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Exploring the Relationship Between Critical Thinking Levels and Learning Obstacles in Students' Understanding of Solid Geometry: A Descriptive Study

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ABSTRACT

This study examined junior high school students' critical thinking skills and learning obstacles in solving problems involving the surface area of geometric solids. A descriptive design integrating quantitative and qualitative analyses was employed with 71 ninth-grade students from one public junior high school in Cimahi and one private junior high school in Cilegon, selected through purposive sampling. Data were collected using a written test comprising three questions with 12 sub-items, designed to assess six critical thinking indicators based on Facione's framework and validated by experts, and through learning document analysis. Quantitative data were analyzed descriptively using scores and categories for each indicator. Qualitative analysis focused on students' written responses to identify reasoning patterns, errors, and learning obstacles, which were classified using the Didactical Design Research framework. The findings revealed that students' overall critical thinking skills were low. Interpretation and analysis were at a moderate level, evaluation and explanation were low, and inference was very low. Self-regulation could not be adequately identified through written responses. The identified learning obstacles comprised epistemological and ontogenic obstacles, including conceptual, instrumental, and psychological dimensions. These findings highlight the need for geometry instruction that connects conceptual understanding, spatial visualization, and mathematical reasoning to address students' difficulties and support the development of critical thinking skills.

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1. INTRODUCTION

Education plays a crucial role in developing human resources capable of facing the challenges of the 21st century. In the context of mathematics education, this role extends

beyond procedural knowledge to the development of higher-order thinking skills. These skills enable students to reason, analyze, and solve complex problems. Alinian et al. [1] emphasize that education is crucial in preparing individuals to face rapid global changes driven by technological advances and globalization. Consequently, contemporary educational frameworks highlight the importance of integrating essential competencies into the learning process [1].

Critical thinking is one of the competencies required in the 21st century, as a key component underlying students' ability to engage in meaningful learning. Trilling and Fadel [2] classify critical thinking as a learning and innovation skill, while Wagner [3] identifies it as one of seven essential survival skills. In mathematics education, critical thinking involves the ability to interpret problems, analyze relationships, evaluate strategies, and draw logical conclusions. Empirical studies consistently show that students' mathematics achievement is strongly related to their level of critical thinking skills [4]. Furthermore, the growing number of studies in this area indicates increasing recognition of critical thinking as a core goal in mathematics learning [5].

In this study, critical thinking is defined based on Facione's framework, which comprises six indicators: interpretation, analysis, evaluation, inference, explanation, and self-regulation [6]. Interpretation refers to understanding information and representations; analysis involves identifying relationships among concepts; evaluation concerns assessing the validity of procedures and solutions; inference involves drawing conclusions from available information; explanation refers to justifying reasoning; and self-regulation involves monitoring and reviewing one's own thinking. In geometry, these indicators are reflected in students' abilities to interpret diagrams, identify relationships among geometric properties, evaluate solution procedures, draw conclusions, justify answers, and review their problem-solving processes. However, written responses may not fully capture self-regulation because this indicator involves monitoring one's own thinking.

Critical thinking skills refer to specific cognitive processes used to analyze information, evaluate arguments, and draw conclusions. Critical thinking ability refers more broadly to the capacity to apply these skills, whereas critical thinking disposition concerns the willingness to think critically. Mathematical reasoning, in contrast, focuses on establishing mathematical relationships, constructing arguments, and drawing conclusions. Although these concepts overlap, they are not interchangeable. Therefore, this study focuses on students' critical thinking skills as demonstrated in their responses to geometry problems, while considering mathematical reasoning as part of the problem-solving process.

Despite its importance, students' critical thinking skills remain insufficiently developed, particularly in geometry learning. Solid geometry, which involves three-dimensional objects, requires students to integrate conceptual understanding with spatial reasoning. However, the abstract nature of geometric representations often leads to difficulties in constructing accurate mental models. Based on van Hiele's theory, many students are still at the lower levels of geometric thinking, namely visualization and analysis [7]. This suggests that students' challenges are not only conceptual but also related to cognitive processes involved in reasoning and representation.

In the field of mathematics education, critical thinking is widely recognized as an essential 21st-century skill [8], [9]. Its application is crucial in various life situations [10]. [11], [12]. Encouraging students to think critically in mathematics education not only supports their academic development but also reveals their potential to contribute to improving the learning process itself [13]. Furthermore, critical thinking is an effective means of enhancing students' conceptual understanding of mathematics [14].

Critical thinking skills are closely related to sub-components of higher-order thinking skills and have been shown to correlate with students' academic achievement. Aksu & Koruklu [15] found a positive and significant correlation between students' critical thinking dispositions and their success in mathematics courses. Similarly, Celik & Ozdemir [16] concluded that there is a significant relationship between critical thinking and sub-dimensions of higher-order thinking, such as reasoning, mathematical thinking, and problem-solving skills. Individuals with strong critical thinking abilities are generally more capable of solving a variety of problems effectively [17], [18], [19]. Despite its importance, Indonesian students' critical thinking ability in mathematics remains suboptimal. This is evidenced by the fact that many junior high school students struggle to solve mathematical problems, with more than 70% failing to demonstrate adequate critical thinking competence in mathematics [20], [21].

Students' difficulties in solving mathematics problems are primarily triggered by internal and external factors. In educational studies, these external factors are conceptualized as learning obstacles. Brousseau [22] classifies these obstacles into three main dimensions: ontogenic (which includes psychological, instrumental, and conceptual aspects), didactic, and epistemological. These obstacles can arise sequentially due to students' lack of cognitive and mental maturity, inappropriate sequencing of material in instructional design, and limited understanding of mathematical objects in specific contexts. Furthermore, Suryadi [23] emphasized that these obstacles related to didactic design are universal and can be experienced by students at various levels, including junior high school. Therefore, comprehensively identifying learning obstacles is crucial for teachers in formulating adaptive didactic designs. Specifically, recognizing epistemological obstacles has proven essential in helping educators understand and anticipate misconceptions experienced by students [24].

Difficulties in solving mathematics problems among junior high school students are not only attributed to weak critical thinking skills but also to the learning obstacles they encounter. This is particularly evident in geometry. Previous studies have reported students' performance on critical thinking tasks and the various learning obstacles they face. Firdaus et al. [25] revealed that more than 75% of students were at low to moderate levels across all indicators of critical thinking. Geometry, often considered complex and abstract, presents unique challenges, though these can be alleviated through visualization. For instance, visual representations of geometric concepts have been shown to enhance students' critical thinking skills. Hidayat & Rosnawati [26] concluded that students' ability to analyze, evaluate, and draw conclusions improved when images accompanied geometry problems compared to those without. Beyond external support, students' independent learning skills are equally

important. Bayuningsih et al. [27] found a positive correlation between students' self-regulated learning in solving geometry problems and their level of critical thinking.

Several studies have provided insights into the learning obstacles faced by students in geometry, which serve as a foundation for subsequent research. For example, junior high school students have been shown to experience epistemological learning obstacles in concepts such as area units, types of triangles, and triangle properties due to limited prior knowledge or contextual understanding [28]. They also encounter ontogenic, epistemological, and didactical obstacles in understanding the volume of cubes and rectangular prisms [29]. Similarly, Rosita et al. [30] reported that students face epistemological obstacles in learning the perimeter and area of circles, particularly in translating mathematical ideas into symbolic and visual representations. Furthermore, Rismawati et al. [31] demonstrated that students struggle with epistemological obstacles in plane geometry due to contextual limitations. Collectively, these studies demonstrate that junior high school students encounter diverse challenges in grasping mathematical concepts, such as plane geometry, solid geometry, and measurement, often due to insufficient prior knowledge, limited contextual exposure, and less effective instructional approaches.

