Integrating STEAM Education and Computational Thinking: Analysis of Students' Critical and Creative Thinking Skills in an Innovative Teaching and Learning

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Abstract

Teaching and learning in the 21st century should equip students with critical and creative thinking skills to be ready to live and contribute productively to society. One suitable learning approach is integrating STEAM education and computational thinking—the STEAM-CT approach. The present study aims to describe students' critical and creative thinking skills in STEAM-CT integrative learning. The descriptive qualitative method was employed in this study. The current study included 26 eighth-grade students from a private middle school in Yogyakarta, Indonesia. According to the analysis, the students demonstrated critical and creative thinking skills during the integrative STEAM-CT learning process, particularly in planning problem solving, flexibility in providing problem solutions, and the aesthetics of their product designs. However, students must still be encouraged to conduct in-depth evaluations and use the results for improvement. For recommendation, to promote students' critical and creative thinking skills, feedback practices could be embedded in teaching and learning.

Keywords: Critical thinking; creativity; STEAM education; computational thinking.

Introduction

Uncertainty and complexity in the twenty-first century necessitate a learning transformation. Learning in the twenty-first century should prepare students to work, live, and become productive citizens in the face of a variety of challenges (Kristanto, 2020). At least this learning needs to equip students with critical and creative thinking skills (Ritter et al., 2020; Shavelson et al., 2019; Van Laar et al., 2020). Both of these skills are important to use in dealing with the emergence of new technologies, especially information and communication technologies that make it easier to move, present, manipulate, and re-present information (Almerich et al., 2020; Higgins, 2014).

Even though critical and creative thinking skills are crucial, many students still lack critical thinking and creativity. A study conducted by Benyamin et al. (2021) discovered that the majority of their subjects' students had moderate or low critical thinking skills. This result is consistent with that revealed by Wayudi et al. (2020). Apart from these two studies, several studies also have demonstrated the need to enhance student's critical thinking skills (Agnafia, 2019; Hidayat et al., 2019; Hidayati et al., 2021; Li et al., 2021; Ridho et al., 2020).

Similar to the problem of critical thinking skills, many students still have low creative thinking skills. A study conducted by Rasnawati et al. (2019) unveiled that the vocational high school students who were their subjects had low creative thinking skills. Rachman and Amelia (2020) also found similar results, specifically, the creative thinking skills of high school students who were their subjects were lacking. Several other studies corroborate the findings of these studies. (Kadir et al., 2022; Siregar, 2019; Suparman & Zanthy, 2019).

The existence of problems related to students' critical and creative thinking skills indicates the need for learning innovation. Vincent-Lancrin et al. (2019) provide learning design principles to develop students' critical thinking skills and creativity. To begin, such learning must pique students' interest and be challenging. The learning should also help students develop technical skills and enable them to create actual products or artifacts. Furthermore, the learning environment must allow students to co-design components of a product or solution. It implies that learning must be open to a wide range of student's interests, ideas, and abilities, as well as provide space for student agency. The principle of respect for diverse perspectives in dealing with problems is as follows. Furthermore, learning also needs to provide space for the unexpected. Finally, the learning also needs to provide space and time for students to reflect as well as to give and receive feedback. Giving and receiving feedback not only encourage students to improve their work but also facilitate them to learn (Kristanto, 2018). One learning approach that follows these principles is STEAM education.

STEAM education is a learning approach that integrates Science, Technology, Engineering, Arts, and Mathematics. STEAM education makes students more appreciative of various fields of knowledge simultaneously. It sparks the development of their critical and creative thinking skills in re-imagining new and old real-world problems (B. Wilson & Hawkins, 2019). The STEAM approach is innovative because it is considered up-to-date in the Industry 4.0 era, which can support critical and creative thinking skills through project-based learning (Lu et al., 2022; Shatunova et al., 2019). This project-based STEAM learning is based on real-world problems and can teach students how to research, propose, and select solutions, as well as design and create products (Chistyakov et al., 2023; Diego-Mantecon et al., 2021).

