Improving Critical Thinking Skills through a Flipped Project-Based Learning Model Integrated with Mockup Media and Augmented Reality

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Abstract: The rapid advancement of the Industrial Revolution 4.0 demands that vocational high school graduates possess not only technical expertise but also higher-order thinking skills, particularly critical thinking. However, many learning practices in vocational education remain limited to procedural instruction with minimal emphasis on cognitive development. This study aimed to evaluate the effectiveness of the Flipped Project-Based Learning (FPjBL) model integrated with mockup and Augmented Reality (AR) media in enhancing vocational students' critical thinking skills compared to conventional learning approaches. This study uses a quantitative approach with a quasi-experimental design, namely pretest-posttest control group design. The research sample was grade X and XI students from six state vocational high schools in the Solo Raya area, consisting of 216 students divided into experimental and control groups. The experimental group used the FPjBL model with mockup and AR media, while the control group used conventional learning. Data were collected through critical thinking ability tests and learning motivation questionnaires. Data analysis used ANCOVA and multiple linear regression. The results showed that the experimental group experienced a significant increase in critical thinking skills compared to the control group ($F(1,213) = 104.192$, $p < .001$, partial $\eta^2 = .329$). The analysis and explanation indicators showed the greatest increase. Linear regression shows that learning motivation, media perception, and student activity significantly affect critical thinking skills ($R^2 = .613$). These results confirm that integrating Integration Media Mockup and Augmented Reality with FPjBL effectively strengthens students' critical thinking and can be adopted in vocational education curricula to better prepare learners for the complex challenges of Industry 4.0.

Keywords: Critical thinking, Flipped project-based learning, Mockup media, Augmented reality, Vocational High School, Industrial revolution 4.0

1. Introduction

The use of Industry 4.0 technologies in factories and manufacturing sectors has generated a demand for new competencies among employees. Learning Factories 4.0 at vocational schools can enhance technical competences pertinent to specific disciplines, yet may not substantially augment multidisciplinary skills that are genuinely applicable in the industry (Roll and Ifenthaler, 2021). With the advancement of the period, platforms for digital learning processes, such as e-learning, are deemed capable of enhancing the 21st-century skills of students in vocational schools (Budiarto et al., 2024). Furthermore, the primary technical competencies for Industry 4.0 encompass data analysis, process optimization, and device maintenance, which are deemed to be attained through the effective implementation of e-learning (Ismail and Hassan, 2019).

The urgency of mastering 21st-century skills for Vocational High School (SMK) students is more significant within the current global educational context, particularly in light of the challenges and opportunities presented by the Fourth Industrial Revolution. UNESCO and several field studies indicate that these skills encompass creativity, critical thinking, collaboration, and communication, which are essential for preparing students to navigate the dynamics of change in the workforce. According to Gündüz (2023), these skills are closely related to lifelong learning and help students develop critical and collaborative thinking skills during their learning process. A study emphasized that in this highly competitive era, vocational education should focus on scientific literacy as a transferable outcome, which enables students to use scientific knowledge meaningfully and solve problems relevant to their lives (Jaedun et al., 2022)

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Subsequent study indicates that secondary school-aged children can attain elevated levels of 21st-century skills, suggesting that education at this stage requires further optimization to enhance the cultivation of these skills (Kocaman, 2022). Consequently, vocational education must be executed proficiently using new pedagogical approaches, including project-based learning and STEAM integration, to provide students with the requisite skills for competitiveness in the labor market (Zayyinah et al., 2022). Moreover, studies indicate that acquiring communication skills via English literacy activities enhances students' active participation and expression of ideas, exemplifying the implementation of 4C skills (creativity, critical thinking, collaboration, communication) within the educational framework (Ratama, Padmadewi and Artini, 2021; Jaedun et al., 2022). Furthermore, understanding digital skills is crucial, as research indicates that the amalgamation of STEM and digital literacy enhances students' competencies in 21st-century skills (Rizaldi, Nurhayati and Fatimah, 2020; Sá et al., 2021). Consequently, it is imperative for all stakeholders in education to dedicate themselves to developing pertinent curricula and pedagogical approaches, enabling students to realize their utmost potential in confronting future difficulties.

Despite the growing recognition of these needs, many vocational learning practices remain focused on procedural knowledge and fragmented skill acquisition, with limited emphasis on higher-order thinking such as critical and analytical reasoning. This gap underscores the need for innovative pedagogical designs that integrate contextual learning, active inquiry, and technological engagement. Accordingly, this study does not focus solely on the technological impact of Augmented Reality (AR), but rather on how its integration within the Flipped Project-Based Learning (FPjBL) model can foster students' critical thinking skills in vocational education settings.

Deep learning and critical thinking are becoming progressively significant in vocational education within the construction sector. Deep learning can be improved via educator training and the provision of innovative teaching resources, while critical thinking is vital for future career contexts (Romero-Tena, Lopez-Lozano and Gutierrez, 2020;Ratama, Padmadewi and Artini, 2021). Deep learning applications in construction encompass automatic progress monitoring, safety notifications, and equipment management (Park et al., 2020; Sollied Madsen, Thorvaldsen and Sollied, 2021). E-learning systems can improve 21st-century competencies, including critical thinking, among vocational students (Budiarto et al., 2024). Despite the introduction of numerous advances in vocational education, practical learning in civil engineering courses, particularly regarding concrete buildings, continues to encounter some substantial hurdles. Current curricula frequently fail to effectively connect theoretical concepts with practical application in the field. This affects the inadequate mastery of advanced cognitive abilities, including critical and analytical thinking, which are essential for contemporary and future civil engineering endeavors (Romero-Díaz de la Guardia et al., 2024).