Previous research has identified various types of learning obstacles in mathematics, including ontogenic, epistemological, and didactic obstacles. These obstacles have been reported in different topics such as lines and angles [32], quadratic equations [33], number patterns [34], and algebraic thinking [35]. However, limited studies have specifically examined learning obstacles in solid geometry in relation to students' critical thinking processes. This gap highlights the need to investigate how students' levels of critical thinking influence the difficulties they encounter in understanding three-dimensional geometric concepts.

In addition, the relationship between critical thinking and learning obstacles is theoretically significant. Students with low levels of critical thinking tend to experience difficulties in analysis, evaluation, and inference, which can lead to misunderstandings. Conversely, students with higher levels of critical thinking are better able to organize information systematically and apply effective problem-solving strategies. Previous studies have also shown that mathematical thinking, including critical thinking, plays a crucial role in supporting students' understanding of geometry [36].

Although several studies have examined critical thinking skills and learning obstacles separately, studies integrating these two aspects are relatively limited. To date, few studies have explicitly analyzed the relationship between students' levels of critical thinking skills and the types of learning obstacles they experience, particularly in the topic of surface area of geometric shapes. However, understanding the relationship between these two aspects is crucial for explaining how critical thinking skills influence the process of understanding geometric concepts and the emergence of various learning obstacles.

Based on this gap, this study aims to explore the relationship between students' levels of critical thinking skills and the learning obstacles they face in understanding the concept of surface area of geometric shapes. (1) describe students' critical thinking skills, both as a whole and based on each indicator; and (2) identify the characteristics of learning obstacles and analyze their relationship with the level of students' critical thinking skills in

understanding the concept of the surface area of geometric shapes. The findings of this study are expected to enrich studies on the relationship between critical thinking skills and learning obstacles, as well as become a basis for designing more effective geometry learning strategies to improve students' critical thinking skills and conceptual understanding.

2. METHOD

This study employs a descriptive method, utilizing both quantitative and qualitative analysis to describe the critical thinking skill levels of junior high school students and to identify the types of learning obstacles they encounter. Quantitative analysis involves interpreting the students' critical thinking skill levels and calculating the percentage of students at each level. Qualitative analysis is conducted through an in-depth examination of students' written responses to identify characteristics of their reasoning, patterns of errors, and difficulties in problem-solving. These findings are then analyzed to categorize the types of learning obstacles based on the specific difficulties revealed in the students' work. The interpretation of each type of obstacle is supported by authentic evidence, such as excerpts or reproductions of the students' responses, accompanied by an analytical explanation of the connection between the responses, the underlying thought processes, and the identified learning obstacles. Thus, the quantitative analysis provides an overview of the distribution of critical thinking skill levels, while the qualitative analysis elucidates the nature of the students' difficulties, serving as a basis for a more profound identification of their learning obstacles.

The research subjects consisted of 71 ninth-grade students from the 2024/2025 academic year, drawn from one public junior high school in Cimahi City and one private junior high school in Cilegon City. The schools were selected purposively, taking into account the alignment of their implementation of the Kurikulum Merdeka (Independent Curriculum) with the research focus, as well as the variation in institutional characteristics, specifically, the distinction between public and private schools. The private school included in the study incorporates additional religious content in accordance with its foundation's policy, thereby providing a diverse context for the delivery of instruction. Furthermore, the selection of specific classes within each school was based on the criterion of comparable mathematical proficiency across classes. According to the mathematics teachers who instruct several ninth-grade classes at each school, the classes possess relatively equivalent levels of mathematical ability. Based on these considerations, one class was selected from each school, resulting in a total of 71 students serving as the research subjects. This procedure was intended to ensure that the subjects aligned with the research objectives, while accounting for the characteristics of the learning environment and the students' academic standing. However, because the schools and classes were selected purposively rather than through random sampling, the research findings must be interpreted in light of the specific characteristics of the subjects and the contexts of the two schools studied; consequently, any generalization of these findings to the broader population of junior high school students should be approached with caution.

To address the research questions, students from both schools were administered a test developed based on critical thinking skill indicators. The indicators adopted were those

proposed by Facione [6], namely: (1) interpretation, (2) analysis, (3) evaluation, (4) inference, (5) explanation, and (6) self-regulation. The instrument consisted of three tiered questions and was accompanied by an assessment rubric designed to measure students' responses objectively.

The research procedure involved several stages: (1) literature review and field observation, (2) development of the critical thinking test instrument, (3) data collection, (4) data analysis, and (5) conclusion drawing. The initial stage involved reviewing literature relevant to the research topic and conducting field observations to obtain a comprehensive understanding of the learning context. In the second stage, the researchers developed the critical thinking test instrument. In the third stage, once the instrument was ready, data were collected in the form of students' test responses and interviews. The fourth stage included analyzing students' critical thinking achievement at both the individual and indicator levels, followed by the identification of learning obstacle types. Finally, in the fifth stage, conclusions were drawn to address the research questions and provide new insights into the issues under investigation.

To enhance clarity of the research design structure, Figure 1 illustrates the research methodology used. The diagram outlines the sequential phases of the research, including the development of assessment instruments based on critical thinking indicators, the data collection process, and data analysis techniques. Furthermore, the diagram emphasizes the application of [6] critical thinking dimensions in the assessment, which serve as the basis for examining students' learning obstacles in spatial geometry.



Figure 1. Research Methodology Framework

Figure 1 shows an overview of the research procedure, outlining the study's stages sequentially. It begins with preliminary activities such as literature review and field observations, then designs assessment instruments based on [6] critical thinking framework, collects data through testing and interviews, analyzes data, and formulates conclusions.

In qualitative research, trustworthiness is built through four important criteria: credibility, transferability, dependability, and confirmability [37]. [38], [39]. Credibility reflects the extent to which findings accurately represent the research context and

participants' perspectives. In this study, credibility was ensured through intensive field involvement, rich and detailed data collection, and the use of triangulation. Furthermore, discussions with colleagues and documentation of supporting evidence enhanced the authenticity of the findings. Transferability relates to the extent to which findings can be applied in other contexts. This was addressed by providing detailed descriptions of the research setting, participants, and procedures, allowing readers to assess the relevance of the findings to similar situations.

Dependability and confirmability further strengthen the rigor of the study. Dependability refers to the consistency and reliability of the research process, which was maintained through systematic documentation and careful examination of each stage, including instrument development, data collection, and data analysis. Meanwhile, confirmability emphasizes the objectivity of the findings by ensuring that interpretations are grounded in the data rather than researcher bias. This was achieved through transparent reporting of analytical procedures and decision-making processes. Together, these four criteria ensure that the study meets the standards of qualitative rigor and enhances the credibility of its conclusions.

Categorization of Critical Thinking Skills

In this study, students' critical thinking skills were categorized into several levels. The categorization of scores is as referred to by [40]. The categories are as follows: very low, low, medium, high, and very high. Table 1 presents a detailed categorization.

Table 1. Categorization of Critical Thinking Skills

Interval	Category
$81{,}25 < x \leq 100$	VH
$62{,}50 < x \leq 81{,}25$	H
$43{,}75 < x \leq 62{,}50$	M
$25 < x \leq 43{,}75$	VL
$0 \leq x \leq 25$	L

Information: VH = Very High, H = High, M = Medium, L = Low, VL = Very Low

The interpretation of the percentage of achievement related to the number of respondents is presented in Table 2.

Table 2. Interpretation of Critical Thinking Skills Achievements

Achievement Score (x) in %	Interpretation Associated with the Number of Respondents
100	All Over
$75 \leq x < 100$	Almost All
$50 < x < 75$	Most of the
50	Half of it
$25 \leq x < 50$	Almost Half
$0 \leq x < 25$	Fraction
0	None

3. RESULTS AND DISCUSSION

3.1 Student Critical Thinking Skills Profile

After the critical thinking ability test was administered to the research subjects, an analysis was conducted to determine the students' level of critical thinking achievement regarding the concept of surface area of three-dimensional shapes. Overall, the students' critical thinking ability fell into the low category, with a score of 0.32. Next, a recapitulation of the number of students in each critical thinking ability category was conducted. The results are presented in Table 3.

