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An Inquiry-Creative Learning Model to Improve Students' Critical Thinking Skills in Machining Engineering Instruction

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Abstract

Vocational education in machining engineering often continues to emphasize the mastery of practical procedures, while students' critical thinking skills in analysing problems, evaluating alternatives, and making technical decisions have not been optimally developed. This study aimed to examine the effectiveness of the Inquiry-Creative Learning model in improving students' critical thinking skills and to identify the supporting and inhibiting factors in its implementation. The study employed a mixed-methods approach with an explanatory sequential design. The quantitative phase used a quasi-experimental pretest-posttest control group design involving 63 eleventh-grade students in the Machining Engineering Program, consisting of 30 students in the experimental group and 33 students in the control group. The qualitative phase involved six students from the experimental group and two mechanical engineering teachers through semi-structured interviews and observations. The test instrument measured four indicators of critical thinking, namely analysis, inference, evaluation, and decision-making. The data were analysed using descriptive statistics, gain, N-gain, ANOVA, Mann-Whitney U test, eta squared, and thematic analysis. The results showed that the mean score of the experimental group increased from 36.00 to 71.20, while that of the control group increased from 37.58 to 47.36. The N-gain score of the experimental group was 0.539, which was in the moderate category, whereas that of the control group was 0.145, which was in the low category. ANOVA showed significant differences in posttest scores ($F = 157.207$; $p < 0.001$; $\eta^2 = 0.720$), gain scores ($F = 110.140$; $p < 0.001$; $\eta^2 = 0.644$), and N-gain scores ($F = 221.174$; $p < 0.001$; $\eta^2 = 0.784$), which were further supported by the Mann-Whitney U test. The qualitative data revealed that group discussion, real problems, hands-on practice, availability of tools, and teacher readiness supported students' critical thinking, whereas limited time, low self-confidence, and student passivity served as inhibiting factors. This study concludes that Inquiry-Creative Learning is effective in improving students' critical thinking skills and has implications for vocational learning that is investigative, reflective, contextual, authentic, and collaborative.

Keywords: Inquiry-creative learning; Critical thinking; Vocational education; Machining engineering; Mixed methods

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INTRODUCTION

Modern education in the twenty-first century is widely described in many studies as being grounded in students' critical thinking skills, although its implementation in practice is not always consistent. Critical thinking is understood as reflective and open reasoning that involves the analysis and evaluation of arguments and information, enabling students not only to receive knowledge but also to weigh evidence, question assumptions, and draw accountable conclusions (Amina, 2025). In life and work contexts marked by uncertainty, this ability is considered relevant because it helps individuals make more reasonable decisions and respond to change. However, this idea becomes meaningful only when it is translated into learning practices that provide space for dialogue, testing ideas, and reflection, rather than merely adding slogans about "critical thinking" to curriculum documents.

The agenda of strengthening critical thinking does not stand alone. It is often linked to the framework of four key competencies, known as the 4Cs: critical thinking, creativity, communication, and collaboration, which have become references for various educational reforms (Thornhill-Miller et al., 2023). The argument is that graduates who can think critically, creatively, and collaboratively will be better prepared to face complex work situations. However, several reports indicate that the shift from memorization-based pedagogy to inquiry-based and collaborative pedagogy remains uneven. On the one hand, curricula emphasize problem solving and projects; on the other hand, classroom teaching practices are still dominated by routine exercises and assessments oriented toward single correct answers. This tension appears at all levels of education, including vocational education, which is often under the dual pressure of meeting technical competency certification requirements and developing soft skills such as critical thinking (Latifa et al., 2022; Jalinus et al., 2023).

Within the landscape of vocational education, the Machining Engineering Program is commonly positioned as one of the strategic fields because it is directly related to the needs of manufacturing, automotive, workshop-based, and other engineering sectors. Machining engineering students engage in various activities, including reading technical drawings, designing machining processes, operating conventional and Computer Numerical Control (CNC) machines, and analysing problems in mechanical systems. These activities do not only require procedural accuracy but also the ability to assess tolerance, safety, efficiency, and the technical consequences of every decision made. In this framework, critical thinking is not merely an "added value," but a prerequisite for ensuring that technical skills do not remain limited to mechanical routines.

Various studies in engineering and vocational education have shown that critical thinking contributes to the ability to analyse complex technical problems, synthesize information from various sources, and make more mature decisions (López et al., 2023; Mahtani et al., 2024). Learning approaches such as project-based learning and experiential learning have been reported to strengthen these skills because students are faced with real problems and are required to design and evaluate their own solutions (Pamungkas et al., 2020; Guo, 2025). However, these findings are generally conditional. Improvements in critical thinking occur when projects are genuinely designed as spaces for exploration, not merely as the execution of steps already determined by the teacher. In many contexts, machining engineering instruction still focuses on completing job sheets and achieving procedural competencies, so analytical and reflective dimensions do not always receive equal attention.

Although the urgency of critical thinking is normatively acknowledged, several empirical findings show that the critical thinking skills of vocational education students remain relatively low. Suarniati et al. (2019), for example, found that vocational high school students demonstrated limited critical thinking skills even though problem-based learning strategies had been implemented. This indicates that a surface-level change in method does not automatically change students' patterns of thinking if it is not accompanied by task design and a classroom culture that supports critical reasoning. Halim et al. (2023) reported that vocational students experienced difficulty in analysing technical problems in depth. Students tended to stop at identifying symptoms without tracing the root causes or considering alternative solutions. Tommasi et al. (2021) described a similar pattern across various vocational contexts, concluding that traditional learning practices still dominate, causing analytical and evaluative skills to develop only partially.

A systematic review by Xu et al. (2023) further noted that although cooperative learning and collaborative problem solving can improve critical thinking, many vocational students still tend to take passive positions and wait for teacher instructions. As a result, opportunities to practise argumentation and critical reasoning become limited. Putra et al. (2021) showed that vocational high school students' critical thinking skills are related to work readiness and entrepreneurship, but the measured level of these skills remains in the medium to low category. In general, these findings point to one pattern: there is a gap between the rhetoric of strengthening critical thinking and the factual conditions of classroom learning, including in machining engineering instruction.

Several studies have associated students' low critical thinking skills with learning characteristics that place insufficient emphasis on scientific creativity and inquiry. Worachak et al. (2023) showed that students who participated in problem-based and inquiry-based learning models demonstrated higher improvement in critical thinking than those who learned through conventional methods, while students who remained in lecture-based and routine exercise patterns tended to stagnate. Ernawati and Sari (2022) found that a free inquiry approach within blended learning could strengthen creativity and collaboration, both of which are important prerequisites for critical thinking. Putri et al. (2024), through a meta-analysis of argument-driven inquiry (ADI), concluded that inquiry models have the potential to improve critical thinking, although their implementation in Indonesia remains sporadic, meaning that most students do not receive sufficient exposure. Indahwati et al. (2023) emphasized that the combination of project-based learning and scientific inquiry is effective in improving critical thinking skills, but its implementation requires teacher readiness and institutional support, which are often limited.

In this context, machining engineering instruction in many vocational high schools tends to be constructed as a sequence of practicum and workshop steps that must be followed accurately, but not always accompanied by the "why" and "what if" questions that encourage exploration. Students may become proficient in operating lathes or milling machines according to standard operating procedures, but they are not always accustomed to questioning the rationale behind cutting parameters, considering alternative processes, or evaluating the consequences of design choices for quality and efficiency. The lack of emphasis on scientific creativity makes practical activities resemble the reproduction of established techniques rather than an arena for testing ideas and developing critical thinking. The issue, therefore, is not practice as an activity, but the pedagogical orientation that accompanies the practice.

Inquiry-based learning models are often proposed as approaches that are more aligned with the goal of developing critical thinking, because they encourage students to formulate questions, develop hypotheses, collect and analyse data, and draw conclusions reflectively. Several studies have shown that inquiry-based learning can stimulate students to move beyond memorizing facts and enter the domains of analysis and evaluation (Hasanah, 2023; Ramli et al., 2023). Harjono et al. (2025) and Wahyudi et al. (2019) emphasized that an emphasis on scientific creativity within an inquiry framework creates opportunities for students to generate ideas, try alternative procedures, and review their work, all of which are related to critical thinking. However, the literature also warns that these positive effects do not occur automatically. The success of inquiry models depends greatly on the quality of task design, teacher scaffolding, and a classroom culture that tolerates mistakes and experimentation.