Although deep learning technology in construction has been employed to automate progress monitoring, safety alerts, and equipment management (Elghaish et al., 2021; Mansoor et al., 2022), its utilization in vocational school learning remains constrained. Conversely, e-learning platforms have demonstrated potential in enhancing 21st-century abilities, including critical thinking (Budiarto et al., 2024), nonetheless, issues such as restricted datasets and the lack of technology interpretability persist as substantial obstacles (You et al., 2023). A study by Peng and Fang (2024) shown no significant link between deep learning and enhanced critical thinking skills, highlighting the necessity for a more contextual and experiential learning strategy. Consequently, creative pedagogical approaches are required that not only enhance the acquisition of technical skills in concrete reinforcing structures but also promote the cultivation of critical thinking abilities through authentic and significant learning experiences.

Vocational education, particularly at the Vocational High School (SMK) level, plays a pivotal role in cultivating exceptional and competitive human resources in the context of the Industrial Revolution 4.0. SMK graduates must not only excel in technical competencies within their respective fields but also possess critical thinking, collaboration, creativity, and communication skills, which are essential 21st-century skills necessary in a dynamic, technology-driven work environment (Budiarto et al., 2024; Gündüz, 2023). In civil engineering vocations, proficiency in concrete structural reinforcement necessitates not only procedural expertise but also analytical capabilities for contextual problem-solving in construction. Consequently, a novel pedagogical strategy is required that can concurrently integrate technical skills and advanced cognitive processes.

Implementing the mockup media into the Flipped Project Based Learning model seeks to fill a novel gap in research pertaining to critical thinking skills of SMK students and vocational education pedagogy. The purpose of this study is to determine the effectiveness of the Flipped Project Based Learning paradigm using mockup media with regards to students' critical thinking skills on the topic of concrete structures taught in grade 11. This study tries to measure the perceptions of learners and motivation quantifiably in order to evaluate catalytic impacts on the learners' critical thinking skills. Although Industry 4.0 has driven the need for 21st-century competencies, many vocational programs particularly in civil engineering, still fail to link theory with authentic practice, resulting in weak critical thinking and problem-solving skills. Previous studies show that deep learning and e-learning approaches alone are insufficient to foster higher-order thinking. Therefore, this study addresses that gap by implementing a Flipped Project-Based Learning model integrated with mockup and augmented reality media to enhance students' critical thinking in vocational education. Based on these objectives, the formulated study question is: (1) How Flipped Project Based Learning model with mockup media differs from conventional learning in terms of critical thinking skills? How do the learners' perceptions of motivation impact the critical thinking abilities after this approach?

2. Literature Review

2.1 Critical Thinking and Deep Learning in Vocational Education

Critical thinking and deep learning are essential components of vocational education, particularly as the employment landscape demands high levels of adaptability and competence. The educational paradigm shift for Industry 4.0 highlights the crucial role of critical thinking, encompassing the ability to analyze, evaluate, and synthesize information in practical scenarios. Hamdani et al. emphasize that addressing contemporary challenges requires a shift from specific skills to broader competencies that foster critical thinking, enabling students to navigate labor market transitions (Hamdani and Suherman, 2021). Critical thinking serves as the foundation for deep learning, emphasizing in-depth understanding over memorization. Sudirta et al. state that enhancing student autonomy and creativity is crucial in vocational environments (Sudirta et al., 2022).

The integration of information and communication technology (ICT) plays a crucial role in developing critical thinking capacity and deep learning. Kang and Zhang (2022) note that combining vocational education with modern pedagogical techniques can foster students' critical thinking skills while preparing them for real-world applications. The application of innovative teaching methodologies has been shown to create more immersive learning experiences (Hu and Xue-yu, 2022). The link between critical thinking and deep learning is evident in the need to solve complex problems as a crucial skill for the 21st century according to Mutohhari et al. (2021)who emphasize that contemporary job demands require a combination of critical thinking and creative problem-solving. The ability to combine theoretical understanding with practical application ensures vocational students are active participants in their learning, illustrating the cyclical relationship between critical thinking and deep learning.

Deep learning is characterized by achieving eight student engagement with the content and requires learners to make connections between concepts and applications. Surface learning, on the other hand, usually entails a more simplistic approach wherein students focus primarily on memorization of content, engage with the material at the lowest level, and as a result, develop inadequate understanding and skills relevant to their field of work (Mishra, Reddy and Pathak, 2021). Deep learning in education emphasizes meaningful knowledge construction, integration of concepts, and the ability to apply understanding in novel contexts (Prianto, Qomariyah and Firman, 2022; Entwistle, 2023). In vocational education, this process encourages learners to move beyond procedural execution toward reflective and analytical reasoning.

