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Assemblr Edu Based Augmented Reality Flipbook Media to Enhance Critical Thinking Skills of Vocational High School Students

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ABSTRACT

Mathematical critical thinking ability is an essential competency that remains a challenge in Vocational High Schools (SMK). This study aimed to (1) develop a valid and practical Augmented Reality (AR) flipbook media based on Assemblr Edu, and (2) examine its effectiveness integrated with the Problem Based Learning (PBL) model on students' mathematical critical thinking ability. The study employed a Research and Development (R&D) approach using the ADDIE model for media development, and a one-group pretest-posttest quasi-experimental design for effectiveness testing. The sample consisted of 35 Grade XI Electrical Power Installation Engineering (TITL) students selected through simple random sampling. The instrument was a descriptive mathematical critical thinking test declared valid and reliable. Validation by three expert validators in language, content, and media indicated that the media was categorized as highly valid. The practicality test confirmed the media was categorized as highly practical. The effectiveness test demonstrated a significant improvement in students' mathematical critical thinking ability from pretest to posttest, classified in the high category. These findings prove that the Assemblr Edu-based AR flipbook media integrated with the PBL model is significantly effective in improving the mathematical critical thinking ability of SMK students.

Keywords: augmented reality Assemblr Edu; mathematical critical thinking; digital flipbook; problem based learning; vocational high school

INTRODUCTION

The rapid development of information and communication technology has driven major transformations in education, including in Vocational High Schools (SMK). In the context of SMK mathematics learning, the demand for students to possess strong critical thinking abilities has grown substantially, as graduates are expected to solve complex, real-world industrial problems systematically. Yet, conventional instructional approaches continue to dominate in vocational classrooms, resulting in limited development of higher-order thinking competencies. One technology increasingly adopted in learning is Augmented Reality (AR), a technology that combines the real world with virtual objects in real-time to create more immersive and interactive learning experiences. According to Koumpouros (2024), the use of AR in learning media has been proven to enhance student enthusiasm, concretize the representation of abstract objects, and support the development of Higher Order Thinking Skills (Anwar et al., 2024).

However, the mathematical critical thinking ability of SMK students remains relatively low. Specifically, based on interviews with mathematics teachers and classroom

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observations at SMK Negeri 2 Kabupaten Tangerang, students' mathematical critical thinking ability in three-dimensional geometry was found to be relatively low, with many students struggling to meet the expected learning competency standards, indicating a persistent gap in students' capacity to apply analytical and evaluative reasoning in mathematical problem-solving. Literature studies show that students frequently experience difficulties in the analysis and evaluation indicators when solving geometry problems (Nurcahyono et al., 2024), Mathematical critical thinking ability is highly necessary for SMK graduates in order to analyze, evaluate, and solve real-world industrial problems systematically (Saputro & Budiarto, 2026). This condition calls for innovative instructional media capable of effectively enhancing students' mathematical critical thinking competence.

One promising instructional media innovation is the AR-based digital flipbook. An AR flipbook combines the digital page turning format with interactive AR based multimedia content, enabling students to observe three dimensional objects, animations, and simulations directly from flipbook pages. The Assemblr Edu platform is an education based AR application accessible via smartphone without requiring programming expertise, making it highly relevant for implementation in vocational settings (Mayang et al., 2026).

To maximize the potential of AR flipbook media, integration with the Problem Based Learning (PBL) model is crucial. PBL places students in authentic problem situations and encourages them to actively engage in analytical thinking while searching for solutions (Nurjaman et al., 2025). Suharti et al. (2021) demonstrated that PBL integrated with AR-based educational games significantly influences students' critical thinking skills. Nevertheless, the application of Assemblr Edu-based AR flipbooks combined with PBL in the vocational context remains very limited in the literature.

Several prior studies support the direction of this research. Alkhabra et al. (2023) found that AR significantly improves learning retention and critical thinking compared to traditional methods. Demircioglu et al. (2023) demonstrated that AR-based argumentation activities foster the development of quality arguments and promote critical thinking in a gradual, scaffolded manner. Building on these foundations, this study aims to: (1) develop an Assemblr Edu-based AR flipbook media that is valid and practical; and (2) examine the effectiveness of its integration with the PBL model on the mathematical critical thinking ability of SMK students.