The integration of technology and approaches such as Science, Technology, Engineering, and Mathematics (STEM) and Science, Technology, Engineering, Arts, and Mathematics (STEAM) within an inquiry framework also shows additional potential. Alkhabra et al. (2023) reported that the use of augmented reality technology in inquiry-based learning can improve learning retention and critical thinking, while Adesope et al. (2015) and Soomro et al. (2025) showed that active learning strategies and inquiry-based science teaching have positive effects on the development of higher-order thinking skills. However, most of these studies have focused on general science or STEM contexts rather than specifically on vocational machining engineering education. In addition, the terms and models used vary considerably, so there is still no framework that explicitly integrates inquiry with scientific creativity in a directed instructional design for workshop or machine-practice contexts.

In this context, the idea of Inquiry-Creative Learning becomes relevant. Conceptually, Inquiry-Creative Learning can be understood as a learning model that combines inquiry steps, including problem formulation, hypothesis development, data collection and analysis, and conclusion drawing, with activities that explicitly require and facilitate students' technical creativity. These activities may include providing space for students to design variations in machining processes, compare several alternative machine settings, or develop new solutions to surface quality problems. Based on the literature review, inquiry approaches and scientific creativity have been widely discussed separately, but Inquiry-Creative Learning as an explicit framework appears not to have been systematically implemented in vocational education, particularly in machining engineering instruction. This is the research gap that needs to be examined further: whether the combination of inquiry and creativity can truly address the weaknesses in critical thinking that have been reported in various vocational studies.

This study aims to implement the Inquiry-Creative Learning model in machining engineering instruction and examine its contribution to students' critical thinking skills. Specifically, this study seeks to answer the following two research questions.

1. How effective is the Inquiry-Creative Learning model in improving students' critical thinking skills in machining engineering instruction?
2. What are the supporting and inhibiting factors in improving students' critical thinking skills in machining engineering instruction within the implementation of the Inquiry-Creative Learning model?

LITERATURE REVIEW

Machining Engineering Instruction in Vocational Education

Machining engineering instruction lies at the heart of vocational education because it is directly related to production processes in various industrial sectors, ranging from manufacturing and automotive industries to the maintenance of mechanical systems. In vocational high schools and vocational education in general, machining engineering does not only require the mastery of technical skills such as operating lathes, milling machines, grinding machines, or Computer Numerical Control (CNC) machines. It also requires the ability to read technical drawings, understand tolerances, and manage occupational safety procedures. In the context of the twenty-first century, a graduate profile that is limited to the ability to operate machines is no longer sufficient, because industry demands workers who can analyse problems, assess alternative solutions, and make responsible decisions. This condition requires machining engineering instruction to move beyond procedural training toward learning experiences that provide space for more complex and contextual problem solving.

Various studies in vocational education emphasize that work-ready graduates need to possess a combination of technical skills, or hard skills, and higher-order thinking skills, including critical thinking and collaborative abilities (Latifa et al., 2022; Jalinus et al., 2023). Mutohhari et al. (2021) argued that when vocational curricula focus too heavily on the mastery of technical procedures without developing critical thinking skills, graduates may find it difficult to adapt to technological changes and changing work procedures in industry. Studies by Efendi et al. (2020) and Ulaini and Fitrisia (2025) showed that project-based learning can improve collaboration and student engagement while providing broader opportunities to practise analytical and problem-solving skills. In the context of machining engineering, such approaches are often implemented through projects involving component production, system repair, or the optimization of machining processes.

Specifically in mechanical engineering, several studies have shown that critical thinking is a key component in technical problem solving. López et al. (2023) and Mahtani et al. (2024) emphasized that students' success in completing engineering tasks is closely related to their ability to analyse situations, integrate information, and consider the implications of design choices. Pamungkas et al. (2020) highlighted the role of experiential learning in engineering education, in which students are exposed to real problems in workshops or laboratories, so that they do not merely imitate procedures but also reason about the logic behind them. Approaches that integrate creativity and design thinking in engineering courses have also been reported to strengthen students' analytical and reflective abilities (Anand et al., 2024), for example when students are asked to compare different jig designs, fixtures, or cutting parameters to achieve quality and efficiency.

On the other hand, the shift in industrial orientation toward a combination of technical competence and cognitive flexibility has made the criteria for vocational graduate success more complex. Pradana and Sundawa (2023) and Sonal et al. (2024) showed that employers now assess graduates not only based on their technical skills, but also on their ability to communicate, work in teams, and make rational decisions under pressure. However, several studies indicate that the critical thinking skills of vocational students, including those in mechanical engineering programs, remain relatively low. Suarniati et al. (2019), Halim et al. (2023), Tommasi et al. (2021), and Putra et al. (2021) indicated that many students still depend on teacher instructions and are not sufficiently accustomed to questioning the reasons behind procedures, testing alternatives, or reflecting on the technical and safety consequences of their decisions. This condition suggests that machining engineering instruction still needs to be designed more explicitly to develop critical thinking skills, rather than merely teaching "how to operate machines" in a narrow sense.

Critical Thinking Skills

Critical thinking is generally defined as reflective and open reasoning that involves analysis and evaluation, enabling individuals to carefully assess arguments and information before accepting or rejecting them (Amina, 2025). This definition is consistent with Robert Ennis' classical view, which describes critical thinking as "reasonable reflective thinking focused on deciding what to believe or do" (Ennis, 2018). Ennis (2015) emphasized that critical thinking consists of two interrelated components, namely abilities and dispositions. Abilities refer to cognitive skills such as analysing arguments, identifying assumptions, drawing logical conclusions, evaluating evidence, and making reasoned decisions. Dispositions refer to the tendency or willingness to actually use these abilities in real situations, such as the willingness to think openly, be careful in making judgments, and take responsibility for decisions.

The literature shows that without adequate dispositions, critical thinking abilities tend not to be used consistently. Abrami et al. (2008), Aizikovitsh-Udi and Cheng (2015), and Kinoshita (2022) argued that education which only emphasizes analytical exercises without fostering attitudes such as curiosity, intellectual perseverance, and openness to new evidence risks producing students who are technically "able" but not accustomed to being critical in practice. Conversely, developing dispositions without equipping students with adequate cognitive skills is also problematic, because it may encourage questioning without the ability to examine arguments systematically. Therefore, the development of critical thinking abilities and dispositions needs to be positioned as a dual goal that works simultaneously. In the context of vocational and technical education, this balance is relevant when students are expected not only to follow work instructions but also to critically examine procedures that may be unsafe or inefficient.

In this study, critical thinking skills are operationalized by referring to the indicators formulated by Prayogi et al. (2018), namely analysis, inference, evaluation, and decision-making. Analysis refers to the ability to break down a problem or situation into smaller components, identify relationships among those components, and recognize relevant and irrelevant information. In machining engineering instruction, this indicator is reflected when students are able to examine possible causes of surface defects, dimensional errors, or cutting tool damage by analysing cutting parameters, machine conditions, and workpiece materials.

Inference relates to the ability to draw logical conclusions based on available data or information, for example when students infer possible causes of excessive vibration from measurement data and workshop observations.

Evaluation involves assessing the credibility of information sources, the strength of arguments, and the quality of evidence. In the context of machining engineering, this may involve critically assessing work procedures, measurement results, or particular technical recommendations. Decision-making refers to the ability to choose the most feasible course of action based on analysis, inference, and evaluation, while also considering risk, occupational safety, and efficiency. This indicator is relevant when students must determine machining parameters, select cutting tools, or decide whether a process should be stopped because of potential hazards. However, strengthening these four indicators does not happen automatically simply by adding the term “critical thinking” to curriculum documents. Empirical evidence shows that vocational students often still have low levels of critical thinking (Suarniati et al., 2019; Halim et al., 2023; Tommasi et al., 2021; Putra et al., 2021), partly because learning is still dominated by lectures, one-way demonstrations, and routine exercises that rarely challenge students to analyse, infer, evaluate, and make decisions independently.