Studies show that learners utilizing deep learning techniques in a vocational education setting outperform their peers academically and in terms of skills gained. There is also evidence that deep learning techniques positively impact student outcomes, indicating that incentives geared towards deep learning are critical for vocational achievement (Janiesch, Zschech and Heinrich, 2021; Lee et al., 2022). In addition, the emphasis placed on project-based learning (PjBL) as an educational approach in vocational institutions supports this evidence because it encourages active inquiry and places emphasis on the application of higher order thinking skills (Zhao, Wu and Li, 2023). This perspective suggests effective designed and delivered immersive learning experiences can bridge the gap between theory and practical application skills. The shift emphasizes how important cultivating knowledge is together with acquiring practical skills that are necessary for securing a job in today's competitive world (Smith and Seal, 2021).

In conclusion, the dichotomy between deep and surface learning holds significant implications for vocational education. These approaches not only enhance student engagement and competencies but also align vocational training with the evolving demands of the labor market (Bouw, Zitter and de Bruijn, 2021). Thus, fostering a culture of deep learning can lead to more effective educational outcomes and better prepare students for future challenges in their respective fields.

2.2 Flipped Classroom and PjBL in The Context of Vocational Schools

Implementation of the Flipped Classroom and Project-Based Learning (PjBL) models in vocational high schools (SMK) enhances students' practical skills within a responsive framework because of the deep content engagement and real-world application required of them. In the Flipped Classroom model, lectures are replaced with student-centered activities having the students access instructional materials online, which frees up class time for projects and cooperative work (Triyanto et al., 2024;Kausar, Maryono and Aristyagama, 2021). This model is useful in vocational education, where skill execution must be learned and practiced. Consequently, class time is spent on discourse, problem solving, and project work which are more suited to vocational education within its aims to develop relevant competencies not just through learning, but through thoughtful execution.

In addition, the combination of Flipped Classroom and PjBL in vocational high schools (SMK) effectively creates a lively class atmosphere that integrates theory with practice. This model enables active learning alongside peer interaction which is fundamental in vocational education and training. As Usmeldi and Amini (2022) note, this synergistic application of these models serves to increase student motivation and learning outcomes, enhancing their academic and vocational pathways.

Some scholars have stated that the application of these models can improve student motivation and learning outcomes tremendously, allowing students to navigate their academic and professional pathways successfully (Rahmawati et al., 2021;Efendi, Sumarmi and Utomo, 2020). The ability of these models to be applied in integrated STEM education makes them even more useful because they promote comprehens as well as critical thinking among students regarding the collaboration of different disciplines. Hence, to effectively equip students for the demands of their future careers, vocational institutions need to actively research and apply such innovative teaching strategies.

In this study, the flipped classroom approach was implemented by having students access digital instructional materials, including video lectures and augmented mockup simulations, before class meetings (Triyanto et al., 2024). This allowed students to gain preliminary understanding independently, so classroom sessions could focus on collaborative project execution, discussion, and problem-solving within the Project-Based Learning framework. This approach aligns with the interactive and practice-oriented nature of vocational education described by Usmeldi and Amini (2022) , but extends it further by integrating mockup-based Augmented Reality media. The novelty of this model lies in combining flipped learning, PjBL, and immersive AR environments to bridge the gap between theoretical knowledge and real-world construction practices, which was an integration that remains limited in current vocational education research.

2.3 Integration Media Mockup and Augmented Reality (IMM&AR) in Contextual Learning

The use of Media Mockups and Augmented Reality (IMM&AR) in the context of engineering learning in vocational schools (SMK) is very important in cultivating one's ability to reason and critically evaluate problems (HOTS) which are fundamental in modern education. This learning practice corresponds to the form of vocational education that requires strong hands-on learning (Sukatiman, Budiwan and Waluyo, 2023). With the initial interaction with IMM&AR, students use and defend their theories while going through an iterative design process, which encourages inquiry, evaluation, and critical reflection on results achieved.

An AR system projects computer-generated augmentations onto real objects, enabling real and virtual objects to function synchronously and provide a proper depth of perception for the user, through this real-time integration, AR environments allow learners to observe complex structures, spatial relationships, and procedural sequences in ways that are not achievable through static instructional media (Siriwardhana et al., 2021). Such perceptual enrichment supports clearer conceptualization, reduces cognitive load during visualization, and promotes more meaningful engagement with learning tasks particularly in vocational settings where understanding three-dimensional structures and technical details is essential.

Incorporating conventional teaching with CAD tools and video instruction has been found to improve the learning achievement of students in technical drawing; moreover, multimedia student-centered learning environments positively affect students' participation in the laboratory (Hendarwati, Nurlaela and Bachri, 2021). Simulation, problem-based learning, and constructivist multimedia methods are effective for teaching many advanced engineering concepts (Wati and Widiansyah, 2020; Jurayev, 2021). Additionally, as these authors report, advanced modeling and visualization platforms facilitate conceptual understanding and design evaluation in devising a product. These reasons emphasized the importance of enhanced media literacy instruction in algorithmic learning environments (Valtonen et al., 2019). In professional settings, this is particularly relevant, as students bridging divergent levels of prior knowledge engage in project-based learning, which features multifaceted challenges. IMM&AR technologies increase understanding of technologies and simultaneously foster evaluative and creative thinking, preparing students to address contemporary engineering challenges with greater confidence and ingenuity.

