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Exploring Student Engagement in STEM Education through the Engineering Design Process

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Abstract

While the engineering is expected to be a catalyst for integrated STEM education, engineering is also problematic, especially in countries with a fixed and centralized curriculum such as Japan. Therefore, translating the framework of integrated STEM into practice and exploring students' engagement are essential. This study explored students' engagement in STEM activities through the Engineering Design Process (EDP) in an elective science class. Our participants were sixteen students (aged 14–15) in a Japanese junior high school (JHS) that chose to participate for one semester. Through a single case study, we analyzed the students' engagement with the activities from the individual and group perspectives. Data from self-assessments, worksheets, presentations, and videos of lessons were collected and analyzed. The results showed that the students' level of engagement was very high. Exploration with co-occurrence network analysis showed that students' engagement was associated with the topic of the activity, designing activity, and students' relationships with their peers. An engineering element in an elective science class was valuable for JHS students and provided a way to enhance science lessons. Also, EPD facilitated essential skills in design and collaboration. Further research in balancing group and individual perspectives is needed.

Keywords: Engineering Design Process, STEM Education, Student Engagement

INTRODUCTION

Even though STEM education is widely accepted as making a significant contribution to education (Chacko et al., 2015; English, 2017a; Hartini et al., 2020; Krajcik & Delen, 2017; NGSS Lead States, 2013), the majority of countries in Asia (such as Japan, China, and Indonesia) do not have a firm commitment to providing STEM education by law. Since the school system in Asian countries tends to follow a fixed curriculum, the integration of new insight in education faces a big challenge (Lee et al., 2019). The boundaries around each subject in the curriculum create a fundamental dilemma (Leung, 2020) that has been identified as the terminology of system science which identified that science is not a single subject but interconnected with others subjects (Mayer & Kumano, 1999). In Japan, science, mathematics, and technology are taught as separate subjects starting from the junior high school (JHS) level (Japan Science and Technology Agency, 2019; MEXT, 2017), while some engineering concepts are explicitly covered in technology education. In Japanese JHS, engineering is not taught as a separate subject. Engineering is part of technology education. Therefore, there is little opportunity to integrate STEM components.

Additionally, teachers should have a deeper understanding of curriculum, instruction, and assessment in which students participate in science classrooms. There are various methods that could be used to promote science literacy and communication skills. The inquiry method has been widely used in science because it can enhance learning competency, but it may produce different outcomes based on classroom contexts (Boelens, et al., 2019). It leads students to have knowledge by hierarchical process of knowledge construction. Some research reported that inquiry can promote thinking classroom by instructional method and teaching strategies that teacher considered (Onsee & Nuangchalerm, 2019). That is, such inquiry learning is entirely invited to science classroom. Students are having not only mind-on activity and hands-on activities but also argumentation about the meaning of inquiry-based science investigation as important classroom practices.

Of the four components of STEM education, the engineering component is expected to enhance STEM education the most (Guzey, 2020; Moore et al., 2014). Engineering is valuable for teaching skills in structuring the stages of design as well as in construction and redesign (English & King, 2015; Li et al., 2019). However, some differences between science and engineering in terms of hands-on activities, depth, content, language use, and the teachers' position in the classroom (Guzey & Ring-Whalen, 2018) introduce some complications in the classroom setting. While science usually starts with well-defined problems (Ting, 2016), engineering is concerned with future problems in which there could be a lack of information and clarity about what is the correct or the best solution (Fortus et al., 2004). Therefore, it is essential to explore the negotiation between science and engineering components, especially in the classroom setting.

To facilitate the integration of STEM education, the engineering design process (EDP) has been proposed (Chikahiko et al., 2017; Yata et al., 2020). Moreover, to clarify the distinction between the science lesson and student group work, insights from other frameworks have been adapted (English, 2017b; EngrTEAMS, 2017; Guzey, 2020). The adapted framework of the EDP is provided in Figure 1. Theoretically, the framework was proposed to facilitate the ability of students to learning integrated STEM. However, the STEM framework's translation to practice remains challenging due to factors reported globally (Hinojo-Lucena et al., 2020; Kelley & Knowles, 2016; Rosicka, 2016), and insights from classroom-based practice are rare, especially from students' perspectives.

