesting (65.15%) and very interesting (33.33%), with only a negligible proportion expressing negative responses. In terms of novelty, the majority of students reported that the learning materials were new (80.00%) or very new (16.36%), suggesting that the instructional approach and content provided a learning experience that differed from their previous classroom practices. Furthermore, all students perceived the learning activities as beneficial (68.18%) or very beneficial (31.82%) in supporting the improvement of their critical thinking skills, with no negative responses reported. Regarding the level of difficulty of the final test, most students considered the questions to be easy (81.82%) or very easy (13.64%), while only a small percentage perceived them as difficult (4.55%). Overall, these findings demonstrate that the developed learning materials are engaging, innovative, beneficial, and easy to understand, indicating their suitability for classroom implementation.

Interpretation of Key Findings

The results showed that the STEAM-based Project-Based Learning (PjBL) learning package contributed to the improvement of students' critical thinking skills in probability learning. This finding is supported by the moderate N-Gain score obtained from the pretest and posttest analysis, indicating that the developed learning tools were effective in facilitating students' cognitive development during the learning process. These findings are consistent with previous studies showing that STEAM-integrated PjBL environments can support higher-order thinking, active engagement, and problem-solving skills. The most notable improvement was seen in analytical and explainable skills. These findings are in line with previous research that showed that project activities that require modeling, measurement, and gradual refinement can help students solve complex problems and articulate reasons more systematically (Hsiao et al., 2022). The improvement in inference and interpretation abilities, although not as large as the previous two indicators, remains consistent with the learning character based on authentic exploration and evidence-oriented problem-solving, a pattern also found in other STEAM and PjBL studies (Loyens et al., 2023; Weng et al., 2023, p. 202). This empirical pattern shows that the development of critical thinking is not uniform between indicators, with analytical abilities and explanations being the most responsive to project activities that focus on design and measurement (Afifah et al., 2025; Chang et al., 2023).

The Role of STEAM and PjBL Dynamics

The findings of this study indicate that the integration of STEAM and Project-Based Learning (PjBL) created an active and meaningful learning environment that supported the improvement of students' critical thinking skills in probability learning. During the implementation process, students were actively involved in project planning, data collection, discussion, and presentation activities, which encouraged them to analyze probabilistic situations and justify their reasoning systematically. The observation results also showed that all phases of the PjBL activities were implemented consistently during classroom learning.

The STEAM approach provided students with opportunities to explore probability concepts through multiple representations, including visual explanations, contextual problem situations, and technology-assisted learning resources. These learning experiences helped students connect abstract probability concepts with real-world situations, thereby supporting deeper conceptual understanding. This finding is consistent with (Weinberg & Sorensen-Weinberg, 2022), who stated that multimodal representations can strengthen conceptual understanding through repeated representational transfer.

Furthermore, the PjBL process encouraged students to engage continuously in inquiry activities, such as identifying problems, testing ideas, and explaining conclusions during project discussions. This learning dynamic aligns with previous studies showing that PjBL supports higher-order thinking and collaborative problem-solving (Loyens et al., 2023; Quigley et al., 2020). In this study, students also demonstrated positive responses toward collaborative learning activities, indicating that peer interaction and project discussions contributed to the development of reasoning and communication skills.

In addition, the integration of contextual and culturally relevant activities within the STEAM-PjBL environment increased students' engagement and participation during learning. These findings support previous research emphasizing that interdisciplinary and contextual learning environments can enhance cognitive engagement and mathematical creativity (Afifah et al., 2025; El Bedewy et al., 2024).

Linkages to Reasoning and Probability Misconceptions

The emphasis on measurement, scaling, and simulation activities helps address the weaknesses of proportional reasoning that are widely reported in research on probability learning (Begolli et al., 2021). When probability problems are framed in the form of real project assignments and computational simulations, students face first-hand misconceptions of probability language and incorrect intuition through the process of evidence gathering and model testing.

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Instructional Design Implications: 4-D Models, Cognitive Load, and Adaptive Support

Design choices based on 4-D models (as well as their similarities to 4C/ID) play an important role in the management of learning sequences and cognitive loads. The provision of structured examples, the gradual increase in the complexity of the task, and the refinement of repeated refinement are in line with the principles of complex skill development and the reduction of unnecessary cognitive load (Xu et al., 2024). Adaptive support through peer feedback, simulation tools, and scaffolding from teachers helps to tailor the level of challenge to the needs of students. These findings are in line with the literature that emphasizes the importance of adaptive modules in improving the fluency of concepts without sacrificing an integrated learning orientation (Nigon et al., 2024; Zhu et al., 2024). The combination of a structured design framework and flexible technology seems to expand students' opportunities to transfer knowledge and solve probabilistic problems (Abouelkhier et al., 2024; Fang et al., 2024, p. 202).

