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Mathematical Logic as a Means to Develop Critical Thinking Skills in Elementary School Mathematics Learning

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Abstract

Mathematical logic is a branch of mathematics that plays a vital role in building systematic, rational, and critical thinking skills. In higher education, understanding mathematical logic is essential not only for grasping mathematical concepts but also for developing students' critical thinking abilities. However, in reality, many students still experience difficulties in formal reasoning and solving complex problems logically. This article aims to examine the nature of mathematical logic, its basic concepts, students' critical thinking skills, and the role of mathematical logic in fostering these skills. The method employed in this study is library research, analyzing various relevant books, scientific articles, and research findings related to the topic. The results indicate that the foundational concepts of mathematical logic—including conjunction, disjunction, implication, bi-implication, and quantifiers—serve as a crucial foundation for mathematical reasoning. Furthermore, students' critical thinking skills, which encompass the abilities to analyze arguments, evaluate statement validity, detect reasoning fallacies, and draw logical conclusions, can be significantly enhanced through contextual mathematical logic learning. Therefore, mathematical logic plays a highly crucial role in shaping a systematic, objective, and critical mindset. Through mastering this material, students are expected to be able to apply logical reasoning not only in the academic field but also in solving various real-world problems in daily life, thereby supporting their academic success.

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INTRODUCTION

Education plays a crucial role in preparing human resources capable of facing the various challenges of the 21st century. The increasingly rapid development of science, technology, and the flow of information require individuals to possess not only extensive knowledge but also higher-order thinking skills that enable them to analyze information, evaluate various alternatives, and make informed and responsible decisions. Therefore, developing critical thinking skills is a primary goal of the educational process at all levels, including higher education.

Critical thinking skills are the ability to think rationally and reflectively, focusing on determining what to believe or do (Ennis, 2011). This ability involves the processes of interpretation, analysis, evaluation, inference, explanation, and self-regulation in addressing a problem (Facione, 2015). Students with strong critical thinking skills tend to be better able to understand information in depth, identify relationships between concepts, evaluate the validity of arguments, and formulate decisions based on logical reasoning and reliable evidence.

In the context of mathematics education, critical thinking skills play a crucial role because mathematics is not solely about calculating but also involves reasoning, proving, and problem-solving. The National Council of Teachers of Mathematics (NCTM, 2000) emphasizes that mathematics learning must develop problem-solving, reasoning, communication, connections, and mathematical representation skills. These skills are closely related to critical thinking skills because they require students to analyze information, evaluate problem-solving strategies, and draw logical conclusions.

Nevertheless, various studies indicate that students' critical thinking skills still require attention. Research by Widodo, Santia, and Jatmiko (2019) indicates that some mathematics education students still experience difficulties in conducting in-depth analysis of mathematical problems and developing systematic arguments. Similar findings were also reported by Wicaksana, Maulana, and Kusumaningrum (2023), who demonstrated that students' critical thinking skills in solving mathematical logic problems vary and are influenced by their ability to understand the logical relationships between statements. Furthermore, Samudra, Mahfudy, and Negara (2024) found that the critical thinking skills of prospective mathematics teachers still need to be improved, particularly in the analysis and evaluation aspects of solving geometric problems.

One mathematical topic that has great potential for developing students' critical thinking skills is mathematical logic. Mathematical logic is a branch of mathematics that studies the principles of correct reasoning based on logical rules. According to Copi, Cohen, and McMahon (2014), logic is the study of the methods and principles used to distinguish valid from invalid arguments. Through learning mathematical logic, students are trained to understand argument structure, evaluate the validity of a statement, and draw conclusions based on correct inference rules.

Mathematical logic covers various basic concepts such as propositions, truth values, conjunctions, disjunctions, implications, biimplications, quantifiers, tautologies, contradictions, and proof methods. Mastering these concepts not only helps students understand the formal structure of mathematics but also fosters systematic and rational thought patterns. Hurley (2015) explains that logic is a tool used to evaluate arguments and ensure that a conclusion is reached through a correct reasoning process. Therefore, learning mathematical logic is closely related to the development of critical thinking skills.

