Working as Scientist and Engineer: A Strategy for Empowering Critical Thinking Skills through the STEM-EDP Learning Design

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Abstract

STEM (Science, technology, Engineering, and Mathematics)-based learning has evolved into an instructional design that accommodates the integration of disciplines to understand properly scientific phenomena. To explain scientific phenomena, students need to imitate the work of scientist and engineer who apply the critical thinking skills (CTS). Hence, this study aims to prove the impact of learning design based on the STEM approach to empower the CTS. The learning follows the steps of the Engineering Design Process (EDP), and the assigned STEM project was a robotic hand inspired by traditional Javanese puppets called *Wayang*. The learning setup relates to the topics of the 8th-grade science curriculum, i.e. body movement system. A pre-experimental design using a one-shot case pretest-posttest design was applied to a single experimental class. The sample was purposefully selected, consisting of all students in class 8A at Public Junior High School 4 Surakarta (N=30). Data collection involved assessing CTS using pretests and posttests. Based on the paired t-test, the results indicate an improvement in students' critical thinking skills, marked by an increasing in CTS scores at the pretest (M = 53.87, SD = 16.783) to post-test scores (M = 82.63, SD = 16.486), with the significant result, sig < α, 0.049 < 0.05, indicating the rejection of H0. This study concludes that the STEM-EDP learning design has a positive impact on the critical thinking skills of 8th-grade students.

Keywords: STEM, Robotic hand, Engineering Design Process, Critical Thinking Skills

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INTRODUCTION

Critical thinking skills (CTS) are one of the higher-order thinking abilities and 4C competencies in 21st-century skills (Chusni et al., 2020). The ability to think critically is one of the life skills that needs to be trained through education. Every human being has the potential to think critically, but not everyone can develop their critical thinking abilities (Lieung et al., 2021). CTS can be used to understand problems in depth, forming open thinking in understanding and evaluating information properly and correctly in making decisions and determining solutions to problems experienced in learning activities (Wahyuni, 2018). CTS correlates with concept mastery and problem-solving (Juhji & Mansur, 2020). According to Alatas (2014), CTS is an important factor in students' understanding of learning and daily life. It can be argued that CTS will bring a good understanding of scientific phenomena, which is the main goal of learning science.

One approach that is expected to improve the quality of students' understanding of the scientific phenomena to be conveyed and can hone students' skills is to set up learning science as an interdisciplinary focus (Al-Fatiha, Ramli, & Rahardjo, 2022). It is common to integrate science, technology, engineering, and mathematics (STEM), the four main disciplines as a learning approach. The STEM approach focuses the learning process on solving real problems in everyday life by using the scientist and engineer way of thinking (Moore et al., 2014; Mangold & Robinson, 2013). As scientists, students will learn how to explain scientific phenomena based on the experiment, while as engineers, students will learn to design something and come up with the best product design by testing, data analysis, and redesign (Slavit, Grace, Lesseig, 2021).

STEM is an integrative approach that represents a shift from conventional classrooms towards implementing pedagogy involving more inquiry and problem-based learning approaches (Breiner et al., 2012; Chaerunisa, Ramli, & Sugiharto, 2023). The integrated STEM approach aims to instill relationships between certain concepts and provide a relevant context for studying content by integrating science, technology, engineering, and mathematics concepts in real life (Kelley & Knowles, 2016; Martín-Páez et al., 2019).

Critical thinking is a skill that allows someone to solve problems logically and try to reflect independently through metacognitive rules regarding problem-solving (Gotoh, 2016). The students are encouraged to be actively involved in groups to solve problems and think critically by integrating STEM disciplines. Through the implementation of STEM education, students can develop 21st-century skills (Bybee, 2010, 2013).

The pros of STEM-based learning to improve the CTS of the students have been massively studied in many subjects. According to a quick search through the Google Scholar Database using the keywords “critical thinking skills” and “STEM-Approach”, there are about 8,130 hints of publications within ten years (2014-2024). However, most of those works are not experimental research, but systematic reviews. A few articles are based on experimental studies. Some examples of those works are in biology (Yaki, 2022), chemistry (Hacıoğlu & Gülhan, 2021; Ariyatun & Octavianelis, 2020), and physics (Adhelacahya, Sukarmin, Sarwanto (2023). All studies confirm that STEM-based learning significantly impacts the CTS. However, the adaptation of the ways of thinking of scientists and engineers in STEM Learning Design is rare. By adding the keywords “critical thinking skills” and “STEM-EDP Approach”, there are only 6 hints found in the Google Scholar Database in the previous ten years.