Despite the growing body of evidence supporting AR in general education, empirical studies specifically examining Assemblr Edu-based AR flipbooks integrated with Problem Based Learning (PBL) in vocational school (SMK) mathematics remain scarce. This research gap underscores the need for a dedicated investigation in the SMK context. Accordingly, this study addresses two primary objectives: (1) to develop an Assemblr Edu based AR flipbook media that is valid and practical for use in SMK mathematics learning; and (2) to examine the effectiveness of its integration with the PBL model on the mathematical critical thinking ability of SMK students. The novelty of this study lies in its unique integration of Assemblr Edu-based AR technology with the PBL model specifically within the vocational (SMK) context an area that has received insufficient empirical attention in existing literature. Unlike prior studies conducted in general secondary or higher

education settings, this research directly addresses the distinctive learning challenges faced by SMK students, particularly in developing mathematical critical thinking ability through three-dimensional geometry material. The significance of this study is therefore twofold: it contributes a validated and practical instructional media innovation, and provides empirical evidence of its effectiveness in a vocational educational environment. Based on the foregoing rationale, the central research problem of this study is: To what extent can Assemblr Edu-based AR flipbook media, integrated with the Problem Based Learning model, improve the mathematical critical thinking ability of Grade XI TITL students at SMK Negeri 2 Kabupaten Tangerang?

Augmented Reality (AR) is a technology that enables the superimposition of virtual elements onto real world environments in real time and in an interactive manner (Koumpouros, 2024). This technology is considered effective because it enhances cognitive engagement through richer visual experiences compared to conventional media (Tian & Ironsi, 2025). Ashari et al. (2023) concluded that AR media consistently trains thinking processes, assists in problem analysis, and effectively improves students' critical thinking abilities. Koumpouros (2024) affirmed that publications on AR in education have doubled every five years, with a primary focus on enhancing higher-order cognitive learning outcomes.

In the vocational context, Saputro & Budiarto (2026) affirm that innovative technology based learning media play a significant role in facilitating content comprehension while simultaneously developing vocational students' critical thinking and creativity. Mobile Augmented Reality (MAR) significantly improves spatial visualization and critical thinking on abstract topics. These findings underscore the particular promise of AR for mathematics learning domains involving three dimensional geometry. A digital flipbook is an instructional medium in the form of a digitally flippable book enriched with interactive multimedia content. Ruhma et al., (2025) developed an E-LKPD based on the flipbook format using the ADDIE model and obtained an average N-Gain of 0.75 (high category) in improving mathematical thinking ability, demonstrating the effectiveness of the digital flipbook format in mathematics learning. In a similar vein, (Syahdia et al., 2025) developed a PBL-assisted AR flipbook e-module that yielded highly valid (≈88–89%), practical (≈85%), and effective (≈90.15%) results in improving conceptual understanding in mathematics.

Assemblr Edu is an education-based AR platform accessible via smartphone without specialized programming expertise (Mayang et al., 2026). Studies have demonstrated that AR Card media developed using Assemblr Edu is feasible, practical, and effective in improving student learning interest and outcomes at the junior high school level. The platform's accessibility and user-friendly interface make it particularly suitable for deployment in vocational educational settings where technological infrastructure may be variable (Luh et al., 2025).

Mathematical critical thinking refers to the ability to analyze, evaluate, and synthesize information logically in order to arrive at accurate conclusions. In the context of mathematics education, Facione's framework identifies six core dimensions of critical thinking: interpretation, analysis, evaluation, inference, explanation, and self-regulation.

Demircioglu et al. (2023) found that AR-based argumentation activities assist the development of quality arguments and encourage the gradual development of critical thinking. Rahman (2025) established that AR specifically supports the analysis and evaluation stages of students' critical thinking processes.

Developed contextual AR media using the ADDIE method and achieved a critical thinking N-Gain of 0.77 (high category) among junior high school students. Furthermore, research has demonstrated a meaningful correlation between mathematical critical thinking ability and students' self-efficacy confirming that AR-based learning effectively improves students' mathematical critical thinking. Muhammad (2022), indicating the importance of addressing psychological dimensions in efforts to cultivate critical thinking competence.