The relationship between mathematical logic and critical thinking skills is also supported by various research findings. Amelia et al. (2026) concluded that an understanding of mathematical logic contributes to reasoning and critical thinking skills in mathematics learning. Meanwhile, Wang and Abdullah (2024) concluded through their systematic review that mathematics learning that emphasizes reasoning, argumentation, and reflection has great potential to improve students' critical thinking skills. These findings indicate that mathematical logic serves not only as foundational material in mathematics but also as a means to develop higher-order thinking skills that are essential in both academics and everyday life.

Although various studies have addressed critical thinking skills and mathematical logic learning separately, studies specifically examining the role of mathematical logic as a means of developing students' critical thinking skills still need to be strengthened. Therefore, this article seeks to comprehensively examine the nature of mathematical logic, the basic concepts of mathematical logic, the characteristics of students' critical thinking skills, and the role of mathematical logic in developing students' critical thinking skills, based on various relevant literature sources.

This study is expected to provide a deeper understanding of the importance of mathematical logic in supporting the development of students' critical thinking skills, thus providing a foundation for lecturers and researchers in designing more effective learning that focuses on the development of higher-order thinking skills.

METHOD

This article applies the literature study method (library research) or theoretical study by studying various scientific sources that are relevant to students' mathematical logic and critical thinking abilities. Literature study is a research method carried out by collecting, understanding and analyzing various sources related to the topic of discussion (Zed, 2014). The data in this article is taken from books, journal articles, and various other scientific sources related to mathematical logic and critical thinking skills. Literature was obtained through exploration on Google Scholar, mathematics education journals, and books that review mathematical logic and critical thinking. Source selection is carried out by considering suitability of the theme, relevance of the content, and relationship to the research objectives.

The data collection process is carried out through several steps, namely determining the literature source, reading and understanding the contents of the reference, then organizing the information based on the focus of the discussion. According to Zed (2014), library research is carried out by analyzing various library sources to obtain data and information related to research. The data that has been collected is then analyzed in a descriptive manner. Descriptive analysis is carried out by explaining the concepts of mathematical logic and the relationship between mathematical logic and students' critical thinking abilities based on research results from various scientific sources. The data analysis steps in this article include collecting literature, selecting sources, grouping data, content analysis, and drawing conclusions. By using this literature study method, it is hoped that the article can present a conceptual picture of the significance of mathematical logic as a tool for improving students' critical thinking skills in the mathematics learning process in higher education.

RESULTS AND DISCUSSION

The Essence of Mathematical Logic

Mathematical logic is a branch of mathematics that studies the principles of correct reasoning based on logical rules. Mathematical logic serves as the foundation for determining the validity of an argument, constructing mathematical proofs, and drawing systematic conclusions. Introduction to Logic explains that logic is the study of the methods and principles used to distinguish valid from invalid arguments (Copi et al. 2014). Therefore, mathematical logic is not only oriented towards the use of formal symbols, but also on developing systematic thought patterns in solving problems. Mathematical logic's scope includes propositions, truth values, logical operations, implication, biimplication, tautology, contradiction, quantifiers, and proof methods.

These concepts form the basis of various branches of mathematics, such as algebra, calculus, discrete mathematics, and set theory. Mastery of mathematical logic is crucial because almost all mathematical proof processes are based on sound logical principles.

In mathematics instruction in higher education, mathematical logic serves as a means to train students in deductive thinking. Deductive reasoning is the process of drawing conclusions based on premises known to be true. This skill is essential for proving theorems, solving mathematical problems, and developing scientific arguments. Through learning mathematical logic, students not only learn to understand concepts but also learn how to reach conclusions logically and responsibly.

Furthermore, mathematical logic is closely related to critical thinking skills. Learning mathematical logic requires students to analyze statements, evaluate the validity of arguments, and determine logical relationships between concepts. These activities involve the skills of interpretation, analysis, evaluation, and inference, which are the main components of critical thinking according to Facione (2015).