In this context, the call for twenty-first-century education to shift its focus from memorization toward the development of the “4Cs”, namely critical thinking, creativity, communication, and collaboration, becomes relevant (Thornhill-Miller et al., 2023). Education systems, including vocational education, are encouraged to provide space for inquiry-based, collaborative, and creative learning so that critical thinking is not merely taught as a concept, but practised in daily learning activities (Latifa et al., 2022; Jalinus et al., 2023; Mutohhari et al., 2021). This is where various active learning models, such as problem-based learning, project-based learning, and inquiry-based learning, are positioned as alternatives to traditional teaching. The question, then, is not only whether critical thinking is important, but what kinds of learning models and conditions can truly develop students’ analysis, inference, evaluation, and decision-making in machining engineering practice.

Inquiry-Creative Learning Model

The Inquiry-Creative Learning model in this study refers to the instructional design developed by Wahyudi et al. (2018, 2019) to integrate scientific inquiry activities with scientific creativity. This model is explicitly designed to train students’ critical thinking skills through a series of activities that require exploration, testing, and reflection. Inquiry-Creative Learning does not stop at the use of standard inquiry steps, but emphasizes creativity at every stage of the learning process. Students are trained to be creative in finding problems, formulating hypotheses, designing experiments, solving problems, and producing scientific products (Wahyudi et al., 2018, 2019; Verawati et al., 2020). This approach is consistent with general findings on the effectiveness of inquiry-based learning in promoting deeper cognitive engagement and improving critical thinking skills (Hasanah, 2023; Ramli et al., 2023; Soomro et al., 2025), but it gives additional emphasis to the dimension of scientific creativity.

Operationally, the Inquiry-Creative Learning model consists of five main phases. The first phase is problem preparation and identification, or problem finding, in which students are invited to observe phenomena or systems and identify problems worthy of investigation, rather than simply receiving problems already prepared by the teacher. In the context of machining engineering, this may involve observing variations in the surface quality of turning results, cutting tool wear, or dimensional inaccuracies in components, and then formulating relevant problems to be studied. The second phase, formulating hypotheses or creating hypotheses, requires students to develop several hypotheses that explain the causes of a problem logically and conceptually, while remaining open to alternative explanations. Creativity appears when students do not simply repeat the “most common” explanation, but consider various technical factors that may contribute to the problem.

The third phase is creatively experiment designing, in which students design experiments or problem-solving procedures creatively. In a machining workshop, this may involve developing variations in cutting parameters, testing several types of cutting tools, or designing different measurement procedures to test hypotheses. The fourth phase, science creatively problem solving, emphasizes the implementation of experiments and the critical interpretation of data. Students are expected not merely to collect data, but also to interpret emerging patterns, compare them with their initial hypotheses, and provide rational explanations for results that may not match their first assumptions. The fifth phase, creatively product design, focuses on developing scientific or technical products based on the findings, such as recommendations for machining parameters, safer work procedures, or simple assistive tool prototypes. This stage provides space for students to express creativity in the form of concrete solutions while also testing the consistency of their reasoning.

The literature examining inquiry-based and creativity-oriented learning provides a theoretical basis for the claim that such an approach has the potential to improve critical thinking. Harjono et al. (2025) and Wahyudi et al. (2019) showed that inquiry integrated with scientific creativity encourages students to move beyond memorizing facts toward idea exploration and more reflective problem solving. Ernawati and Sari (2022) found that a free inquiry approach in a blended learning setting could improve creativity and collaboration, both of which are closely related to the development of critical thinking. Putri et al. (2024), through a meta-analysis, showed that argument-driven inquiry (ADI) contributes to the improvement of critical thinking, although students' levels of critical thinking in many Indonesian educational contexts remain relatively low. Indahwati et al. (2023) and Worachak et al. (2023) emphasized that strategies combining inquiry with PjBL or PBL tend to produce more consistent improvement in analytical and problem-solving abilities.

Several studies also show that the integration of technology in inquiry settings can enrich learning experiences. Alkhabra et al. (2023) demonstrated that the use of augmented reality within an inquiry-based STEAM learning framework can improve learning retention and critical thinking. Findings by Adesope et al. (2015) also indicate that inquiry-based active learning strategies encourage students to build internal connections among concepts and engage in higher-order thinking. However, these findings do not automatically guarantee the success of every implementation of the Inquiry-Creative Learning model. Its success depends strongly on the quality of task design, teacher support, and a classroom culture that allows students to try, fail, and revise their ideas.

In the context of vocational education, particularly machining engineering, the literature explicitly reporting the implementation of the Inquiry-Creative Learning model remains very limited. Many studies on vocational education discuss the effectiveness of inquiry-based or project-based learning in improving critical thinking, but few have examined the systematic integration of inquiry phases and scientific creativity as formulated by Wahyudi et al. (2018, 2019). This gap provides space to examine whether the five phases of Inquiry-Creative Learning, namely problem finding, creating hypotheses, creatively experiment designing, science creatively problem solving, and creatively product design, can be realistically operationalized in machining workshops while contributing meaningfully to the improvement of students' analysis, inference, evaluation, and decision-making skills. This study is based on the assumption that such potential exists, but its effectiveness as well as the supporting and inhibiting factors still need to be empirically examined in the context of vocational machining engineering education.

METHOD

Research Design

This study employed a mixed-methods approach with an explanatory sequential design, in which the quantitative phase was conducted first, followed by the qualitative phase (Creswell

& Creswell, 2018). The quantitative phase was used to examine the effectiveness of the Inquiry-Creative Learning model in improving students' critical thinking skills in machining engineering instruction. The qualitative phase was used to further explain the quantitative findings, particularly in relation to students' and teachers' experiences during model implementation, as well as the supporting and inhibiting factors affecting the improvement of critical thinking skills.

In the quantitative phase, this study used a quasi-experimental design with a pretest-posttest control group design. This design was selected because the experimental and control groups were drawn from existing classes, or intact classes, so individual random assignment to treatment groups was not conducted. One class was assigned as the experimental group and received instruction using the Inquiry-Creative Learning model, while another class was assigned as the control group and received expository instruction. The research design is presented in Table 1.

Table 1. Research design

Group	Pretest	Treatment	Posttest
Experimental	O_1	Inquiry-Creative Learning model	O_2
Control	O_1	Expository instruction	O_2

Both groups were first given a pretest to determine their initial critical thinking skills. After that, the experimental group participated in learning using the Inquiry-Creative Learning model, while the control group participated in expository instruction commonly used in machining engineering learning. At the end of the learning process, both groups were given a posttest to determine changes in critical thinking skills. The pretest and posttest results were then analysed using gain and N-gain scores to compare the improvement of critical thinking skills in the two groups.

After the quantitative phase was completed, the qualitative phase was conducted through semi-structured interviews with students and teachers in the experimental group. The qualitative data were used to explain the quantitative findings, particularly how the phases of Inquiry-Creative Learning encouraged or hindered the development of students' critical thinking skills in machining engineering instruction.

Participants

The quantitative participants in this study were eleventh-grade students in the Machining Engineering Program at SMK Negeri 1 Pringgabaya. A total of 63 students were involved, consisting of 30 students in the experimental group and 33 students in the control group. The students were between 15 and 16 years old. Based on participant data, the gender composition consisted of 62 male students and 1 female student. The experimental group participated in learning using the Inquiry-Creative Learning model, while the control group received expository instruction.

The qualitative participants consisted of six students from the experimental group and two mechanical engineering teachers involved as the teaching team. The six students were selected purposively based on variations in relative improvement and participation during learning, namely students with high relative improvement, moderate relative improvement, and low relative improvement. The profile of the research participants is presented in Table 2.

Table 2. Profile of research participants

Participant	Number	Age	Program/Role	Gender	Description
Experimental-group students	30	15-16 years	Vocational high school students, Machining Engineering.	30 male students	Participated in Inquiry-Creative Learning.

Participant	Number	Age	Program/Role	Gender	Description
Control-group students	33	15-16 years	Vocational high school students, Machining Engineering.	32 male students, 1 female student.	Participated in expository instruction.
Mechanical engineering teachers	2	30-35 years	Mechanical engineering teachers/teaching team.	1 male, 1 female	More than five years of teaching experience.
Student interview informants	6	15-16 years	Experimental-group students.	Adjusted to selected participants	Selected based on variations in relative improvement and participation.

