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Development of STEAM Project-Based Learning Tools to Enhance Students' Critical Thinking and Mathematical Argumentation Skills

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Abstract: This study aims to develop a valid, practical, and effective STEAM Project-Based Learning (PjBL) instructional device to improve junior high school students' critical thinking and mathematical argumentation skills. The study employed a Research and Development (R&D) method using the Dick and Carey instructional design model, which consists of nine systematic stages. The participants were eighth-grade students in Bandung Regency. The instruments included expert validation sheets to assess validity, teacher and student response questionnaires to evaluate practicality, and pre-test and post-test instruments to measure effectiveness. The product was validated by two experts in media and subject matter. Practicality was determined based on teacher and student responses, while effectiveness was measured using the N-gain score. The results indicated that the developed instructional device was highly valid and feasible for implementation. The material expert validation achieved an average score of 96.48%, and the media expert validation reached 95.25%, both categorized as very high. The practicality test showed very positive responses, with teacher responses averaging 95% and student responses 93%. Furthermore, the effectiveness test demonstrated high N-gain scores of 0.75 for mathematical critical thinking and 0.77 for mathematical argumentation skills, indicating significant improvement in both competencies.

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Introduction

In facing the challenges of the 21st century, the increasing spread of mobility and information obtained directly by each individual places society in ignorance of contexts and situations that require analytical decision-making and problem-solving so that effective education is needed in developing critical thinking skills, creativity, communication, and collaboration (Ananda et al., 2023). With these demands, there is an urgent need worldwide to provide critical thinking skills at the tertiary level that are up-to-date and comprehensive in meeting modern work needs, driven by the expansion of major economic forces such as technology, customer service, and globalization (Shaw et al., 2020).

Critical thinking skills are defined as thinking accurately and systematically according to the principles of logic and scientific reasoning (Leest & Wolber, 2021). Critical thinking, as it relates to scientific learning, plays a crucial role in assessing facts and ideas through logical reasoning in decision-making (Faridi et al., 2021). Therefore, complex problem-solving can be achieved through in-depth learning that requires critical thinking skills (Uzumcu & Bay, 2020; Varenina et al., 2021).

Paul, R & Elder, L (2020) state that critical thinking is the art of analyzing and evaluating self-directed thought processes with the intention of improving them. This

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thinking requires effective communication and problem-solving skills, as well as a commitment to advancing the character and sensitivity of a dedicated individual through clear intellectual development. A well-trained critical thinker will raise questions from each problem, formulate them clearly and precisely, collect and evaluate relevant information, use abstract ideas to interpret them effectively, and design good solutions to solve problems.

From the description above, the importance of critical thinking in problem solving is clear, but often the focus is on the efficiency of problem solving, thus neglecting expressing statements in the argumentation process, resulting in weak changes in knowledge, arguing in groups, learning motivation, collaboration, and learning achievement that almost does not increase. In addition, some students are passive and inactive in expressing statements when arguing, tending not to share their thoughts with others, thus causing the collaborative learning process to be unsatisfactory (Sen et al., 2023). To anticipate this problem, it is necessary to develop mathematical argumentation skills (Lee & Lai, 2024).

Mathematical argumentation conducted by students can consider the best options, provide causal reasons, and propose the most appropriate solution to a problem rationally (Landrieu et al., 2023; Zhou, 2023). Argumentation theory is a contextual interaction, communicative and psychological dynamics, logical structures, and rhetorical theory, which are arranged based on argumentative strategies described from an interdisciplinary perspective (Mirza & Clermont, 2009). The purpose of argumentation encourages students' thinking in expressing their mathematical thinking (Router, 2023).

Argumentation is a special tool that systematically collects and organizes reasons that support the truth of a claim through a series of statements collected to establish a definite proposition to provide support or justification or evidence for the truth of other claims (Foresman, GA, Peter, S & Watson, JC 2016). Mirza & Clermont (2009) stated that argumentation is increasingly important in education not only because of the competencies that must be learned, but also because argumentation can be used to encourage learning in the fields of philosophy, history, science, and mathematics, as well as other fields. Argumentation is increasingly attracting attention as a linguistic, logical, dialogical, and psychological process that supports or provokes reasoning and learning. The practice of argumentation becomes a powerful resource for dealing with cognitive contradictions, doubts, controversies, and complex decision-making, thereby engaging students in reasoning and information seeking.

