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Enhancing self-regulated learning and critical thinking in STEM through flipped classroom models

Ali Akhmad Setiyawan *, Arief Agoestanto, Isnarto

Department of Mathematics Education, Universitas Negeri Semarang, Central Java, Indonesia

* Correspondence: ali7akhmad@students.unnes.ac.id

Abstract

One of the causes of low proficiency among high school students in mathematical critical thinking is their lack of willingness to learn independently. This study investigated the mathematical critical thinking skills and self-regulated learning of high school students through the Flipped Classroom STEM approach. The research employed a sequential explanatory design, beginning with quasi-experimental pre-tests and post-tests for quantitative assessment of the learning process, followed by qualitative methods such as questionnaires, interviews, and observations for deeper analysis. Data analysis utilized quantitative techniques, including normality and homogeneity tests and hypothesis testing in SPSS, alongside qualitative methods for data reduction, data presentation, and conclusion. The findings revealed that flipped classroom learning significantly improved students' abilities in critical mathematical thinking, particularly highlighting the importance of self-regulated learning. There was a notable difference in post-test scores compared to those from traditional learning methods. Moreover, the study found that students with higher self-regulated learning skills were more effective in critical thinking, underscoring the effectiveness of the flipped classroom approach in fostering independent learning and enhancing essential thinking abilities in mathematics education.

Keywords: flipped classroom; mathematical critical thinking; self-regulated learning; STEM

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Introduction

Critical mathematical thinking is a high-level cognitive skill students must develop to compete in the global marketplace (Ramadhanti et al., 2022). It is a component of the Higher Order Thinking Skills (HOTS) stage, which highlights the necessity for students to take specific actions when confronted with the facts of a problem or concept (Susilowati & Sumaji, 2021; Puspitasari et al., 2017). Mathematical critical thinking skills continually sharpen students' abilities to identify and elaborate on subject matter, leading to discoveries and logical problem-solving (Ulfa, 2020; Winda & Hendro, 2022). Afriansyah et al., (2020) contend that critical thinking skills in mathematics study can enable students to gain a deep understanding and solve problems associated with diverse mathematical concepts. Furthermore, Ariawan and Zetriuslita (2021) suggested that to possess the foundational skills required for critical mathematical thinking, students must be capable of comprehending ideas, applying and synthesizing facts, and evaluating the data they receive. Teaching mathematics to children is crucial in theoretical terms, as well as developing critical thinking skills, enabling them to tackle various challenges they face (Agoestanto et al., 2017). Critical thinking is mastering fundamental thought processes for analyzing arguments, fostering insights into particular meanings, and understanding certain conditions' assumptions (Angkotasan & Jalal, 2019). According to these perspectives, mathematical critical thinking is the capacity for effective thinking that aids in assessing and making decisions regarding the objectives to be achieved. However, reality does not always align with these ideals.

The research by Lestari and Roesdiana (2021) at SMP N 3 West Karawang revealed that students' mathematical critical thinking skills (MCTS) are low, with 19.44% categorized as less and 80.55% as very low. Similarly, surveys at SMA Islam Sultan Agung 2 Kalinyamatan, where the minimum grading score is 70, showed that up to 34% of eleventh graders did not meet the requirements for a satisfactory Semester Middle Grading score (ATS). Achieving the minimum grading score indicates that a student has successfully learned, suggesting the presence of MCTS. However, for students to succeed and meet the minimum grading scores, they must deeply understand the learning material. The ability of students to understand material hinges on the provision of an appropriate learning method/model, as the conceptual framework by Isnarto et al. (2018) illustrate a system flow that offers students learning experiences to reach the intended peak of learning. By employing appropriate and varied learning models, teachers can give instructions that enhance the quality of student learning to accomplish the intended goals (Szabo et al., 2020). Therefore, various learning models and methods are essential for delivering mathematics material (Widiastuti & Rahmah, 2023). Similarly, to improve students' MCTS, a learning model that supports student learning is required. Thus, when developing MCTS, alignment with teaching methods is necessary to ensure a comfortable learning experience (Widiastuti & Rahmah, 2023). Furthermore, as we enter the era of 21st-century globalization, also known as the Industrial Revolution 4.0, the rapid development of technology to meet the evolving demands of science necessitates that humans continue to develop to keep pace with these changes (Aspi & Syahrani, 2022). Consequently, learning must adapt to technological advancements, in this case, by incorporating technology into material delivery, such as the flipped classroom (FCs) learning approach.

The latest development in the realm of education in Indonesia has seen the introduction of Flipped Classrooms (FCs) across various educational levels, driven by their distinctive learning process that demands students independently manage their study time, sometimes even collaboratively within the classroom (Al-Samarraie et al., 2020). Flipped Classrooms are highly regarded for optimizing time, integrating technology, and adapting processes to individual needs (Colomo-Magaña et al., 2020). Furthermore, the Science, Technology, Engineering, and Mathematics (STEM) approach in 21st-century education enhances students' critical thinking by engaging them in real-life situations and interdisciplinary problems (Tonkin et al., 2019; Topsakal et al., 2022). This approach, combined with Flipped Classrooms, encourages active and independent learning, allowing students to absorb materials at their pace outside of class and engage in depth during class sessions through discussions and project-based activities. Both methods synergize to increase student engagement and understanding, laying a solid foundation for critical thinking skills development. A study by Li et al., (2020) highlighted the international significance of STEM education from 2000 to 2018, demonstrating its contribution to learning at various levels. The integration of FCs with STEM (FCs-STEM) aligns with constructivist learning theories by Jean Piaget and Lev Semyonovich Vygotsky, emphasizing the active role of students in the learning process with teachers serving as mentors and facilitators (Agustyaningrum et al., 2022). Moreover, to enhance Metacognitive Thinking Skills (MCTS), students must develop self-regulated learning (SRL) skills, such as perseverance and a willingness to learn. The Indonesian Ministry of Education and Culture's Regulation Number 16 of 2022 supports this by advocating for effective and efficient learning processes to optimize students' potential and SRL (Kemendikbudristek, 2022). Research by Siagian et al., (2020) at SMA Negeri 7 Bekasi revealed that the level of SRL significantly influences MCTS. However, a study at SMA Sultan Agung 2 Kalinyamatan in 2023 showed that 34% of students still needed to meet the minimum grading score, indicating a gap in understanding. This underscores the importance of fostering SRL to improve students' MCTS development, suggesting that providing varied learning experiences can facilitate critical mathematical thinking and overall skill development.