Moreover, this research argues that to imitate the work of scientists and engineers, the topic of the human body movement system or skeletal system is one of the relevant and suitable topics. Therefore, to prove this argument, by projecting the hand robotic that is inspired by the work system of a traditional Javanese puppet, Wayang, the research team first developed the STEM-EDP learning design, which was supposed to influence the critical thinking skills of students.

METHODS

This research has a hypothesis that the STEM-EDP Learning Design has a significant influence on the students' CTS. To test this hypothesis, a pre-experimental design with a one-group pretest-posttest research design was applied.

The research was conducted at Public Junior High School 4 Surakarta. There were eight classes of grade 8 in this school, and then one class (N=30) was selected randomly to be an experimental group of this research. The class consisted of 14 boys and 18 girls aged 14 years old. All students in the experimental class have agreed to be the participants of the research by getting the written permission from the authority of the school.

The treatment given was the application of STEM learning using the EDP (Engineering Design Process) step technique. According to White (2016), the steps in EDP are empathize (problem development), define (brief problem description), ideate (exchange of ideas), prototype (product creation), and test (product testing).

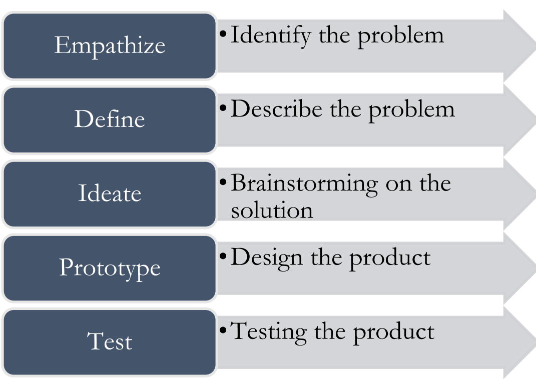

Figure 1. The Flow of EDP Procedures

The procedure of the treatment or learning process is described in Figure 1. To introduce the students to the problem (**the empathize stage**), the teacher showed the case of people with no hand or disabled and how scientists and engineers invented the robotic hand to assist those disabilities. In the **define stage**, students explored the body movement systems among plants, animals, and humans. They analyzed the limitations of plant movement systems and compared the similarities and differences of human and animal movement systems. After that, at **the identify** what is needed stage, students were asked to observe their hands to understand what types of motion the human hand can do, and how it works. They also try to identify the structure of the hand (bones, joints, and muscles) assisted by PowerPoint slides. Next, at the **brainstorming solution stage**, students were divided into 6 groups to discuss problem-solving and sketch a robotic hand prototype design by imitating the *Wayang* using the available tools and materials. The next step was **prototyping**, in which students created a prototype design and presented their design in front of the class the next day. All the learning process was run for two meetings each of 70 minutes. The first meeting was for doing the Empathize, Define and Ideate stage, while the rest of the phases were accomplished in the second meeting.

To unpack the STEM element at the learning process, the learning outcomes in each element had been formulated before the class run. The details of learning outcomes to represent the STEM element is figured out in Table 1.

Table 1. Unpacking the learning outcomes of STEM

Science	**Technology**	**Engineering**	**Mathematics**
Students understand the concept of human body movement system and demonstrate the knowledge through designing the robotic hand	Student able to utilize the digital sources to get the information about hand robotic design	Students demonstrate ability to design and create the robotic hand using the given materials	Students demonstrate the calculation and measurement of the robotic hand

Data on CTS was measured using a sort of item of the pretest and posttest which was developed based on Facione's six indicators of CTS (inference, analysis, evaluation, interpretation, and explanation) (Facione, 2011, 2015). The test was a 10-item essay test that was validated before implemented. The responses of the students regarding the learning process were asked by the 12 items of questionnaires which were distributed at the end of the second meeting. Pearson product-moment was used to check the validity of the instrument, and the reliability of the instrument was tested by Alpha Cronbach.