Model Implementation Procedure

The implementation procedure of the model in the experimental group began with a planning stage involving the mechanical engineering teachers as the teaching team. At this stage, the researchers and teachers prepared teaching modules, learning scenarios, student worksheets, and practical activities that integrated the syntax of the Inquiry-Creative Learning model with the machining engineering competencies being studied. The syntax of the model referred to five main phases: problem preparation and identification or problem finding, formulating hypotheses or creating hypotheses, creatively experiment designing, science creatively problem solving, and creatively product design.

Before the treatment was administered, students in both the experimental and control groups took a critical thinking skills pretest. The pretest was used to identify students' initial abilities in analysis, inference, evaluation, and decision-making. After that, learning was conducted according to the treatment assigned to each group.

In the experimental group, learning was implemented through the five phases of Inquiry-Creative Learning. In the problem finding phase, students were guided to identify authentic problems relevant to machining engineering practice, such as the quality of turning results, efficiency in tool use, dimensional accuracy, or occupational safety. In the creating hypotheses phase, students developed preliminary assumptions or possible technical solutions based on data, observation, and group discussion. In the creatively experiment designing phase, students designed work steps or experimental procedures in the workshop, including considerations of process parameters, tools, materials, and work sequence. In the science creatively problem solving phase, students carried out the procedures, observed the results, analysed errors, improved the work steps, and discussed solutions. In the creatively product design phase, students prepared a final product, report, or work procedure recommendation that reflected their critical and creative reasoning.

In the control group, learning was conducted through expository instruction. The teacher explained concepts and demonstrated work procedures, after which students followed relatively structured exercises or practice activities. The materials, learning outcomes, and time allocation were made as equivalent as possible to those in the experimental group, so that differences in learning outcomes could be more closely associated with differences in the instructional model used. After the entire sequence of learning activities was completed, both groups took a critical thinking skills posttest.

Data Collection and Instruments

Quantitative data were collected through a critical thinking skills test administered as a pretest and posttest to both the experimental and control groups. The test instrument was developed based on four indicators of critical thinking skills adapted from Prayogi et al. (2018), namely analysis, inference, evaluation, and decision-making. The analysis indicator measured students' ability to break down technical problems and identify relevant information. The inference indicator measured students' ability to draw conclusions or develop assumptions based on data. The evaluation indicator measured students' ability to assess the feasibility of procedures, arguments, or solutions. The decision-making indicator measured students' ability to determine alternative actions based on technical considerations.

The test items were contextualized within machining engineering learning situations, such as analysing the causes of product defects, interpreting measurement data, evaluating work procedures, and selecting process parameters. The instrument was reviewed through expert judgment to assess content suitability, language clarity, and the representation of critical thinking indicators. The maximum score used in calculating the results was 100.

Qualitative data were collected after the quantitative phase had been completed. The main technique used was semi-structured interviews with six students from the experimental group and two mechanical engineering teachers. Student interviews focused on their experiences during the five phases of Inquiry-Creative Learning, including situations in which they felt supported or encountered difficulties in analysing problems, formulating hypotheses, designing procedures, evaluating results, and making decisions. Teacher interviews focused on learning readiness, model implementation, changes in students' learning behaviour, and supporting and inhibiting factors during model implementation. In addition to interviews, qualitative data were also strengthened through classroom and workshop observations during the learning process.

Data Analysis

Quantitative data analysis was conducted in stages. First, pretest and posttest data were analysed descriptively by calculating the mean, standard deviation, minimum score, and maximum score for the experimental and control groups. Second, score improvement was calculated using gain and N-gain. Gain was calculated as the difference between posttest and pretest scores, while N-gain was calculated using the following formula:

$$\textit{N-gain} = (\textit{posttest} - \textit{pretest}) / (\textit{maximum score} - \textit{pretest})$$

The N-gain category was classified into three levels: high if N-gain ≥ 0.70, moderate if $0.30 \leq$ N-gain < 0.70, and low if N-gain < 0.30.

Third, assumption tests were conducted. The normality test was conducted using the Shapiro-Wilk test because the sample size in each group was less than 50. The homogeneity of variance test was conducted using Levene's test. Fourth, a one-way ANOVA was conducted to examine differences in pretest, posttest, gain, and N-gain scores between the experimental and control groups. The effect size was calculated using eta squared to determine the magnitude of the contribution of group differences to the variation in outcomes. Because the normality test results showed that most of the data were not normally distributed, the Mann-Whitney U test was used as a nonparametric comparison analysis. Thus, the interpretation of quantitative results was based on descriptive statistics, N-gain, ANOVA, effect size, and the Mann-Whitney U test.

Qualitative data were analysed using thematic analysis. Interview and observation data were read repeatedly to identify units of meaning related to students' and teachers' experiences during the implementation of Inquiry-Creative Learning. These meaning units were then coded and grouped into themes, such as students' experiences in the problem finding phase, hypothesis formulation, experiment design, problem solving, product design, supporting factors, and inhibiting factors. These themes were then interpreted to explain how the Inquiry-Creative Learning model contributed to students' analysis, inference, evaluation, and decision-making skills.

The integration of quantitative and qualitative data was conducted at the interpretation stage. Quantitative findings were used to show whether students' critical thinking skills improved, while qualitative data were used to explain the processes and conditions that supported or hindered this improvement. In this way, the study's conclusions were based not only on score differences, but also on a contextual understanding of model implementation in the classroom and machining engineering workshop.

Research Ethics Approval

This study was conducted after obtaining permission from Universitas Pendidikan Mandalika as the researchers' institution and from SMK Negeri 1 Pringgabaya as the research site. Before data collection, the school, teachers, and students were informed about the objectives of the study, the types of data collected, the learning activities conducted, and the use of data for academic purposes. Student participation was voluntary, and the identities of all participants were protected through the use of codes or pseudonyms. Test, interview, and observation data were used only for research analysis and reporting.

RESULTS

Quantitative Data

Quantitative analysis was conducted to determine the improvement in students' critical thinking skills after the implementation of the Inquiry-Creative Learning model in the experimental group and expository instruction in the control group. The analysed data included pretest, posttest, gain, and N-gain scores. The experimental group consisted of 30 students, while the control group consisted of 33 students. N-gain was calculated using the formula: (posttest - pretest) / (maximum score - pretest), with a maximum score of 100 as used in the research data tabulation.

Table 3 presents the descriptive statistics of students' critical thinking skills scores in the experimental and control groups, both in the pretest and posttest.

Table 3. Descriptive statistics of students' critical thinking skills scores

Group	N	Pretest Mean ± SD	Min-Max	Posttest Mean ± SD	Min-Max
Experimental	30	36.00 ± 11.47	20-52	71.20 ± 5.52	60-80
Control	33	37.58 ± 13.23	20-60	47.36 ± 8.98	30-62

As shown in Table 3, the mean pretest score of the experimental group was 36.00, while that of the control group was 37.58. The difference between the mean pretest scores of the two groups was relatively small, indicating that students' initial critical thinking skills in both groups could be regarded as nearly comparable. After the treatment, the mean posttest score of the experimental group increased to 71.20, while that of the control group increased to 47.36. This difference in improvement patterns indicates that the experimental group experienced a greater score change than the control group.

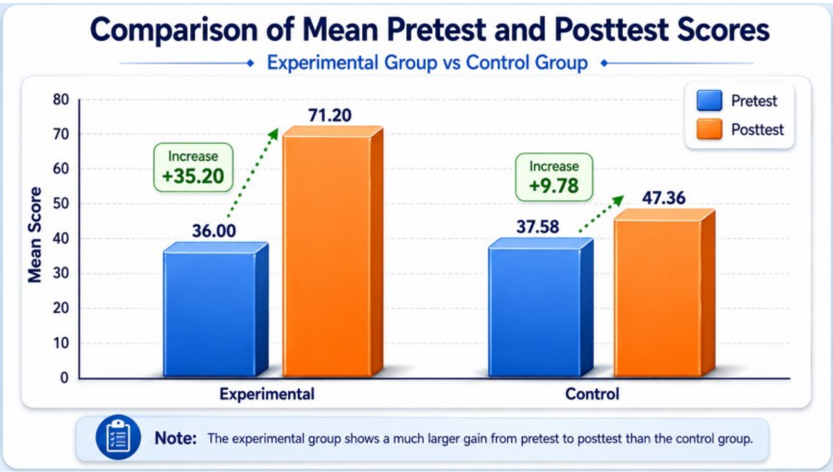

Figure 1. Comparison of mean scores between the experimental and control groups

Figure 1 visualizes the comparison of mean pretest and posttest scores in the experimental and control groups. Based on Figure 1, both groups showed improvement from pretest to posttest, but the increase in the experimental group was much sharper than that in the control group. The experimental group increased from 36.00 to 71.20, while the control group increased from 37.58 to 47.36. Descriptively, this visualization reinforces the findings in Table 3 that the implementation of the Inquiry-Creative Learning model was associated with a greater increase in critical thinking skills scores than expository instruction.