Table 3. Recapitulation of Students' Critical Thinking Ability

Category of critical thinking ability	Number of Students	Percentage (%)
VL	29	40,84
L	23	32,39
M	13	18,3
H	4	5,63
VH	2	2,82

Table 3 illustrates the distribution of students' critical thinking skills across five categories. The research findings indicate that the majority of students fall into the very low (40.84%) and low (32.39%) categories, while a small proportion of students reach the moderate (18.3%), high (5.63%), and very high (2.82%) levels. This distribution indicates that only a small proportion of students' critical thinking skills demonstrate higher-order thinking performance, while the majority remain underdeveloped. This pattern suggests that students experience significant difficulties in engaging with tasks that require deeper reasoning and structured problem-solving.

3.2 The Relationship between Critical Thinking Skills and Learning Obstacles

By simultaneously analyzing critical thinking performance levels and various types of learning obstacles, this study seeks to uncover patterns that reflect cognitive limitations and instructional influences. Such an approach is crucial, as low scores on critical thinking indicators cannot be fully understood without considering the epistemological and ontogenetic obstacles that shape students' reasoning processes. Based on this, the combined analysis provides a more descriptive interpretation of students' learning conditions and supports the development of targeted, theoretically grounded instructional interventions. A comprehensive summary of students' performance on each indicator, along with the types of learning obstacles identified, is presented in Table 4.

Table 4 presents students' achievement in critical thinking skills across each indicator, along with the learning obstacles identified. The results show that the highest achievement was recorded for indicator 1 (51.51%), while indicator 6, self-regulation, received a score of 0%. This score should not be interpreted as evidence that students lack self-regulation skills; rather, it indicates that such skills were not captured through the written responses provided in the instrument used. This highlights a limitation of the three-

tier test instrument in directly revealing metacognitive processes. Consequently, future research should supplement written tests with reflective questions or "think-aloud" protocols to obtain a more comprehensive picture of students' self-regulation.

Table 4. Critical Thinking Skills Achievements and Learning Obstacles Findings

Critical Thinking Ability Indicators			Learning Obstacle (LO) Findings				
No	Achievement (%)	Category	Didactic LO	Epistemological LO	Ontogenic LO		
					Conceptual	Psychological	Instrumental
1	51,51	M	√	√	√		
2	45,21	M				√	√
3	39,67	L		√		√	
4	11,97	VL		√	√		
5	25,74	L		√	√		
6	0	Not yet					

From the perspective of Facione's critical thinking framework [6], the dominance of low-level categories reflects students' limited abilities in several key components, particularly analysis, evaluation, and self-regulation. Students in the low-level categories tend to have difficulty examining relationships between concepts, assessing the correctness of their reasoning, and reviewing their own solutions. This condition is closely related to the emergence of learning obstacles. Epistemological learning obstacles can arise when students lack an adequate conceptual understanding of geometric principles, while ontogenic learning obstacles, particularly in the conceptual and cognitive aspects, hinder students' ability to process abstract information. Furthermore, didactic learning obstacles contribute when the learning approach does not adequately support the development of higher-order thinking skills. Therefore, these findings highlight that low critical thinking performance is not solely a matter of individual ability but is influenced by the interaction between cognitive limitations and teacher learning factors. This underscores the need for instructional designs explicitly targeted at fostering critical thinking while addressing the underlying learning obstacles in spatial geometry.

In this section, we further analyze the pattern of the relationship between the achievement of each critical thinking indicator (interpretation, analysis, evaluation, inference, and explanation) and the overall critical thinking ability categories (very low, low, medium, high, and very high). The distribution pattern is presented in Figure 2.

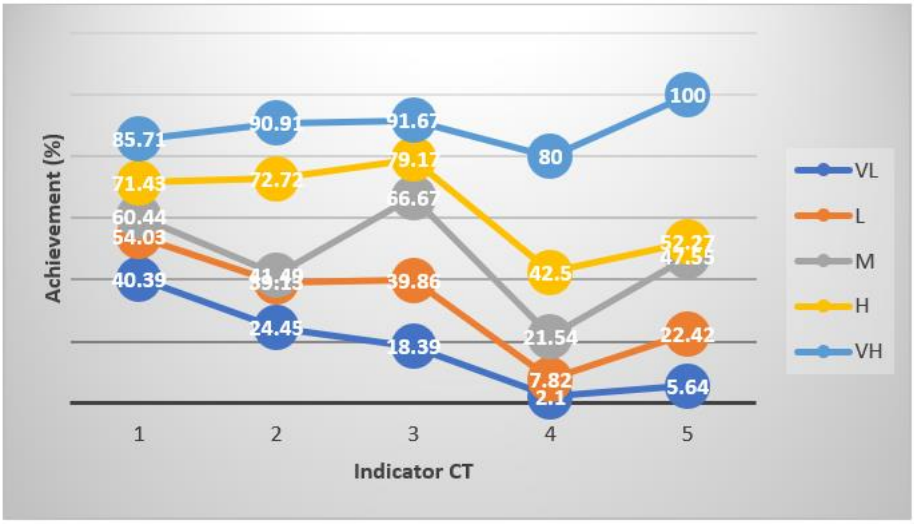


Figure 2. Distribution Pattern of Critical Thinking Skills Achievement by Indicator and Ability Category

Figure 2 shows a linear relationship between critical thinking ability categories (ranging from very low to very high) and achievement in each indicator (interpretation, analysis, evaluation, inference, and explanation). A consistent pattern emerges across each indicator: the higher the critical thinking ability category, the higher the achievement in each indicator. For example, in the interpretation indicator, students in the very low category performed lower than those in the low category, and this pattern continues consistently up to the very high category, which reaches the highest score. Thus, it can be concluded that the higher the category of students' overall critical thinking abilities, the higher their scores on each critical thinking indicator.

Specifically, the inference indicator emerged as a point of difficulty across all categories, including students at higher levels. This finding is highly significant, given that inference represents a high-level cognitive process that requires the integration of prior knowledge, logical reasoning, and evidence-based judgment, as emphasized in [6] framework. Consistently low performance on this indicator suggests that students are not yet fully engaged in reflective reasoning but tend to rely on procedural approaches. From a learning obstacle perspective, this difficulty can be attributed to epistemological obstacles, where students struggle to meaningfully connect concepts, as well as ontogenetic obstacles related to cognitive readiness to handle abstract reasoning tasks.

Furthermore, students in the high category still showed striking gaps, particularly in inference and explanation, while students in the very high category showed relatively stable performance across all indicators. This condition suggests that students have not fully developed the metacognitive awareness and self-regulation skills necessary to validate and justify their reasoning, even for students with relatively strong abilities. Meanwhile, students in the other categories showed uniformly weak performance. This indicates that their difficulties are more fundamental and encompass all components of critical thinking. These findings highlight that the development of critical thinking is not simply gradual but requires deliberate instructional support that explicitly targets reasoning, reflection, and conceptual integration. Without such support, students tend to remain at the procedural level of understanding, which will limit their ability to engage in meaningful mathematical thinking.

The analysis in this section prioritizes students' performance across the first five critical thinking indicators, while the sixth indicator, self-regulation, is examined implicitly when deficiencies in monitoring and evaluating reasoning become evident. Rather than treating each indicator in isolation, the analysis adopts an integrated perspective that links students' achievement with the underlying learning obstacles observed in their responses. This approach allows for a deeper examination of not only *what* difficulties occur, but also *why* such difficulties persist within the learning process.