Problem Based Learning (PBL) is a student centered instructional model that employs authentic real world problems as the starting point for knowledge development. (Nurjaman et al., 2025) demonstrated that PBL has a significant effect on improving mathematical critical thinking ability. Kritis & Materi (2023) confirmed that PBL significantly outperforms conventional instruction on critical thinking in the domain of circle geometry. When PBL is integrated with AR technology, its effectiveness is further amplified. Saputro & Budiarto (2026) further demonstrated that the Flipped Project Based Learning (FPjBL) model assisted with AR improves visualization, engagement, and reflective reasoning, resulting in enhanced critical thinking performance.

RESEARCH METHODS

This study employed two complementary approaches. First, a Research and Development (R&D) approach using the ADDIE model (Analysis, Design, Development, Implementation, Evaluation) was applied to develop the Assemblr Edu-based AR flipbook media. Second, a quantitative approach with a one-group pretest-posttest quasi-experimental design was employed to test the media's effectiveness on students' mathematical critical thinking ability.

Table 1. One-Group Pretest-Posttest Quasi-Experimental Research Design

Group	Treatment (X)	Pre-Test	Post-Test
Experimental Group (EG)	Flipbook AR (Assemblr Edu) + PBL	O_1	O_2

(Sugiyono, 2019)

Note: O_1 = Pre-test; O_2 = Post-test; X = Treatment using Assemblr Edu-based AR flipbook media and the PBL

Based on Table 1, the research employed a one-group pretest–posttest quasi-experimental design. In this design, only a single group (the Experimental Group/EG) was utilized without a control group. The procedure was as follows: O_1 (Pretest): prior to the treatment, participants were administered an initial test to assess their baseline ability. X (Treatment): the same group received the treatment, namely learning using the Assemblr Edu-based AR Flipbook media integrated with the Problem Based Learning (PBL) model. O_2 (Posttest): following the treatment, participants were given a final test to measure the change and improvement in students' mathematical critical thinking ability.

The study was conducted at SMK Negeri 2 Kabupaten Tangerang. The population comprised all Grade XI students majoring in Electrical Power Installation Engineering (TITL), consisting of three classes: XI TITL 1 (45 students), XI TITL 2 (45 students), and XI TITL 3 (44 students), yielding a total population of 134 students. The sample of 35 students (12 from TITL 1, 12 from TITL 2, and 11 from TITL 3) was selected through simple random sampling, representing 26.12% of the total population.

The AR flipbook media was developed following the ADDIE model stages. The analysis phase involved identifying student learning needs, analyzing three dimensional geometry content, and assessing students' technological infrastructure (smartphone access). The design phase encompassed the creation of storyboards and flipbook interface designs. The development phase involved producing AR content using Assemblr Edu (3D objects, animations, and interactive simulations) and integrating these into the digital flipbook platform.

Media validation was conducted by three expert validators: one language expert, one content expert, and one media expert, using a validation sheet with a 1–5 scale. Practicality testing was administered through a limited trial with 15 students using a student response questionnaire. Instrument validation involved two stages: (1) content validity by three experts using Aiken's V formula; and (2) empirical validity through a trial with 35 students outside the main sample (from the same population), yielding a Cronbach's Alpha coefficient of 0.940 (highly reliable). The research instrument consisted of a mathematical critical thinking ability test in essay format comprising 6 items developed based on six critical thinking indicators: Interpretation (Item 1), Analysis (Item 2), Evaluation (Item 3), Inference (Item 4), Explanation (Item 5), and Self-Regulation (Item 6). Scoring used a polytomous scale ranging from 0–4 per item, with a maximum total score of 24.

The effectiveness of the intervention was measured using the Normalized Gain (N-Gain) formula (Hake, 1999):

$$\text{N-Gain} = \frac{\text{Posttest Score} - \text{Pretest Score}}{\text{Maximum Score} - \text{Pretest Score}}$$

N-Gain values were interpreted as follows: $g > 0.70$ = High; $0.30 \leq g \leq 0.70$ = Medium; $g < 0.30$ = Low. A Paired Sample t-test was subsequently employed to verify the statistical significance of the improvement ($p < 0.05$).

RESULTS AND DISCUSSION

This study aimed to develop an Augmented Reality (AR) Flipbook Media based on Assemblr Edu as a mathematics learning medium to improve the mathematical critical thinking ability of SMK students. Media development was carried out using the ADDIE model consisting of five stages: Analysis, Design, Development, Implementation, and Evaluation (Koumpouros, 2024). The following describes the results of each development stage and the effectiveness testing outcomes.