To ensure the STEM-EDP learning design has been implemented perfectly, the observation was conducted by three observers who have been trained to conduct the observation. The observation sheet has been validated as well.

Data was analyzed statistically using the SPSS 26. The inferential statistics was applied in analyzing the data. Two main analyses were run, i.e. the prerequisites (normality and homogeneity test) and the hypotheses analysis.

RESULTS AND DISCUSSION

1. Prerequisite Test Results

The results of the validity test of the pretest and post-test showed r-count > r-table, which was 0.367, or it can be concluded that the instrument was declared valid. In testing the reliability of the pretest and posttest question instruments, Alpha Cronbach's value was 0.962 > 0.6, hence it was concluded that the research instrument was reliable.

Both pretest and post-test data were distributed normally which can be indicated by the pretest significance value of 0.243 and the post-test was 0.220. According to the significance score (Sig > 0.05), the data is normally distributed. Furthermore, in the homogeneity test using Levene's, sig. was 0.977. By using a significance level of 5% (0.977>0.05), the research data is homogeneous. This indicates that research data is worthy of being used as a requirement for data analysis.

2. The Hypothesis Testing Results

The hypothesis testing results in significant differences between the pre and post-test CTS scores (Table 2). The results show that the significance value is less than α or sig < 0.05, which is 0.049 < 0.05, and T-count ≥ T-table, which is 8,390 ≥ 2.042, resulting in the conclusion that H0 was rejected or H1 was accepted. It can be concluded that the treatment of the STEM-EDP Learning design effects the CTS of the students significantly.

Table 2. T Test Results

Sample	T *test*			Ratio		Test result
	T_{count}	sig	T_{table}	T-value	Sig with α	
30	8.390	0.049	2.042	8.390 ≥ 2.042	0.049 < 0.05	H_0 rejected

3. The Impact of STEM-EDP Learning

The impact of STEM-EDP Learning Design may be noticed in the gap between the pretest and post-test scores. The post-test shows that students performed CTS scores better after the treatment of STEM-EDP Learning. The gap in the Mean between the pretest and post-test scores is 28.76 points, indicating the significant impact of the STEM-EDP learning design (Table 3).

Table 3 Pretest and Posttest of CTS

Items	Pre-test	Post-test
N	30	30
Mean	53.87	82.63
Std. Deviation	16.784	16.486
Variance	281.689	271.775
Range	53	60
Minimum	33	40
Maximum	86	100
Sum	1616	2479

STEM-EDP Learning design accommodates the students with adequate training on CTS, through its syntax. For instance, in the empathize stage, the student will learn how to break down the problems into some causative factors and try to analyze the roots of the problems. These activities may contribute strongly to the ability of the students to do inference and analysis. The positive impact of STEM-EDP learning is in line with some studies on STEM and CTS, such as Allanta & Puspita (2019), Indriyana & Susilowati (2020). A similar result is also confirmed by Retnowati, Riyadi, & Subanti (2020) in their research on the STEM Approach to understanding the concepts of rectangular in mathematics.

During the process of solving the problem of the robotic hand which was presented to the students at the STEM-EDP learning, the students experienced the process of deep thinking to find the best solution on how to create the imitated hand which was able to lift a paper cup and move it to another place. Through this activity, the students are supposed to understand the concepts of skeletal, muscles, and joints to be able to design the robotic hand.

It can be assumed that training the students with real problems and giving them the time and space to analyze the problem adequately will be the best way to challenge their critical thinking skills. Moreover, there was a chance to share ideas on the stage of ideates and do engineering practices in prototyping and testing the robotic hand will also be an opportunity for them to practice their critical thinking skills. A similar result of introducing STEM activity based on the real problem is presented by (Topsakal, Yalcin, & Cakir, 2023).

4. Element Analysis of the Critical Thinking Skills

To detail the impact of STEM-DT Learning Design on the CTS, the analysis of each element of the CTS was conducted. The students performed each element of CTS differently before and after the treatment (Figure 2).