Previous studies relevant to FCs-STEM learning, such as Study Karunia and Ridlo (2022) have similarly explored implementing the flipped classroom model integrated with the STEM approach to enhance students' critical thinking abilities. This study and the research above utilized quantitative and qualitative methods to collect and analyze data, adopting random sampling techniques. Study by Karunia and Ridlo (2022) focused on the development of learning tools usable during the COVID-19 pandemic, while this study takes a broader approach, covering aspects of students' self-regulated learning in the context of mathematics learning. Study Weinhandl et al. (2020) focused on teachers' professional development in implementing the flipped classroom and STEM approaches. This study and the others underscore the importance of education and professional development for teachers to integrate educational innovations, such as the flipped classroom, into mathematics and STEM teaching. Puspitasari et al. (2020) identified the need for innovative teaching materials to enhance students' critical thinking abilities, such as e-modules integrated with the flipped classroom and STEM approaches. Specifically, Study by Puspitasari et al. (2020) explored the needs of teachers and students regarding integrated e-modules, whereas this study examines the implementation and effectiveness of these approaches in a broader context. The difference is that study Karunia and Ridlo (2022) specifically developed and evaluated learning tools during the COVID-19 pandemic. This study has a broader scope by evaluating the influence of the flipped classroom STEM on students' mathematical critical thinking abilities and self-regulated learning without the context of the pandemic being a limitation. While study by Weinhandl et al. (2020) focused on the professional development of teachers for applying the flipped classroom approach in mathematics and STEM education, this study is more focused on the effectiveness of flipped classroom-STEM learning from the student's perspective, especially in enhancing mathematical critical thinking abilities and self-regulated learning skills. Study by Puspitasari et al. (2020) focused on the needs analysis for integrated e-modules for flipped classrooms and STEM learning. In contrast, this study directly evaluates the implementation and impact of these approaches on student abilities, providing empirical evidence about their effectiveness.

This research novelty integrates the flipped classroom approach with STEM education, emphasizing self-regulated learning in the context of mathematics. Unlike prior studies, which centered on the development of learning tools, needs for e-modules, or teacher professional development, this study offers empirical evidence on how the combination of flipped classrooms and STEM can enhance students' mathematical critical thinking abilities and foster self-regulated learning skills. This provides fresh insights into effective learning designs to support 21st-century skills among high school students, especially in preparing them for independent and lifelong learning. The research aims to investigate various scenarios wherein flipped classroom-STEM (FCs-STEM) learning is utilized. It is anticipated that this experiment will successfully establish the students' mathematical critical thinking skills (MCTS) and self-regulated learning (SRL). The study's implementation aims to demonstrate that students who undergo FCs-STEM learning are more likely to complete the course, these students exhibit higher MCTS compared to those in conventional classes, FCs-STEM learning significantly improves students' MCTS, and these students show a greater degree of SRL than their counterparts in traditional classrooms.

Methods

This study employed a mixed-methods approach, specifically the sequential explanatory design, starting with the collection and analysis of quantitative data, followed by the collection and analysis of qualitative data to reinforce the findings from the initial quantitative analysis. This research focused on the collection and analysis of quantitative data, as well as the integration of quantitative findings to inform qualitative data collection. The sequential explanatory design was chosen based on Creswell's (2010) explanation that it is easy to describe and report because it emphasizes straightforwardness and transparency.

The quantitative study used a quasi-experimental approach, employing a non-equivalent control group design that included pretests and posttests to evaluate the effects of FCs-STEM and PBL on students' mathematical critical thinking abilities. Two classes, A (experimental) and B (control) were given pretests to assess students' initial abilities, followed by different treatments, FCs-STEM for the experimental class and PBL for the control class, before conducting posttests to evaluate the learning outcomes. This research was conducted in three stages: initial preparation with validation of the learning instruments, the quantitative phase with the implementation and evaluation of learning, and the qualitative stage involving interviews to analyze further the learning methods' impact on students' self-directed learning and mathematical critical thinking abilities.

The population of this study consisted of students from Sultan Agung 2 Islamic High School in Kalinyamatan, with samples taken from classes XI F2 and XI F8. The material used in the study was Mathematics Vectors in R2. The research was carried out in the experimental class (XI F8) code A and the control class (XI F2) code B in five sessions during the Spring Semester of the 2023–2024 academic year, or approximately one month. Classes XI F2 and XI F8 each had 34 students. In this study's quantitative data collection phase, the instruments used were a pretest to assess students' initial mathematical abilities and a posttest MCTS. Triangulation was conducted in the qualitative stage to support the quantitative data findings.

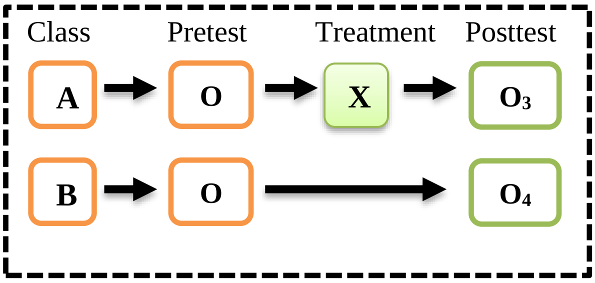


Figure 1. Research design

First, SRL questionnaire was presented to each class (A and B), and the results were categorized into three categories: high, medium, and low. Then in the self-regulated learning questionnaire, the indicators used are reductions from (Sumarmo, 2004; Sundayana, 2016), namely (1) learning initiation, (2) setting goals, (3) diagnosing learning needs, (4) sorting learning resources, (5) applying learning strategies, (6) learning motivation, (7) cooperating, and (8) self-control. In the SRL test, the evaluation according to Table 1 is taken into consideration and the value per sub-indicator is utilized to test the student's SRL level.