Analysis Phase

The analysis phase involved the identification of learning needs, student characteristics, and targeted competencies. Observations and interviews with mathematics teachers at the vocational school revealed that students' mathematical critical thinking ability

was relatively low, particularly in the domain of three dimensional geometry (solid figures). Students experienced difficulty in visualizing three dimensional objects in abstract form, necessitating instructional media capable of delivering concrete and interactive visual experiences (Anwar et al., 2024). The needs analysis also confirmed that the majority of students had access to smartphones, making AR application-based technology highly appropriate for the instructional context (Saputro & Budiarto, 2026). An alignment analysis with the Learning Achievement Standards (Capaian Pembelajaran/CP) of the SMK curriculum was also conducted to ensure the developed media addressed the targeted competencies (Saputro & Budiarto, 2026).

Design Phase

Based on the analysis results, the design phase focused on the preparation of storyboards, flipbook interface design, and planning of AR content to be embedded in each page. The media was designed using an attractive and interactive visual approach by integrating AR-based 3D objects into the digital flipbook format (Eriadyahningrum et al., 2022). Assessment instruments in the form of expert validation sheets and student response questionnaire sheets were also designed in this phase. Development of the mathematical critical thinking ability test instrument referred to six critical thinking indicators: (Item 1) Interpretation, (Item 2) Analysis, (Item 3) Evaluation, (Item 4) Inference, (Item 5) Explanation, and (Item 6) Self Regulation (Mayang et al., 2026),

Development Phase

In the development phase, AR Flipbook media was produced using the Assemblr Edu platform, which allows embedding of AR based 3D objects into digital flipbook pages. The development of AR in mathematics learning is aligned with the framework outlined by (Pujiastuti & Haryadi, 2024) which emphasizes AR integration to strengthen students' understanding of abstract mathematical concepts (Mayang et al., 2026). The material content presented includes elements of cubes, face diagonals, space diagonals, diagonal planes, and the concept of cube volume. Each flipbook page is equipped with AR markers that can be scanned using a smartphone to bring up interactive 3D objects.

Figure 1. Augmented Reality Flipbook Design

Figure 1, shows the Assemblr Edu-based AR Flipbook Media displaying 3D geometry objects (cube, prism, pyramid, cylinder, cone, and sphere) as visual representations of solid geometry material. It displays the Learning Outcome (CP) and Learning Achievement Indicator (IPK) page with a structured two-column layout that supports visual, interactive, and gradual learning of solid geometry. It displays Meetings 1–2 along with their evaluation quizzes, each equipped with instructions for using the Assemblr Edu application, QR codes, and online access links. The design of this media demonstrates the integration of the digital flipbook format with AR technology, enabling students to access interactive 3D objects by scanning markers, which then directs them to links that access Augmented Reality media through the Assemblr Edu application or website, bringing up interactive visual displays that allow students to interact with Three-Dimensional Geometry objects more realistically.

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Figure 2. Assemblr Edu-Based AR Display

Figure 2, illustrates that the development of AR Flipbook Media using the Assemblr Studio Web platform has produced various systematically structured learning scenes. Each scene is equipped with interactive 3D objects, explanatory avatars, information boards, navigation buttons, and integrated evaluation quizzes. This design allows students to independently explore three-dimensional geometry objects from various perspectives, thereby supporting the formation of spatial understanding and mathematical critical thinking ability effectively.

After the media was completed, validation testing was conducted by experts consisting of content experts, language experts, and media experts. The Assemblr Edu-based AR Flipbook Media developed was declared highly feasible for use as a mathematics learning medium in SMK, with minor revisions in the language aspect and content improvement as suggested by validators. The validation process aimed to obtain assessments and input from experts to ensure the feasibility of the media before being implemented to students (Saputro & Budiarto, 2026).

Expert Validation Results

Media validation was conducted by three validators: content expert, language expert, and media expert. The following presents a recapitulation of validation results from all three aspects.