Generally, implementing the STEAM approach administers an Engineering Design Process (EDP) (Ozkan & Umdu Topsakal, 2021). Although a variety of EDP cycles is found in the literature (Haik et al., 2017, p. 9; Hubka, 2015, p. 31), these cycles typically include problem clarification, program assembly for needs, design planning, prototype construction, testing, and optimization, product analysis, and product presentations to clients or target groups (Vossen et al., 2020). These stages can be simplified into five: asking, imagining, planning, creating, and improving (Hester & Cunningham, 2007). The EDP can bridge science and mathematics concepts in making or using technology while also considering aesthetics in the STEAM approach.

According to the literature, the STEAM approach has the potential to develop or improve students' critical and creative thinking skills. This approach can provide students with the opportunity to create products that will help them develop their creativity and problem-solving skills (Katz-Buonincontro, 2018). The implementation of STEAM teaching and learning by Wilson et al. (2021) for elementary and middle school students illustrated that this approach effectively increased critical and creative thinking skills. Furthermore, numerous other studies have discovered similar results, which indicate the STEAM approach can help students develop critical and creative thinking skills (Alkhabra et al., 2023; Anggraeni & Suratno, 2021; Engelman et al., 2017; Priantari et al., 2020; Rahmawati et al., 2019).

Problem-solving is a central activity in STEAM education. The problem-solving activities can be supported by learning designs that support the development of computational thinking (CT) dimensions (Barr & Stephenson, 2011; Wu & Su, 2021). Decomposition, pattern recognition, abstraction, and algorithm are the CT dimensions. (Google, 2023). Decomposition

is the process of breaking down a complex problem into smaller problems in order to make the problem easier to understand, handle, or manage. The search for similarities between different problems is referred to as pattern recognition. Focusing on important information while ignoring irrelevant details is what abstraction entails. The final dimension, algorithm, refers to the process of creating steps or rules to solve problems. The four CT dimensions can be embedded in STEAM learning activities (Barr & Stephenson, 2011).

CT support in teaching and learning is often carried out using computers, especially programming. It is because programming includes making computer-readable instructions so that the computer can complete specific tasks or problems (Wang et al., 2022). It is in line with one of the dimensions of CT, namely the algorithm. Programming is also essential to support critical tasks related to CT (Grover & Pea, 2013). The programming activities are also often integrated into STEAM education, such as using Scratch (Oh et al., 2013; Tan et al., 2020) and Lego Mindstorm (Ding et al., 2019; Ruiz et al., 2019).

CT support in teaching and learning can also be implemented without the use of a computer. This strategy is appropriate for implementation in schools that lack technological infrastructure (Brackmann et al., 2017). Thus, integrating CT and STEAM education has a greater potential to be widely implemented. Furthermore, this integration in learning that does not use computers or other expensive technology makes it easier for teachers or other practitioners to adopt or adapt it (Padmi et al., 2022).

In summary, on the one hand, critical and creative thinking skills are two essential skills for students to live and contribute productively in the 21st century. On the other hand, many students still lack these two skills. STEAM education that supports the development of CT, which hereinafter we refer to as STEAM-CT, can potentially develop students' critical and creative thinking skills. Such teaching and learning can be implemented without a computer so that learning activities can be widely adopted or adapted. Therefore, the present study aimed to analyze students' critical and creative thinking skills in the STEAM-CT approach, which did not use computers or other digital technologies.

Methods

The present study employed a descriptive qualitative method. This method is employed to achieve the research objectives because it is appropriate for describing events or experiences and seeking in-depth knowledge of the phenomena being studied (Kim et al., 2017; Neergaard et al., 2009).

Learning Design

The STEAM-CT approach in the present study provided experiences for students to design and develop seesaw miniatures that are fun, efficient, and safe. The training was conducted over four meetings. At each meeting, respectively, the students (1) imagine and design a seesaw; (2) create the designed seesaw; (3) test and present the seesaw; and (4) improve and reflect on the seesaw.

During the first meeting, students imagined and designed a seesaw that meets three criteria: fun, efficiency, and safety. Students were guided to learn art, simple machines, the types and strengths of the constituent materials, and linear functions while decomposing the

characteristics of the seesaw. With this knowledge, the students devised a list of the tools and materials required, sketched the design, and planned the sequential steps that would be used to construct the seesaw.