Various factors need to be explored in depth before integrated STEM through EDP can become more widespread, especially the factors that affect student engagement, which is thought to be closely related to the position of the student at the center of the learning process (Struyf et al., 2019). Student-centered learning has become one of the long-term goals of world-wide education reform (Kaput, 2018; O'Neill & Mcmahon, 2005). Student engagement refers to complex behavioral intensity and emotional quality during an activity (Reeve et al., 2004). Disengagement in students can be defined as passivity and discouragement that lead students to give up on the lesson activity (Skinner, Kindermann, 2009; Skinner, Saxton, Currie, & Shusterman, 2017; Skinner et al., 2008).

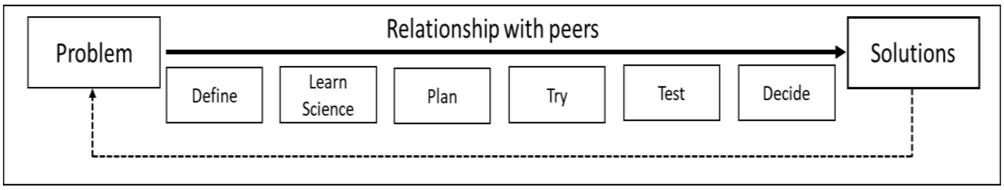

Figure 1. Engineering design process syntax

Various measurements of student engagement have been reported in the literature, depending on the context of the research. Previous research has explored student engagement through observation and interviews (Struyf et al., 2019) and through questionnaires for large-scale samples (Barlow et al., 2020). Considering that STEM activities nurture students' relationships with their peers and emphasize the importance of individual engagement, a balance between both individual and group perspective is needed. Therefore, this research focuses on a single case study that explores student engagement and group results. This issue is valuable but less explored by former studies (Krajcik & Delen, 2017; Struyf, et al, 2019). To guide the study, several research questions were developed as follows:

1. How well did students engage overall in the STEM activities through the EDP steps?
2. How well did individual students engage in the STEM activities through the EDP steps?
3. How well did students engage in STEM activities through the EDP steps when working as a group?

METHOD

In this section, the framework of our research, the participants, the data sources, and the analysis used to interpret the data are described. This research comprised a single case study that integrated quantitative and qualitative data. This approach has several benefits, especially to explore the realistic setting in the educational field (Almalki, 2016; Kanga et al., 2015). The research framework is summarized in Figure 2.

Introduction to the Research Site

The study was conducted in a JHS in Shizuoka prefecture in Japan. Compared to other schools in the prefecture, the school's policies focus on research and practice for the children's future. The school was built in 1947 for boys only and, since 1949, it has been open to both boys and girls. The school offers classes from seventh to ninth grade and has around 400 students. For the core science lessons, this school has two dedicated full-time science teachers, supported by two part-time science teachers. Well-known for the quality of its lessons, since 1999, this school has held a one-day demo science class each year where other science educators can see how the school's science lessons are conducted.