Regarding learning obstacles, epistemological obstacles consistently emerged across most indicators, indicating that students experienced difficulties in constructing and applying conceptual understanding. Didactic obstacles appeared less frequently, suggesting that instructional factors contributed but were not the primary source of difficulties. Ontogenic obstacles of conceptual, psychological, and instrumental types were also evident, particularly in indicators with low achievement levels. Conceptual obstacles predominated, reflecting students' limited understanding of basic geometric concepts, while psychological and instrumental obstacles further hampered higher-order thinking skills. Importantly, the findings revealed a pattern in which lower levels of critical thinking achievement were associated with more complex learning obstacles. This relationship highlights that students' difficulties are not isolated but interconnected across cognitive and instructional dimensions. Therefore, addressing these obstacles requires instructional interventions explicitly aimed at supporting the development of critical thinking while strengthening conceptual understanding in spatial geometry.

Indicator 1

The results showed that 51.51% of students met the first critical thinking indicator, indicating that most students had developed interpretive competence. This competence relates to the ability to understand and convey the meaning of the situation presented in the problem. The interpretive aspect of critical thinking was evaluated through items 1a, 2a, and 3a.

Various difficulties identified in indicator 1, namely interpretation skills, include:

Many students struggled with question 1a, "Before wrapping the box, what should you do to ensure you use enough paper?" They generally gave non-mathematical answers, such as "We should measure it so that there is not too much or too little" or "choose a large piece of paper." Only one student tried the mathematical approach of breaking the cube into nets (see Figure 3). While a good idea, he inaccurately determined the minimum paper size, instead giving the dimensions of the rectangle formed by the net of the cube.

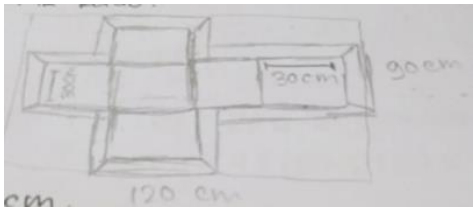


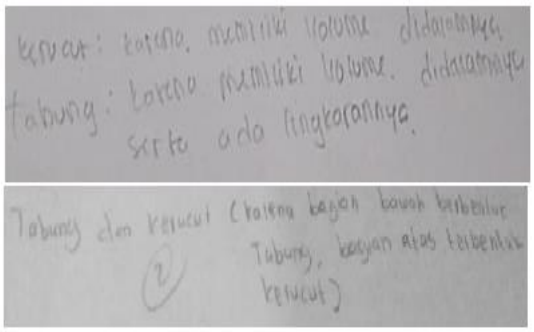
Figure 3. Net of a cube

In short, the students' answers indicate that they do not yet understand the concept of surface area of geometric shapes and often confuse edges with sides. These answers indicate

that students experience an epistemological learning obstacle, where they are unfamiliar with questions that require them to analyze problems. They are usually asked to directly determine the required surface area of a cuboid. This can also be categorized as a didactic learning obstacle, as the textbooks they use do not present problems that train students to think analytically, but instead proceed directly to calculations.

In question 2a, which asked about the geometric shapes that make up a tent, many students correctly answered that the tent is made of cuboids and prisms. However, they were unable to explain their reasoning precisely. This indicates that they only recognize these shapes visually, not based on their mathematical characteristics. Some students even confused the difference between plane shapes (such as rectangles and triangles) and 3-dimensional shapes (such as cuboids and prisms). This difficulty indicates an ontogenetic learning obstacle, where students have difficulty answering because they do not fully understand the basic concepts of prisms and cuboids.

For question 3a, what geometric shapes form a lighthouse? Why? Give a reason. Some students visually recognize the shapes of cylinders and cones, but they struggle to identify the characteristics of these shapes accurately. Some of the characteristics of cylinders and cones provided by students are shown in Figure 4.



Author's Translation
A cone because it has volume inside.
A cylinder is a shape because it has volume and a circle inside.

Cylinder and cone because the lower part is a cylinder.
And the lower part is a cone.

Figure 4. Characteristics of Cylinders and Cones According to S13 and S10

The answers given show that students in classes S13 and S10 experienced conceptual ontogenic learning obstacles because students had difficulty answering questions due to their lack of mastery of the characteristics of cylinders and cones.

Indicator 2

The research findings indicate that only 45.21% of students achieved the second critical thinking indicator. This indicates that less than half of them possessed adequate analytical skills. This ability is reflected in students' capacity to recognize and connect relationships between statements, questions, and their underlying concepts. Conversely, the majority of students (54.79%) still experienced difficulty establishing these relationships, indicating weaknesses in processing and organizing relevant information in a problem. The analytical dimension of critical thinking was measured through items 1b, 2b, and 3b.

Various difficulties identified in fulfilling indicator 2, namely analytical skills, include:

In question 1b, which asks for the size of wrapping paper needed, many students had difficulty answering correctly. The main errors found were: weak conceptual understanding, students were unable to differentiate between the perimeter of a plane figure and the surface

area of a solid figure, some students even tried to calculate by multiplying the number of edges by the length of the edge (i); lack of understanding of formulas, many students calculated directly without writing down the formula they used, this indicates a shallow understanding (ii); arithmetic operation errors, some students understood the concept of surface area, but made errors in calculations, for example when multiplying or simplifying numbers (iii); some students converted units of measurement when not asked, while others misinterpreted the surface area of a cube as the area of a rectangle made from the net of a cube (iv and v).

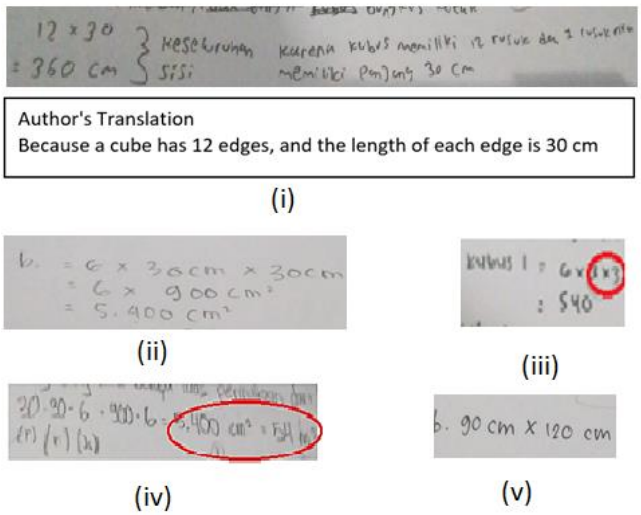
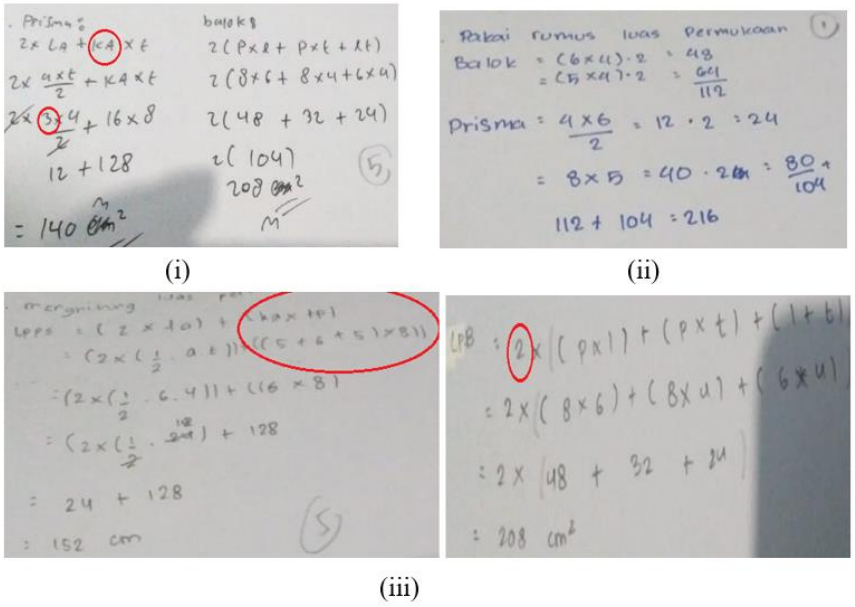


Figure 5. Answers S67, S39, S43, S61, and S63 related to the Surface Area of a Cube

Students who gave answers as shown in Figure 5 parts (i) and (v) are indicated to experience an ontogenic learning obstacle of the conceptual type, because students do not understand the concept of the surface area of a cube. Students who provide answers as shown in Figure 5 parts (iii) and (iv) are indicated to experience ontogenic learning obstacles of the instrumental type, because students do not master the technical aspects that are key in solving the requested problem, in this case, integer operations and the surface area of a cube.