Students made seesaws at the second meeting, using the tools and materials planned and the design sketches drawn at the first meeting. Students did this by listing and explaining what needs to be considered when building a seesaw. In addition, the students were asked to analyze and explain what influences the balance of the seesaw.

Students tested and presented their seesaws at the third meeting. They tested the seesaw and evaluated it to discover if it was enjoyable, efficient, and safe. They also analyzed areas for improvement and observed the seesaw patterns of other groups to inspire them to improve their own. Following that, the students presented their seesaws in classical.

In the fourth meeting, students improved their seesaw and reflected on their learning experiences. The learning activities at this meeting began with decomposing the steps to improve the seesaw. After that, students identified the variables so that the seesaw fits the fun, efficient, and safety criteria. Finally, students reflected on their learning experiences to abstract the factors that support successful seesaw development. They also modelled the seesaw using linear functions.

Table 1 illustrates the learning experiences mapping in each meeting with STEAM content and CT dimensions. The learning design was discussed with the Mathematics, Natural Sciences, and Arts teachers of the students who were the subjects of the present study.

Table 1

Mapping Learning Activities, STEAM Content, and CT Dimensions

Meeting	Learning experience	STEAM content	CT dimensions
1	Imagining and designing seesaws	Simple machine (Natural Science); simple product engineering (Craft); model image (Arts and Culture); straight line equations (Mathematics)	Decomposition, algorithm
2	Creating seesaws	Simple machine (Natural Science); creating simple products (Crafts)	Decomposition
3	Testing and presenting seesaws	Simple machine (Natural Science); testing and communicating of phenomena (Informatics); Testing and presenting of engineering works (Craft)	Pattern recognition
4	Improving seesaws and reflecting on learning experiences	Simple machine (Natural Science); Engineering procedures (Craft); application of linear functions (Mathematics)	Decomposition, abstraction

Research Subject

The subjects of the present study were 26 eighth-grade students, consisting of 14 boys and 12 girls. All of the subjects came from one class at a private junior high school in Yogyakarta, Indonesia. The subject selection was conducted by first discussing with the teachers so that the selected students were usually active and had good verbal skills. Thus, the data obtained from

these subjects can provide rich and valuable information about their critical and creative thinking skills (Campbell et al., 2020; Kelly, 2010).

Data Collection

The data in the present study were the students' answers in their worksheets and the seesaw construction they created. The sequence of the questions and instructions in the worksheet is adjusted to the EDP cycle (see Appendix A). The questions and instructions in the worksheet are also structured following indicators of critical and creative thinking skills, as shown in Table 2. Critical thinking skills indicators are obtained by synthesizing critical thinking skills indicators from Ennis (2015), Sihotang et al. (2012), and Wade (1995). Formulating the problem, gathering facts, planning, devising a strategy, and providing additional explanation were the obtained critical thinking skills indicators. The indicators of creative thinking skills were synthesized from Treffinger et al. (2002), Mahmudi (2010), and Guilford (1976). The synthesis obtained four indicators: fluency, flexibility, authenticity, and detailedness. These indicators were used to create tasks in student worksheets as well as guidelines for scoring students' products. Table 2 depicts the mapping of indicators of critical and creative thinking skills, student worksheet tasks, and student products.

Table 2
*Mapping of Critical and Creative Thinking Indicators, Student Worksheet Tasks, and Student Product*

Skill	Indicator	Student Worksheet's Tasks	Student's Product
Critical thinking	Formulating the problem	I.5	
	Gathering facts	I.1, I.2, I.3, IV.3	
	Planning	I.4, I.5	
	Devising strategy	II.1, IV.1	Purpose
	Providing further explanation	II.2, III.1, III.2, IV.2, IV.3, IV.4	Purpose
Creative thinking	Fluency	II.1, IV.1	
	Flexibility	I.4, I.5	
	Authenticity	I.4, I.5, III.2, IV.3	Design and construction
	Detailedness	II.2, III.1, III.2, IV.2, IV.3, IV.4	Relevance

Data Analysis

The data analysis process began with the development of a rubric for scoring student answers on worksheets and the products they created. The rubric is divided into two parts: a rubric for students' worksheet answers and the resulting seesaw product.