Pedagogical and Curricular Implications

Pedagogically, this study shows the importance of presenting STEAM artifacts and critical thinking spark questions in probability learning so that students do not stop at formula calculations, but are able to provide reasons and build modeling independently (Diego-Mantecón et al., 2021; Perales & Aróstegui, 2024). The use of ethnomathematical contexts increases the relevance of learning, while digital making and block-based programming activities provide a more intuitive means of computational exploration (Afifah et al., 2025; Weng et al., 2023). Teacher preparation is key, as the facilitation of PjBL in a STEAM environment demands new pedagogical competencies, including more domain-specific critical thinking assessments and the ability to adapt modules to the classroom context (Spyropoulou & Kameas, 2024).

Development Limitations and Evaluation Challenges

This research faces several typical limitations in the development of educational products, such as limited trial time, a single research location, and existing resources. ((Chavarria et al., 2025; Yıldız & Harwood, 2024) Evaluation challenges also still arise, especially the need for critical thinking assessment instruments that are more sensitive to the material domain and able to distinguish changes in cognitive abilities from changes in students' epistemic attitudes (Monteleone et al., 2023) This condition reinforces the need for a more comprehensive evaluation framework as well as the implementation of multi-site and long-term studies to map the potential generalization and consistency of implementation (McDougal et al., 2025; Ngadiman et al., 2021).

Scalability Direction and Advanced Research Agenda

Efforts to expand the use of STEAM-PjBL teaching materials require a design that is modular, adaptable, and involves teachers in the development process. Rapid prototyping and continuous improvement cycles, accompanied by cross-contextual feedback, have been proven effective in STEM innovation research (Burkhardt & Schoenfeld, 2021; Tan, 2022). The use of low-cost technology, easy-to-share project templates, and integration of cultural contexts can make replication easier across different schools. Further research needs to examine which components are most influential, such as ethnomathematical contexts or digital activities, and conduct longitudinal studies to look at student retention, transfer, and affective impact (Ludwig et al., 2024; Mohsen et al., 2025).

CONCLUSION AND SUGGESTIONS

This study demonstrates that the integration of STEAM and Project-Based Learning (PjBL) in probability learning effectively improves students' critical thinking skills. The learning tools developed through the 4-D model were validated as highly feasible, practical, and effective for classroom implementation. The implementation results showed that STEAM–PjBL learning activities encouraged active participation, collaborative inquiry, and deeper conceptual understanding of probability concepts.

The findings of this study contribute to mathematics education by providing an integrated instructional design that combines interdisciplinary STEAM elements with project-based learning to support higher-order thinking skills. In addition, the developed learning tools offer practical guidance for teachers in designing meaningful and contextual probability learning activities.

Future research is recommended to conduct broader implementation across different educational settings and to develop more domain-specific assessment instruments for critical thinking in mathematics learning. Longitudinal studies are also needed to examine the long-term impact of STEAM–PjBL learning on students' reasoning abilities, motivation, and conceptual retention.

REFERENCES

Abouelkhier, N., Shafiq, M. T., Rauf, A., & Alsheikh, N. (2024). Enhancing construction management education through 4D BIM and VR: Insights and recommendations. *Buildings*, *14*(10), 3116. https://doi.org/10.3390/buildings14103116

Afifah, A. D. N., Indiati, I., & Rahmawati, N. D. (2025). Keefektifan model project based learning terintegrasi steam berbasis etnomatematika terhadap kemampuan berpikir kreatif matematis ditinjau dari efikasi diri siswa. *SCIENCE : Jurnal Inovasi Pendidikan Matematika dan IPA*, *5*(3), 1437–1446. https://doi.org/10.51878/science.v5i3.6754

Aini, S. D., Tafrilyanto, C. F., Subaidi, A., & Amalia, L. (2023). Pengembangan buku ajar digital berbasis STEAM-PjBL pada mata kuliah metode numerik. *JMPM: Jurnal Matematika dan Pendidikan Matematika*, *8*(2), 173–185. https://doi.org/10.26594/jmpm.v8i2.4295

