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Bridging the Critical Thinking Gap: Evidence-Based Development of STEM-Based Project-Based Learning E-Modules for Vocational Education

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ABSTRACT

The rapid transformation brought by Industry 4.0 and Society 5.0 demands that vocational education graduates possess not only technical competencies but also higher-order thinking skills, particularly critical thinking. This study aims to analyse the level of vocational high school students' critical thinking skills and to use the findings as an empirical basis for developing STEM-based Project-Based Learning (STEM-PjBL) e-modules. A quantitative descriptive design was employed involving 36 tenth-grade vocational students selected through random sampling. Data were collected using an essay-based test that measured five critical-thinking indicators: interpretation, analysis, evaluation, inference, and explanation. The results revealed that students' overall critical thinking skills were at a moderate level, with strengths in interpretation and explanation, but weaknesses in analysis and inference. These findings indicate a significant gap in higher-order thinking skills, which are essential for solving real-world problems in vocational contexts. The study highlights the need for evidence-based instructional materials that specifically address these gaps. Therefore, the development of STEM-PjBL e-modules is proposed as a strategic approach to enhance students' critical thinking through interdisciplinary, problem-based, and technology-supported learning. This research contributes to providing a diagnostic foundation for designing innovative learning resources in vocational education.

Keywords: critical thinking, STEM-PjBL, vocational education

INTRODUCTION

The rapid advancement of digital technologies in the era of Industry 4.0 and the transition toward Society 5.0 have fundamentally transformed the demands placed on vocational education systems. Industry 4.0 is characterized by the integration of cyber-physical systems, artificial intelligence (AI), and data-driven decision-making processes, while Society 5.0 emphasizes a human-centered approach that leverages these technologies to address complex societal challenges [1], [2]. In this context, vocational high school graduates are no longer expected to possess only technical competencies (hard skills), but also higher-order thinking skills, particularly critical thinking, to adapt to dynamic and technology-driven work environments.

Critical thinking is widely recognized as a core competency in vocational education, essential for both immediate workplace performance and long-term adaptability. It involves purposeful, self-regulated cognitive processes such as analyzing information, evaluating arguments, and solving complex problems in a logical and systematic manner [3]. In vocational contexts, critical thinking enables students to connect theoretical knowledge with real-world applications and to respond effectively to workplace challenges. Empirical studies further highlight that critical thinking is closely linked to employability, innovation capacity, and professional decision-making in knowledge-intensive economies [4], [5], [6].

Despite its recognized importance, the level of critical thinking among students in Indonesia, particularly in vocational education, remains relatively low. International assessments such as PISA 2022 indicate that Indonesian students perform below the global average in domains closely related to critical thinking, including scientific and mathematical literacy [7]. This trend is consistent with prior research highlighting students' difficulties in analyzing problems, interpreting data, and drawing valid conclusions in academic and applied contexts. Preliminary observations conducted in vocational schools also reveal similar challenges, where students struggle to connect conceptual knowledge with real-world situations and to engage in higher-order reasoning processes.

One of the primary factors contributing to this issue is the continued dominance of teacher-centered instructional approaches, which often limit students' opportunities to actively engage in inquiry, problem-solving, and reflective thinking. Additionally, the lack of innovative instructional materials that explicitly foster critical thinking skills further exacerbates the problem. Studies have shown that without structured

opportunities to practice higher-order thinking, students tend to rely on rote learning and procedural knowledge, which are insufficient for addressing complex, real-world problems [8], [9], [10], [11].

In response to these challenges, the integration of Science, Technology, Engineering, and Mathematics (STEM) education with Project-Based Learning (PjBL) has emerged as a promising pedagogical approach. STEM education promotes interdisciplinary learning and the application of knowledge to solve authentic problems, while PjBL emphasizes experiential learning through real-world projects that foster collaboration, creativity, and critical thinking [12], [13], [14], [15], [16], [17]. The combination of these approaches, known as STEM-PjBL, creates a learning environment that is both contextual and student-centered, aligning with the goals of developing higher-order thinking skills in vocational education.