Each item on the worksheet has a maximum score of 10 or 15. The difference in the maximum score indicates a difference in cognitive demand in each question. As an illustration, we consider question number I.4, which asks students to name the tools and materials they will use, had a smaller cognitive demand than question number IV.1, which asks them in groups to discuss and write down the strategies they need to improve their works. It aligns with our findings in the Results and Discussion that students experience difficulties developing

improvement strategies. Thus, questions I.4 and IV.1 have a maximum score of 10 and 15, respectively. We administered the same considerations to determine the maximum score for the other questions. To demonstrate how we score students' answers on the worksheet, identify the example of one group's answers shown in Figure 1.
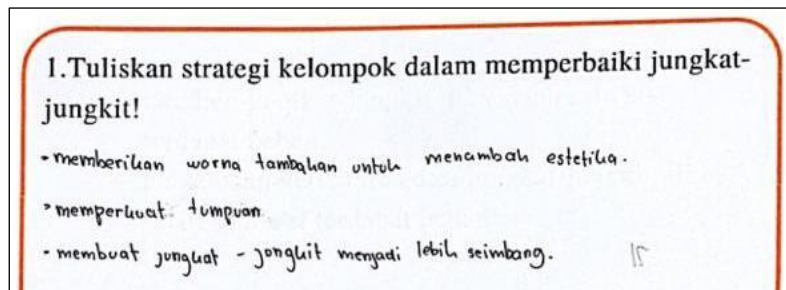
Figure 1. A sample of students' answers on the worksheet

Based on Figure 1, the group mentioned its improvement strategy and its purpose clearly and fluently. Therefore, we suggested that the group has demonstrated devising strategy and fluency skills.

There are three scoring aspects that we use for students' seesaw products, i.e. relevance, design and construction, and purpose of the product. Product relevance was related to detailedness, product design and construction were related to authenticity, and product purpose was related to devising strategy and providing further explanation. We scored each aspect of the scoring with a range of 1 to 4. As an illustration of the scoring process that we carried out on student products, consider Figure 2 below.

Figure 2. A sample of students' seesaw product

Figure 2 depicts a product that is distinct from those produced by other groups. The originality comes from the use of various colors and decorations while maintaining a balance of seesaws. Thus, we proposed that the group's work was authentic. We provided this product with a four for product form or authenticity. We scored the other aspects using similar criteria.

After completing the scoring process, we utilized descriptive statistics, specifically percentages, to summarize the scores for each indicator of critical and creative thinking skills. In addition, we use thematic analysis to identify key themes in students' worksheet answers. Braun and Clarke (2006) proposed a procedure for conducting thematic analysis.

Results and Discussion

The results of the analysis of students' critical and creative thinking skills are presented and discussed in the following three sections.

Students' Critical Thinking Skills

Table 3 displays the average score of critical thinking skills based on the students' answers on the worksheet and the seesaw product presented for each indicator. Based on these five indicators, the student's critical thinking skills averaged 73.97.

Table 3
Students' Critical Thinking Skills

Indicator	Average
Formulating the problem	72
Gathering facts	75.5
Planning	86
Devising strategy	66
Providing further explanation	70.38
Average	73.97

The skill of planning is the indicator of critical thinking skills with the highest average score. Two themes of planning skills can be discovered in the student's worksheet answers. First, students can meticulously plan the tools and materials to be used. Second, students can design each design's function or usability.

Translation:
Write down the tools and materials that will be used (tools and materials provided: glue gun and popsicle sticks)
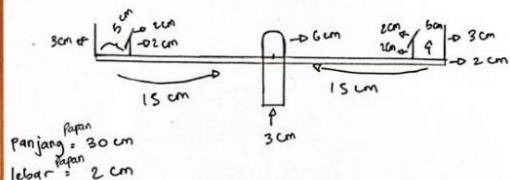Answer:
Tools:
- A hot glue gun (to hold the sticks together)
- Markers (to draw)
- Scissors/cutter (to cut cardboard and sticks)
Materials:
- Popsicle sticks (as the arm of the seesaw)
- A cardboard/paperboard (as base and pedestal)
- Loads (coins) (to check the seesaw's balance)

Figure 3. Planning for tools and materials in one group's answer.