Argumentation is a term commonly used in mathematics education, but its domain defines specific components, and its distinction from other constructs, such as reasoning and proof, is defined in various ways. The scholarly literature on argumentation in mathematics education sometimes states that the prominent role of argumentation stems from the perception of mathematics as a domain of deductive reasoning within an axiomatic system and that mathematical argumentation can be seen as an early form of mathematical proof (Reuter 2022).

The Science, Technology, Engineering, Arts, and Mathematics (STEAM) approach can help develop critical thinking and mathematical argumentation skills. STEAM can make lectures more engaging by expressing creativity through visual arts and science, thereby increasing enthusiasm for learning (Conradty & Bogner, 2020). This approach is related to creativity, aesthetics, ethics, and innovation (Colucci et al., 2019; Quigley et al., 2020). It is

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related to intercultural knowledge (Chu et al., 2019; Diego et al., 2021). This approach is a design-based learning approach that can foster problem-solving and creativity that can facilitate the acquisition of mathematical knowledge collaboratively, resulting in discussion, open communication, and collaborative conflict resolution (Li & Schoenfeld, 2019; English & King, 2019; Diego et al., 2019; Chaaban et al., 2021). STEAM projects are used as a problem-solving method that can be applied in the real world (Graham, 2020). These projects are derived from the learning process carried out by students, thus being called project-based learning or STEAM project-based learning (Ananda et al., 2023).

Mathematics learning in junior high schools often uses mathematics learning modules without integration with science, technology, and the arts. To overcome this obstacle, a mathematics learning module for junior high schools was designed with spatial geometry as the subject. This learning method is an approach that combines science, mathematics, arts, and technology. In mathematics learning, various pedagogical methods and educational technologies have been designed to support a more focused and in-depth understanding of concepts. One of the main approaches used is STEAM Project-Based Learning, which combines science, mathematics, arts, and technology to foster cognitive principles, arts, and technology. This theory not only provides a theoretical framework for optimal information processing in working memory but also serves as a basis for creating more flexible and adaptive learning designs.

Learning activities using STEAM can foster students' logical, mathematical, practical, and scientific thinking skills, as well as their ability to understand the subject matter. This is because increased student motivation can be achieved through problem-solving by connecting the learning gained to real-life situations. In addition to implementing STEAM, a suitable learning model is needed to bridge the gap in academic knowledge and to apply it concretely. Project-based learning (PjBL) is a learning model that encourages students to be active and able to apply their knowledge and develop various thinking skills and concrete skills. This project learning engages students in authentic situations to explore and apply acquired knowledge to solve problems and directs students to select and organize learning activities as well as investigate and synthesize information (Mantecon et al., 2021).

Based on the description above, the development of STEAM project-based learning tools needs to be carried out with the aim of improving the critical thinking and mathematical argumentation skills of junior high school students. The uniqueness of this research lies in the design of STEAM Project-Based Learning learning tools on spatial geometry material that utilizes modern digital media and appropriate technology, namely digital TV, in accordance with the launch of the digitalization movement by the government in Indonesia. The choice of digital TV as a learning medium has a strong theoretical basis. First, according to Mayer's multimedia learning theory, large, colorful visual displays can enhance dual-channel processing, helping students process spatial information more effectively than small screens like laptops or tablets. Second, digital TV supports collaborative, project-based learning because it allows the entire group to observe visual objects simultaneously, discuss observations, and conduct collective analysis processes that are crucial for developing critical thinking skills. Third, digital TV is more stable, easily accessible, and does not require as much technical expertise as personal devices (laptops/tablets), thus minimizing distractions and students' cognitive load. Thus, the use of digital TV provides an optimal visual and

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collaborative environment to foster students' critical thinking skills in the context of STEAM learning.

Although various studies have developed mathematics learning tools, most remain procedural and fail to develop critical thinking skills and mathematical argumentation, particularly in geometry, which requires spatial visualization (Leest & Wolber, 2021; Reuter, 2022). Conventionally developed learning tools are also less effective in representing three-dimensional objects, leading to misconceptions and minimal cognitive stimulation (Sen et al., 2023). Furthermore, previous studies have failed to link geometry to authentic contexts or real-world problem-solving, thus failing to meet the demands of 21st-century learning (Ananda et al., 2023). This gap highlights the limitations of traditional media in facilitating higher-order thinking processes. Therefore, the development of STEAM project-based modules that integrate science, technology, art, and mathematics and utilize digital technologies, such as digital TV, is needed to enhance visualization, interactivity, and students' critical thinking and argumentation skills (Conradty & Bogner, 2020).