In question 2b, which asks how to find the minimum size of parachute fabric for a tent (the bottom is a cuboid, the roof is a prism), many students experienced difficulty. The main error they made was calculating the total surface area of the cuboid and prism as a whole, without realizing that some sides do not need to be covered by fabric because they are not part of the tent's surface. This error indicates that students are not yet able to evaluate their own thinking process, an important indicator of critical thinking skills (Indicator No. 6). Because of this error, their answers to the next question, which involves calculating the cost of building a tent, were also incorrect. The students' answers are presented in Figure 6.



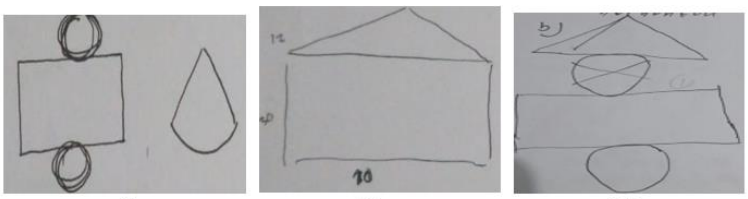
(i) (ii)

(iii)

Figure 6. Answers to S65, S70, and S6 Regarding the Surface Area of the Tent

Students who gave answers as in Figure 6 parts (i) and (iii), combining the surface area of a cuboid and a prism as a whole, were identified as experiencing a conceptual ontogenic learning obstacle because they did not understand the concept of the surface area of a geometric figure, which is a combination of two geometric figures. In addition, students who gave answers as in Figure 6 part (i) were identified as experiencing an instrumental ontogenic learning obstacle because they did not master the technique in determining the base of a triangle as the base of a prism. An interesting finding in this case is that some students called the geometric shape that forms the tent a pentagonal prism, because they considered the shape to be a combination of a cuboid (with 4 sides) and a triangular prism (with three sides). This finding further strengthens the conclusion that students experience ontogenic learning obstacle of the conceptual type.

In question 3b, students were asked to calculate the number of paint cans needed by first drawing the net of the tower. However, most students immediately calculated the surface area of the tower without drawing the net of the tower first. Some students who tried to draw the net of the tower first still made mistakes. These mistakes include: drawing the net of a whole cylinder and cone without a base, drawing the net of a cylinder as a rectangle, and the net of a cone as a triangle with the wrong base size, drawing the net of a cylinder with a base and the net of a cone separately, which is also inaccurate. The net of the tower given by the students is presented in Figure 7.



(i) (ii) (iii)

Figure 7. Answers S54, S61, and S41 Regarding Tower Nets

The students' answers showed that they did not yet understand the relationship between different mathematical concepts. They did not know that the length of the rectangle (the cylinder's cover) must be equal to the circumference of the cylinder's base. They also did not realize that the net of a cone is a sector of a circle, not a triangle, where the arc length is equal to the circumference of the cone's base.

Before calculating the paint requirements, students had to calculate the surface area of the tower. Several student answers showed various errors: Student S54, although he did not draw the tower's net correctly, managed to calculate the tower's surface area correctly; Student S61 calculated the surface area by multiplying the dimensions in the drawing, without using the correct formula; Student S43, besides not drawing the tower's net correctly, also used the formula for the surface area of a cylinder and a cone incorrectly. Various answers related to the tower's surface area are presented in Figure 8.

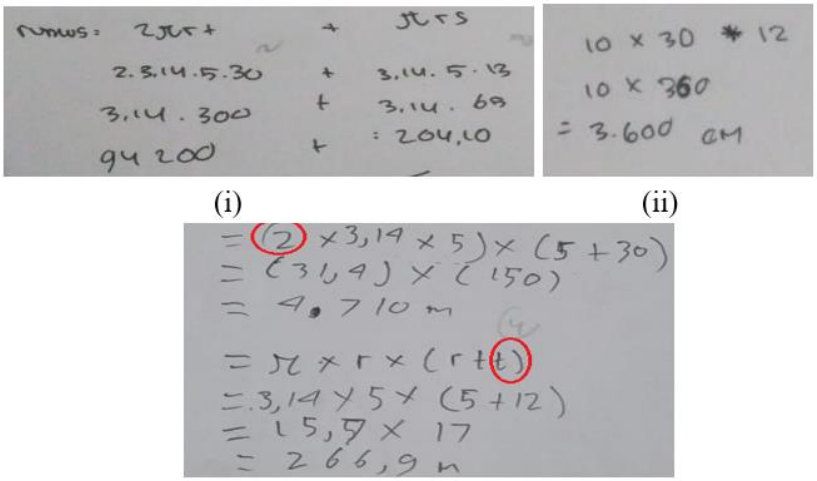


Figure 8. Surface Area Answers of Students S54, S61, and S41

Students who gave answers as shown in Figure 8 parts (ii) and (iii) are indicated to experience ontogenic learning obstacles of the psychological type, because students have low interest in solving problems, marked by weak prerequisite knowledge related to the area of flat shapes; in this case, the area and circumference of a circle. Another finding is that S64 wrote the formula for the surface area of a cylinder correctly, but did not understand the use of the value of π. The value of π is used simultaneously in one formula, as depicted in Figure 9.

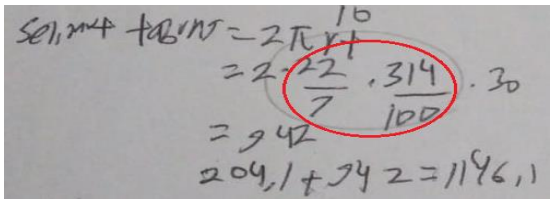


Figure 9. Surface Area of Cylinder from Student S64

Indicator 3

The test results showed that only 39.67% of students met the evaluation ability indicator in critical thinking, which means that the majority (60.33%) of students were

unable to assess the reliability of information or draw conclusions from the relationships between concepts. This made it difficult for them to complete questions that tested these abilities, namely, questions 1c and 3b.

Various difficulties identified in fulfilling indicator No. 3, namely analytical skills, include:

In question 1c, which asks for the area of the wrapping paper for a cube whose edges are enlarged 3 times, most students do not understand the concept of changes in surface area. They do not know how to calculate the surface area of the cube after the size is enlarged. Some common errors are: Student S46 multiplies the enlargement (3 times) by the surface area of the original cube that he has calculated correctly; Student S67 does the same, but he multiplies the enlargement by the surface area of the original cube that he has calculated incorrectly. An error in calculating the surface area of the gift box in this section will lead to incorrect conclusions about the consequences of changing edge lengths on the surface area ratio when the edge size is increased/decreased, particularly in relation to the surface area of the original shape. An error in calculating the initial surface area of the box will lead to incorrect conclusions about the surface area ratio when the edge size is changed. These answers are presented in Figure 10.