In the worksheet, all students described the tools and materials in detail. Figure 3 depicts the response of one group of students. The diagram shows that the group was able to not only plan tools and materials in detail but also provide a comprehensive classification of tools and materials. In other words, they can create categories and then determine who the members of those categories are. Furthermore, the group provided functional descriptions of the tools and materials they intend to employ to construct a seesaw.

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Translation:
Draw a seesaw design as detailed and attractive as possible! Write down the reasons too!
Answer:
Board length = 30 cm
Board width = 2 cm
Fulcrum height = 6 cm, fulcrum width = 3 cm
Load weight = 3 grams (1 coin)
The length and height of the handle = 2 cm
Reason
a. The length is 30 cm, thus, it is not too short
b. The width is 2 cm, thus, it is not too thick
c. The height of the fulcrum is 6 cm, thus, it can seesaw
d. The weight of the load is 3 grams, thus, it balances
e. The length of the handle is 2 cm, thus, it is not too long
f. The handle length of the horizontal part is 2 cm to match the length of the handle

Figure 4. Mentioning the function of the design from one group's answer.

The second theme is that students design the designs' function or usability. Almost every group created a seesaw based on the size and design of the seesaw drawn. The group includes reasons for each size and explains its function, especially for those shown in Figure 4.

However, developing strategy skills is the indicator of critical thinking skills that receives the lowest score. There are three themes associated with strategy development: (1) product development strategy, (2) evaluation awareness, and (3) improvement strategy.

Figure 5. The initial and final product of one group.

Figure 5 demonstrates the seesaw product before (left) and after (right) revision. During the trial and presentation, the students who constructed the seesaw saw their mistakes and received feedback from the teacher. The feedback relates to the balance, comfort, and aesthetics of the seesaw. Nonetheless, these students have not used the feedback to develop improvement strategies and have not used these strategies to improve the seesaw.

Students' Creative Thinking Skills

Table 4 displays the average score of creative thinking skills based on the worksheet answers and seesaw products of each indicator. Based on these four indicators, the average creative thinking skills of students are 73.05.

Table 4
Students' Creative Thinking Skills

Indicator	Average
Fluency	57
Flexibility	86
Authenticity	78.83
Detailedness	70.38
Average	73.05

Four indicators of creative thinking skills are evaluated, with each indicator receiving a different average score. Flexibility is the creative thinking skills indicator with the highest average score. There are two themes that emerged from students' work in terms of their flexibility: (1) variations in answers and problem-solving; and (2) flexibility in creating appealing designs.
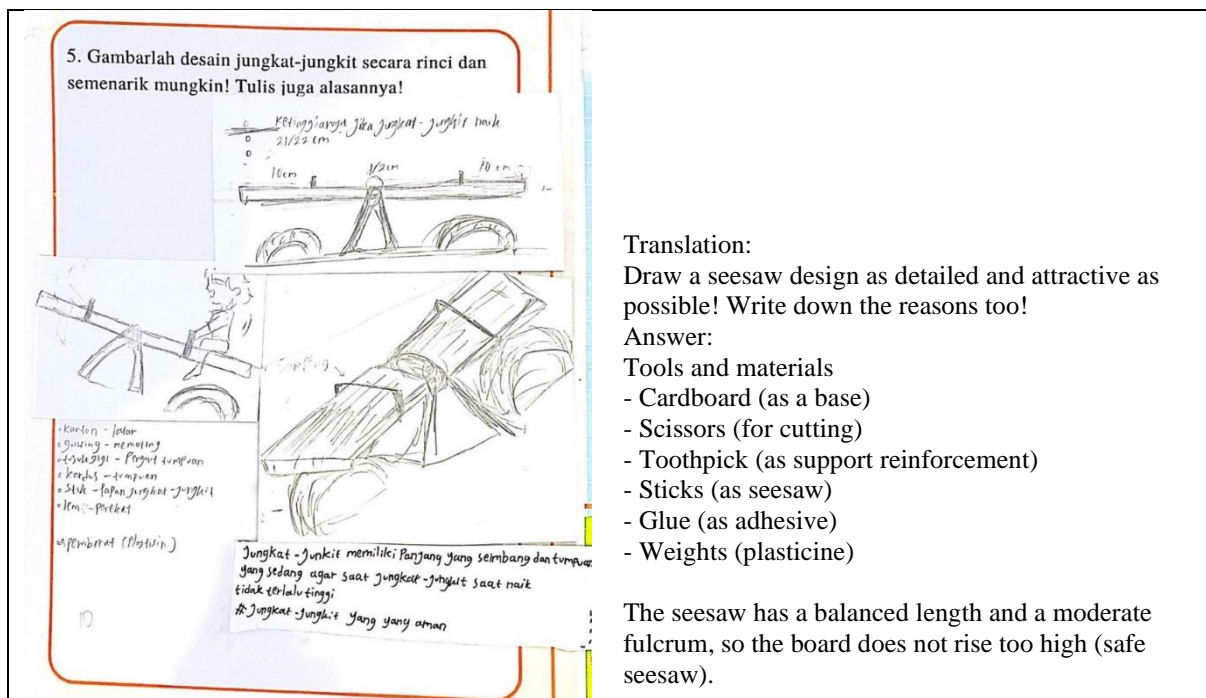