Table 4 presents the gain and N-gain calculations of students' critical thinking skills in both groups.

Table 4. Gain and N-gain results of critical thinking skills

Group	N	Gain M ± SD	N-gain Mean ± SD	Category
Experimental	30	35.20 ± 11.63	0.539 ± 0.116	Moderate
Control	33	9.79 ± 7.28	0.145 ± 0.094	Low

As shown in Table 4, the mean gain score of the experimental group was 35.20, while that of the control group was 9.79. In terms of N-gain, the experimental group obtained a mean score of 0.539, which was in the moderate category, while the control group obtained a mean score of 0.145, which was in the low category. Thus, the improvement in critical thinking skills in the experimental group was higher not only in raw score form but also when calculated as the proportion of improvement relative to the maximum score.

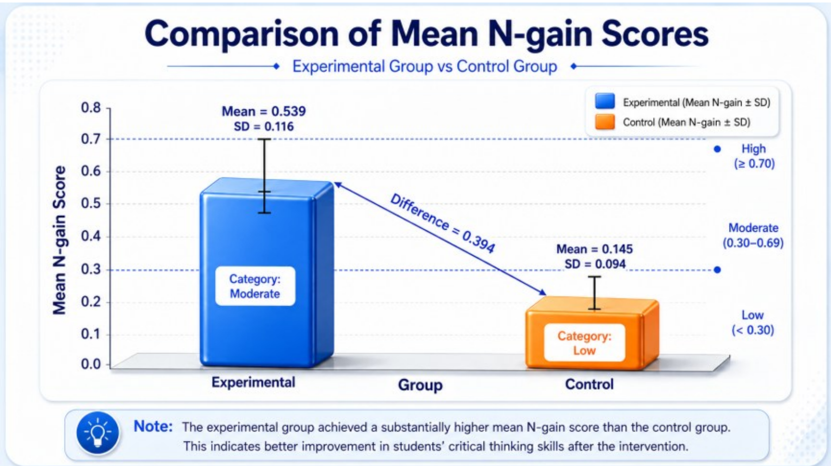

Figure 2. Comparison of mean N-gain scores between the experimental and control groups

Figure 2 presents the comparison of mean N-gain scores between the experimental and control groups, including standard deviations, N-gain categories, and the threshold lines for low, moderate, and high categories.

Based on Figure 2, the experimental group obtained an N-gain of 0.539 with a standard deviation of 0.116, while the control group obtained an N-gain of 0.145 with a standard deviation of 0.094. The difference in mean N-gain scores was 0.394, indicating that the improvement in critical thinking skills in the experimental group was greater than that in the control group. This visualization also shows that the experimental group was in the moderate category, while the control group was in the low category.

Table 5 presents the distribution of students' N-gain categories in the experimental and control groups. The categories used were low, moderate, and high, based on the N-gain criteria established in the research data tabulation.

Table 5. Distribution of students' N-gain categories

Group	Low	Moderate	High
Experimental	1 student or 3.33%	29 students or 96.67%	0 students or 0.00%
Control	31 students or 93.94%	2 students or 6.06%	0 students or 0.00%

As shown in Table 5, most students in the experimental group were in the moderate N-gain category, namely 29 students or 96.67%. In contrast, most students in the control group were in the low N-gain category, namely 31 students or 93.94%. No students in either group reached the high N-gain category. This finding indicates that improvement in the experimental group was relatively even among most students, while improvement in the control group remained limited.

Table 6 presents the results of the Shapiro-Wilk normality test for pretest, posttest, gain, and N-gain scores in the experimental and control groups. This test was conducted to determine whether the data met the assumption of normal distribution before difference testing was performed.

Table 6. Results of the Shapiro-Wilk normality test

Variable	Group	Shapiro-Wilk	Sig.	Description
Pretest	Experimental	0.834	< 0.001	Not normal
	Control	0.881	0.002	Not normal
Posttest	Experimental	0.917	0.022	Not normal
	Control	0.904	0.007	Not normal
Gain	Experimental	0.966	0.440	Normal
	Control	0.914	0.013	Not normal
N-gain	Experimental	0.885	0.004	Not normal
	Control	0.929	0.034	Not normal

As shown in Table 6, most of the data were not normally distributed because the significance values were less than 0.05. Only the gain data in the experimental group met the normality assumption. Therefore, the results of parametric tests needed to be interpreted cautiously and strengthened with nonparametric tests as a comparison.

Table 7 presents the results of the homogeneity of variance test using Levene's test for pretest, posttest, gain, and N-gain scores. This test was used to determine whether the data variance in the experimental and control groups was homogeneous.

Table 7. Results of Levene's homogeneity of variance test

Variable	Levene Statistic	Sig.	Description
Pretest	2.171	0.146	Homogeneous
Posttest	14.294	< 0.001	Not homogeneous
Gain	6.792	0.011	Not homogeneous
N-gain	0.065	0.799	Homogeneous

As shown in Table 7, the variances of pretest and N-gain scores were homogeneous because the significance values were greater than 0.05. In contrast, the variances of posttest and gain scores were not homogeneous. Because N-gain is a measure of improvement that takes students' initial scores into account, the homogeneity result for N-gain provides a relevant basis for comparing the improvement in critical thinking skills between the experimental and control groups.

Table 8 presents the results of the one-way ANOVA used to determine differences in pretest, posttest, gain, and N-gain scores between the experimental and control groups. This test was used to examine whether the differences between the groups were statistically significant.

Table 8. Results of one-way ANOVA

Variable	F	Sig.	Eta squared	Interpretation
Pretest	0.253	0.617	0.004	Not significantly different
Posttest	157.207	< 0.001	0.720	Significantly different
Gain	110.140	< 0.001	0.644	Significantly different
N-gain	221.174	< 0.001	0.784	Significantly different

As shown in Table 8, the pretest scores of the experimental and control groups were not significantly different, with F = 0.253 and Sig. = 0.617. This indicates that students' initial critical thinking skills in both groups were relatively equivalent before the treatment. After the treatment, significant differences were found in posttest, gain, and N-gain scores. The difference in N-gain showed F = 221.174, Sig. < 0.001, and eta squared = 0.784. This eta squared value indicates that group differences explained a large proportion of the variance in N-gain improvement in the analytical model used.

Table 9 presents the results of the Mann-Whitney U test as a comparison analysis because the normality test results in Table 6 showed that most of the data were not normally distributed. The U value in this table is presented as the smaller U value of the two possible U statistics.

Table 9. Results of the Mann-Whitney U test as a comparison analysis

Variable	Mann-Whitney U	Sig.	Interpretation
Pretest	444.500	0.484	Not significantly different
Posttest	7.000	< 0.001	Significantly different
Gain	33.000	< 0.001	Significantly different
N-gain	13.000	< 0.001	Significantly different

As shown in Table 9, the pretest scores of the two groups were not significantly different, while the posttest, gain, and N-gain scores were significantly different. The Mann-Whitney U test results strengthen the ANOVA results in Table 8, indicating that the improvement in students' critical thinking skills in the experimental group was higher than that in the control group.

Based on the overall quantitative analysis, the Inquiry-Creative Learning model can be considered effective in improving students' critical thinking skills in machining engineering instruction. This effectiveness is reflected in three main findings. First, the mean posttest score of the experimental group was much higher than that of the control group. Second, the mean gain and N-gain scores of the experimental group were greater than those of the control group. Third, the ANOVA and Mann-Whitney U test results showed significant differences in improvement between the two groups. These quantitative findings provide the basis for further analysis through qualitative data, particularly to explain how the phases of problem finding, hypothesis formulation, experiment design, problem solving, and product design in the Inquiry-Creative Learning model contributed to the development of students' critical thinking skills.