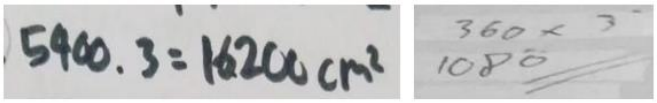
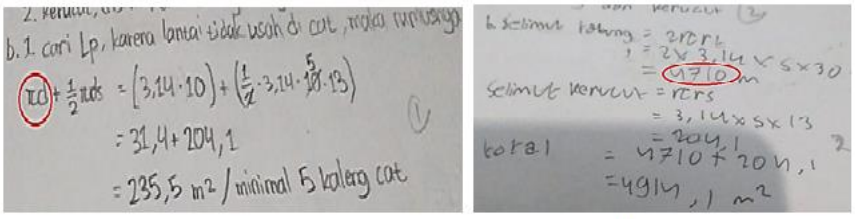


Figure 10. Answers Student S46 and S67

For question No. 3b, regarding the question: How many cans of paint are needed to coat the outer surface of the tower? S43 knows what to do, namely, determine the surface area of the cylinder and cone. However, the formula given for the surface area of the shape is wrong, as shown in Figure 11, part (i). It can be seen that S43 is not quite right in determining the formula for the surface area of the cylinder; he only uses the formula for the circumference of the base circle, which should be multiplied by the height of the cylinder. Meanwhile, the formula for the surface area of the cone is correct even though it does not use the commonly used formula, namely $L = \pi rs$.



(i) (ii)

Author's Translation

Find the surface area, because the tower floor doesn't need to be painted, so the formula is:
= ....
= 255.5 cm²/minimum five cans of paint

Author's Translation
Circumferential surface area =
Cubecumferential surface area =
Total =

(i) (ii)

Figure 11. Answers of Students S43 and S45 Regarding the Surface Area of the Tower

Student S 45 knew he had to calculate the surface area of the tower to determine the amount of paint needed. Although he correctly used the formulas for the surface area of a cylinder and a cone, he made a mistake in the multiplication operation. This error not only resulted in an incorrect answer for the amount of paint but also affected the calculation of the total cost required. This condition indicates that the student failed to reflect on or evaluate his thinking process, which means he has not achieved one indicator of critical thinking skills.

Based on the identified answers, students' ability to conclude the relationship between information and concepts is still relatively low. This condition refers to two types of learning obstacles. First, epistemological obstacles, where students have difficulty integrating new information with prior knowledge or applying concepts to different situations. Second, psychological ontogenic obstacles, characterized by minimal mastery of prerequisite concepts, particularly regarding the surface area formula and integer multiplication operations.

Indicator 4

The findings showed that only 11.97% of students demonstrated proficiency in the inference component of critical thinking, indicating that the majority (88.03%) were unable to draw conclusions from the data and evidence provided. This suggests that students have limited ability to integrate information and construct logical inferences. As a result, they face significant challenges in answering questions that specifically require these skills, particularly questions 1d, 2d, and 3c.

Various difficulties identified in fulfilling indicator 4 of critical thinking skills include:
In problem 1d, which asks for a formula to compare the size of the second wrapping paper to the first, some students who successfully found the ratio still had difficulty presenting it in a general formula (if the magnification is k times). More than 85% of students were unable to solve this problem at all because they were unable to calculate the surface area of the initial cube and the surface area after the magnification. The answers given indicate that they do not yet understand the basic concepts needed to solve the problem. Some answers are presented in Figure 12 below.

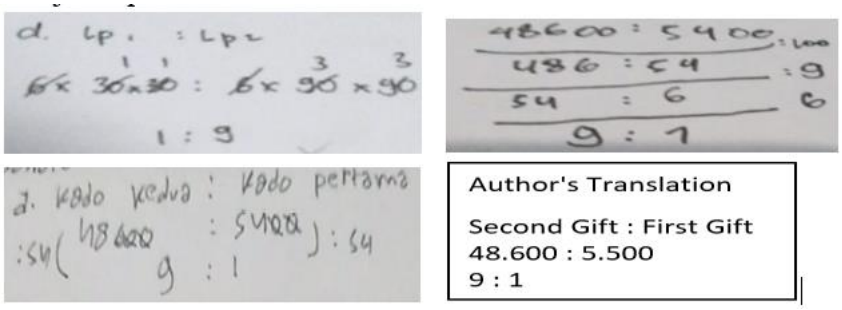


Figure 12. Answers S43, S45, and S47 Regarding Comparison of the Surface Area of Gifts

Based on the analysis of students' answers, it can be concluded that their ability to draw conclusions based on data, information, or evidence remains limited. The answers also indicate that students experience an ontogenic learning obstacle of the conceptual type, as they do not understand the concept of the surface area of a cube when its edges are enlarged.

A significant number of students failed to arrive at the correct solution for item 2d, which required calculating the cost of constructing a tent. This problem was largely due to incorrect determination of the total surface area to be covered, including the base, sides, and roof. Errors in the initial step led to further inaccuracies in determining the required cost. This suggests that student errors are interconnected, with errors in the initial stage influencing subsequent stages of problem-solving.

From a learning obstacle perspective, these findings indicate that students experience epistemological and ontogenic learning obstacles. Epistemologically, students have limited ability to apply the concept of surface area in contextual situations. Ontogenically, particularly in the conceptual type, students struggle to integrate geometric understanding with the context of practical problems. The errors observed in item 2d are closely related to those identified in item 2b, indicating that students' reasoning processes remain low and coherent across related tasks. These findings highlight the importance of teaching strategies that emphasize conceptual integration and support the development of more structured mathematical reasoning.

Student S65 used a seemingly appropriate strategy of multiplying the calculated surface area by the cost of fabric per meter; However, the solution was ultimately incorrect due to an error in determining the surface area itself. In contrast, students S43 and S45 determined the correct surface area but failed to accurately interpret the problem context, calculating the cost for only one tent, rather than all four required. This finding illustrates that failures in problem-solving can occur at various stages, both at the level of conceptual understanding and in applying the solution to the given context.

Considered within [6] framework, these patterns indicate deficiencies in evaluation and self-regulation. Evaluation requires students to critically assess the accuracy and completeness of their reasoning, while self-regulation involves monitoring and adjusting one's cognitive processes. The students' inability to ensure that their answers fully meet the criteria for problem solutions indicates limited engagement in reflective thinking. Instead of reviewing and validating their solutions, they relied on partial reasoning without confirming its adequacy. This suggests that their difficulties go beyond procedural errors and are closely related to underdeveloped higher-order thinking skills, particularly in evaluating and regulating their own reasoning processes. Selected student responses are presented in Figure 13.

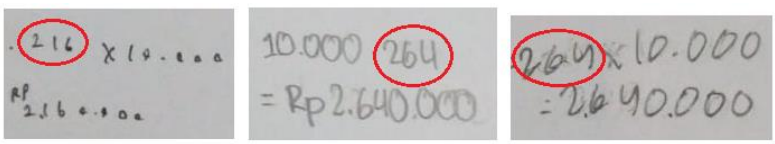


Figure 13. Answers S65, S43, S45 Regarding Tent Construction Costs

Students who provide answers as illustrated in Figure 13 can be identified as experiencing epistemological learning obstacles, due to their limited ability to interpret and apply problem contexts outside of routine situations. From the perspective of [6] framework, this difficulty is closely related to weaknesses in interpretation and application (analysis), where students fail to accurately understand the problem's demands and relate them to the

information provided. Their reasoning reflects a tendency to rely on familiar procedures without critically examining their appropriateness for the specific context presented.

Furthermore, these response patterns indicate that students' prior experience was largely limited to solving tasks involving single objects, such as calculating surface area, cost, or quantity of material in simple situations. Consequently, when faced with problems requiring extension or adaptation, such as considering multiple objects, they struggled to transfer and adapt their knowledge. These limitations reinforce the existence of epistemological obstacles, where students' understanding remains fragmented and context-bound, preventing them from engaging in more flexible and comprehensive reasoning processes.