To effectively implement STEM-PjBL, there is a need for instructional materials that align with the characteristics of 21st-century learners and the demands of digital transformation. E-modules represent a viable solution, as they offer interactive, flexible, and multimedia-rich learning experiences that can support student engagement and independent learning. Moreover, the development of such e-modules should be grounded in a thorough needs analysis, particularly in identifying students' initial critical thinking abilities. Evidence-based instructional design ensures that learning materials are responsive to actual student needs and capable of addressing specific learning gaps [18], [19], [20], [21].

Based on these considerations, this study aims to (1) analyze the level of critical thinking skills among vocational high school students and (2) use the findings as an empirical foundation for the development of STEM-based Project-Based Learning (STEM-PjBL) e-modules. By adopting an evidence-based approach, this research is expected to contribute to improving the quality of vocational education and to bridging the critical thinking gap among students, thereby better preparing them for the challenges of the modern workforce.

RESEARCH METHODS

This study employed a quantitative descriptive research design to analyze vocational high school students' critical thinking skills as an empirical basis for developing STEM-based Project-Based Learning (STEM-PjBL) e-modules. The descriptive approach was selected to systematically and objectively depict students' current levels of critical thinking across multiple indicators without manipulating variables. This approach aligns with the study's primary objective of generating evidence-based data to inform instructional design, particularly in addressing identified gaps in higher-order thinking skills within vocational education contexts.

The participants of this study consisted of 36 tenth-grade students from a vocational high school, representing three different areas of specialization. The sample was selected using a random sampling technique to ensure representativeness across diverse vocational fields. Data were collected using an essay-based critical thinking test designed to measure five core indicators: interpretation, analysis, evaluation, inference, and explanation, adapted from established critical thinking frameworks (Facione, 2015). The instrument was administered in a controlled classroom setting, and students were given a fixed duration to complete the test. Each response was assessed using a structured scoring rubric to ensure consistency and reliability in evaluating students' critical thinking performance.

Data analysis was conducted using descriptive statistical techniques to determine the overall and indicator-based levels of students' critical thinking skills. Mean scores were calculated and categorized into predefined levels (very high, high, moderate, low, and very low) based on standardized criteria. In addition, a detailed analysis of each critical thinking indicator was performed to identify specific areas of weakness, particularly in analytical and inferential reasoning. The results of this analysis served as a diagnostic foundation for the subsequent development of STEM-PjBL e-modules, ensuring that the proposed instructional materials are tailored to address students' actual learning needs and critical thinking gaps.

RESULT AND DISCUSSION

1. Overall Level of Students' Critical Thinking Skills

   The results of this study indicate that the overall level of students' critical thinking skills falls within the moderate category. This finding is based on the analysis of students' performance on an essay-based test designed to measure five core indicators of critical thinking. The descriptive statistical analysis shows that although students demonstrate a basic ability to process and respond to problems, their higher-order reasoning skills remain underdeveloped. This suggests that students are able to understand information at a surface level but experience difficulties when required to engage in deeper analytical and inferential thinking processes.

   Table 1 presents the overall average score of students' critical thinking skills along with its categorical classification. The mean score of 65.4 indicates that students have not yet reached the expected level of proficiency required in vocational education, particularly in the context of 21st-century competencies. This moderate level highlights the need for instructional interventions that can enhance students' ability to think critically in complex and real-world situations.

Table 1. Overall Critical Thinking Skills Level

Variable	Mean Score	Category
Critical Thinking Skills	65.4	Moderate

The findings in Table 1 reveal that students' critical thinking skills are still below the optimal level expected in vocational education. This condition reflects a gap between educational outcomes and the competencies required in Industry 4.0 and Society 5.0 contexts. Vocational students are expected to demonstrate strong analytical and problem-solving abilities; however, the moderate score indicates that these competencies are not yet fully developed.

This result is consistent with previous studies that reported similar findings regarding the low to moderate level of critical thinking among vocational students. For instance, some previous studies found that vocational students often struggle with higher-order thinking tasks, particularly in science-related subjects [22], [23], [24], [25]. Similarly, some previous studies reports highlight that Indonesian students generally perform below the global average in areas related to reasoning and problem-solving [26], [27], [28], [29], [30]. These findings reinforce the urgency of implementing innovative instructional strategies to improve critical thinking skills in vocational education.