Bates, J., Cheng, S., Ferris, M., & Wang, X. (Frank). (2025). Cultivating critical thinking skills: a pedagogical study in a business statistics course. *Journal of Statistics and Data Science Education*, *33*(2), 166–176. https://doi.org/10.1080/26939169.2024.2394534

Begolli, K. N., Dai, T., McGinn, K. M., & Booth, J. L. (2021). Could probability be out of proportion? Self-explanation and example-based practice help students with lower proportional reasoning skills learn probability. *Instructional Science*, *49*, 441–473. https://doi.org/10.1007/s11251-021-09550-9

Burkhardt, H., & Schoenfeld, A. (2021). Not just "implementation": The synergy of research and practice in an engineering research approach to educational design and development. *ZDM - Mathematics Education*, *53*, 991–1005. https://doi.org/10.1007/s11858-020-01208-z

Chang, C.-Y., Du, Z., Kuo, H.-C., & Chang, C.-C. (2023). Investigating the impact of design thinking-based STEAM PBL on Students' creativity and computational thinking. *IEEE Transactions on Education*, *66*(6), 673–681. https://doi.org/10.1109/te.2023.3297221

Chavarria, M. A., Ortiz-Escobar, L. M., Bacca-Cortes, B., Romero-Cano, V., Villota, I., Muñoz Peña, J. K., Londoño Sánchez, J. R., Campo, O., Suter, S., Cabrera-López, J. J., Sanchez Patiño, M. F., Caicedo-Bravo, E. F., Stein, M., Hurst, S., Schönenberger, K., & Rivas Velarde, M. (2025). Challenges and opportunities of the human-centered design approach: Case study development of an assistive device for the navigation of persons with visual impairment. *JMIR Rehabilitation and Assistive Technologies*, *12*, e70694. https://doi.org/10.2196/70694

Conde, M. Á., Rodríguez-Sedano, F. J., Fernández-Llamas, C., Gonçalves, J., Lima, J., & García-Peñalvo, F. J. (2021). Fostering STEAM through challenge-based learning, robotics, and physical devices: A systematic mapping literature review. *Computer Applications in Engineering Education*, *29*(1), 46–65. https://doi.org/10.1002/cae.22354

Coronado, J. M., Moyano, A., Romero, V., Ruiz, R., & Rodríguez, J. (2021). Student long-term perception of project-based learning in civil engineering education: An 18-year ex-post assessment. *Sustainability*, *13*(4), 1949. https://doi.org/10.3390/su13041949

Davis, R. L., Schneider, B., Rosenbaum, L. F., & Blikstein, P. (2024). Hands-on tasks make learning visible: A learning analytics lens on the development of mechanistic problem-solving expertise in makerspaces. *Educational Technology Research and Development*, *72*, 109–132. https://doi.org/10.1007/s11423-023-10318-w

Diego-Mantecón, J.-M., Blanco, T.-F., Ortiz-Laso, Z., & Lavicza, Z. (2021). STEAM projects with KIKS format for developing key competences. *Comunicar*, *29*(66), 33–43. https://doi.org/10.3916/C66-2021-03

El Bedewy, S., Lavicza, Z., & Lyublinskaya, I. (2024). STEAM practices connecting mathematics, arts, architecture, culture and history in a non-formal learning environment of a museum. *Journal of Mathematics and the Arts*, *18*(1–2), 101–134. https://doi.org/10.1080/17513472.2024.2321563

Fang, X., Ng, D. T. K., Leung, J. K. L., & Xu, H. (2024). The applications of the ARCS model in instructional design, theoretical framework, and measurement tool: A systematic review of empirical studies. *Interactive Learning Environments*, *32*(10), 5919–5946. https://doi.org/10.1080/10494820.2023.2240867

Groth, R. E., Bergner, J. A., & Austin, J. W. (2020). Dimensions of learning probability vocabulary. *Journal for Research in Mathematics Education*, *51*(1), 75–104. https://doi.org/10.5951/jresematheduc.2019.0008

Hsiao, H.-S., Chen, J.-C., Chen, J.-H., Zeng, Y.-T., & Chung, G.-H. (2022). An assessment of junior high school students' knowledge, creativity, and hands-on performance using PBL via cognitive–affective interaction model to achieve STEAM. *Sustainability*, *14*(9), 5582. https://doi.org/10.3390/su14095582