Table 1. SRL scoring guidelines for each sub-indicator

Indicators	Very often	Often	Seldom	Rarely
Learning Initiative	4	3	2	1
Diagnosing Learning Needs	4	3	2	1
Setting Learning Goals	4	3	2	1
Selecting and Using Sources	4	3	2	1
Selecting and Implementing Learning Strategies	4	3	2	1

Indicators	Very often	Often	Seldom	Rarely
Independent Learning	4	3	2	1
Cooperate with others	4	3	2	1
Self control	4	3	2	1

Following that, a pretest is administered to ascertain the student's baseline mathematical proficiency, and they are subsequently treated in accordance with their class. After that, the experiment class did the posttest. Subsequently, the posttest data was triangulated. For conventional classes, learning is provided using a problem-based learning path. Meanwhile, in the experimental class, learning is provided using a flipped classroom model with a STEM approach.

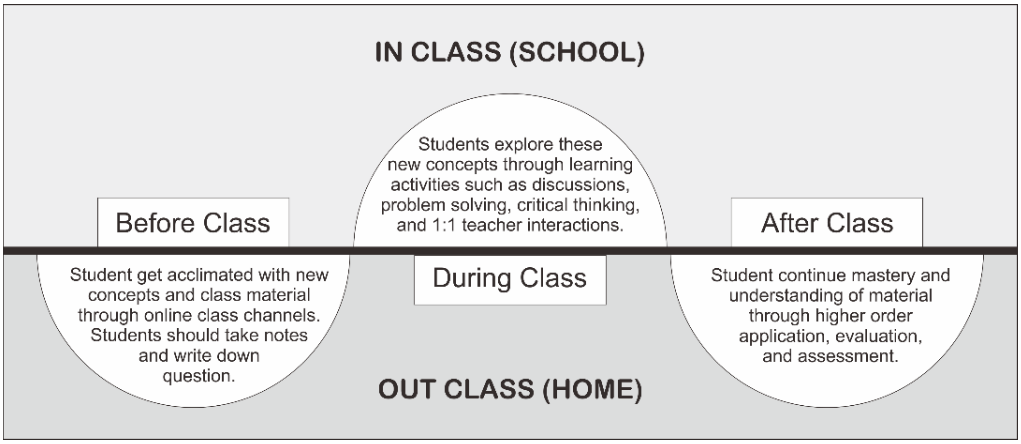


Figure 2. Flipped classroom steps

In session 1, students learn independently without teacher assistance. Students are informed via the WhatsApp group, then each student accesses the online class on Google Classroom with the link https://classroom.google.com/c/NTQyODEwMTA2Mzg0. In this online class, students fill out an attendance list, study basic material based on trigger questions, and fill out a "question" form to be answered and discussed at real class meetings. Students who do not attend the asynchronous session will receive punishment in the form of additional assignments from the teacher.

In session 2, students study, in a real classroom accompanied by a teacher. Students are given a mathematical worksheet that relates to the material they have previously studied. The worksheets are structured using the STEM approach. Apart from discussing the worksheet, students and the teacher discuss questions that have been previously asked during e-learning. Then in session 3, students are given complete material according to what they learned in real classes via e-learning. Then, students carry out assessments provided by the teacher in e-learning, to find out the extent of students' understanding of the discussion of the material.

Sessions 1 to 3 take place repeatedly at the first to sixth meetings. The STEM approach is integrated into real classroom learning, which allows students to explore their potential and think critically mathematically. After all meetings were finished, experimental class students were given a posttest. The posttest is used to find out whether there are differences in students'

MCTS compared to the previous pretest. The MCTS test employs indicators that are based on expert opinions (Ennis, 2011; Glaser, 1942; Marzano, 1988), which are reductions for the purposes of this research. These indicators include (1) answer questions with pertinent justifications; (2) verifying the accuracy of the procedure; (3) make inferences from solutions; (4) dissecting questions and give explanations; also (5) evaluate and consider reliable sources. The complexity of the problems in each indicator can be seen in Table 2.

Table 2. MCTS question per indicators

No.	Indicators	Question
1	Answer questions with pertinent justifications	The KRI Cakra-401 submarine at a depth of 1 km has detected the presence of a mysterious box at a depth of 2x-5y+3z. Calculations of objects at sea use the formula $x\begin{pmatrix}2\\5\\-2\end{pmatrix}+y\begin{pmatrix}-1\\-6\\5\end{pmatrix}=\begin{pmatrix}-7\\-21\\2z-1\end{pmatrix}$ with $x, y,$ and z in meters. Regarding this fact, does it mean that the mysterious box is located deeper than a submarine? Give your reasons!
2	Verifying the accuracy of the procedure	Vectors $\vec{a}=4\vec{i}-3\vec{j}+2\vec{k}$, $\vec{b}=2\vec{i}-2\vec{j}+\vec{k}$, and $\vec{c}=3\vec{i}+4\vec{j}+5\vec{k}$ are the position vector of points A, B, and C. These three points form an equilateral triangle. Is this statement true? Explain your process!
3	Get inferences from solutions	Point P is the center of the regular hexagon ABCDEF. If $\overrightarrow{PA}=a$ and $\overrightarrow{CD}=b$, then, which is correct between $\overrightarrow{FD}=b+2a$ or $\overrightarrow{FD}=-2a-b$? Give your explanation!
4	Dissecting questions and give explanations	O is the starting point, where $\vec{a}$ is A's position vector, $\vec{b}$ is B's position vector, and $\vec{c}$ is C's position vector. So we get $\overrightarrow{CD}=\vec{b}$, $\overrightarrow{BE}=\vec{a}$, and $\overrightarrow{DP}=\overrightarrow{OE}$. Determine the position vector of point P! Explain your process!
5	Evaluate and consider reliable sources	Roni made a rectangle OABC with base OA = 12 and height AB = 5. $\vec{u}$ represents OA and vector $\vec{v}$ represents OB, is the value of $\vec{u}\cdot\vec{v}$ greater than the area of rectangle OABC? Show your workflow and give a reason!