In problem 3c, which focused on calculating the cost of painting a tower, many student responses indicated difficulty aligning conceptual understanding with proper procedures. A significant number of students were unable to correctly determine the surface area of the tower, and this initial inaccuracy impacted subsequent stages of their work, resulting in incorrect calculations of paint volume and overall cost. This pattern suggests that student errors are interconnected, with early misunderstandings affecting the entire problem-solving process, reflecting a lack of coherent understanding of geometric concepts in an applied context.

From a critical thinking perspective, the results revealed limitations in students' ability to engage in reflective judgment and make reasoned decisions, particularly with regard to the evaluation and self-regulation components [6]. Evaluation involves determining the validity and completeness of one's reasoning, while self-regulation refers to the ability to monitor and refine one's thinking processes. The observed responses indicate that students tended to perform procedural calculations in isolation, without critically assessing whether their reasoning was coherent and fully addressed the demands of the problem.

As a result, students often arrive at solutions that are only partially correct and do not fully solve the problem. This indicates a lack of continuous checking and refinement in their reasoning processes, which are essential elements of higher-order thinking. These findings underscore the need for teaching approaches that intentionally foster evaluation and self-regulation skills, especially in mathematics tasks involving multi-step processes and contextual interpretation. Illustrations of student responses are presented in Figure 14.

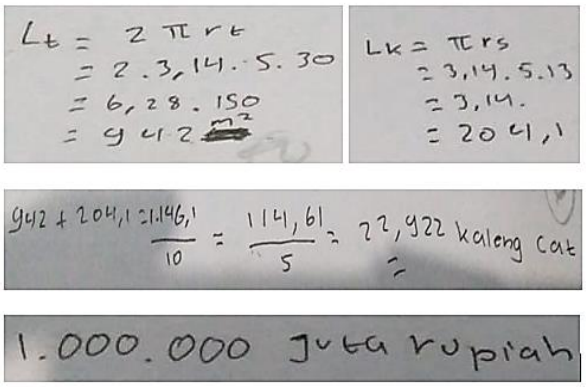


Figure 14. Answer S15 for Painting Costs

Indicator 5

The results showed that only 25.74% of students achieved the critical thinking ability indicator for explanation. The majority of students (74.26%) were unable to express their reasoning in a structured and logical manner, including providing adequate justification for their conclusions. This weakness hampered their ability to respond effectively to items that specifically require explanatory reasoning, particularly questions 1e and 2c.

Various difficulties identified in fulfilling the five critical thinking ability indicators include:

In problem 1e, which required students to estimate the amount of wrapping paper needed, many students failed to provide a correct solution, primarily due to an incomplete understanding of the concept of surface area. This suggests that a lack of conceptual understanding significantly limited their ability to solve the problem effectively. Even when students attempted the problem, analysis revealed a variety of errors stemming from different types of learning obstacles. For example, student S16 made a calculation error related to multiplication, indicating an instrumental-type oncogenic obstacle that impacted the accuracy of his results. Student S6 demonstrated an understanding of surface area but failed to consider the size of the packaging available in a real-world context, reflecting a gap in applying mathematical reasoning to practical situations.

Meanwhile, student S68 failed to distinguish between the different sizes of wrapping paper provided, indicating difficulty interpreting key information in the problem. These findings suggest that student errors stem from a combination of conceptual misunderstandings, procedural weaknesses, and contextual misinterpretations. Examples of student responses are presented in Figure 12.

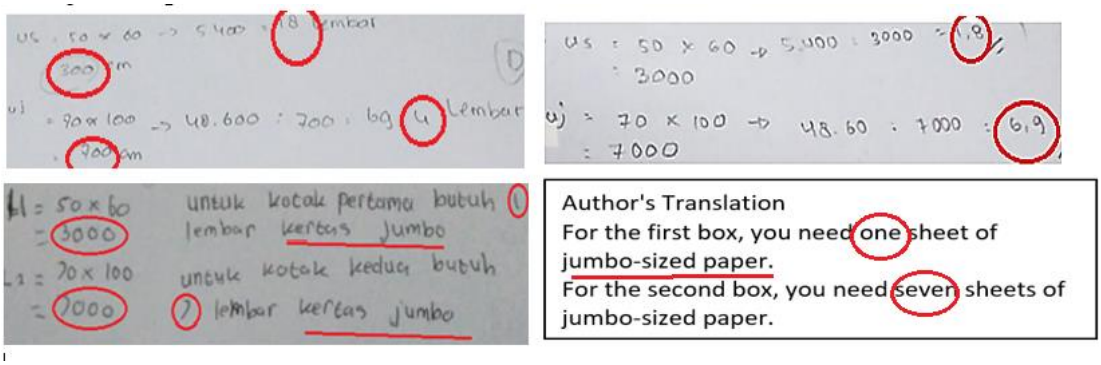


Figure 12. Answers of S16, S68, and S6 Regarding the Amount of Wrapping Paper

The students' answers, as shown in Figure 12, indicate that their ability to explain is still low, as they are unable to provide explanations for the conclusions they have drawn. The students' answers in Figures 12(ii) and (iii) indicate an epistemological learning obstacle in the form of difficulty applying concepts to more complex situations. Based on document analysis, this obstacle, resulting from limited context, stems from students' habit of working on exercises that are too simple, such as simply determining paper size from surface area calculations.

In question 2c, students were asked to evaluate whether 240 m² of parachute fabric was sufficient to construct a tent. However, the majority of students answered incorrectly due to technical errors in calculating the surface area of the tent. The main errors found

included calculating all sides of the cuboid and prism without realizing that there were sides that did not need to be covered, and ignoring the base of the tent that should have been included. In addition to calculation difficulties, students also experienced difficulties in reasoning and communicating their answers. As shown in Figure 12, both students who calculated incorrectly and those who calculated correctly failed to provide logical arguments and conclusions relevant to the context of the problem. Based on this series of errors, students are indicated to experience ontogenic learning obstacles of the conceptual type, which are rooted in a fundamental lack of understanding of the concept of surface area of geometric shapes, especially for combinations of cuboids and prisms.

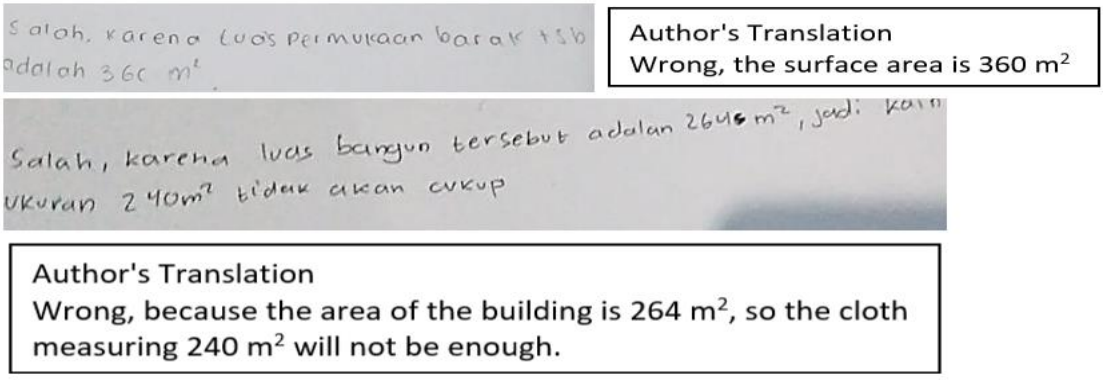


Figure 12. Answers to S6, S8, and S15 related to the conclusion of surface area

The average level of students' critical thinking is in the low category, as found in this study, reinforcing the results of [41], which concluded that students' critical thinking skills in solving geometric problems are generally low, mainly due to inadequate mastery of basic material. The results of this study are in line with the results of [42], which concluded that students' critical thinking skills are in the low category. Students' difficulty in determining the surface area of a geometric figure is caused by their inability to understand the concept of geometric nets, which are a combination of two basic geometric figures they have learned, in line with [43], which states that mathematical visualization is the formation and use of images or mental representations to facilitate a more effective understanding of mathematical concepts.