Qualitative Data

Qualitative data analysis was conducted to further explain the quantitative findings regarding the improvement of students' critical thinking skills after the implementation of the Inquiry-Creative Learning model. Qualitative data were obtained through student interviews, teacher interviews, and classroom/workshop observations. The analysis focused on students' experiences in each phase of the learning model, changes in critical thinking behaviour observed during learning, and the supporting and inhibiting factors in model implementation. The qualitative informants in this study are presented in Table 10.

Table 10. Qualitative interview informants

Informant code	Status	Group/Role	Selection criteria	Description
S-High Relative-01	Student	Experimental	High relative improvement/active	Very active in discussion and able to explain concepts well.
S-High Relative-02	Student	Experimental	High relative improvement/active	Quickly understood the material and was active in group work.
S-Moderate Relative-01	Student	Experimental	Moderate improvement/ moderate participation	Showed fairly good participation but still needed guidance.

Informant code	Status	Group/Role	Selection criteria	Description
S-Moderate Relative-02	Student	Experimental	Moderate improvement/ moderate participation	Active in several learning sessions.
S-Low Relative-01	Student	Experimental	Low improvement/ experienced difficulties	Experienced difficulty understanding certain concepts.
S-Low Relative-02	Student	Experimental	Low improvement/ experienced difficulties	Had low self-confidence and needed further guidance.
G-01	Teacher	Teaching team	Mechanical engineering teacher	Provided information related to the learning process and model implementation.
G-02	Teacher	Teaching team	Mechanical engineering teacher	Provided evaluation of student engagement during learning.

As shown in Table 10, the qualitative informants consisted of six students from the experimental group and two mechanical engineering teachers involved in the teaching team. Students were selected purposively by considering variations in learning improvement and participation levels during learning. With this composition, the qualitative data did not only describe the experiences of active students who achieved high relative improvement, but also included students who still experienced difficulties in participating in Inquiry-Creative Learning activities.

Table 11 presents the results of student interviews based on the main phases of the Inquiry-Creative Learning model. Each phase is linked to the critical thinking indicators (CTI) that emerged during learning, namely analysis, inference, evaluation, and decision-making.

Table 11. Results of student interviews based on the phases of Inquiry-Creative Learning

Learning phase	Student response excerpt	Meaning of findings	Observed CTI
- Problem finding	"I felt challenged by the problems presented by the teacher during learning."	Students were encouraged to pay attention to the technical problems presented by the teacher and began to identify aspects that needed to be analysed.	Problem analysis
- Hypothesis formulation	"Before determining a preliminary answer, I tried to look at the data and discuss it with my friends so that the hypothesis we made would make more sense."	Students began to use data, discussion, and logical reasoning before formulating preliminary assumptions.	Inference and reasoning
- Experiment/work procedure design	"I learned to arrange the right work steps so that the experimental results matched the objectives to be achieved."	Students learned to design work steps systematically, rather than merely following instructions mechanically.	Strategic planning and procedural analysis
- Problem solving	"When the experimental results did not match, we tried to find the mistakes and improve the work steps until we found the correct solution."	Students evaluated errors, traced causes, and improved work procedures based on observation results.	Evaluation and decision-making
- Product design	"In making the product, I had to consider function,	Students considered various technical aspects before	Decision-making and

Learning phase	Student response excerpt	Meaning of findings	Observed CTI
	materials, and final results so that the product could work properly."	producing a final product or solution.	application of conclusions

As shown in Table 11, students' experiences indicate that each phase of Inquiry-Creative Learning provided opportunities for critical thinking activities to emerge. In the problem finding phase, students did not merely receive information from the teacher, but were guided to recognize technical problems that needed to be solved. In the hypothesis formulation phase, students began to use data and discussion to construct more rational assumptions. In the experiment design phase, students learned to prepare work procedures systematically. In the problem-solving phase, students evaluated errors and improved their work steps. Meanwhile, in the product design phase, students considered function, materials, and final results before making technical decisions. These findings indicate that the Inquiry-Creative Learning model supported the development of critical thinking through activities that required analysis, inference, evaluation, and decision-making.

Table 12 presents the results of teacher interviews related to readiness for model implementation, learning challenges, supporting factors, and observed changes in students' critical thinking skills during the learning process.

Table 12. Results of teacher interviews on the implementation of Inquiry-Creative Learning

Interview focus	Teacher response excerpt	Meaning of findings	Implications
- Teacher readiness to implement the model	"Before the learning was carried out, we prepared teaching materials, learning scenarios, and task distribution so that the learning process could run according to the steps of the model used."	The teachers prepared learning materials, scenarios, and role distribution before instruction.	Teacher preparation helped learning proceed in a more directed way and in accordance with the model syntax.
- Challenges in learning implementation	"Some students still lacked confidence in expressing their opinions, and the learning time was sometimes not sufficient to complete all stages of the activities."	The main challenges were the low self-confidence of some students and limited time.	Strengthened scaffolding, time management, and student participation strategies are needed.
- Supporting factors for learning success	"Students' enthusiasm in group discussions and the availability of adequate practical tools really supported the success of learning."	Group discussions and practical tools were important factors supporting inquiry-creative activities.	An adequate practical environment strengthened student engagement in learning.
- Changes in students' critical thinking skills	"After the learning, students appeared more active in asking questions, were able to provide reasons for their answers, and became more skilled in solving problems than before."	The teachers observed changes in students' questioning activity, ability to provide reasons, and problem-solving skills.	The learning model contributed to the improvement of students' critical thinking behaviour.

As shown in Table 12, the teachers viewed the success of Inquiry-Creative Learning implementation as strongly influenced by the readiness of learning materials, role distribution within the teaching team, group discussion, and availability of practical tools. The teachers also observed changes in students' learning behaviour after the learning process, particularly in their willingness to ask questions, ability to provide reasons, and skill in solving problems. However, the teachers also noted that not all students could immediately meet the demands of the model. Some students still lacked confidence in expressing opinions, while limited time prevented several learning stages from being carried out optimally.

Table 13 summarizes the supporting and inhibiting factors affecting the improvement of students' critical thinking skills based on student interviews, teacher interviews, and classroom/workshop observations.

Table 13. Supporting and inhibiting factors in improving critical thinking skills

Data source	Identified factor	Factor type	Data evidence	Impact on critical thinking
- Student interview	Active group discussion and real problem solving	Supporting	"It became easier for us to understand the material because we could discuss and find solutions together."	Improved analysis and argument expression skills.
- Student interview	Lack of confidence in expressing opinions	Inhibiting	"Sometimes I hesitated to answer because I was afraid of being wrong."	Hindered students' courage to express ideas and draw conclusions openly.
- Teacher interview	Problem-based model and hands-on practice	Supporting	The teacher stated that students were more active in asking questions and discussing during learning.	Helped students think systematically in solving problems.
- Teacher interview	Limited learning time	Inhibiting	The teacher stated that some learning stages were not optimal because time was limited.	Reduced students' opportunities to conduct in-depth analysis and evaluation.
- Classroom/ workshop observation	Availability of practical tools and collaborative atmosphere	Supporting	Students actively practised and discussed during the activities.	Encouraged the application of concepts in real situations and decision-making.
- Classroom/ workshop observation	Some students remained passive	Inhibiting	Some students were observed merely following along without contributing many ideas.	Limited engagement in the critical thinking process.

As shown in Table 13, the main supporting factors in improving students' critical thinking skills were active group discussion, the use of real problems, hands-on workshop practice, the availability of tools, and a collaborative learning atmosphere. These factors helped students connect concepts with the technical situations they encountered during machining engineering learning. In contrast, the main inhibiting factors were lack of self-confidence, limited time, and the passivity of some students. These challenges indicate that Inquiry-Creative Learning requires good classroom management, adequate scaffolding, and sufficient time allocation so that each phase can run optimally.

Table 14 presents the integration of quantitative and qualitative findings. This integration is important because the study used an explanatory sequential design, in which qualitative data were used to explain the quantitative results obtained earlier.