A significant body of research has identified Augmented Reality (AR) as an effective tool for enhancing teaching methodologies, while numerous studies have demonstrated the positive impact of Virtual Reality (VR) on the learning process by facilitating interaction with virtual and real objects, fostering learning through experimentation, participation, and interactivity, thereby increasing learner motivation and attention, and making learning more engaging and effective, especially when dealing with abstract concepts or complex phenomena (Elmqaddem, 2019). As can be seen that recent studies highlight that AR-based mockup environments enhance visualization and contextual understanding, bridging abstract concepts with real-world applications (Kassutto, Baston and Clancy, 2021; Kozov and Ivanova, 2023). Within the FPjBL framework, IMM&AR serves as an immersive medium that strengthens deep learning engagement by enabling students to manipulate, test, and reflect on virtual construction models—transforming abstract theoretical knowledge into experiential learning.

As noted along with IMM&AR, developing critical thinking skills via active learning techniques has recently been acknowledged as a fundamental component of effective vocational education. Citing Omelchenko, the author's assertion is supported that critical thinking strategies used in the context of media education technologies cultivated the foundational competencies indispensable for students to thrive in the contemporary workforce (Omelchenko, 2022). Evidence showing that interactions with mockups enable students to test their design hypotheses and evaluate the outcomes of their actions, thus exercising deeper reasoning and reflective judgment, which is part of the higher-order thinking synergy, also supports this (Sukatiman, Budiwan and Waluyo, 2023). Moreover, Flipped Project-Based Learning has been shown to foster participation and understanding within context, allowing students to engage with concepts theoretically. Such approaches are especially important in civil engineering education where the theory-practice divide tends to hinder the development of critical thinking skills (Kausar, Maryono and Aristyagama, 2021; Budiarto et al., 2024).

To conclude, the integration of Media Mockups and Augmented Reality (IMM&AR) as part of vocational engineering education shows that strategies designed to foster critical thinking are responsive and proactive to the concerns of the gap between teaching in classrooms and the needs of industries. This literature review focuses on the critical analysis of teaching strategies and appropriate instructional media in vocational education, especially in cultivating critical thinking and other 21st century competencies.

3. Theoretical Framework

The incorporation of Deep Learning alongside Flipped Learning, Project Based Learning (PjBL), and Constructivism gives rise to a practical pedagogical approach that improves practical learning skills in vocational high schools (SMK). These integrations are beneficial for vocational education because there is a need to provide students with both theory and practice as preparation for employing. Deep Learning, which is developed by Biggs, focuses on the understanding and application of information as opposed to rote memorization, which is more aligned with the requirements of vocational education that demands real-life problem solving (Rahayu, Sutikno and Indriyanti, 2023). (Sandal, 2023) states that Flipped Learning adds to this by allowing students to part outside the classroom which enhances classroom participation during lessons. This model supports knowledge implementation using simulations of actual and theoretical industrial environments which is ideal for vocational education. Utilizing Augmented Reality (IMM&AR), learning can be done before and after school hours, enabling students to complete tasks assigned by instructors at any time.

Furthermore, PjBL methodology excels within this integration because it promotes an environment in which students expertly work on projects that replicate real-life situations, improving their higher order thinking skills, creativity, and problem solving abilities (Xiong, 2024). Rahayu, Sutikno and Indriyanti (2023) claims that this model develops decision making and creativity capabilities, while strongly supporting the constructivist approach in which learners build understanding and meaning through real-world activities and reflection. The critical link with Constructivism is emphasized as learners apply their prior knowledge to acquire new skills, which increases engagement and motivation—factors particularly critical in vocational education where active participation is central to learning (Chang and Chen, 2022). As a result, students skillfully tackle multifaceted problems within their domains, preparing them for the realities

In wake of the current trends in the job market, the integration of specific teaching methodologies has become ever more essential as vocational institutions continue accommodating to educational paradigms. The development of collaborative, creative, and critical educational practices distinguishes learning in SMK toward successful career pathways, demonstrating the importance of practical educative work to the students' value system. Deep Learning in vocational high schools with Flipped Learning, PjBL, and constructivism enhances personal and professional growth for students through comprehensive vocational education.

4. Method

4.1 Types of Research and Research Design

This study adopts a quantitative approach with a quasi-experimental type design, specifically a pretest-posttest control group design (Cresswell et al., 2003; Abdullah, 2015). This was done to measure the critical thinking ability of students after the implementation of the Flip Learning Project Based Learning (FPjBL) model with Immersive Multimedia & Augmented Reality (IMM&AR) Media. The experimental group learned through FPjBL-IMM&AR while the control group learned through conventional teaching. The study focused on assessing the pedagogical impact of the FPjBL model, with IMM&AR functioning as a supporting medium rather than a stand-alone technological intervention. Students in the experimental group accessed augmented mockup simulations of a two-storey building prior to class and collaborated in small groups during project activities using structured worksheets (LKPD). Both groups covered identical content and were evaluated through pre- and post-tests on critical thinking performance.