As per Table 3, each question is evaluated using a rubric based on MCTS indicators.

Table 3. Guidelines for scoring MCTS answering

Aspect measure	Student Responses	Score
Answer questions with pertinent justifications	No solution	0
	Answering questions but not correctly	1
	Answer the questions correctly, but do not provide reasons	2
	Answer the question correctly, but the reason is irrelevant	3
	Answer questions correctly and accompanied relevant reasons	4
Verifying the accuracy of the procedure	No solution	0
	Answering questions, but not correctly	1
	The solution flow is not correctly	2
	The solution flow and statements provided are not correct	3
	The solution flow and statements provided are correct	4

Aspect measure	Student Responses	Score
Get inferences from solutions	No solution	0
	Answering questions but not correctly	1
	The solution is correct but there is no explanation	2
	The solution and explanation are correct but there is no inference	3
	Solutions and explanations are correct and accompanied by inferences	4
Dissecting questions and providing clarification	No solution	0
	Give the solution, but not correctly	1
	Correct in analyzing the question, but not correct in answering	2
	Correct in analyzing questions and answering, but not accompanied by arguments	3
	Correct in analyzing questions and answering, but not accompanied by solid arguments	4
Evaluate and consider the reliable sources	No solution	0
	Mistakes in evaluating sources	1
	Mistakes in evaluating and considering sources	2
	Evaluate sources clearly but misjudge them	3
	Evaluate and consider sources clearly	4

After obtaining the posttest data, various tests were then carried out to carry out this research, with further discussion in the Results section.

This research included two main parts, quantitative data analysis, preliminary data analysis, and hypothesis testing analysis, to examine the effectiveness of STEM-based FC learning. The preliminary data analysis utilized normality and homogeneity tests to ensure the research sample's quality. At the same time, the hypothesis testing included classical completeness tests, mean difference tests, and a one-sample t-test to evaluate the completeness of learning and differences in students' abilities using SPSS 25 software. On the other hand, qualitative research used questionnaires, interviews, and observations to delve deeper into the learning process and students' independence in learning. The qualitative analysis involved data reduction, data presentation, and conclusion drawing, with data validity verification through techniques such as triangulation.

Results

Based on the initial analysis, the pretest data for mathematical critical thinking skills (MCTS) were tested for normality and homogeneity. The normality test analysis, utilizing the Kolmogorov-Smirnov test with the aid of SPSS software version 25, indicates that the pretest data for the experimental class has a p-value of 0.83 ($p > 0.05$). The control class's p-value is 0.144 ($p > 0.05$). Both results indicate a normal distribution of data. Based on these findings, the study proceeded to the homogeneity test, where the p-value was 0.431 ($p > 0.05$). This value indicates that the MCTS pretest data come from populations with uniform variance, meaning that both research groups (experimental and control) are homogeneous. Thus, the study can proceed to the hypothesis testing stage using an independent t-test to measure the difference in test scores between the experimental and control classes using SPSS. The results of the tests are as follows in Table 4.

Table 4. Levene's t-test hypothesis test results

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig.(2-tailed)	Mean Difference	St. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Pre-test Score	Equal Variances assumed	.050	.823	1.113	66	.270	1.676	1.506	-1.331	4.684
	Equal Variances not assumed			1.113	65.995	.270	1.676	1.506	-1.331	4.684

As can be seen in Table 4, there is no difference in the average pre-test score between the two classes, given that t-count = 1.113 < t-table = 2.000298 and that t-value in the t test for line equality with a significant level of both classes is 0.05, with 2.000298 serving as the critical value of t 0.05 with df = 66. After going through the pretest stage, learning is carried out according to the class that is classified, namely the experimental class gets FCs-STEM on, and the control class uses conventional learning. Posttest of MCTS was conducted to determine student scores after treatment. The test results are listed in Table 5. The average score was calculated from the collected data to see if the experimental class and the control class differed from each other. Using SPSS, an independent sample t-test is used for testing.

Table 5. Levene's t-test hypothesis test results

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig.(2-tailed)	Mean Difference	St. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Post-test Score	Equal Variances assumed	.237	.628	5.570	66	.000	5.735	1.030	3.679	7.791
	Equal Variances not assumed			5.570	63.394	.000	5.735	1.030	3.678	7.793

Table 5 indicates that the t-count is 5.570 for both classes. With df = 66 and a critical value of t of 2.000298 for actual level 0.05. It can be inferred that there is a difference in the average post-test score between FCs-STEM learning and traditional learning since t-table = 2.000298 < t-count = 5.570.

Further test the MCTS of students who reach minimal value limit using the classical completeness test, where with a significance level of 0.05 it is obtained $z_{0.5-0.05} = z_{0.45}$ and the value of $z_{0.45} = 0.1736$. Based on the calculation of the classical completeness test $\mathrm{z_{count}} = 2.96242 \geq \mathrm{z_{table}} = 0.1736$ then it is concluded that the level of student completeness in FCs-STEM is more than 79.5%. To determine if students in the experimental class differed from those in the control class following treatment, the mean difference test was computed using SPSS. The results of the independent t test indicated that the t_{count} value was 7.451 and the test's significant value was 0.000. Because the significant value of the calculation is 0.000 < 0.05, and / or when viewed from the calculation obtained the value of $t_{count} > t_{table}$, namely 7.451 > 1.998, it can be interpreted that the experimental class is superior.

Furthermore, the N-Gain test was used to compare FCs-STEM learning to traditional learning and identify which type of learning was superior. The results are displayed in Table 6.

Table 6. N-Gain value calculation results

	Experiment			**Control**		
	Pre-Test	*Post-Test*		*Pre-Test*	*Post-Test*	
Mean	57.32	88.32	56.62 (N-Gain %)	55.65	68.59	28.23 (N-Gain %)
Std. Deviation	6.236	4.656	9.773	6.183	3.791	10.602
Variance	38.892	21.680	95.506	38.235	14.371	112.407

Table 6 shows that the experimental class has 9.773 with a variance of 95.506, while in the control class, the standard deviation is 10.602, accompanied by a variance of 112.407. For the experimental class (FCs-STEM), the average N-Gain score of 56.62 indicates that it falls into the effective category. However, the N-Gain score with an average of 28.23 indicates that the control class was not effective when only given conventional learning. Because the experimental class received different learning regimens than the control class, their N-Gain scores did not compare. The experimental class outperforms the control class in terms of N-Gain, suggesting that FCs-STEM learning is superior to conventional learning.