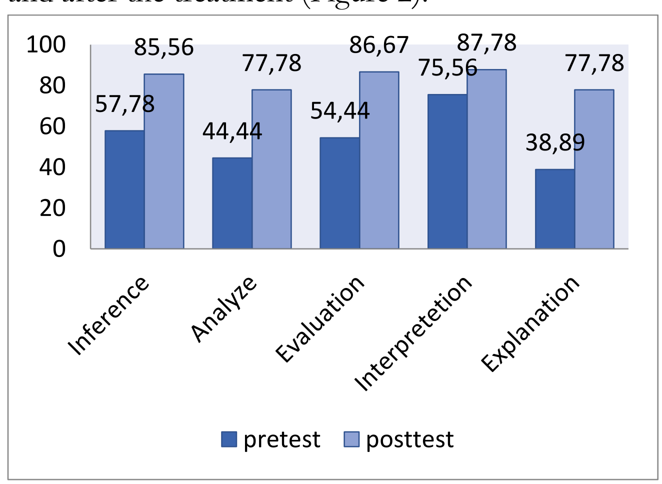

Figure 2. Pretest and Posttest Score Data Diagram

The highest average CTS post-test score lies in the "interpretation" with a value of 87.78, while the lowest value lies in the "analysis and explanation", which is 77.78. The skills of analysis and explanation are supposed to be trained adequately in the stages of ideating, interpretation, and explanation. However, though the stages of ideate, prototype, and test are expected to facilitate the students' skills in evaluation, interpretation, and explanation, it seems this stage needs to be repeated frequently. Since "the skill of explanation" is the highest skill that should be based on the ability to claim and to reason, which happens after the students do the experiment or testing, thus it is assumed that the STEM-EDP in the robotic hand has not given the students a sufficient time to do the experiment or testing. Reasoning in scientific explanation is a difficult part to train and needs some duration of time according to some research (Novak & Treagust, 2023).

5. STEM Learning Outcomes

Each STEM component has different learning outcomes. In the science component, students can use science concepts and apply them to create robotic hand designs. In the technology component, students used online platforms to look for design references. Next, in the engineering component, students can design a robotic hand using simple but adequate materials. And finally, in the mathematics component, students can design a robotic hand using calculations. However, it seems the training of each element of STEM needs to be expanded by introducing other themes or projects, thus the students repeat the same activities in two or three different cycles of projects. The work of Topsakal, Yalcin, & Cakir (2023) reveals this issue.

6. STEM Learning Implementation Results

The implementation of STEM learning in this research was controlled through observation sheets, interviews with teachers, and student response questionnaires. The results of observing the implementation of the learning process at the first meeting received a score of 89.37%. Meanwhile, at the second meeting, it was 90.27%, then it can be concluded that the implementation of the teaching and learning activities has exactly followed the lesson plan.

Based on the teacher interviews, teachers responded the process of learning using the STEM-EDP gave a very good experience to the students and teacher as well. She argued that regarding the implementation of STEM and CTS learning was considered very good.

While the student responses to STEM learning show very good criteria. Student responses are divided into several assessment aspects, namely, interest in learning, effectiveness, cooperation, and understanding of concepts and thinking skills. Overall, the results of student responses to STEM learning had a score of 49.36, with a maximum score of 60. The overall percentage of student response results was 81.72%, so it can be concluded that student responses to STEM learning were very good (Table 4).

Table 4. Student Response Results

Assessment aspects	Average	Maximum Score	Percentage (%)	Criteria
Interest in learning	16.79	20	83.96	Very Good
Learning effectiveness	7.51	10	75.17	Good
Cooperation	8.48	10	84.82	Very Good
Understanding of concepts and thinking skills	16.58	20	82.93	Very Good
Total Score	49.36	60	81.72	Very Good

CONCLUSION

The implementation of STEM-EDP learning in this research, using the project of a robotic hand as a phenomenon that students must solve by adapting the concepts of the human body system, has shown a positive impact on students' CTS. All indicators of CTS (interference, analysis, evaluation, interpretation, and explanation) have been increasingly changed after the training of ST EM-EDP learning. However, to optimize the results, more duration of time and more similar activities need to be added to the learning process. It also needs more cycles of learning to ensure the results are consistently confirmed.

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