The results of the study indicate that students' critical thinking skills still vary across indicators, indicating that not all aspects of critical thinking are optimally developed. This finding is in line with [44], who stated that critical thinking skills require learning designs that explicitly facilitate the processes of analysis, evaluation, and reasoning through structured learning activities. In addition, this study also found that students' learning obstacles primarily arise when they have to connect three-dimensional representations with geometric nets and determine the area of each side accurately. These results are consistent with the findings of [45], who showed that students' main difficulties in surface area material are caused by the inability to connect concrete objects with their geometric representations. Overall, these two findings indicate that low critical thinking skills have the potential to strengthen the emergence of conceptual learning obstacles in geometry material, so that learning designs are needed that can develop reasoning while facilitating effective concept visualization.

Previous studies on geometry learning have highlighted the importance of identifying students' learning obstacles as a basis for developing effective instructional designs. Novianda and Turmudi [46] emphasized the occurrence of ontogenic, epistemological, and didactical obstacles in geometry learning, while Pauji et al. [47] identified similar obstacles across studies employing the Didactical Design Research (DDR) framework. These findings suggest that students' difficulties should not be addressed solely through repeated practice or formula memorization but through instructional designs that respond to the underlying sources of learning obstacles. In particular, didactical redesign should provide meaningful learning experiences, appropriate visual representations, and guided opportunities for students to develop conceptual understanding and mathematical reasoning.

Students' difficulties in connecting three-dimensional geometric objects with their two-dimensional representations can also be understood through the literature on spatial visualization and spatial reasoning. Spatial visualization involves the mental manipulation and transformation of visual representations, whereas spatial reasoning requires students to coordinate visual information with geometric properties and mathematical relationships [48], [49]. Fujita et al. [49] demonstrated that interpreting two-dimensional representations of three-dimensional geometric shapes requires students to integrate spatial visualization with analytical reasoning based on geometric properties. This perspective provides a complementary explanation for the learning obstacles identified in this study, particularly students' difficulties in interpreting geometric nets and determining surface areas accurately. These findings suggest that geometry instruction should not focus solely on formula recall and procedural calculations but should also incorporate concrete models, visual representations, and guided activities that help students connect geometric diagrams with the properties of three-dimensional objects.

Meanwhile, the finding that students experienced ontogenic and epistemological learning obstacles in this study aligns with the research of [50], which concluded that junior high school students faced ontogenic and epistemological learning challenges in understanding the concept of geometric shapes. The results of this study also strengthen the research of [51], which concluded that students experienced epistemological learning obstacles due to limited knowledge in mathematical concepts related to algebraic forms, as well as the research of [52], which concluded that in mathematics learning, most students experienced learning obstacles in learning mathematics meaningfully. This study found didactic learning obstacles because the textbooks used did not develop students' analytical skills. The questions in the textbooks tended to be directly calculation-oriented, a weakness that teachers could ideally address in the classroom. This finding aligns with research [53], which states that the quality of education is determined by competent educators and supported by sound policies. In an education system, education policy, curriculum, teachers, and textbooks are interconnected. Policy sets the direction, the curriculum outlines that direction, teachers implement the curriculum, and textbooks serve as the primary tool.

An analysis of students' answers indicates difficulties in correctly applying formulas for the perimeters of geometric shapes. These difficulties are likely related to conceptual understanding, mastery of the formulas, or the ability to recall relevant mathematical procedures. This finding is relevant to research [54] and [55], which emphasized that poor

memory is one of the main inhibiting factors in learning mathematics. More specifically, Zakiyah [56] stated that poor memory can trigger learning difficulties, especially for students who are classified as slow learners. This is in line with the conclusion of [57], who stated that the aspect of memory is a determining factor that influences both students' interest and level of difficulty in learning mathematics.

4. CONCLUSION

The findings indicate that students' critical thinking skills in solving geometry problems were generally low, with varying levels of achievement across the six indicators. Interpretation and analysis were classified as moderate, evaluation and explanation as low, and inference as very low. Interpretation showed the highest achievement, whereas inference showed the lowest, indicating that students experienced greater difficulty drawing logical conclusions from geometric information and mathematical relationships than interpreting information presented in problems. Self-regulation was not demonstrated in the students' written responses; however, this finding should not be interpreted as evidence that students lacked self-regulatory skills, since the written test did not directly capture their metacognitive processes.

Analysis of students' responses and learning documents identified indications of ontogenic, epistemological, and didactical learning obstacles. Difficulties in applying prerequisite knowledge and mathematical procedures suggested possible ontogenic obstacles, although further evidence is needed to establish their underlying causes. Epistemological obstacles were reflected in students' difficulties connecting geometric concepts with different representations, particularly in interpreting geometric nets and determining surface areas. Meanwhile, the analysis of the examined textbooks revealed an emphasis on direct calculations and formula application, suggesting limited opportunities for students to engage in more varied forms of geometric reasoning. Nevertheless, these findings do not establish a direct causal relationship between textbook characteristics and students' learning difficulties.

These findings highlight the need for geometry instruction that integrates conceptual understanding, spatial visualization, mathematical reasoning, and opportunities to evaluate and justify solutions. Future research should examine the relationship between specific critical thinking indicators and learning obstacles using more detailed analyses of students' responses and interviews. Reflective questions or think-aloud protocols should also complement written tests when investigating self-regulation. The resulting evidence can inform the development and evaluation of didactic designs that address conceptual, procedural, and representational difficulties in geometry learning.

Based on the research findings, several recommendations are proposed for future research development and the improvement of instruction. First, the development and implementation of instructional models should focus on redesigning didactic situations that specifically target identified weaknesses in critical thinking skills and learning obstacles. Drawing upon the Didactical Design Research (DDR) framework and Brousseau's theory of learning obstacles, instructional improvements can be achieved by strengthening didactic transposition, providing concrete visual scaffolding, and structuring learning activities in a

phased manner that accounts for the nature of students' epistemological and ontogenetic obstacles. In the context of geometry instruction, for instance, students should be supported in distinguishing between the concepts of perimeter and area, understanding the relationship between three-dimensional shapes and their nets, and developing the ability to draw conclusions through exploration, the comparison of representations, the testing of strategies, and reflection on errors. The learning process should also provide students with opportunities to articulate their reasoning, validate their own thinking, and independently evaluate their problem-solving strategies. In this regard, the use of immersive digital environments, including the metaverse, could be considered as a supporting medium, provided it is designed based on identified didactic needs; for example, to visualize geometric objects, dynamically manipulate representations, and facilitate collaborative problem-solving. Digital documentation and reflection features also hold the potential to support the development of self-regulation. Thus, technology is not positioned as the primary solution, but rather as a tool whose effectiveness must be evaluated based on its alignment with the didactic design and the specific learning obstacles faced by students. Second, future research should delve deeper into the underlying factors that give rise to learning obstacles, including psychological aspects such as interest, motivation, and mathematics anxiety, while also analyzing textbooks, teaching materials, and instructional practices to identify potential didactic obstacles. Third, research needs to be extended to different educational levels, school characteristics, and learning contexts to examine the consistency of patterns regarding learning obstacles and students' critical thinking skill attainment. Further research could also involve developing, implementing, and evaluating didactic designs, refined through the Didactic Design Research (DDR) cycle, so that the effectiveness of these improvements can be assessed based on students' responses and shifts in their thinking processes.

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