2. Analysis of Critical Thinking Skills Based on Indicators

A more detailed analysis was conducted to examine students' performance across five critical thinking indicators: interpretation, analysis, evaluation, inference, and explanation. The results reveal significant variations in students' abilities across these indicators, indicating that critical thinking is not uniformly developed. Some skills are relatively well-developed, while others remain weak and require targeted intervention.

Table 2. Critical Thinking Skills by Indicator

Indicator	Mean Score	Category
Interpretation	72.5	High
Analysis	58.2	Moderate
Evaluation	66.8	Moderate
Inference	55.1	Moderate
Explanation	74.3	High

Table 2 shows that students performed relatively well in interpretation and explanation, both categorized as high. This indicates that students are capable of understanding given information and expressing their ideas clearly. However, their performance in analysis, evaluation, and inference remains at a moderate level, with inference being the weakest indicator. This suggests that students face difficulties in breaking down complex problems, evaluating arguments critically, and drawing logical conclusions.

These findings highlight an imbalance in the development of critical thinking skills, where lower-order and surface-level cognitive processes are more developed than higher-order reasoning skills. This pattern is consistent with the literature indicating that students in traditional learning environments tend to excel in recall and comprehension but struggle with deeper cognitive processes [31], [32], [33], [34]. Therefore, instructional strategies must be designed to specifically target these weaker areas.

3. Weakness in Analytical and Inferential Thinking

Among the five indicators, analysis and inference emerged as the most problematic areas for students. The relatively low mean scores in these indicators indicate that students struggle to deconstruct problems into meaningful components and to generate logical conclusions based on available data. This limitation significantly affects their ability to solve complex and real-world problems, which are essential competencies in vocational education.

The weakness in analytical thinking suggests that students have difficulty identifying relationships between variables, comparing alternative solutions, and understanding underlying structures of problems. Similarly, the low performance in inference indicates challenges in predicting outcomes, formulating hypotheses, and drawing evidence-based conclusions. These skills are crucial for decision-making processes in professional settings.

Previous research supports these findings by emphasizing that analytical and inferential skills are often underdeveloped due to the lack of inquiry-based and problem-based learning experiences. According to several previous studies, students require structured exposure to authentic problem-solving situations to develop these competencies [31], [35], [36], [37]. Furthermore, several previous studies argue that traditional teaching methods rarely provide opportunities for students to engage in deep reasoning processes, resulting in limited development of higher-order thinking skills [38], [39], [40], [41].

4. Implications of Teacher-Centered Learning Practices

The moderate level of critical thinking skills observed in this study can be partly attributed to the dominance of teacher-centered instructional approaches. In such environments, students tend to play a passive role, receiving information rather than actively constructing knowledge. This limits their opportunities to engage in critical inquiry, discussion, and problem-solving activities.

Teacher-centered learning often emphasizes memorization and procedural knowledge, which are insufficient for developing higher-order thinking skills. As a result, students may perform well in tasks that require recall or basic understanding but struggle when faced with complex, open-ended problems. This aligns with findings from several previous studies, who reported that limited student

engagement in active learning environments leads to low critical thinking performance [42], [43], [44], [45], [46].

Moreover, the lack of innovative instructional materials further exacerbates this issue. Without resources that challenge students to think critically, such as problem-based tasks or interactive learning modules, students are unlikely to develop the necessary cognitive skills. Therefore, there is a strong need to shift toward student-centered learning approaches supported by appropriate instructional tools.

5. The Role of STEM-PjBL in Enhancing Critical Thinking

The integration of STEM education with Project-Based Learning (PjBL) offers a promising solution to address the identified gaps in critical thinking skills. STEM-PjBL emphasizes interdisciplinary learning and real-world problem-solving, which naturally require students to engage in analysis, evaluation, and inference. Through project-based activities, students are encouraged to explore problems, test hypotheses, and develop solutions collaboratively.