4.2 Samples and Sampling Techniques

Participants were selected using purposive sampling, considering their relevance to the research objectives and accessibility in real classroom settings (Etikan, Musa & Alkassim, 2016; Cohen, Manion & Morrison, 2018). This technique ensures that the selected participants possess characteristics aligned with the competencies studied, particularly in building and construction programs (Mingers and Willcocks, 2017; Bostley and Peters, 2023). From this sample, a proportional split into two groups was made, one experimental group of 108 learners who were exposed to flipped project-based learning with mockup media in IMM&AR (Immersive Multimedia & Augmented Reality) alongside 108 in a control group with conventional instruction. All participants underwent identical pretest and posttest assessments.

4.3 Research Procedures

The research procedure commenced with the preparation of instructional materials and learning media. The instructor, assisted by student teachers (PPL), developed scaled prototype models representing multi-storey concrete reinforcement structures based on authentic industrial data. These prototypes were subsequently transformed into three-dimensional AutoCAD designs and embedded within an augmented application known as the Immersive Multimedia and Augmented Reality (IMM&AR) media. The IMM&AR platform enabled students to visualize and manipulate structural components through interactive simulations accessible via mobile devices, thereby supporting independent pre-class learning activities. In the experimental group, the Flipped Project-Based Learning (FPjBL) model was implemented through three stages: (1) a pre-class phase, where students accessed digital instructional videos and IMM&AR simulations to study core concepts independently; (2) an in-class phase, focusing on collaborative project execution, analysis, and discussion guided by the instructor; and (3) a reflection phase, where students evaluated design outcomes and articulated reasoning processes. The control group received the same instructional content and assessment procedures but without the use of IMM&AR media. Both groups were taught by the same instructor to maintain instructional consistency. This structured approach ensured procedural validity and effectively integrated theoretical understanding with authentic construction practices.

4.4 Data Collection Technique

Data collection was conducted through two primary methods: (1) assessment of critical thinking abilities via group work analysis involving reinforcement calculations, presentation of results, and structural drawings utilizing the AutoCAD application to evaluate intervention effectiveness, and (2) administration of closed questionnaires employing a Likert scale to gauge learning motivation and student perceptions of the implemented instructional approach (Fukuzawa, Boyd and Cahn, 2017;Yaki, 2022). The data collection technique consists of the following stages: familiarization with teachers and students, administration of pretests, execution of learning sessions across 4-5 meetings, administration of posttests, and completion of questionnaires by students in the experimental group. Data were gathered throughout two semesters in two vocational schools for grades 10 and 11.

4.5 Data Collection Instruments and Grids

The main instrument in this study was a critical thinking ability test designed to measure students' higher-order thinking skills in the context of concrete structure learning. This test was designed based on The Delphi Report framework by Facione, which includes five main indicators: analysis, inference, evaluation, explanation, and self-regulation. Each indicator is represented by two questions, so that there are a total of 10 essay questions based on construction project case studies. These questions are designed to test students' abilities in identifying technical problems, drawing logical conclusions from technical data, evaluating alternative solutions, explaining the reasons for decision making, and reflecting on their thinking processes. All questions were developed by considering the suitability of the vocational context, content validity, and the measurability of students' critical thinking competencies, as can be seen in table 1.

Table 1: Critical thinking test grid

Indicator	Description
Analysis	Identifying structural components in a project
Inference	Drawing conclusions from project technical data
Evaluation	Evaluating technical solutions in case studies
Explanation	Explaining the results of technical decisions taken
Self-Regulation	Reflecting on the problem-solving process

Adaptation from research Tang, Vezzani and Eriksson (2020) and Yaki (2022)

4.6 Instrument Validity and Reliability Test

All research instruments have undergone content validity testing which was consulted with three experts in the field of vocational education and learning evaluation. To maintain internal validity, the same procedures and criteria were applied across both experimental and control groups, while the testing environment, timing, and instructions were standardized to minimize bias and external interference. The results of the validity and reliability tests can be seen in table 2.

Table 2: Results of Statistical Validity Tests of the Critical Thinking Test

No	Critical Thinking Aspects	Number of Items	Validity Coefficient Range (r)	Validity Category
1	Analysis	2	0,61 – 0,74	High
2	Inference	2	0,65 – 0,71	High
3	Evaluation	2	0,52 – 0,68	Medium – High
4	Explanation	2	0,58 – 0,72	Medium – High
5	Self-Regulation	2	0,60 – 0,76	High

The results of the statistical validity test on the critical thinking ability test instrument show that all items across the five critical thinking indicators such as analysis, inference, evaluation, explanation, and self-regulation showed validity coefficients ranging from 0.52 to 0.76 ($p < 0.05$), indicating medium to high validity levels. Furthermore, the reliability analysis using Cronbach’s Alpha yielded a coefficient of 0.82, demonstrating strong internal consistency and stability of the measurement instrument (Elshareif and Mohamed, 2021). These findings indicate that the critical thinking test instrument has good internal consistency and is suitable for use in research.

4.7 Data Analysis Techniques

The data in this study were analysed utilising SPSS statistical software version 26. The analytical procedure was conducted in two primary phases. An Analysis of Covariance (ANCOVA) was performed to evaluate the efficacy of the Flipped Project-Based Learning model, utilising the Integration of Mmockup Media and Augmented Reality (IMM&AR) to enhance students' critical thinking skills, while controlling for pretest scores as a covariate (Patten and Newhart, 2018). Additionally, a multiple linear regression analysis was performed to assess the degree to which motivation and student perspective in learning influenced critical thinking skills postintervention (Collis, 2021). All analyses were performed at a significance threshold of α = 0.05, signifying that results are deemed statistically significant if the p-value is below 0.05.