Table 7. Number of students based self-regulated learning

SRL	Experiments	Control
High	7	9
Medium	22	19
Low	5	6
Total	**34**	**34**

Table 7 presents information on the student SRL derived from the previous survey in early before pretest. Triangulation is used to do qualitative testing, which comes after quantitative testing is completed. Qualitative testing was carried out to corroborate the quantitative testing data that had been carried out previously. Furthermore, based on the research methodology, two people from each category were selected to become respondents through *purposive sampling* technique. Students' MCTS in terms of SRL can be seen from the following description. The researchers tried to classify students' work on MCTS on the fifth indicator, according to their level of independence.

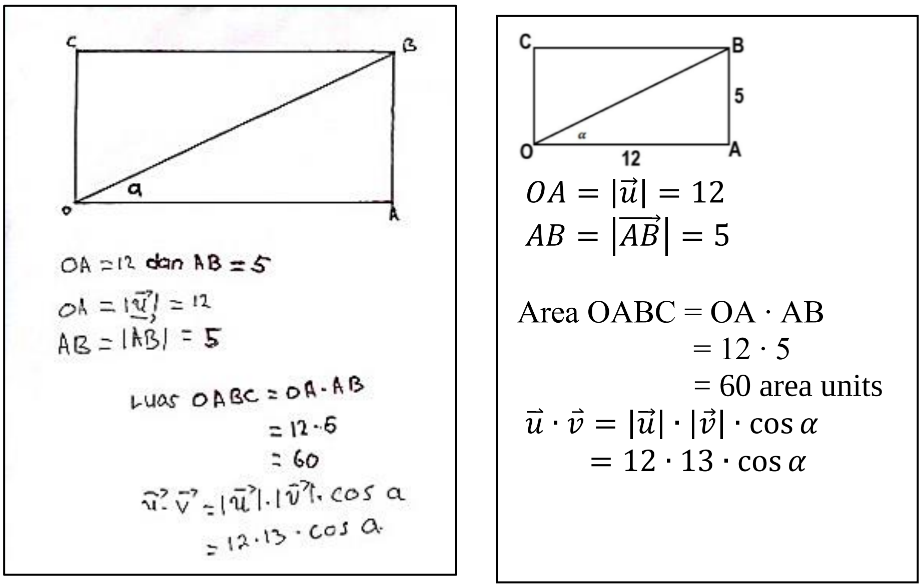
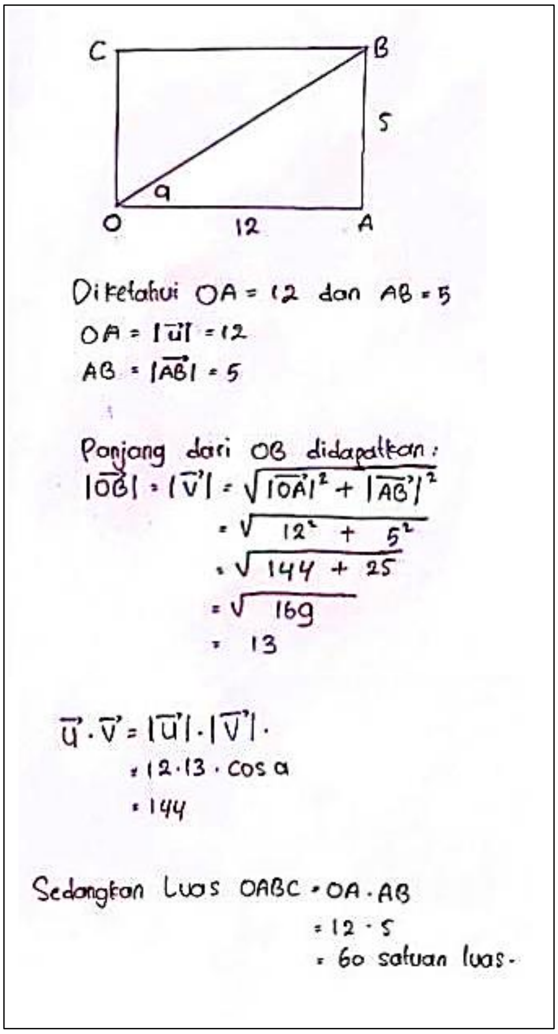


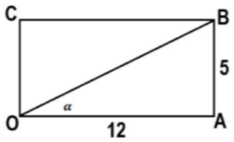
Figure 3. Respondents' answers of SRL low

Looking at the respondent's answer in Figure 3, based on the indicator of answering questions with relevant reasons, The only details the respondent recorded were the known equation, the first step in the solution, and the step that ended there. In the indicator of checking the correctness of the process, despite having written all the information of the problem, the respondent was not sufficient to solve it. In addition, it was not explained what to solve in the problem, indicating that he was unable to show the indicators of analyzing questions and clarifying arguments. In addition, there were no reasons or statements to support the answer, which made her less able to master the indicator of making inferences.

The results of the interviews showed that the interviewed respondents said they were a little confused and hesitant about the known elements in the problem. As a guideline for solving the problem, the respondents could only mention the lengths of OA and AB, and the area of OABC. After that, the researcher asked what to look for in the problem; the respondents could not answer well because they did not really understand the meaning of the problem. The researcher then asked about the concept of solution; the respondents answered with a little confusion, but finally found the answer that was on the test results, which only reached the initial stage without any final continuation.