Table 14. Integration of quantitative and qualitative findings

Quantitative findings	Supporting qualitative data	Preliminary explanation	Research interpretation
- Critical thinking scores in the experimental group improved more than those in the control group.	Student interviews showed that students became more active in analysing technical problems.	The model provided space for students to identify problems and develop solutions.	Inquiry-Creative Learning has the potential to improve critical thinking through problem finding and problem-solving activities.
- Improvement was more evident in analytical ability.	Observations showed that students actively broke down the causes of machining problems.	The problem finding phase encouraged students to observe and distinguish causal factors.	The initial phase of the model was effective in training analytical ability.
- Some aspects of evaluation still needed strengthening.	Teachers stated that students still had difficulty assessing the feasibility of solutions.	Students were not yet fully accustomed to comparing evidence and technical alternatives.	Evaluation rubrics and reflective discussion need to be strengthened.
- Some students showed lower improvement than others.	Interviews showed that some students had difficulty formulating hypotheses and designing experiments.	The demands of the model were relatively new for students accustomed to direct instruction.	Stronger scaffolding is needed in the hypothesis and experiment design phases.

As shown in Table 14, the qualitative findings provide explanations for the quantitative finding that the experimental group experienced better improvement in critical thinking skills than the control group. This improvement can be explained by the characteristics of the Inquiry-Creative Learning model, which provides space for students to find problems, formulate hypotheses, design work procedures, solve problems, and produce products. These activities encouraged students not only to follow procedures, but also to analyse situations, provide reasons, evaluate errors, and make technical decisions. However, the qualitative data also showed that the effectiveness of the model was not fully even across all students. Students who lacked confidence or were not accustomed to inquiry-based learning still required more intensive guidance, particularly in the hypothesis formulation and experiment design phases.

Thus, the qualitative analysis strengthened and explained the quantitative findings. The improvement in critical thinking skills in the experimental group was not only reflected in posttest and N-gain scores, but also in changes in students' learning behaviour during the learning process. Students became more active in discussion, more willing to provide reasons, more involved in problem solving, and more capable of considering various technical aspects when making decisions. Nevertheless, the success of the model was still influenced by teacher readiness, the availability of practical tools, time allocation, and students' level of self-confidence.

DISCUSSION

The results of this study show that the Inquiry-Creative Learning model made a positive contribution to improving students' critical thinking skills in machining engineering instruction. This is reflected in the increase in the mean score of the experimental group from 36.00 in the pretest to 71.20 in the posttest, while the control group showed a more limited increase from 37.58 to 47.36. The difference in improvement was also reflected in the N-gain scores, with the experimental group obtaining 0.539 in the moderate category and the control group obtaining 0.145 in the low category. The ANOVA and Mann-Whitney U test results showed significant differences between the two groups in posttest, gain, and N-gain scores, while the pretest scores were not significantly different. This means that the two groups had relatively equivalent initial abilities, but after the treatment, the experimental group demonstrated greater improvement in critical thinking skills than the control group.

These findings are consistent with the idea that critical thinking is an essential skill in twenty-first-century education. Critical thinking is not limited to the ability to answer questions, but includes the ability to analyse information, evaluate evidence, question assumptions, and draw accountable conclusions (Amina, 2025). Within the 4Cs framework, critical thinking is also closely related to creativity, communication, and collaboration as competencies needed in modern life and work contexts (Thornhill-Miller et al., 2023). Therefore, the improvement in critical thinking skills in the experimental group indicates that machining engineering instruction can be directed not only toward the mastery of work procedures, but also toward strengthening reflective, argumentative, and evidence-based thinking processes.

In the context of vocational education, the findings of this study are important because machining engineering students do not only need to master technical skills such as reading technical drawings, operating machines, or following safety procedures. They also need to be able to analyse technical problems, assess alternative solutions, and make decisions based on considerations of function, efficiency, safety, and work quality. López et al. (2023) and Mahtani et al. (2024) showed that students' success in completing technical tasks is closely related to their ability to analyse situations, integrate information, and consider the implications of design choices. Similarly, Mutohhari et al. (2021) emphasized that vocational education that focuses too heavily on technical procedures without developing critical thinking risks producing graduates who are less adaptive to technological changes and changing work procedures in industry.

The improvement in critical thinking skills in the experimental group can be explained through the characteristics of the Inquiry-Creative Learning model, which positions students as active participants in learning. This model integrates scientific inquiry with scientific creativity through activities such as finding problems, formulating hypotheses, designing experiments, solving problems, and producing scientific or technical products (Wahyudi et al., 2018, 2019; Verawati et al., 2020). These characteristics align with the needs of machining engineering instruction because students are not only asked to follow predetermined work steps, but are also challenged to understand problems, test ideas, interpret results, and improve solutions. Such learning is closer to the demands of technical work, which requires reasoning rather than mere compliance with procedures.

In the problem finding phase, students were guided to identify technical problems relevant to machining practice. This activity encouraged analytical ability because students needed to recognize problem symptoms, distinguish relevant from irrelevant information, and connect practical conditions with the technical concepts they had learned. The qualitative data showed that students felt challenged by the problems presented by the teacher, indicating that authentic problems can trigger cognitive engagement from the beginning of learning. This finding is consistent with the view that inquiry-based learning can stimulate students to move beyond memorizing facts and enter the domains of analysis and evaluation (Hasanah, 2023; Ramli et al., 2023). In machining engineering instruction, this phase is important because students need to become accustomed not only to seeing "what happened," but also to investigating "why it happened" and "what factors may have caused it."

The hypothesis formulation phase contributed to the development of students' inference skills. In this phase, students did not immediately receive answers from the teacher, but developed preliminary assumptions based on data, observation, and group discussion. Interview data showed that students tried to examine data and discuss it with peers before determining preliminary answers, making their hypotheses more reasonable. This process reflects evidence-based reasoning, which is an important part of critical thinking. Ennis (2015, 2018) defines critical thinking as reflective and reasoned thinking focused on deciding what to believe or do. In machining engineering instruction, inference skills appear when students estimate the causes of product defects, connect machining parameters with product quality, or assess the possible consequences of certain procedural choices.

The creatively experiment designing and science creatively problem solving phases contributed to students' evaluation and decision-making skills. In the experiment design phase, students learned to arrange work steps that matched the learning objectives while considering tools, work sequence, process parameters, and possible risks. In the problem-solving phase, students evaluated errors when experimental results did not match expectations, improved their work steps, and determined more appropriate solutions. Interview data showed that students tried to identify mistakes and revise procedures until they found a correct solution. This finding supports Harjono et al. (2025) and Wahyudi et al. (2019), who emphasized that inquiry combined with scientific creativity provides space for students to try alternative procedures, re-examine their work, and develop more reflective problem solving.

The creatively product design phase strengthened the relationship between critical thinking and technical creativity. In this phase, students considered function, materials, and final product outcomes before making technical decisions. This activity shows that critical thinking in machining engineering is not only visible in written answers, but also in the process of designing, selecting, and assessing the feasibility of solutions. Approaches that integrate creativity and design thinking in engineering education have been reported to strengthen students' analytical and reflective abilities, especially when they are asked to compare various designs, parameters, or technical solutions to achieve particular quality and efficiency standards (Anand et al., 2024). In this pattern, creativity is not positioned as free activity without direction, but as part of technical reasoning that must be explainable and accountable.

The results of this study are also consistent with previous studies showing that problem-based, project-based, experiential, and inquiry-based learning can improve critical thinking skills. Pamungkas et al. (2020) emphasized that experiential learning in vocational education can strengthen critical thinking because students are exposed to real problems in workshops or laboratories. Worachak et al. (2023) showed that problem-based and inquiry-based learning models produced better improvement in critical thinking than conventional learning. Putri et al. (2024), through a meta-analysis of argument-driven inquiry, also showed that inquiry models contribute to the improvement of critical thinking. The present study extends this empirical support to the context of machining engineering instruction, a vocational field that has received relatively limited attention in the systematic implementation of the Inquiry-Creative Learning model.

The qualitative data help explain why the experimental group achieved greater improvement. Group discussion, real problem solving, hands-on practice, availability of tools, and a collaborative learning atmosphere were the main supporting factors. The teachers stated that students' enthusiasm in group discussion and the availability of practical tools supported the success of learning. This finding is consistent with the view that the development of twenty-first-century skills in vocational education requires collaborative learning spaces that allow students to practise critical thinking in real activities (Latifa et al., 2022; Jalinus et al., 2023). In the context of machining engineering, practical tools are not merely supporting facilities, but part of the thinking process because students can test ideas, observe the consequences of their actions, and connect concepts with real work outcomes.