According to Aidifa Asti Amelia et al. (2026), an understanding of mathematical logic contributes to reasoning and critical thinking skills in mathematics learning. A literature review on understanding mathematical logic in mathematics learning concluded that mathematical logic is closely related to critical thinking skills, metacognitive abilities, and mathematical problem-solving. Learning that emphasizes logical reasoning has been shown to help students understand mathematical concepts more deeply and improve the quality of their thinking processes.

According to Dinar Anggit Wicaksana et al. (2023), their research on students studying mathematical logic also showed that solving logical problems involves a high level of critical thinking skills. Students are required to identify relevant information, analyze relationships between statements, and draw conclusions based on applicable logical rules. The study found that students' critical thinking skills are evident through the analysis and evaluation processes when solving mathematical logic problems.

Thus, the essence of mathematical logic lies not only in the study of symbols and formal rules, but also in its role as a means of developing rational, systematic, and critical thinking patterns. Mastery of mathematical logic is an important foundation for students in understanding mathematical concepts, compiling proofs, and developing critical thinking skills needed in learning and academic life.

Basic Concepts of Mathematical Logic

According to Subhan (2017), every statement, called a proposition, is always clear in meaning and unambiguous, so there are only two conclusions about it: true or false, and there are no other options than both. Examples of propositions: "A triangle has an interior angle of 1" and "Nine is a prime number." According to Hurley (2015), a proposition is a statement whose truth can be assessed based on certain conditions. Understanding propositions helps students understand the basic structure of mathematical argumentation. A conjunction is a compound statement that uses the conjunction "and." Conjunctions are represented by the symbol (∧). A conjunction is true if both of its constituent propositions are true.

A disjunction, on the other hand, is a compound statement that uses the conjunction "or" and is represented by the symbol (∨). A disjunction is false only if both propositions are false. Understanding conjunctions and disjunctions helps students analyze logical relationships between statements (Syariful and Soffi, 2018). According to Subhan (2017), an implication is a compound statement in the form of "if...then..." and is symbolized by (⇒). The statement "$P \Rightarrow Q$" can be read as "if P then Q." In this case, P is called the antecedent, while Q is called the consequent. Implication is very important in mathematical proof and deductive conclusion drawing. According to Copi et al. (2014), implications are used to show the logical relationship between premises and conclusions in an argument.

Meanwhile, a biimplication is a compound proposition related to the words "...if and only if..." which is symbolized by (⇔) so that the statement "$P \Leftrightarrow Q$" is read as "P if and only if Q." According to Syariful and Soffi (2018), a biimplication is true if both statements have the same truth value and false if the two single statements have different truth values.

According to Subhan (2017), quantifiers express the quantity of an object and come in two types:

a. The universal quantifier is denoted by the words "all," "for every," and the like. Its symbol is $\forall x, P(x)$.
b. The existential quantifier is denoted by the words "exists," "there are," "some," and the like. Its symbol is $\exists x, P(x)$.

Understanding quantifiers helps students grasp the structure of mathematical proofs formally and systematically.

Students' Critical Thinking Skills

Critical thinking skills are one of the essential competencies students must possess to face the demands of learning. This ability enables students to analyze information, evaluate arguments, draw logical conclusions, and make decisions based on valid evidence. In higher education, critical thinking is an indicator of learning success because students are not only required to master knowledge but also to be able to use that knowledge to rationally solve various problems.

According to "Critical Thinking: What It Is and Why It Counts" (2015), critical thinking is a thought process involving interpretation, analysis, evaluation, inference, explanation, and self-regulation. This ability enables a person to deeply understand information before making a decision or forming a conclusion. Thus, critical thinking is not only related to the ability to remember information but also the ability to process and evaluate it objectively.

In mathematics learning, critical thinking skills play a crucial role because mathematics demands systematic and logical reasoning. Students need to understand concepts, connect various pieces of information, evaluate solution procedures, and provide justifiable reasons for their answers. Therefore, critical thinking skills are an integral part of the mathematics learning process.

According to the National Council of Teachers of Mathematics (2000), mathematics learning must develop problem solving, reasoning, communication, connection and mathematical representation abilities. These abilities are closely related to critical thinking because students are required to analyze problems, choose the right strategy, and evaluate the results obtained in the problem solving process.