Hull, M. M., Jansky, A., & Hopf, M. (2021). Probability-related naïve ideas across physics topics. *Studies in Science Education*, *57*(1), 45–83. https://doi.org/10.1080/03057267.2020.1757244

Loyens, S. M. M., Van Meerten, J. E., Schaap, L., & Wijnia, L. (2023). Situating higher-order, critical, and critical-analytic thinking in problem- and project-based learning environments: A systematic review. *Educational Psychology Review*, *35*, 39. https://doi.org/10.1007/s10648-023-09757-x

Ludwig, C. M., Howsmon, R. A., Stromholt, S., Valenzuela, J. J., Calder, R., & Baliga, N. S. (2024). Consequential insights for advancing informal STEM learning and outcomes for students from historically marginalized communities. *Humanities and Social Sciences Communications*, *11*, 351. https://doi.org/10.1057/s41599-024-02797-w

McDougal, E., Gilligan-Lee, K. A., Gilmore, C., & Farran, E. K. (2025). School-delivered intervention research: Lessons learned from the BLOCS Project. *Journal of Cognition and Development*, *27*(2), 306–322.

https://doi.org/10.1080/15248372.2025.2541736
Mohsen, M., Khalil, I., AlZahrani, A., Awaji, B., & Abdullah, K. (2025). Synthesizing STEAM integration in language education literature: Trends, themes, and outcomes. *International Journal of Multilingualism*, *22*(4), 2396–2420. https://doi.org/10.1080/14790718.2024.2423664
Monteleone, C., Miller, J., & Warren, E. (2023). Conceptualising critical mathematical thinking in young students. *Mathematics Education Research Journal*, *35*, 339–359. https://doi.org/10.1007/s13394-023-00445-1
Ngadiman, N., Sulaiman, S., Idris, N., Samingan, M. R., & Mohamed, H. (2021). Systematic review on software quality in educational applications. *IEEE Access*, *9*, 60187–60200. https://doi.org/10.1109/ACCESS.2021.3072223
Nigon, N., Tucker, J. D., Ekstedt, T. W., Jeong, B. C., Simionescu, D. C., & Koretsky, M. D. (2024). Adaptivity or agency? Educational technology design for conceptual learning of materials science. *Computer Applications in Engineering Education*, *32*(6), e22790. https://doi.org/10.1002/cae.22790
Orcos Palma, L., Jiménez Hernández, C., & Magreñán Ruiz, Á. A. (2022). Learning itineraries to work ‘mathematic probability’ with future teachers in an online scenario with deck.toys tool. *RIED-Revista Iberoamericana de Educación a Distancia*, *25*(2), 195–214. https://doi.org/10.5944/ried.25.2.31748
Perales, F. J., & Aróstegui, J. L. (2024). The STEAM approach: Implementation and educational, social and economic consequences. *Arts Education Policy Review*, *125*(2), 59–67. https://doi.org/10.1080/10632913.2021.1974997
Purnomo, H., Abdullah, A. H., Afnia, P. N., & Shiddieqy, A. A. (2025). Project-based learning in mathematics classrooms: How it improves students’ problem-solving skills. *JMPM: Jurnal Matematika dan Pendidikan Matematika*, *10*(1), 29–42. https://doi.org/10.26594/jmpm.v10i1.5590
Quigley, C. F., Herro, D., King, E., & Plank, H. (2020). STEAM designed and enacted: Understanding the process of design and implementation of STEAM curriculum in an elementary school. *Journal of Science Education and Technology*, *29*, 499–518. https://doi.org/10.1007/s10956-020-09832-w
Rosenberg, J. M., Kubsch, M., Wagenmakers, E.-J., & Dogucu, M. (2022). Making sense of uncertainty in the science classroom: A bayesian approach. *Science & Education*, *31*, 1239–1262. https://doi.org/10.1007/s11191-022-00341-3
Rott, B. (2021). Inductive and deductive justification of knowledge. *In Epistemological beliefs and critical thinking in mathematics: Qualitative and quantitative studies with pre-service teachers* (pp. 121–145). Springer Spektrum. https://doi.org/10.1007/978-3-658-33539-7_6
Schneider, B., Krajcik, J., Lavonen, J., Salmela-Aro, K., Klager, C., Bradford, L., Chen, I.-C., Baker, Q., Touitou, I., Peek-Brown, D., Dezendorf, R. M., Maestrales, S., & Bartz, K. (2022). Improving science achievement-is it possible? Evaluating the efficacy of a high school chemistry and physics project-based learning intervention. *Educational Researcher*, *51*(2), 109–121. https://doi.org/10.3102/0013189X211067742
Schukajlow, S., Krawitz, J., Kanefke, J., Blum, W., & Rakoczy, K. (2023). Open modelling problems: Cognitive barriers and instructional prompts. *Educational Studies in Mathematics*, *114*, 417–438. https://doi.org/10.1007/s10649-023-10265-6
Spyropoulou, N., & Kameas, A. (2024). Leveraging communities of practice for STEAM education: A Study on engagement and professional development. *European Journal of Education*, *59*(4), e12806. https://doi.org/10.1111/ejed.12806
Syahrani, P., & Miatun, A. (2025). The effect of problem-based learning model on