Research Method

This research uses R&D development with the aim of producing valid, practical, and effective STEAM Project-Based Learning learning tools to improve students' critical thinking and mathematical argumentation skills based on the need to innovate to create new products as solutions and systematically with the Dick & Carey development model. ADDIE is one of the product development concepts, consisting of Analyze, Design, Development, Implementation, and Evaluation. ADDIE: This is that learning that must be intentionally centered on students, innovative, authentic, and inspiring (Branch, 2009). This development model uses the ADDIE process because it is effective, and ADDIE is only a process. Which functions as a framework guide. For situations that are complex, it is very appropriate for developing educational products and other learning resources (Branch, 2009). These development steps refer to the design development model. instructional model ADDIE according to Branch (2009) and Aldoobie (2015), and adopt study design Akker (2013).

The first step of this development is preliminary research, or pre-development, which aims to identify learning objectives and analyze learning, then continues with the analysis process, namely the analysis of student characteristics and the learning context that is usually carried out in the school to ensure that the STEAM Project-Based Learning learning model is needed relevant to the needs in improving students' critical thinking and mathematical argumentation skills. The next stage is the design of a valid research instrument by testing the validity by experts, and the practicality instrument involves teacher and student responses to the developed learning device. The subjects of this study were eighth-grade junior high school students in Bandung Regency. The instruments used in this study are instruments for the validity, practicality, and effectiveness of the STEAM Project-Based Learning learning device. Product validation was carried out by two experts, namely media and material experts; practicality was carried out based on teacher and student responses; and effectiveness was measured using the N-Gain score.

The effectiveness testing of the learning device product was conducted using This study used a Experimental Design with a Non-Equivalent Control Group Design, involving one class as the experimental group and one class as the control group. School selection was carried out by purposive sampling, namely determining one junior high school in Bandung

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Regency that met the criteria for facility readiness and willingness to cooperate in the study. After the school was selected, the determination of the experimental class and the control class was carried out using cluster random sampling, namely selecting classes randomly from the available class groups. The experimental group consisted of 35 students, while the control group consisted of 36 students. by randomly selecting one junior high school located in the Bandung Regency area with 35 students in the experimental class and 36 students in the control class. The experimental group was given treatment with STEAM project-based learning, and the control class was given conventional learning. The improvement of students' critical thinking and mathematical argumentation skills was carried out using data analysis of the initial pretest score and the final posttest score for both learning using STEAM Project-Based Learning and conventional learning. To see the significant improvement seen from the increase in the initial and final scores, a normalized gain analysis was conducted.

Results and Discussion

Product Validity Test Results

This R&D development research conducted a validation test to ensure the validity of the learning device product using STEAM project-based learning. The results of the study showed that the LKS learning device product developed was very feasible and valid for use. The results of the material expert validation averaged 96.48%, and the media validation averaged 95.25%, both of which reached the very high category. This validity test was conducted to ensure that the learning device could be used. Dick & Carey (2015) stated that a series of validity tests are important to ensure that the resulting product is not only innovative but also meets academic standards and technical feasibility in supporting learning objectives.

Table 1. Validity Test Results

Rated aspect	Percentage Subject Matter Expert	Percentage Media Expert	Category
Content Suitability	97%	97%	Very High
Conformity of Content to Characteristics	96%	95%	Very High
Construction Aspect Compliance	96%	95%	Very High
Technical Aspect Compliance	96%	96%	Very High
Average value	96.48%	95.25%	Very High

Based on Table 1, Validation results by material experts and media experts indicate that the STEAM Project-Based Learning learning tool is categorized as highly valid, with average scores of 96.48% and 95.25%, respectively. These scores indicate that the tool meets the criteria for content feasibility, construct validity, and validity according to learning development standards.

These findings align with research by Conradty & Bogner (2020) and Chaaban et al. (2021), which emphasized that STEAM-based learning tools require a clear activity structure, interdisciplinary integration, and representative media support to facilitate students' higher-order thinking skills. The high validity in this study indicates that the tool design accommodates these principles.

Furthermore, the validation results confirm that the tool meets the key characteristics of Project-Based Learning (PjBL) is authentic activities, open-ended exploration, tangible products, and inquiry cycles. This is consistent with the findings of Li & Schoenfeld (2019),

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who stated that theoretically stable Project-Based Learning (PjBL) tools must reflect the relationship between content and real-world applications.

Product Practicality Test Results

A practicality test was conducted to determine teacher and student responses to the use of the STEAM Project-Based Learning learning tool during classroom implementation. The practicality test also resulted in a very high teacher response rate, reaching an average of 95%, and a student response rate of 93%, thus confirming the product's high practicality. These data indicate that the learning tool is supported by teachers' ease of use, and students also find it easier to use during the learning process, especially in improving critical thinking and mathematical argumentation skills.