Research conducted by Widodo, et al (2019) regarding the critical thinking skills of mathematics education students in solving Real Analysis problems shows that critical thinking is a reflective and reasonable thinking ability that focuses on making decisions regarding what one believes or does. This research also shows that students who have good critical thinking skills tend to be better able to analyze problems and organize mathematical arguments systematically.

The results of other research conducted by Samudra, et al (2024) on prospective mathematics teacher students show that critical thinking skills are very necessary in solving geometric problems because they involve logical reasoning, information analysis, and evaluation of the solutions obtained. This research confirms that critical thinking skills are one of the main competencies that need to be developed in mathematics education in higher education.

In addition, research by Wulan and Rahayu (2023) shows that students' critical thinking skills in solving mathematical problems develop through activities that require students to analyze information, identify contradictions, evaluate evidence, and draw logical conclusions. This ability helps students understand mathematical concepts in more depth and reduces errors in the problem solving process.

A systematic review conducted by Wang and Abdullah (2024) concluded that critical thinking skills are an essential competency in mathematics education in higher education. Various mathematics learning strategies have been shown to help students develop analytical, evaluation, inference, and decision-making skills, key indicators of critical thinking. The study also suggests that developing critical thinking skills should be a primary goal in modern mathematics learning.

Based on this description, students' critical thinking skills can be understood as the ability to think rationally, reflectively, systematically, and objectively in analyzing information, evaluating arguments, and drawing conclusions based on available evidence. In mathematics learning, critical thinking skills play a crucial role in supporting the processes of reasoning, proof, and problem-solving, and therefore need to be continuously developed through various learning activities that require active student involvement.

The Role of Mathematical Logic in Developing Students' Critical Thinking Skills

Mathematical logic is a branch of mathematics that plays a crucial role in developing students' critical thinking skills. Through learning mathematical logic, students not only learn symbols, rules, and formal procedures but are also trained to think systematically, rationally, and objectively when analyzing problems. These abilities are key characteristics of critical thinking required in higher education.

Copi et al. (2014) explain that logic is the study of the principles of reasoning used to distinguish valid from invalid arguments. Through learning mathematical logic, students learn to analyze propositions, evaluate relationships between statements, and draw conclusions based on logical rules. This process directly trains the analysis, evaluation, and inference skills that are part of critical thinking skills.

Critical thinking skills develop when students habitually evaluate information before accepting or rejecting it. In mathematical logic, students are not only required to know the final result of a statement but also to be able to explain the reasons underlying the truth or falsity of an argument. This process encourages students to think reflectively and use relevant evidence to draw conclusions. In line with this, Facione (2015) explains that critical thinking includes the ability to interpret, analyze, evaluate, infer, and explain which are used in rational decision making.

Learning mathematical logic also contributes to the development of students' deductive reasoning skills. Deductive reasoning is the process of drawing conclusions based on premises known to be true. In solving mathematical logic problems, students are required to connect various available information, identify logical relationships between statements, and determine appropriate conclusions based on applicable rules. This ability is crucial for developing critical thinking because students learn not to accept statements without clear and provable reasons.

Research conducted by Dinar Anggit Wicaksana et al. (2023) showed that students solving mathematical logic problems use critical thinking skills through the processes of analyzing information, evaluating arguments, and drawing conclusions. These results demonstrate that learning mathematical logic can be an effective tool for developing students' critical thinking skills because it requires the systematic use of reasoning at every stage of problem-solving.

These findings are supported by a systematic review conducted by Wang and Abdullah (2024), which concluded that mathematics learning in higher education has significant potential for improving students' critical thinking skills. Various mathematics learning strategies that emphasize analysis, argumentation, problem-solving, and reflection have been shown to significantly develop critical thinking skills. The study also emphasized that developing critical thinking skills should be a primary goal of mathematics learning in higher education.

Furthermore, mathematical logic plays a role in developing structured thinking habits. When students solve a logic problem, they are required to identify premises, determine logical relationships between statements, evaluate possible solutions, and draw consistent conclusions. These thinking habits help students develop the ability to face more complex problems, both in mathematics and in everyday life.