Table 2. Recapitulation of AR Flipbook Media Validation Results

No	Validation Aspect	Total Score	Max Score
1	Content Expert	66	75
2	Language Expert	50	56
3	Media Expert	78	90
	Overall Average		85%

Based on Table 2, the validation results by the content expert yielded a percentage of 88%, the language expert validation 80%, and the media expert validation 87%. The overall average of the three validation aspects was 85%. Referring to the feasibility criteria used in this study, this percentage falls into the Highly Feasible category (81%–100%) (Saputro & Budiarto, 2026).

Table 3. Media Feasibility Interpretation Criteria

Percentage (%)	Feasibility Criteria
81% – 100%	Highly Feasible
61% – 80%	Feasible
41% – 60%	Fairly Feasible
21% – 40%	Less Feasible

The Assemblr Edu-based AR Flipbook Media developed was declared highly feasible for use as a mathematics learning medium in SMK, with minor revisions in the language aspect and content improvement according to validator suggestions. The content expert validator gave the highest score (88%) particularly on the aspects of alignment with the Learning Outcomes (CP), material accuracy, and the media's ability to support students' critical thinking. The media expert validator gave a score of 87% particularly on the aspects of visual design appeal, clarity of 3D objects, and AR display quality. The language expert validator gave a score of 80%, reflecting that the language aspect was already good with some notes for improvement in sentence accuracy and terminology consistency.

Practicality Test Results

The practicality test was conducted through student response questionnaires with 15 students in a limited trial. The practicality test results are presented as follows:

Table 4. Practicality Test Results

Aspect	Score	Max Score	Percentage
Display & Media Ease of Use	61	70	87,1%
Understanding of Solid Geometry Elements	93	105	88,6%
Volume and Surface Area of Solids	20	21	95,2%
Overall Average	—	—	89%

Based on Table 4, the practicality test results with 15 students showed an average score of 89% in the "Highly Practical" category. The aspects of media attractiveness, ease of use, and usefulness received very positive responses from students. These findings are consistent with the research (Luh et al., 2025).

Implementation Phase

In the implementation phase, the AR Flipbook Media was implemented with 35 Grade XI TITL SMK students. Before learning began, students were given a pretest to measure initial critical thinking ability. Then, learning was carried out using Assemblr Edu-based AR Flipbook Media over several meetings. The following shows students' activities implementing the AR Flipbook Media.

Figure 3. Student Activities Using AR

Based on Figure 3, it can be seen that students can access AR content easily via their respective smartphones by scanning markers contained on the flipbook pages. This marker scanning process allows the 3D objects developed in Assemblr Studio Web to appear in real-time on smartphone screens, so students can view, rotate, and interact with three-dimensional geometry objects from various perspectives.

At the end of learning, students were given a posttest to measure the improvement in critical thinking ability after using the media. The following shows an example of a student's posttest answer.

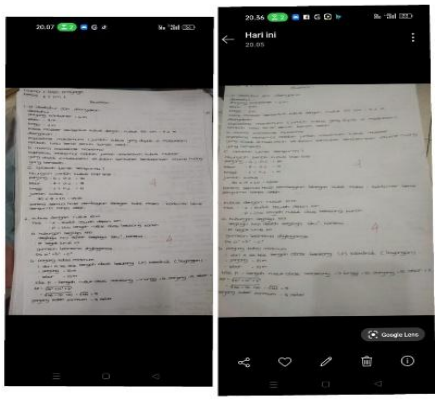

Figure 4. Example of Posttest Answer Results

Figure 4, displays student posttest results showing a significant improvement in answer quality. Students were able to compose answers with more structured solution steps, containing identification of known information, formulas used, systematic calculations, and clear final conclusions. The striking difference between pretest and posttest results illustrates that the use of AR Flipbook Media has been effective in encouraging students to develop mathematical critical thinking ability, particularly in the aspects of interpretation, analysis, evaluation, inference, explanation, and self-regulation.

Pretest and Posttest Results of Mathematical Critical Thinking Ability

Measurement of mathematical critical thinking ability was conducted through pretest and posttest with a maximum score of 24. Analysis of improvements in students' critical thinking ability used the N-Gain (Normalized Gain) formula:

$$\text{N-Gain} = \frac{\text{Posttest Score} - \text{Pretest Score}}{\text{Maximum Score} - \text{Pretest Score}}$$

The N-Gain formula is used to measure the improvement of students' mathematical critical thinking ability by taking into account the initial score (pretest) and final score (posttest) relative to the maximum score that could be achieved. The N-Gain criteria used is shown in the N-Gain Criteria Table based on Hake's (1999) classification. N-Gain is used to measure the effectiveness of learning outcome improvement from pretest to posttest. The higher the g value, the greater the improvement that occurs relative to the maximum possible improvement.