Translation:
Draw a seesaw design as detailed and attractive as possible! Write down the reasons too!
Answer:
Tools and materials
- Cardboard (as a base)
- Scissors (for cutting)
- Toothpick (as support reinforcement)
- Sticks (as seesaw)
- Glue (as adhesive)
- Weights (plasticine)

The seesaw has a balanced length and a moderate fulcrum, so the board does not rise too high (safe seesaw).

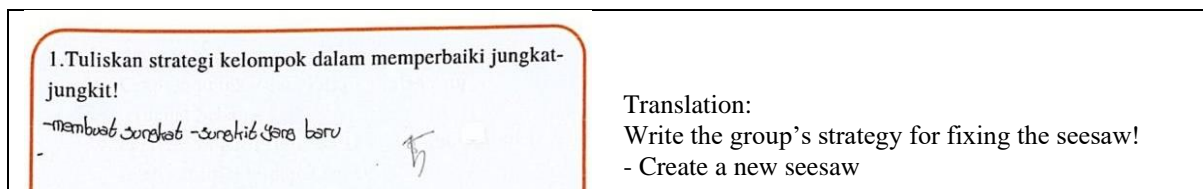*Figure 6.* Students work showing the theme of variation

Figure 6 displays students who provide a variety of answers and problem-solving ideas, as well as flexibility in creating appealing designs. The students documented the tools and materials. Surprisingly, these students documented the function of each tool and material. This answer is also unique in that it mentions "play dough" as the weight. It means that the students come up with different problem-solving ideas for seesaw weights.

Furthermore, Figure 6 demonstrates that these students are adaptable in creating appealing designs. These students present three variations of the image, each with a unique perspective and function. The students each contribute a unique nuance to the product designs. Figure 7 depicts the finished seesaw, whose design is depicted in Figure 6. Even though the seesaw is imperfect, in that it is not balanced and the weight is not the same as planned, the students have created a seesaw that is nearly identical to the design they worked on.

Figure 7. Seesaw product

The fluency indicator, on the other hand, receives the lowest score for creative thinking skills. Several factors contribute to the current study's average student fluency score, which is still relatively low. These factors include (1) insufficient problem solutions and (2) a lack of understanding of the errors.

1.Tuliskan strategi kelompok dalam memperbaiki jungkat-jungkit!

—membuat jungkat-jungkit yang baru

Translation:
Write the group's strategy for fixing the seesaw!
- Create a new seesaw

Figure 8. Example of low fluency

Figure 8 portrays one of the students' incomplete answers in writing solutions, as well as a lack of comprehension of the errors. The student devised a plan to improve the seesaw by replacing it with a new one. These students may develop the notion that the seesaw they construct must be replaced due to numerous errors. These students, however, did not provide a detailed solution to improve it. The students are aware of errors in their previous designs but are unable to write down ideas for how to correct them fluently.