5. Results

5.1 Descriptive Statistical Analysis

Based on the results of data collection from 216 respondents divided into experimental groups (n=108) and control groups (n=108), the following table 3 is descriptive statistics results.

Table 3: Descriptive Statistics of Pretest and Posttest Scores of Critical Thinking Ability

Group	N	Pretest			Posttest			N-Gain
		Mean	SD	Min-Max	Mean	SD	Min-Max	Mean
Experiment	108	58.42	8.76	42-75	78.63	7.14	65-92	0.49
Control	108	57.96	8.94	40-76	68.21	7.68	55-84	0.24

Table 3 indicates that the average pretest scores for the experimental group (M = 58.42, SD = 8.76) and the control group (M = 57.96, SD = 8.94) are comparable, exhibiting a negligible difference. Post-treatment, a notable disparity emerged in the average posttest scores, with the experimental group (M = 78.63, SD = 7.14) demonstrating superior performance compared to the control group (M = 68.21, SD = 7.68). The experimental group exhibited an N-Gain value of 0.49, categorising it as medium, whereas the control group recorded an N-Gain of 0.24, placing it in the low category as shown in table 4.

Table 4: Comparison of Scores Per Critical Thinking Ability Indicator

Indicator	Experimental Group		Control Group	
	Pretest (Mean)	Posttest (Mean)	Pretest (Mean)	Posttest (Mean)
Analysis	60.74	82.25	60.42	70.48
Inference	58.17	79.38	57.85	68.22
Evaluation	55.96	75.40	56.18	65.73
Explanation	59.84	80.94	58.26	69.45
Self-Regulation	57.39	75.18	57.09	67.17

Table 4 describes the comparison of scores per indicator of critical thinking skills. In the experimental group, the highest increase occurred in the Analysis indicator (21.51 points), followed by Explanation (21.10 points), while in the control group, the highest increase also occurred in the Analysis indicator (10.06 points). Overall, the experimental group that followed the Flipped Project-Based Learning model based on mockup media showed a greater increase in all indicators of critical thinking skills compared to the control group that followed conventional learning.

5.2 Significant Differences between Experimental and Control Groups

To test the effectiveness of the Flipped Project-Based Learning model based on mockup media, an analysis of covariance (ANCOVA) was conducted with the pretest score as a covariate. The results of the ANCOVA analysis are presented in the following table 5.

Table 5: Results of ANCOVA Test of Critical Thinking Ability

Source of Variation	Sum of Squares	df	Mean Square	F	Sig.	Partial η²
Corrected Model	7845.263	2	3922.632	74.518	.000	.411
Intercept	5827.418	1	5827.418	110.721	.000	.342
Pretest	1624.841	1	1624.841	30.872	.000	.127
Group	5483.726	1	5483.726	104.192	.000	.329
Error	11225.159	213	52.700			
Total	1126473.000	216				
Corrected Total	19070.422	215				

The results of the ANCOVA analysis in Table 5 show that there is a significant difference in the critical thinking ability scores between the experimental group and the control group after controlling for the influence of the pretest score, $F(1, 213) = 104.192$, $p < .001$, with an effect size (partial η^2) of 0.329 which is included in the large category. This finding confirms that the Flipped Project-Based Learning model based on mockup media is significantly more effective in improving students' critical thinking skills compared to conventional learning.

Table 6 displays the adjusted estimated marginal means of posttest results, accounting for variables (pretest). The experimental group exhibited an adjusted mean of 78.42 (SE = 0.70), whereas the control group had an adjusted mean of 68.42 (SE = 0.70), resulting in a mean difference of 10.00 points. The 95% confidence intervals for the two groups do not intersect, so reinforcing the significance of the difference between them.

Table 6: Estimated Marginal Mean Posttest Scores After Covariate Adjustment

Group	N	Adjusted Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Experiment	108	78.42	0.70	77.04	79.80
Control	108	68.42	0.70	67.04	69.80

Subsequent analysis in Table 7 indicates that all metrics of critical thinking skills have considerably improved according to the ANCOVA test results ($p < .001$), with effect size values (partial η^2) ranging from 0.227 to 0.317, categorising them as large. The indicator exhibiting the greatest mean difference is Analysis (11.74 points), succeeded by Explanation (11.19 points), whereas the smallest difference is observed in Self-Regulation (8.01 points).

Table 7: ANCOVA Test Results Per Critical Thinking Ability Indicator

Indicator	F	Sig.	Partial η^2	Mean Difference
Analysis	98.473	.000	.317	11.74
Inference	87.215	.000	.291	10.45
Evaluation	67.891	.000	.242	9.38
Explanation	92.746	.000	.303	11.19
Self-Regulation	62.518	.000	.227	8.01

The findings demonstrate that the Flipped Project-Based Learning paradigm utilising mockup media is successful in enhancing all dimensions of critical thinking, particularly in analytical and explanatory skills. These findings substantiate the research aims and address the initial inquiry concerning the disparities in critical thinking skills between students engaged in the innovative learning model and those in traditional learning settings.