In the context of higher education, critical thinking skills are a competency that students must possess to adapt to developments in science and technology. Therefore, learning mathematical logic serves not only as a means of mastering mathematical concepts but also as a medium for developing higher-order thinking skills. Students who have a good understanding of mathematical logic tend to be better able to analyze problems, evaluate information objectively, and make decisions based on logical and accountable reasons.

Based on this description, it can be concluded that mathematical logic plays a crucial role in developing students' critical thinking skills. Through a systematic process of analysis, evaluation, deductive reasoning, and argumentation, learning mathematical logic helps students develop rational, objective, and reflective thought patterns. Thus, mathematical logic is not only a foundation for learning mathematics but also a strategic tool in developing the critical thinking skills needed by students in the 21st century.

Mathematical Logic in the Perspective of 21st Century Skills

The development of science and technology in the 21st century requires students to master not only factual knowledge but also higher-order thinking skills. One skill that receives significant attention in modern education is critical thinking. This ability is necessary for individuals to analyze complex information, evaluate various sources of information, and make informed decisions based on logical reasoning and reliable evidence.

Within the framework of modern education, critical thinking is included among the 21st-century skills that must be developed through the learning process. The OECD, through its Future of Education and Skills 2030 program, emphasizes that students need to be equipped with various competencies that enable them to adapt to ever-evolving social, economic, and technological changes. These competencies include knowledge, skills, attitudes, and values that support problem-solving, decision-making, and lifelong learning.

In the context of mathematics education, mathematical logic plays a strategic role in supporting the development of these skills. Mathematical logic not only serves as a foundation for understanding mathematical concepts but also serves as a means to train systematic, analytical, and reflective thinking skills. When students study propositions, implications, quantifiers, and proof methods, they are indirectly developing critical thinking skills needed to address various real-life problems.

According to Facione (2015), critical thinking encompasses the skills of interpretation, analysis, evaluation, inference, explanation, and self-regulation. All of these components can be found in mathematical logic learning activities. Therefore, learning mathematical logic can be seen as an effective tool in preparing students to face the challenges of the 21st century.

Furthermore, mastery of mathematical logic also contributes to students' ability to filter information circulating in society. In the digital age, individuals are confronted with a variety of information that may not be accurate. The ability to examine the validity of arguments, identify fallacies in reasoning, and draw conclusions based on evidence is crucial. In this regard, mathematical logic serves as an intellectual tool that helps students think objectively and rationally.

Implementation of Mathematical Logic Learning in Developing Critical Thinking

Mathematical logic learning can be designed in such a way that it focuses not only on mastering concepts but also on developing students' critical thinking skills. One way to do this is by presenting problems that require students to analyze and reason before determining a solution.

During the learning process, students can be presented with a statement or argument, which is then analyzed for its validity using the rules of logic. This activity trains students to identify premises, determine relationships between statements, and evaluate the validity of the conclusions reached. Such activities help students develop analytical and evaluative skills, which are essential components of critical thinking.

In addition to argument analysis, critical thinking skills can also be developed through mathematical proof activities. Proof is a process that requires logical and systematic thinking skills because each step must be based on correct rules. In constructing a proof, students are not only required to obtain the correct final result but also to be able to explain the rationale behind each step.

Group discussions can also be used to enhance students' critical thinking skills. During discussions, students are given the opportunity to present arguments, defend their opinions, and respond to the opinions of others. This activity encourages students to use logical reasoning and consider various points of view before drawing a conclusion.

The use of learning technology can also support the development of critical thinking skills through mathematical logic. Various mathematical software and digital learning media enable students to visualize the relationships between logical concepts more clearly. This makes abstract concepts easier to understand, thus making the learning process more effective.

Through these various learning strategies, mathematical logic can serve as an effective tool for developing systematic, rational, and reflective thought patterns. These abilities are an important foundation for developing students' critical thinking skills.

Examples of Mathematical Logic Activities that Develop Critical Thinking

Developing critical thinking skills through mathematical logic can be achieved through various learning activities involving analysis and reasoning. One frequently used example is implication and contrapositive analysis.