Discussion

The present study has described the students' critical and creative thinking skills in integrative STEAM-CT teaching and learning. Based on the analysis of critical thinking skills, the students are able to make a reasonable plan. It is because they are given a space to make a plan through one of the EDP stages, namely planning (National Research Council, 2012). Planning is an essential activity in learning. It is because planning necessitates students to consider their objectives and devise strategies to achieve them (Eilam & Aharon, 2003). Such

planning can trigger the desired learning behaviors and ultimately lead to higher learning outcomes (Raković et al., 2022).

Based on an analysis of creative thinking skills, the students are adaptable in providing alternative solutions and can create an appealing design. The students have provided reasons and functions for the design aspects on which they are working. Their design drawing is also visually appealing. It is inextricably associated with the critical role of the arts in STEAM integrative learning, which encourages student creativity (Liao, 2016).

The present study also found that several aspects of critical and creative thinking skills need attention. This research shows that some students still lack detail in providing solutions to problems. In general, the students are less aware of the errors made. The students need to evaluate the errors so that the errors can be corrected and not repeated. In addition, they also need to use the feedback they receive for improvement. Therefore, evaluation practices supported by students' feedback literacy are essential for solving problems (Carless & Boud, 2018; Ifenthaler, 2012). It can be corroborated in an integrative STEAM-CT approach by providing peer feedback activities (Chang et al., 2021; Kristanto, 2018). This feedback practice supports the growth of students' critical thinking skills and creativity (Vincent-Lancrin et al., 2019).

There are several limitations to the current study. Following the characteristics of the research method used, namely descriptive qualitative, this study only directly describes the critical and creative thinking skills of students who are the subject of this study. Thus, the findings of this study cannot be generalized to different contexts and settings. Second, this study uses students' answers on worksheets and their final product. Thus, the description of students' critical and creative thinking skills presented here is their skills during the learning process.

Conclusion

The current study explained students' critical and creative thinking skills in innovative STEAM and CT teaching and learning practices. This practice has sparked students to be able to make plans to solve problems, be flexible in providing solutions, and create aesthetic product designs. Nonetheless, this study also found that it was necessary to support students in carrying out in-depth evaluations so that they could provide accurate solutions. In addition, students also need to be supported in acquiring feedback literacy. Therefore, we recommend that the STEAM-CT approach needs to provide space for students to develop their feedback literacy.

Acknowledgements

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Appendix A. Student Worksheet

Worksheet I: Let's think about and design a seesaw!

Let's think about it! A playground in one of the cities has a variety of children's toys. The seesaw is one of the park's children's toys. How do we make seesaws that are enjoyable, efficient, and safe?

Task I.1: Identify the characteristics of a fun seesaw!

Task I.2: Identify the characteristics of an efficient seesaw!

Task I.3: Identify the characteristics of a safe seesaw!

Let's design! Let's design and decide on the tools and materials to use now that we've identified fun, efficient, and safe seesaws!

Task I.4: Write down the tools and materials utilized (tools and materials provided: hot glue gun and popsicle sticks)

Task I.5: Draw a seesaw design in detail and as attractive as possible! Write down the reasons too!

Worksheet II: Let's make seesaws!

Let's build a seesaw! Let's build a fun, efficient, and safe seesaw using the pre-made designs and the tools and materials provided!

Task II.1: What factors do you consider when creating seesaws? For instance, the pedestal's location, the length and width of the board, or the weight of the load)

Task II.2: According to the group, what influences the seesaw to be balanced?

Worksheet III: Let's test and present the seesaw!

Let us test and then present! Check the results of the seesaw product to see if they are in accordance with the success indicators, consult with the teacher, and present it to the class!

Task III.1: Write down the evaluation results and analyze your group's mistakes!

Task III.2: Write down the improvement/improvement efforts that the group will do in the seesaw project!

Worksheet IV: Let's fix and reflect on the seesaw!

Let's fix the seesaw! It's time to fix the seesaw based on the results of trials, evaluations, and improvement efforts.

Task IV.1: Write down the group's strategy for fixing the seesaw!

Task IV.2: Which combination of variables influences the correctly constructed seesaw?

Let's reflect! Reflect on the results of doing a seesaw project with your group mates!

Task IV.3: Draw the final design of the finished product, and determine the following: (a) the seesaw gradient, if one side is loaded; and (b) the straight-line equation of the seesaw if one side is loaded.

Task IV.4: Write down your conclusions after doing a seesaw project!