5.3 The Influence of Motivation, Media Perception, and Activeness on Critical Thinking

To identify factors that influence students' critical thinking skills in the experimental group, multiple linear regression analysis was conducted with learning motivation, perception of mockup media, and student activity as predictors, the result of the analysis summarized in table 8 and 9.

Table 8: Regression Model Summary

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	.783	.613	.602	4.503

Table 9: Regression Coefficient Analysis

Variabel	B	Std. Error	Beta	t	Sig.
(Constant)	21.843	4.217		5.180	.000
Learning Motivation	.352	.088	.368	4.005	.000
Media Mockup Perception	.279	.076	.301	3.671	.000
Student Activeness	.264	.071	.287	3.718	.000

The regression model indicates that the three predictor factors collectively account for 61.3% of the variance in students' critical thinking ability scores ($R^2 = .613$). The ANOVA findings indicate a statistically significant model

(F(3, 104) = 54.687, $p < .001$), confirming the validity of the overall regression model. The regression coefficients indicate that learning motivation exerts the most significant influence ($\beta = .368$, $p < .001$), followed by the perception of simulated media ($\beta = .301$, $p < .001$), and student activity ($\beta = .287$, $p < .001$). All factors provide a favourable and significant influence on critical thinking capacity. The subsequent analysis is the effect size test, illustrated in Table 10.

Table 10: Summary of Effect Size Analysis

Analysis	Metric	Score	Interpretation
ANCOVA (Overall)	Partial η^2	.329	Big effect
Linear Regression	R^2	.613	Big effect
Analysis Indicator	Partial η^2	.317	Big effect
Inference Indicator	Partial η^2	.291	Big effect
Evaluation Indicator	Partial η^2	.242	Big effect
Explanation Indicator	Partial η^2	.303	Big effect
Self-Regulation Indicator	Partial η^2	.227	Big effect

The results of the effect size measurement show that the Flipped Project-Based Learning model based on mockup media has a major impact on improving students' critical thinking skills. The partial η^2 value for the overall critical thinking skills reached 0.329, which according to Cohen is included in the large effect category. All indicators also show effect sizes in the same category (partial $\eta^2 > 0.14$). In addition, the regression analysis shows that three predictor variables such as motivation, perception of media, and activeness simultaneously explain 61.3% of the variance in critical thinking scores ($R^2 = 0.613$), which is also quite large. These findings indicate that learning interventions are not only statistically effective but also practically meaningful in encouraging the development of high-level thinking skills of vocational high school students in the subject of concrete structures. Thus, this model is proven to be able to create a conducive learning environment for improving 21st century competencies.

6. Discussion

The substantial enhancement of critical thinking abilities in the experimental group validates the hypothesis of deep learning theory as articulated by Biggs, Students participating in the FPjBL paradigm with mockup media showed remarkable improvements in their abilities to analyze and synthesize complex technical problems as well as evaluate alternative solutions. Going by the findings of deep learning (Rahayu, Sutikno and Indriyanti, 2023;Xiong, 2024). further emphasized how learning enhancement motivates learners to be actively engaged in the learning process. Most importantly, this study's results showed that the highest gains were seen in Analysis (21.51 points) and Explanation (21.10 points) which demonstrates the students' ability to integrate intricate technical concepts instead of just superficial ones. These results indicate that the observed improvement in students' critical thinking is attributable not solely to the use of technology, but to the pedagogical integration of AR-based mockups within the FPjBL framework, which facilitated active engagement, reflection, and conceptual understanding.

This conclusion supports the findings of other studies that have noted a positive correlation between the application of the deep learning technique and the academic achievement of vocational students (Natarajan et al., 2022;Park et al., 2020). Suwarno, Wahidin and Nur (2020), as well pointed out that contextual learning helps prepare students in the construction industry from facing certain realities. The results from the ANCOVA test F (1, 213) = 104.192, $p < .001$, partial $\eta^2 = .329$ also confirm the effectiveness of the Flipped Project-Based Learning model in developing skills of higher order thinking. This model combines flipped learning and project-based learning to create a setting that encourages participation as well as the development of higher order thinking skills. This pattern of education is in agreement with research conducted by Jaedun et al. (2022) which emphasizes the role of inquiry-based learning towards the enhancement of critical and analytical skills in vocational institutions. In addition, the research conducted by Rahim et al. (2024) demonstrates that applied learning through Project-Based Learning (PjBL) not only improves technical skills, but also enhances soft skills which are highly valued in contemporary workplaces.

The regression analysis indicates that learning motivation ($\beta = .368$), perception on mockup media ($\beta = .301$), and student activeness ($\beta = .287$) have important contributions to the critical thinking skills with the $R^2 = .613$ (high category). This result validates the active and context-based learning's roles in vocational schools as

Sukatiman, Budiwan and Waluyo (2023), remarked, “mockups assist students in visualizing technical concepts and promote iterative design and exploration, encouraging reflection.” Furthermore, these findings support constructivist theory which highlights reflection and authentic experience as the basis for understanding. (Chang and Chen 2022) highlighted the fact that a constructivist perspective in vocational education enables a learner to combine previous knowledge with fresh experiential learning in a practical challenge. Overall, these findings empirically confirm that the integration of deep learning theory, IMM&AR with the application of FPJBL, and the constructivist learning approach is effective in the context of vocational education. This approach not only significantly improves critical thinking skills, but also prepares students to face the complexity of the world of work in the era of the Industrial Revolution 4.0.