For example, given the following propositions:

P: The student understands mathematical logic.

Q: The student is able to think critically.

Based on these two propositions, an implication can be formed:

"If the student understands mathematical logic, then the student is able to think critically."

Students are then asked to determine the converse, inverse, and contrapositive forms of these implications. This activity helps students understand the logical relationships between statements while also practicing their analytical and evaluation skills.

In a mathematical logic learning activity, students are given an argument to analyze using the following truth table:

1. If someone studies hard, then they pass the exam.

2. If someone passes the exam, then they get a job.

3. Someone doesn't get a job.

4. Therefore, someone doesn't study hard.

For example:

p: Someone studies hard

q: Someone passes an exam

r: Someone gets a job

The logical form is:

$p \rightarrow q$

$q \rightarrow r$

$\neg r$

Conclusion: $\neg p$

Students are then asked to construct a truth table for all possible values of p, q, and r, and determine the column of the combined premise $(p \rightarrow q) \wedge (q \rightarrow r) \wedge \neg r$, then compare it with the conclusion $\neg p$.

Based on the constructed truth table, the main step is to identify the rows where all premises are true. In this case, the premises consist of three parts: $p \rightarrow q$, $q \rightarrow r$, and $\neg r$. Therefore, the focus of the analysis is directed at the row that makes all three premises true simultaneously. From the evaluation results, the condition $\neg r$ is true only when r is false. In this case, for the implication $q \rightarrow r$ to remain true, q must be false (because if q is true and r is false, the implication is false). Furthermore, for the implication $p \rightarrow q$ to remain true, with q being false, p must also be false. Thus, the only condition that makes all premises true is when $p = S$, $q = S$, and $r = S$ (in the sense that r is false and therefore $\neg r$ is true). In this case, the conclusion $\neg p$ is also true.

There is not a single row in the truth table where all premises are true but the conclusion is false. This indicates that the argument meets the criteria for logical validity. Conceptually, this argument form is a combination of a hypothetical syllogism and a contraposition, which are generally recognized as valid forms of reasoning.

Through this activity, students not only practice constructing truth tables but also understand how the relationships between propositions affect the validity of an argument. This process helps develop deductive reasoning skills and reinforces the understanding that validity is determined by logical structure, not by the content or context of the statement.

Challenges and Opportunities for Developing Critical Thinking through Mathematical Logic

Although mathematical logic has great potential for developing critical thinking skills, its implementation still faces various challenges. One major challenge is the perception that mathematical logic is difficult and abstract. Many students struggle to understand logical symbols and the formal rules used in reasoning.

Furthermore, some students are still accustomed to memorization-oriented learning, making them less adept at conducting in-depth analysis and evaluation. This situation results in underdevelopment of critical thinking skills.

On the other hand, technological developments and learning innovations offer significant opportunities to improve the effectiveness of mathematical logic learning. The use of digital media, interactive simulations, and online learning platforms allows students to learn logical concepts in a more engaging and understandable way.

The OECD emphasizes that future education needs to emphasize the development of competencies that enable students to think critically, solve problems, and adapt to rapid change. Therefore, learning mathematical logic is highly relevant in supporting the achievement of 21st-century educational goals.

CONCLUSION

Conclusion contains a description that should answer the problem(s) raised and Based on the research conducted, mathematical logic plays a crucial role in developing students' critical thinking skills. Through learning mathematical logic, students are trained to analyze information, evaluate arguments, draw logical conclusions, and solve problems systematically. These skills are key components of critical thinking. In addition to providing a foundation for mathematical reasoning and proof, mathematical logic also helps students develop rational, objective, and structured thought patterns. Therefore, learning mathematical logic can be an effective tool to support the development of students' critical thinking skills in higher education.

Based on the conclusions obtained, there are recommendations that are expected to be considered in further learning and research. Learning mathematical logic should be utilized as a means to train students' critical thinking skills. Therefore, lecturers are expected to provide learning activities that encourage students to think logically and systematically. Future research can examine the influence of mathematical logic on critical thinking skills through fieldwork.

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