Table 2. Results of Product Practicality Test

Rated aspect	Percentage of Respondents	Category
Teacher Response	95%	Very Practical
Student Response	93%	Very Practical

Based on Table 2, Practicality data shows that the device received a very positive response from teachers, reaching 95% and students, reaching 93%. This demonstrates that the learning device using STEAM Project-Based Learning is easy to use, the flow of activities is clear, the instructions are easy to understand, and the learning activities are relevant to the students' context. Theoretically, the practicality of STEAM-PjBL learning is strongly influenced by the practicality of the learning device in providing step-by-step directions, opportunities for collaboration, and flexibility in project completion. These results align with research by Quigley et al. (2020) and English & King (2019), which reported that good STEAM learning devices should enable students to experience the design process (design thinking) in a structured manner. The results of this study confirm that the developed device meets these characteristics. Therefore, the high practicality of the learning device reflects that the device is not only feasible to use but also easy to implement in junior high school mathematics learning.

Product Effectiveness Test Results

Before conducting the effectiveness test on the product, prerequisite tests were first carried out, namely normality and homogeneity tests. In this study, the normality test using Shapiro-Wilk was carried out on the experimental class with treatment using STEAM Project Based Learning, obtaining a result of 0.300, and the control class using conventional learning obtained a result of 0.200, so that both came from normally distributed data, thus fulfilling the prerequisites for conducting a homogeneity test between the experimental class and the control class using the homogeneity test of variance with the Levene test by showing a significance result of 0.352 so that the data was distributed homogeneously.

After the data was known to come from normally and homogeneously distributed data, it was then continued with a t-test, which obtained a result of 0.007 so that this means there is a very significant difference between the posttest scores of the two groups. Then, to measure the magnitude of the improvement between the two groups, a normalized gain test, or N-Gain, was conducted, with the experimental class reaching 0.75, or derived from high category data, and the control class reaching 0.012, or derived from low category data. Thus, the STEAM Project-Based Learning tool is effective in improving students' critical thinking and mathematical argumentation skills.

Table 3. Results of N-Gain Critical Thinking

Rated Aspect	N-Gain	Category
Critical Thinking	0.75	High

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Based on Table 3, students' critical thinking skills significantly improved after participating in the developed learning. An N-Gain value of 0.75 indicates that the improvement in critical thinking skills is in the high category. This finding indicates that the learning tools and interventions used were able to encourage students to think more analytically, evaluate information in depth, and draw appropriate conclusions. The high N-Gain value also indicates that the learning provided successfully bridged the gap between initial and post-treatment abilities, particularly in facilitating higher-level cognitive processes.

Table 4. Results of N-Gain Argumentation Skills

Rated Aspect	N-Gain	Category
Argumentation Skills	0.77	High

Based on Table 4, the results showed that students' argumentation skills also experienced significant improvement, with an N-Gain value of 0.77, which is considered high. This demonstrates that the learning process developed students' ability to construct logical arguments, provide relevant reasons, and present evidence to support their claims. This significant improvement confirms that the learning approach applied was not only effective in enhancing critical thinking skills but also simultaneously strengthened students' ability to deliver quality arguments.

Overall, the N-Gain results for the two main aspects of critical thinking (0.75) and argumentation skills (0.77) were both in the high category. This finding confirms that the developed learning tool, namely the student worksheet using the STEAM project-based learning model, has strong effectiveness in developing high-level cognitive abilities. Thus, the learning tool can be declared feasible and effective for use in learning contexts that emphasize critical thinking and argumentation literacy.

This research contributes to students' mathematics learning by improving critical thinking and mathematical argumentation skills, as evidenced by the validity, practicality, and effectiveness of the developed learning tools. This product represents a concrete solution for implementing quality mathematics learning. The results of this study can significantly address the challenges of 21st-century learning, especially in instilling critical thinking and mathematical argumentation skills in students. This product is strengthened by research results showing that the developed learning device product is very feasible and valid for use. The results of material expert validation reached an average of 96.48%, and media validation reached an average of 95.25%, both of which reached a very high category.

Thus, this product can be used. Practicality testing also resulted in very high teacher responses, reaching an average of 95%, and practicality of student responses of 93%, thus confirming that the product is very practical or easy to use by teachers and students. Effectiveness testing achieved an average N-Gain score in the experimental class reaching 0.75 for critical thinking and 0.77 for argumentation skills, which is classified as a high category; thus, this product is effective for use in efforts to improve students' mathematical literacy and disposition skills. Therefore, the purpose of this study was to develop a valid, practical, and effective STEAM Project-Based Learning learning device to improve critical thinking and mathematical argumentation skills in junior high school students.