Figure 4 below indicated that the answers of respondents with medium self-regulated learning, it can be seen that they have a good flow of analysis. The respondent demonstrated mastery of the indicators of assessing and taking into account credible sources because he wrote all the information required to answer the problem, including the lengths of OA and AB. The respondent also explained what had to be solved in the problem, namely the difference in the area of the OABC square by multiplying OA and AB, which is in accordance with the indicator of analyzing the question $\vec{u} \cdot \vec{v}$. This is in accordance with the indicators of analyzing questions and clarifying arguments. There is a clear synthesis stage in solving this problem, as shown by the answer presented, as per indicator of checking the correctness of the process. The phases of synthesis displayed show that the person can comprehend the requirements for providing an answer to the issue as well as the pertinent logic. However, after the respondent found the result, he did not include a bound statement that became the decisive answer to the question. The answer given only includes problem solving, and does not include steps that lead to the conclusion of the answer, so the participant only answers the question correctly without including relevant reasons, then he cannot show the indicator of answering with relevant reasons, and there is no inference.





Given OA = 12 and AB = 5

$OA = |\vec{u}| = 12$
$AB = |\overrightarrow{AB}| = 5$

The length of OB is obtained:

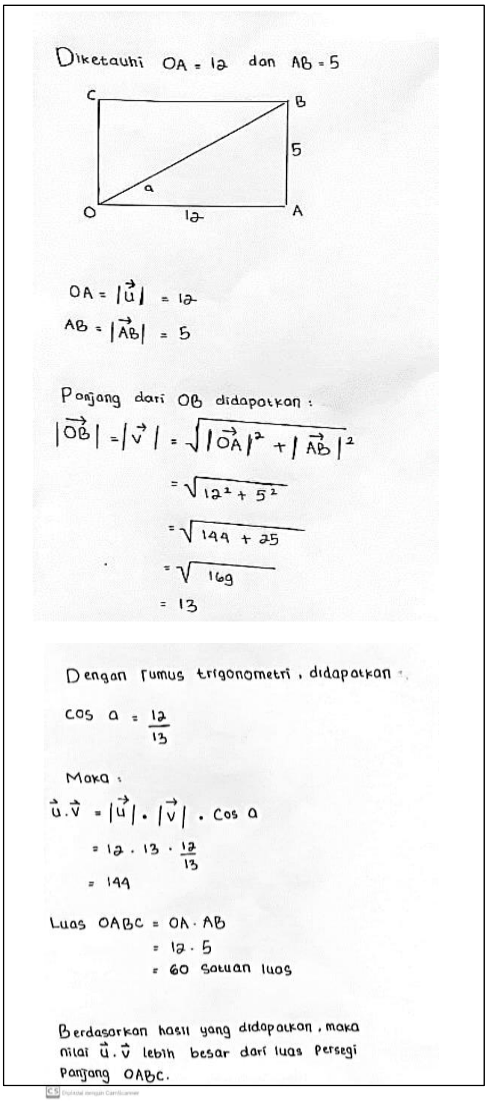
$$|\overrightarrow{OB}| = |\vec{v}| = \sqrt{|\overrightarrow{OA}|^2 + |\overrightarrow{AB}|^2}$$
$$= \sqrt{12^2 + 5^2}$$
$$= \sqrt{144 + 25}$$
$$= \sqrt{169}$$
$$= 13$$

$$\vec{u} \cdot \vec{v} = |\vec{u}| \cdot |\vec{v}|$$
$$= 12 \cdot 13 \cdot \cos\alpha$$
$$= 144$$

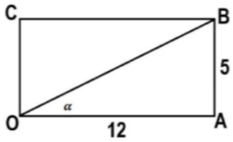
while the area of OABC = OA · AB
= 12 · 5
= 60 area units

Figure 4. Respondents' answers of SRL medium

Regarding the interview results, the researcher asked what the respondents knew about the problem, the respondents answered clearly and fluently, and could also mention the lengths of OA and AB used to find the solution. Furthermore, the researcher asked the purpose sought from the problem, the respondents answered well because they knew what they were looking for in the problem, namely the area of the OABC square with multiplication. $\vec{u} \cdot \vec{v}$. Then the researcher asked about the absence of a final statement as a reason that binds the solution to the problem, the respondent only answered that when he had gotten the solution number, he thought that it was the final answer without the need for a further connecting sentence. This indicates that the respondent only answered the question correctly but not accompanied by relevant reasons.



Given OA = 12 and AB = 5



$OA = |\vec{u}| = 12$

$AB = |\overrightarrow{AB}| = 5$

The length of OB is obtained:

$$|\overrightarrow{OB}| = |\vec{v}| = \sqrt{|\overrightarrow{OA}|^2 + |\overrightarrow{AB}|^2}$$
$$= \sqrt{12^2 + 5^2}$$
$$= \sqrt{144 + 25}$$
$$= \sqrt{169}$$
$$= 13$$

Using trigonometry formulas, we get:

$$\cos\alpha = \frac{12}{13}$$

so, $\vec{u} \cdot \vec{v} = |\vec{u}| \cdot |\vec{v}| \cdot \cos\alpha$

$$= 12 \cdot 13 \cdot \frac{12}{13}$$
$$= 144$$

the area of OABC = OA · AB
= 12 · 5
= 60 area units

According to the results, the value $\vec{u} \cdot \vec{v}$ is larger than the area of the rectangle OABC.

Figure 5. Respondents' answers of SRL high

The results in Figure 5 that show the respondent has good analytical skills. The respondent has written all the information needed to solve this problem, including the lengths of OA and AB, found the value of $\cos\alpha$, and found the goal of the problem. The answers given show a clear synthesis stage in problem solving. This indicates that the respondent understands and understands the indicators requested. The approach taken to solve the problem is suitable; it begins with using phytagoras to calculate the value of $\cos\alpha$ and as well as for additional computations. After that, the respondent made a conclusion in the form of a statement or logical reasoning. Furthermore, it is known that the respondent has the ability to answer questions according to relevant indicators and explain why he did it. The flow shown by the respondent indicates that she has fulfilled all the required indicators.