Table 5. N-Gain Criteria

N-Gain Value (g)	Percentage (%)	Category
$g > 0.70$	$g > 70\%$	High
$0.30 \leq g \leq 0.70$	$30\% \leq g \leq 70\%$	Medium
$g < 0.30$	$g < 30\%$	Low

Below is a summary of the statistical results of the pretest and posttest, as well as the N-Gain values for the improvement of students' mathematical critical thinking skills

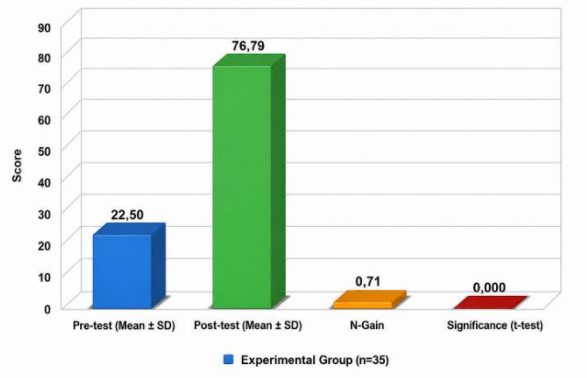

Figure 5. Recapitulation of Mathematical Critical Thinking Ability Analysis Results

Based on Figure 5, there was a significant improvement in critical thinking ability after using the AR Flipbook Media. The class average N-Gain was 0.71, which falls into the High category (> 0.70) (Nurjaman et al., 2025). The Paired Sample t-test yielded a value of $p = 0.000 < 0.05$, indicating a very significant difference between pre-test and post-test. This result is consistent with the findings. A critical thinking N-Gain of 0.71 (high) through the use of contextual AR media. Haryadi et al. (2026) reported that AR significantly improved students' critical thinking performance with high N-Gain in the context of thermodynamics, confirming the effectiveness of AR across the fields of science and mathematics. Septian et al. (2025) also affirmed that students' cognitive-emotional factors interact with mathematical critical thinking ability, so attractive and interactive media such as AR flipbooks are relevant to encouraging such improvements.

This is consistent with the findings of (Demircioglu et al., 2023) that AR-based activities help develop quality arguments and encourage critical thinking in a gradual manner, as well as a Rahman (2025) who found that AR concretely supports the analysis and evaluation stages of students' critical thinking.

These results can be explained through several interacting mechanisms grounded in established cognitive and pedagogical theory. The AR flipbook facilitated concrete visualization of three-dimensional geometry objects, which directly addressed the root cause of students' difficulties namely, their inability to mentally represent abstract spatial structures. As affirmed by Tian & Ironsi (2025), AR enhances cognitive engagement through richer visual experiences, and Ashari et al. (2023) confirmed that AR media consistently trains thinking processes and assists students in problem analysis. The interactive 3D objects in Assemblr Edu provided a concrete scaffold that bridged students' visual-spatial understanding and their symbolic (formula-based) reasoning in solid geometry. Furthermore, the PBL model required students to engage in authentic problem-solving sequences, activating higher-order thinking processes from the very first stage of problem orientation. The synergy of AR as a cognitive tool and PBL as a pedagogical framework ensured that students were not passive consumers of visual content, but active constructors of mathematical understanding, which is consistent with the findings of Suharti et al. (2021) who demonstrated that PBL integrated with AR-based educational approaches significantly influences students' critical thinking skills. In contrast to prior studies that used AR as a standalone supplementary resource, this study demonstrates that combining AR with a structured problem-based pedagogy produces a qualitatively different and more effective learning experience. This novelty the deliberate and systematic integration of Assemblr Edu-based AR within the PBL cycle specifically in the vocational (SMK) context constitutes a meaningful empirical contribution to the growing literature on technology enhanced mathematics education.

After using the AR Flipbook Media in learning, students were given a response questionnaire to assess the attractiveness and usefulness of the media. The questionnaire consisted of 8 statement items covering two aspects: Display & Ease of Media Use and Understanding of Solid Geometry Elements and 3D Solid Geometry (Luh et al., 2025). Scores were calculated using a 1–4 scale and converted to percentages (Septian et al., 2025).