Discussion

The results of this study indicate that the STEAM Project-Based Learning (PBL) learning tool developed through R&D has high validity, practicality, and effectiveness. High validity (average score of 96.48% for subject matter experts and 95.25% for media experts) confirms that the worksheets (LKS) meet academic and technical standards. This finding aligns with Dick & Carey's (2015) principle that validity testing is essential to ensure innovative products while meeting feasibility criteria. This demonstrates that the tool

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incorporates STEAM principles, including interdisciplinary integration, a clear activity structure, and representative media support (Conradty & Bogner, 2020; Chaaban et al., 2021). Furthermore, key characteristics of PjBL, such as authentic activities, open-ended exploration, tangible products, and inquiry cycles, are also met, reinforcing the tool's relevance to real-world mathematics learning contexts (Li & Schoenfeld, 2019). Thus, high validity is not simply a number, but reflects the tool's pedagogical quality and readiness for classroom implementation. The device's practicality also received high scores, with 95% approval from teachers and 93% from students. This indicates that the device is easy to use, the flow of activities is clear, and the instructions are understandable to all users. High practicality supports the effective implementation of STEAM-PjBL learning, as teachers are able to facilitate activities without technical barriers, and students can focus on developing critical thinking and mathematical argumentation skills (Quigley et al., 2020; English & King, 2019). In other words, the device's practicality supports the transition from theory to practice, which is a key indicator of successful implementation of learning innovations.

The device's effectiveness was demonstrated through an N-Gain test, where the experimental class achieved a score of 0.75 (high category), while the control class only achieved 0.012 (low category). The significant difference between the two groups indicates that the use of STEAM-PjBL significantly improved critical thinking and mathematical argumentation skills. These findings strengthen the argument that the integration of STEAM and PjBL approaches not only enhances students' motivation and creativity but also encourages them to connect mathematical concepts to real-world situations, as suggested by recent literature. This extreme difference occurred because conventional learning in the control class was more passive and did not provide activities that encouraged higher-order thinking, so the improvement was barely noticeable. Instruments and procedures were consistently applied, so the low N-Gain in the control class reflects the limitations of conventional methods in developing critical thinking and mathematical argumentation skills.

Overall, the findings of this study confirm that the developed STEAM-PjBL learning toolkit significantly contributes to the development of junior high school students' mathematical literacy and dispositions. The novelty of this research lies in the systematic integration of STEAM and PjBL, with a focus on mathematical argumentation—an aspect previously underexplored in STEAM-PjBL research. This product is not only valid and practical but also effective, making it a learning model ready to be replicated in other school contexts with similar characteristics. Thus, the discussion demonstrates that this learning toolkit is capable of addressing 21st-century challenges, particularly in enhancing students' critical thinking and mathematical argumentation skills. It also demonstrates that STEAM-PjBL-based R&D innovations can be successfully implemented in authentic and meaningful mathematics learning.

Conclusion

The research results show that the developed STEAM Project-Based Learning device is valid, practical, and effective, making it suitable for use in junior high school mathematics learning. This learning device is suitable for use in mathematics learning. The STEAM learning device based on Project-Based Learning (PjBL) is valid, practical, and effective because it is able to integrate science, technology, engineering, art, and mathematics concepts contextually through real projects that are relevant to students' lives. The validity of the device is seen from the suitability of the material to the curriculum, clear learning objectives, and expert assessments stating that learning activities and resources can encourage literacy, mathematical dispositions, and 21st-century skills such as creativity, collaboration, and

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critical thinking. This device is also practical because of clear instructions, efficient implementation time, and easily accessible resources so that teachers and students can use it without difficulty. In addition, the device is proven to be effective in improving students' conceptual understanding, critical thinking skills, creativity, and learning motivation, because the project-based learning process requires active participation, problem solving, and reflection on the results achieved. The advantages of STEAM PjBL lie in its integrative, contextual approach and its orientation towards developing soft skills, encouraging students to learn independently, and creating learning experiences.

Recommendation

For further research, it is recommended to expand the development of STEAM learning tools across various grade levels and mathematics subtopics to achieve broader impact. For teachers, the results of this study can serve as a reference for implementing more innovative project-based learning and optimally utilizing digital media to enhance students' critical thinking and argumentation skills.

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