As a result of the interview, the researcher asked what the respondent knew about the problem. The respondent answered clearly and fluently. Respondents can show the length of OA and AB measurements used to start the calculation. Furthermore, the researcher asked what was sought about the problem, the respondents answered well because they understood the purpose of the question, namely determining the result of calculating the area of OABC when compared to the result of multiplication. $\vec{u} \cdot \vec{v}$. Respondents also answered well and clearly about the procedures needed to solve all that. It was explained that to get the value of OB, the respondents used phytagoras, so they could use the length of OB to find the value of OB. $\cos a$. Then the value obtained is used to find the square area of OABC and multiplications of $\vec{u} \cdot \vec{v}$. The researcher then asked the respondent about her reasons for evaluating her answers. The respondent told the researcher that he wanted to know whether the result showed that the result produced was in accordance with the required conditions. If the result shows that the area of OABC square is different from the multiplication of $\vec{u} \cdot \vec{v}$, then the respondent examined the answer to determine which was greater between the area of OABC square and the multiplication of $\vec{u} \cdot \vec{v}$. This is a good and important evaluation process.

Discussion

Considering the information gathered and the previously described research findings, this confirms the findings of earlier studies (Rahmawati et al., 2018) which indicated that students can achieve the requirements for higher critical thinking skills when they have a high degree of independence. Additional research (Siagian et al., 2020) has also collaborated this conclusion, showing a correlation between high and low levels of self regulated learningand critical thinking abilities. Some of the topics covered by this research are the existence of learning process factors, students' MCTS, their SRL, and the connection between students' beginning mathematical ability and the learning that is done.

Learning factors

The Flipped Classroom approach in the STEM (Science, Technology, Engineering, and Mathematics) field innovates traditional teaching methods by encouraging students to learn the material through lecture videos at home before applying it in interactive classroom activities. This shifts the role of students from passive recipients of information to active participants in the learning process, positively affecting the enhancement of Mathematical Critical Thinking Skills (MCTS) and independence in learning. This model is based on the Constructivism theory, which posits that learning occurs optimally when students actively construct their knowledge through experience (Marougkas et al., 2023). It also aligns with the Self-Determination Theory (SDT), highlighting the importance of autonomy, competence, and social relationships in motivating students (Howard et al., 2021). The Flipped Classroom meets these needs by giving students control over their learning pace, challenging them with tasks that enhance competence, and encouraging student collaboration and discussion (Aidoo et al., 2022). Flippedlearning.org outlines a 6-step guide to flipping the classroom, including planning, recording, sharing, evolving, forming groups, and regrouping. The first step is to make a plan by determining which lessons to flip and outlining the main learning outcomes and lesson plans. The second step is recording; in other words, create videos instead of delivering these lectures live. This allows students to repeat the teacher's explanations if not understood in one sitting.

Conversely, during direct instruction, the teacher presents content once in front of the class. The third step is to share and send out the created videos and then send them to students, emphasizing that the video content will be thoroughly discussed in class. The fourth step is to evolve, meaning students are prepared to move further than before after viewing the learning material. The fifth step, forming groups, is an effective way to discuss topics by dividing into groups where students are given tasks to work on. Finally, the sixth step, regrouping, means bringing the class back together to share individual group work with everyone. After each step is completed, review, revise, and repeat the action or step. Based on the previous explanation, there is a difference in the methods teachers use in teaching the two learnings. Each step is designed to reinforce student engagement and promote deep learning, from preparing students to actively engage in learning to sharing their overall understanding. Research shows that the FC approach in STEM education enhances students' MCTS by engaging them in high-level thinking activities during class, resulting in a more active and dynamic learning environment. This supports findings that students in flipped STEM classes achieve greater progress in critical thinking and problem-solving skills than in traditional learning environments (Hsia et al., 2021; Rehmat & Hartley, 2020). In conclusion, the advantages of the FC-STEM approach in facilitating active learning and enhancing MCTS and students' learning independence have been recognized to equip students with the skills needed for lifelong learning and problem-solving in the modern world.

Mathematical critical thinking skills (MCTS)

FCs-STEM learning was applied as an effort to improve students' MCTS in the experimental class. The first stage of FCs-STEM helps students understand the material by providing the material as a whole in the form of files or videos, so that students can find relevant information. This stage also helps students improve their MCTS. To achieve this, students' basic skills are needed to encourage students to solve problems and find new ideas. Students have the opportunity to use their minds. Students' MCTS is also developed during the learning process as well as in order to show their work. This happens when students have the opportunity to ask questions, make suggestions, criticize, and assess the work of the presenting group. All of the students MCTS indicators grew, according to the results, although the experimental class outperformed the control group. Based on the N-Gain data, there was a 0.2823 gain in mathematical critical thinking skills among students in the control class and a 0.5662 rise among students in the FCs-STEM class.

Some previous literature also shows the same thing, that FCs learning can improve students' MCTS (Inayah et al., 2021; Lin et al., 2021; Al-Zoubi & Suleiman, 2021). Students are better prepared to face problems in class if they receive material from online classes before face-to-face classes. Having an initial understanding of the material also makes students more prepared and critical when faced with a problem. The application of FCs has a higher quality than conventional classes (Orhan, 2023). Test findings and discussion indicate that subject exposure and critical thinking ability development are given equal weight in conventional classrooms during face-to-face time. However, FCs learning provides more time intensity as well as opportunities to improve specific skills such as critical thinking skills during hands-on learning. As is the case with FCs learning, (L. Rahmawati et al., 2022) looked at the research produced by various researchers from 2015 to 2022 on the effectiveness of STEM-based learning. A total of 28 articles that fit the needs of the review were collected for further evaluation. The result is that STEM methods help students or students think critically mathematically. The effect of increasing FCs will be greater by providing a combination of FCs- STEM. The applicability of the material, particularly the video that students watch during the FCs process, is what ultimately determines whether or not this strategy is successful. Students are encouraged to watch videos in order to get ready for in-person instruction.