Although the findings show strong improvement in the experimental group, the implementation of this model still faced several challenges. Some students still lacked confidence in expressing their opinions, while the learning time was not always sufficient to complete all stages optimally. These challenges indicate that Inquiry-Creative Learning cannot succeed simply by replacing instructional syntax. Students who are accustomed to direct instruction need support in formulating hypotheses, designing experiments, expressing reasons, and evaluating solutions. The literature also reminds us that the success of inquiry-based learning depends strongly on task design, teacher scaffolding, and a classroom culture that allows students to try, fail, and revise their ideas (Harjono et al., 2025; Wahyudi et al., 2019). Therefore, teachers need to provide guiding questions, case analysis examples, evaluation rubrics, group role distribution, and final reflection so that every student is genuinely involved in the critical thinking process.

The finding that no students in the experimental group reached the high N-gain category also needs to be interpreted proportionally. Although 96.67% of students in the experimental group were in the moderate category, the absence of students in the high category indicates that the development of critical thinking requires a sustained process. Critical thinking does not develop optimally through a single intervention period because it is related to habits of thinking, confidence in giving reasons, skills in evaluating evidence, and the ability to reflect on decisions. Abrami et al. (2008), Aizikovitsh-Udi and Cheng (2015), and Kinoshita (2022) emphasized that critical thinking development involves not only cognitive abilities but also dispositions such as curiosity, intellectual perseverance, and openness to new evidence. Therefore, the Inquiry-Creative Learning model is better understood as an instructional approach that needs to be applied consistently across several topics or practical projects, rather than as a one-time intervention.

Although most students in the experimental group achieved improvement in the moderate category, students' responses to Inquiry-Creative Learning still varied. Some students were able to participate more actively in learning, especially in discussion, reasoning, and problem solving. Others still needed guidance, particularly when they were required to formulate hypotheses and design work procedures independently. This variation shows that the success of the model is not determined only by instructional syntax, but also by students' readiness to engage in inquiry activities, their confidence in expressing opinions, and their previous experience with open-ended tasks. Therefore, the implementation of Inquiry-Creative Learning needs to be accompanied by gradual support so that students with different levels of participation and initial ability have equal opportunities to develop critical thinking skills.

When connected to vocational learning, the findings of this study reinforce the importance of shifting from dominantly expository instruction toward learning that is more investigative, reflective, and grounded in real problems. Expository instruction still has a function in explaining basic concepts and work procedures, but the data in this study show that the improvement in critical thinking skills in the control group was much lower than that in the experimental group. This condition is consistent with the findings of Suarniati et al. (2019), Halim et al. (2023), Tommasi et al. (2021), and Putra et al. (2021), which showed that vocational students often still depend on teacher instructions and are not accustomed to questioning the reasons behind procedures, testing alternatives, or reflecting on the technical consequences of their decisions. Therefore, machining engineering instruction needs to be designed more explicitly to develop analysis, inference, evaluation, and decision-making.

The overall findings of this study show that the effectiveness of the Inquiry-Creative Learning model lies in its ability to connect practical experience with critical thinking processes. The quantitative score improvement was supported by qualitative data showing that students became more active in discussion, more willing to provide reasons, more involved in problem solving, and more capable of considering technical aspects when making decisions. These results support the position of Inquiry-Creative Learning as a relevant alternative for machining engineering instruction to improve critical thinking skills, particularly because this model integrates inquiry, creativity, hands-on practice, and reflection. However, the success of its implementation still requires teacher readiness, the availability of practical facilities, adequate time allocation, and support strategies for students who are passive or lack confidence.

CONCLUSION

Based on the findings of this study, the Inquiry-Creative Learning model was effective in improving students' critical thinking skills in machining engineering instruction. This was indicated by the increase in the mean score of the experimental group from 36.00 in the pretest to 71.20 in the posttest, while the control group showed a lower increase from 37.58 to 47.36. The N-gain score of the experimental group was 0.539, which was in the moderate category, whereas the control group obtained an N-gain score of 0.145, which was in the low category. The ANOVA and Mann-Whitney U test results also showed significant differences between the two groups in posttest, gain, and N-gain scores, while the pretest scores were not significantly different. Thus, the greater improvement in critical thinking skills in the experimental group can be more strongly associated with the implementation of the Inquiry-Creative Learning model than with expository instruction.

The improvement in critical thinking skills occurred because the Inquiry-Creative Learning model provided space for students to engage in more active and reflective thinking processes. Through the phases of problem finding, hypothesis formulation, experiment design, problem solving, and product design, students were trained to analyse technical problems, develop assumptions based on data, evaluate errors, improve work procedures, and make technical decisions. These activities supported the development of critical thinking indicators, particularly analysis, inference, evaluation, and decision-making.

The supporting factors for improving students' critical thinking skills included active group discussion, the use of real problems, hands-on practice in the workshop, the availability of practical tools, teacher readiness in preparing learning materials, and a collaborative learning atmosphere. These factors helped students connect machining engineering concepts with practical situations, so that learning was not merely procedural but also encouraged reasoning and problem solving. In contrast, the inhibiting factors identified in this study were the low self-confidence of some students in expressing opinions, limited learning time, and the presence of passive students in group activities. These challenges indicate that the implementation of Inquiry-Creative Learning requires adequate scaffolding, time management, and student support strategies.

In general, the Inquiry-Creative Learning model is feasible to use as an alternative approach in machining engineering instruction to improve students' critical thinking skills. However, the effectiveness of this model does not depend only on its instructional syntax, but also on teacher readiness, the quality of the problems presented, the availability of practical facilities, and students' active engagement during the learning process.

LIMITATIONS

This study has several limitations that should be considered when interpreting the findings. First, the study involved only eleventh-grade students in the Machining Engineering Program at one school, SMK Negeri 1 Pringgabaya, with a total of 63 students, consisting of 30 students in the experimental group and 33 students in the control group; therefore, the findings cannot yet be widely generalized to other vocational education contexts or technical expertise programs with different student characteristics, facilities, school cultures, and learning patterns. Second, the study used intact classes as the experimental and control groups, so although the pretest results showed relatively equivalent initial abilities, possible external factors such as class dynamics, student motivation, learning habits, and participation levels in practical activities could not be fully controlled. Third, the implementation of the Inquiry-Creative Learning model was limited to a specific learning period, whereas critical thinking is a complex skill that requires sustained habituation over a longer duration. Fourth, the quantitative analysis focused on total critical thinking scores and did not separately present improvement for each indicator, namely analysis, inference, evaluation, and decision-making, so the discussion of indicator-level development still relied partly on qualitative data. Fifth, the qualitative data were obtained from six students and two teachers, which provided useful explanatory insights but did not fully represent the range of all students' learning experiences. Finally, the implementation still faced practical challenges, including limited learning time, low self-confidence among some students, and student passivity in group activities, indicating that the effectiveness of the model depends not only on its syntax but also on teacher readiness, classroom management, practical tool availability, and scaffolding strategies.

RECOMMENDATIONS

Based on the findings and limitations of this study, the Inquiry-Creative Learning model is recommended as an alternative approach for machining engineering instruction, particularly in topics or practical activities that allow students to identify problems, formulate assumptions, design work procedures, evaluate results, and produce technical solutions. Teachers should design the model systematically so that each phase is clearly connected to critical thinking indicators, namely analysis, inference, evaluation, and decision-making, rather than using it only as a variation of teaching method. Sufficient scaffolding is needed, especially in the hypothesis formulation and experiment design phases, because students who are accustomed to expository instruction may require guidance through guiding questions, technical case examples, problem-based worksheets, evaluation rubrics, and brief reflection formats. Schools also need to ensure the availability of practical tools, work materials, adequate learning time, and a collaborative workshop atmosphere, since machining engineering instruction strongly depends on direct practical experience. The model should be implemented continuously across several topics or practical projects so that students can develop not only higher scores but also stronger habits of critical thinking, confidence in expressing reasons, and maturity in evaluating technical decisions. Future studies are encouraged to involve larger samples, more than one school, and different expertise program contexts, as well as to analyse critical thinking indicators separately and use longitudinal designs to examine whether the improvement in students' critical thinking skills can be sustained over time.

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AUTHOR CONTRIBUTIONS STATEMENT

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CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

ETHICAL APPROVAL

The researchers meticulously followed ethical protocols throughout the research process, adhering to the principles outlined in the Declaration of Helsinki.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available due to privacy considerations of research participants.

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