The results of this study align with several investigations that highlight the efficacy of project-based learning and interactive media in vocational education. The notable enhancement in critical thinking abilities, particularly in the Analysis and Explanation metrics, corroborates the findings of Pando Cerra et al. (2020) and Sukatiman; et al. (2020), which demonstrate that the application of CAD, video, and hybrid methodologies, facilitated by visual-interactive technology, can augment the engagement and comprehension of engineering students significantly. Numerous data corroborate that mockup and simulation media enhance the visualisation of technical concepts and promote reflective inquiry-based learning (Sukatiman, Budiwan and Waluyo, 2023; Wati and Widiansyah, 2020). These results align with the findings of Ruijuan, Srikhoa and Jantharajit (2023), which demonstrate that the deep learning technique in vocational education greatly enhances academic performance and the mastery of advanced cognitive skills. This study demonstrates that motivation variables, media perceptions, and student activity significantly contribute to critical thinking skills (R^2 = .613), indicating a high level of cognitive engagement among students during the learning process (Budiarto et al., 2024).

Additionally, these findings help address the gaps in previous studies (Park et al., 2020), that did not find any association between deep learning and critical thinking skills. Here, the achievement of deep learning implementation successfully worked hand-in-hand with project-based instructional design and contextual learning media like mockups that have been shown to promote student engagement and active reflection (Omelchenko, 2022; Chang and Chen, 2022). These findings reaffirm that the improvement in critical thinking was primarily driven by the pedagogical arrangement of the FPjBL model, in which IMM&AR served as a facilitative tool to support contextual learning and engagement rather than as an independent technological intervention. This reinforces the view that the effectiveness of technology in education depends largely on how it is pedagogically integrated within constructivist and project-based learning frameworks.

Based on the results of this study, it seems that the FPjBL model based on IMM&AR could be effectively implemented in Vocational High Schools (SMK) focused on Building Model Dasar and Konstruksi dan Perumahan Teknik (TKP) as well as in Civil Engineering vocational colleges. This approach enables the seamless integration of theoretical teaching and practical exercises while ensuring that students actively participate in the learning process. To tackle the challenges posed by Industry 4.0, which demands highly skilled and deep-thinking graduates, educators in vocational institutions need to adopt a project-based approach integrated with visual, structural, and functional aids like mockups (Sukatiman, Budiwan and Waluyo, 2023;Rahim et al., 2024). This methodology is deemed pertinent to the demands of the progressively intricate, dynamic, and technology-driven professional environment (McGunagle and Zizka, 2020).

This study has several advantages, including the use of a quasi-experimental design with a large sample, the integration of pedagogical approaches and field-based media in the context of civil engineering, and robust data analysis through ANCOVA and linear regression. However, this study also has limitations, such as the limited scope of one subject (concrete structures) in two vocational schools in Solo Raya, the short duration of the intervention (4–5 meetings) so that the discussion of structures was not fully discussed, and it has not included other variables such as collaboration and communication as part of 21st century skills. Further studies with longitudinal designs are recommended to evaluate long-term impacts, as well as exploring the integration of this model with the STEAM approach, digital fabrication, or Teaching factories to address the challenges of vocational education in the industrial era 4.0.

7. Conclusion and Suggestions

This study demonstrates that the Flipped Project-Based Learning model utilising mockup media (FPjBL-IMM&AR) is effective in enhancing the critical thinking skills of vocational high school students, with notable improvements particularly in the indicators of analysis and explanation. Regression results also revealed that learning motivation, media perception, and student engagement significantly contributed to critical thinking performance. These findings validate the importance of integrating deep learning methodologies, project-based learning, and contextual technologies within vocational education. The use of AR-based mockup media has been shown to enhance visualization, engagement, and reflective reasoning, allowing students to connect abstract construction concepts with real-world applications more effectively. However, the successful implementation of such technology-assisted learning depends on adequate digital infrastructure, teacher preparedness, and students' ability to use technology meaningfully. Therefore, balanced integration between pedagogy and technology remains crucial to sustain meaningful learning outcomes and the long-term development of critical thinking skills.

It is recommended that vocational educators adopt this model to promote active learning, engagement, and employability readiness among students. Policymakers should also support capacity building through teacher training and the development of immersive learning resources to ensure sustainable implementation of technology-enhanced instruction. While this study focuses on Augmented Reality integration, future research could extend this approach by incorporating Artificial Intelligence (AI) to enable adaptive feedback, personalized learning pathways, and real-time performance analytics in vocational learning environments.

AI Statement: AI tools were used in a limited and supervised manner. QuillBot supported language refinement, and Elicit assisted in identifying relevant literature. No AI tool contributed to original ideas, analysis, or interpretation. All content was reviewed and verified to ensure academic rigor and authorship integrity.

Ethics Statement: This study complied with ethical research standards. All participants received clear information about the study and provided written informed consent prior to participation. The protocol was approved by the Health Research Ethics Committee of Dr. Moewardi General Hospital, Surakarta, Indonesia (Approval No. 2.427/XI/HREC/2025), and the research adhered to the Declaration of Helsinki.

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