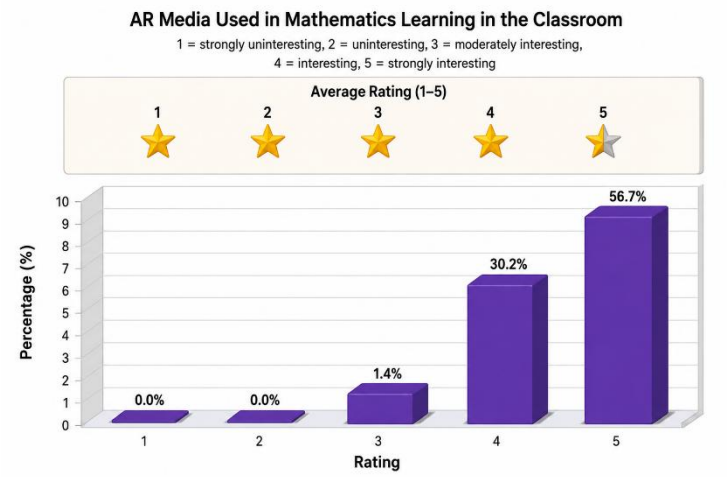

Figure 6. Student Response Results towards AR Flipbook Media

Based on Figure 6, the overall average score of the student response questionnaire was 3.67 out of a maximum score of 4.00, which when converted to a percentage yields a value of 91.75%. This value falls into the Very Attractive category (81%–100%) based on the attractiveness interpretation criteria used. This indicates that students gave very positive responses to the use of AR Flipbook Media in mathematics learning.

Overall, the findings of this study affirm that the synergy between Assemblr Edu-based AR Flipbook Media and the Problem Based Learning (PBL) model has been proven effective in improving the mathematical critical thinking ability of SMK students. This effectiveness is supported by three main pillars: (1) the very high validity of the media (average 85%) guarantees the quality of content and accuracy in presenting three-dimensional geometry material; (2) the very good practicality of the media (89%) ensures ease of use in the actual SMK classroom environment; and (3) significant effectiveness, reflected in an N-Gain of 0.7081 (high category) and Paired Sample t-test ($p = 0.000 < 0.05$). Real-time 3D object visualization through AR facilitates the problem orientation stage in PBL by providing concrete representations that encourage students to move from merely observing to analyzing, evaluating, and inferring the core indicators of mathematical critical thinking. These findings reinforce and expand on previous studies that affirm the relevance of AR in improving critical thinking across levels and learning contexts Demircioglu et al. (2023), Rahman (2025) and Suharti et al., (2021) while also providing specific empirical contributions in the vocational education (SMK) context, which has been limited in research.

CONCLUSION

This study produced three main conclusions that are interrelated. First, the Assemblr Edu-based AR Flipbook Media developed through the ADDIE model was declared highly valid and highly practical as a mathematics learning medium in SMK. Validation by three experts (content, language, and media) yielded an average percentage of 85% (highly valid category), while the practicality test with 15 students yielded a score of 89% (highly practical category).

Second, the AR flipbook media integrated with the Problem Based Learning (PBL) model was significantly effective in improving the mathematical critical thinking ability of

SMK students. This improvement was evidenced by an average N-Gain value of 0.7081, which falls in the high category ($g > 0.70$), with the Paired Sample t-test yielding a significance value of $p = 0.000 < 0.05$ ($t(34) = 5.12$).

Theoretically, these findings confirm that real-time 3D object visualization through AR can bridge students' abstract thinking towards concrete understanding, while simultaneously stimulating higher-order thinking processes that include interpretation, analysis, evaluation, inference, explanation, and self-regulation. Practically, this study recommends that SMK teachers adopt Assemblr Edu-based AR flipbook media as an alternative innovative learning medium, particularly for material with three-dimensional visual components. Integration with the PBL model should be planned systematically so that both components can mutually reinforce each other. For future researchers, it is recommended to use an experimental design with a control group so that effectiveness comparisons can be made more rigorously, to expand the sample scope across schools, to explore the influence of media on other variables such as motivation, creativity, and mathematical problem solving, and to examine the sustainability of the long-term impact of AR use.

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