vocational students' mathematical concept understanding in solving numerical problems. *JMPM: Jurnal Matematika Dan Pendidikan Matematika*, *10*(1), 83–94, https://doi.org/10.26594/jmpm.v10i1.5718

Tan, S. C. (2022). Transfer and scaling of knowledge building practices: A journey from diffusion approach to situative knowledge creation community approach. *Research and Practice in Technology Enhanced Learning*, *9*(1), 107–121. https://doi.org/10.58459/rptel.2014.9107-121

Thiagarajan, S. Semmel. DS & Semmel, MI (1974). Instructional Development for training teachers of Exceptional Children a Sourcebook. Leadership Training Institute/Special Education,University of Minnesota.

Thornhill-Miller, B., Camarda, A., Mercier, M., Burkhardt, J.-M., Morisseau, T., Bourgeois-Bougrine, S., Vinchon, F., El Hayek, S., Augereau-Landais, M., Mourey, F., Feybesse, C., Sundquist, D., & Lubart, T. (2023). Creativity, critical thinking, communication, and collaboration: assessment, certification, and promotion of 21st century skills for the future of work and education. *Journal of Intelligence*, *11*(3), 54. https://doi.org/10.3390/jintelligence11030054

Vasconcelos, P. N., & Zambroni de Souza, A. C. (2022). A problem-based introduction to technical, social, and systemic thinking in engineering courses. *IEEE Access*, *10*, 73521–73532. https://doi.org/10.1109/ACCESS.2022.3189654

Vincent-Lancrin, S. (2023). Fostering and assessing student critical thinking: From theory to teaching practice. *European Journal of Education*, *58*(3), 354–368. https://doi.org/10.1111/ejed.12569

Vithanage, V., & Nakashima, N. (2025). Evaluating the effectiveness of a project-based STEM curriculum in the acquisition and development of 4Cs of 21st-century skills. *School Science and Mathematics*. Advance online publication. https://doi.org/10.1111/ssm.18388

Weinberg, P. J., & Sorensen-Weinberg, E. K. (2022). Embodied cognition through participatory simulation and mathematical description: Supporting mechanistic reasoning and explanation. *Science Education*, *106*(3), 505–544. https://doi.org/10.1002/sce.21697

Weng, X., Ng, O.-L., Cui, Z., & Leung, S. (2023). Creativity development with problem-based digital making and block-based programming for science, technology, engineering, arts, and mathematics learning in middle school contexts. *Journal of Educational Computing Research*, *61*(2), 304–328. https://doi.org/10.1177/07356331221115661

Xu, Z., Özek, U., Levin, J., & Hoon Lee, D. (2024). Effects of large-scale early math interventions on student outcomes: Evidence from Kentucky's math achievement fund. *Educational Evaluation and Policy Analysis*, *48*(1), 1–32. https://doi.org/10.3102/01623737241303142

Yıldız, A., & Harwood, N. (2024). The art of the possible: The constraints associated with writing local tesol textbooks. *Applied Linguistics*, *46*(6), 857–876. https://doi.org/10.1093/applin/amae058

Yousef, W., Abduljaber, M., & Onder, M. (2025). Widening gap between college students' perceptions and abilities: The Dunning-Kruger phenomenon in critical thinking appraisal in higher education. *F1000Research*, *14*, 553. https://doi.org/10.12688/f1000research.157874.1

Zhu, Y., Zhou, R., & Zhang, Y. (2024). Designing preschool children's educational games for enlightenment through decision analysis methods. *Multimedia Tools and Applications*, *83*, 78331–78360. https://doi.org/10.1007/s11042-024-19803-7