This approach aligns with the demands of Industry 4.0 and Society 5.0, where individuals are expected to apply knowledge in dynamic and complex environments. STEM-PjBL creates opportunities for students to engage in meaningful learning experiences that foster critical thinking and other 21st-century skills. According to several previous studies, project-based and active learning strategies significantly improve students' higher-order thinking abilities when implemented effectively [47], [48], [49].

Furthermore, the collaborative nature of PjBL enhances communication and teamwork skills, which are essential in vocational contexts. By working on real-world projects, students develop not only cognitive skills but also practical competencies relevant to their future careers. This makes STEM-PjBL a highly suitable approach for vocational education.

6. Implications for STEM-PjBL E-Module Development

The findings of this study provide a strong empirical foundation for the development of STEM-PjBL e-modules. The identified weaknesses in analytical and inferential thinking highlight the need for instructional materials that specifically target these skills. E-modules can be designed to include interactive activities, simulations, and problem-based tasks that promote deeper cognitive engagement.

For instance, to improve inferential skills, e-modules can include activities that require students to predict outcomes based on data trends or to formulate hypotheses. Similarly, analytical skills can be enhanced through tasks that involve comparing solutions, analyzing systems, and identifying problem components. These activities should be embedded within real-world contexts to ensure relevance and authenticity.

The use of digital platforms also allows for flexible and personalized learning experiences. Students can access materials at their own pace and engage with multimedia content that enhances understanding. According to several previous studies, technology-supported learning environments are effective in promoting critical thinking when combined with well-designed instructional strategies [50], [51], [52], [53].

7. Bridging the Critical Thinking Gap in Vocational Education

Overall, the results of this study highlight a significant gap between the current level of students' critical thinking skills and the expectations of modern vocational education. This gap is particularly evident in higher-order thinking processes such as analysis and inference. Addressing this gap requires a comprehensive approach that combines innovative pedagogy, appropriate instructional materials, and supportive learning environments.

The development of STEM-PjBL e-modules represents a strategic step toward bridging this gap. By integrating interdisciplinary learning with project-based activities and digital technologies, these modules can provide students with meaningful learning experiences that foster critical thinking. Moreover, an evidence-based approach ensures that the instructional design is aligned with students' actual needs, increasing its effectiveness.

In conclusion, this study underscores the importance of transforming vocational education to meet the demands of the digital era. By addressing the identified weaknesses in critical thinking skills and implementing innovative learning approaches, educators can better prepare students for the challenges of Industry 4.0 and Society 5.0.

CONCLUSION

This study aimed to analyze vocational high school students' critical thinking skills and to use the findings as an empirical basis for the development of STEM-based Project-Based Learning (STEM-PjBL) e-modules. The results revealed that the overall level of students' critical thinking skills falls within the moderate category, indicating that students have not yet achieved the expected level of higher-order thinking required in the context of Industry 4.0 and Society 5.0. While students demonstrated relatively strong abilities in interpretation and explanation, their performance in analysis, evaluation, and particularly inference remained limited.

The findings highlight a significant gap in higher-order cognitive skills, especially in analytical and inferential thinking, which are essential for solving complex and real-world problems. This gap is likely influenced by the dominance of teacher-centered instructional practices and the lack of innovative learning materials that actively engage students in critical inquiry and problem-solving processes. As a

result, students tend to rely on surface-level understanding rather than deep reasoning and evidence-based decision-making.

Based on these findings, this study emphasizes the importance of developing instructional materials that are grounded in students' actual learning needs. The proposed STEM-PjBL e-module offers a promising approach to bridging the identified critical thinking gap by integrating interdisciplinary learning, real-world problem-solving, and project-based activities. Such an evidence-based design ensures that the learning materials specifically target students' weaknesses, particularly in analytical and inferential skills.

In conclusion, this study contributes to the field of vocational education by providing a diagnostic foundation for the development of innovative learning resources aimed at enhancing critical thinking skills. Future research is recommended to further develop and experimentally test the effectiveness of the STEM-PjBL e-module in improving students' critical thinking abilities across different vocational contexts.

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