Self-regulated learning (SRL)

The Flipped Classroom approach (FCs-STEM) within the STEM (Science, Technology, Engineering, and Mathematics) context plays a crucial role in enhancing students' Self-Regulated Learning (SRL) and Mathematical Critical Thinking Skills (MCTS). Through this method, the initial learning orientation encourages students to study the material or watch videos independently before face-to-face sessions. This process facilitates the construction of personal knowledge, allowing students to manage their learning process through goal setting, selection of learning strategies, and progress evaluation. The constructivist learning theory emphasizes students' active learning in building their knowledge through experience. It supports the findings that pre-class self-learning enhances students' ability to manage their learning, deepening understanding and application of knowledge in broader contexts (Shah, 2019). Further research by Holisin and Mursyidah (2021) shows that students in experimental classes using the FCs-STEM approach achieved significant improvements in SRL, with classical activities reaching a percentage of 66.07% in the adequate category. This indicates that students with high SRL capabilities can more effectively manage learning resources, identify their learning needs, and adjust learning strategies to enhance understanding. As a result, this reinforces material comprehension and encourages the application of knowledge in broader contexts, enhancing mathematical critical thinking and problem-solving skills.

Zimmerman's self-learning theory further reinforces the importance of SRL in education. Successful students are proactive in their learning process, using metacognitive strategies to plan, monitor, and evaluate their learning (Akdeniz, 2023; Qiu et al., 2024; Sutiono et al., 2023). This aligns with the FCs-STEM approach, where students are expected to take the initiative in their early learning, thus strengthening the SRL cycle. Relevant research indicates that SRL involves cognitive, emotional, and behavioral aspects of learning (S. Li & Lajoie, 2022). This affirms that the FCs-STEM approach, emphasizing self-learning and applying knowledge in face-to-face sessions, promotes a supportive environment for the holistic development of SRL skills, including emotion regulation and learning motivation. The relationship between enhanced SRL and improved MCTS in the context of FCs-STEM emphasizes the importance of this method in supporting students' academic and metacognitive abilities. By prioritizing self-learning as the foundation of the learning experience, FCs-STEM enhances students' ability to understand material and strengthens their capability to apply and critically reflect on knowledge. This demonstrates how student-centered learning approaches can significantly impact academic achievement and the development of critical thinking skills essential for success in STEM disciplines.

The relationship between students' initial mathematical ability and their progress in developing mathematical critical thinking skills and self-regulated learning

The study explored the relationship between students' early mathematical abilities, learning processes, Mathematical Critical Thinking Skills (MCTS) development, and Self-Regulated Learning (SRL). Initial theories and related research posited a significant correlation among these components. However, empirical results revealed no substantial link between the learning process and students' initial mathematical abilities. This unexpected outcome could be attributed to several factors, including the specific implementation of learning activities, particularly in experimental classes employing Flipped Classrooms (FCs) with a Science, Technology, Engineering, and Mathematics (STEM) approach. The average competency of teachers in managing learning activities was recorded at 74.5% in the initial meeting, gradually increasing to 75.7% in the second, 77.4% in the third, and stabilizing at 78.3% in the fourth and fifth meetings, with an overall average of 76.8%, categorized as good. Observations indicated that this mode of learning implementation is effective for enhancing MCTS. The impact of FCs-STEM on student learning outcomes was more pronounced than that of initial mathematical ability, as evidenced by test scores, suggesting a significant relationship in efforts to improve MCTS between initial mathematical ability and the learning process. According to the findings, students participating in FCs-STEM learning displayed higher MCTS than those in conventional classes.

Moreover, the results showed a direct correlation between SRL and MCTS, where students with high levels of SRL tended to exhibit significant MCTS. This underlines that the development of MCTS and SRL depends not solely on students' initial mathematical abilities but also on the learning methods and approaches adopted. In this context, the FCs-STEM application has proven effective in enhancing both components, offering new perspectives on mathematics learning design that supports the development of critical abilities and independent learning among students. Further research highlights that the FC approach deepens mathematical concept understanding and facilitates the development of critical thinking and problem-solving skills (Cevikbas & Kaiser, 2023; Lin et al., 2021). Studies have also illuminated the critical role of teacher competence in successfully implementing FCs-STEM, with observed improvements in teacher management skills contributing to enhanced learning outcomes(Karunia & Ridlo, 2022; Subramaniom & Adnan, 2022). Thus, the FCs-STEM approach in mathematics education is pivotal for encouraging the development of MCTS and SRL in students. These findings challenge traditional assumptions regarding the predominance of early mathematical abilities in learning success and emphasize the importance of innovative teaching methods in supporting students' progress in critical and independent learning.

Conclusion

This study successfully demonstrates that the implementation of STEM-based Flipped Classroom learning (FCs-STEM) has a significant influence on the enhancement of students' Mathematical Critical Thinking Skills (MCTS), especially when viewed from the aspect of Self-Regulated Learning (SRL). The quantitative results confirm that students who participated in FCs-STEM learning recorded a significant difference in post-test MCTS scores compared to students who experienced conventional learning, evidenced by significant t-values and a high difference in average N-Gain scores between the two groups. Meanwhile, the qualitative results of this study reveal that students with high SRL tend to have better critical thinking skills. In contrast, FCs-STEM learning has proven effective in supporting the development of these skills through an approach that facilitates independent learning, management of learning resources, and self-reflection. Thus, this study strengthens the argument that FCs-STEM learning is effective in improving students' MCTS and advancing their SRL abilities.

Therefore, the implications of this study provide valuable insights for mathematics education, especially in designing learning that supports the development of students' mathematical critical thinking skills through a student-centered approach that promotes independent learning. However, there are several limitations, such as the sample being limited to a specific context, which may affect the generalization of findings. Further research is needed to explore the application of FCs-STEM in various learning contexts and with a broader sample to strengthen the validity of the findings. In addition, future research could explore specific strategies and techniques in FCs-STEM that are most effective in supporting the development of MCTS and SRL, as well as their long-term impact on students' academic achievement.

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Conflicts of Interest

This research does not have any conflicts of interest concerning the publication of this manuscript. The authors have examined the work and have addressed ethical concerns, including plagiarism, omissions, data fabrication and falsification, and issues of duplicate publication and submission.

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Author Contributions

Ali Akhmad Setiyawan: Writing - review & editing, analysis, methodology, discussion, supervision and the correspondence author; **Arief Agoestanto**: Conceptualization, collection data, analysis, writing an original draft, editing, and visualization; **Isnarto**: Validation and supervision.

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