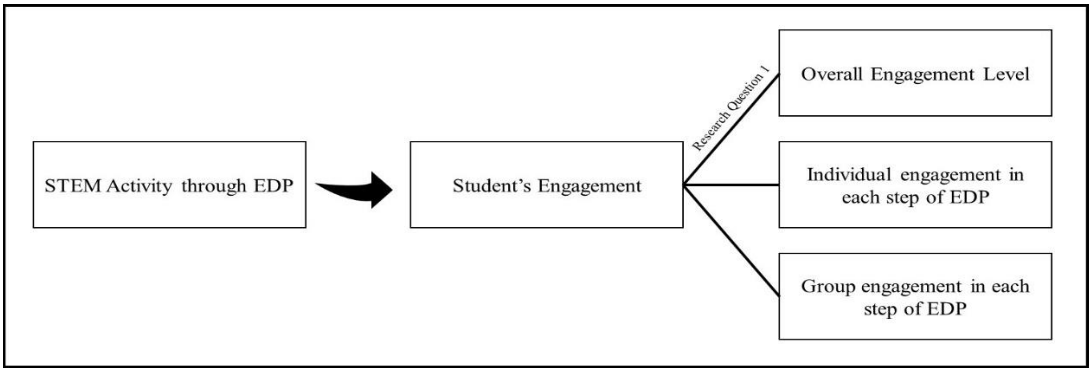

Figure 2. Visualized Scheme of the Research Questio

In addition to the core lessons, this school helps students develop their interests through an elective class that is conducted in collaboration with the National University and various non-profit organizations located in the prefecture. While in JHS in Japan, elective science classes are rarely offered, this school offers an elective science class every semester. Because this research focused on integrating STEM through EDP in an elective class, the school was considered a suitable research site, representing a unique opportunity to infuse STEM into formal education in Japan through its elective science classes.

Characteristics of participants

Sixteen ninth-grade students (ten boys and six girls) who had voluntarily applied for the elective science class were chosen as our research participants. These students were very interested in science. They divided themselves into four groups, and the composition of the groups remained the same for 12 meetings. The classroom was designed to facilitate interaction among the students in their groups throughout the activities.

Curricular Context

Considering that STEM activity through EDP was new for the students, the first, second, and third meetings were used to introduce concepts and prepare the groups. Exploration of student's perception of engineering profession showed that the they have positive perceptions especially related to design activity and technology (Sulaeman et al., 2020). The fourth through the twelfth meetings were devoted to STEM activities. During nine meetings (50 minutes each), two STEM activities were conducted with a focus on renewable energy topics. The learning materials were developed as part of the Shizuoka STEM Academy Project, involving professors in science education, science teachers, and post-graduate students in Japan. All the project followed the EDP from problem to solution in Figure 1.

The goal of the first activity (the wind activity) was to have the students designate the location of wind power technology around their school by considering wind speed and environmental issues. The goal of the second activity (the solar activity) was to have students to design a boat powered by solar energy. Each activity started with an introduction to the problem and continued with group activities related to planning, learning, trying out their design, testing, and decision-making.

Specific science or mathematics learning took place during group activities. Students had the opportunity to work with their group members to explore the problem and propose solutions. The STEM activities took place indoors and outdoors around the school area, such as the schoolyard (for the wind activity) and the swimming pool (for the solar activity). Moreover, each group also made a presentation at the end of each activity.

Data sources and analysis

The primary data were collected from group worksheets, group presentations, and students' self-assessments (Table 1) and were supported by video-audio data (12 x 50-minute lesson videos and audio). For the first research question, analysis of students' responses to the self-assessment instruments about their overall engagement was conducted. The question related to overall engagement was a Likert-type item with four possible responses in which students were asked to select their level of engagement from "almost not participating" to "fully participating." This was followed by an open-ended question in which students were asked to write the reasons for their response. The quantitative data were analyzed using descriptive analysis to identify the students' central ideas about their engagement. To extract the central ideas, co-occurrence network analysis was used with the KH Coder software (Hirsch & Andrews, 2016; Li et al., 2018; Liu et al., 2017) using a software called KH Coder (Higuchi, 2016a, 2016b).

Table 1. Summary of Data Analysis

Research question	Aim	Instrument	Scale	Analytical techniques
1	Overall engagement	Self-assessment	Likert scale (1–4)	Descriptive analysis
		Self-assessment	Open-ended question	Co-occurrence network analysis
2	Individual engagement in each EDP step	Self-assessment	Dichotomous scale (1–0)	Descriptive analysis
3	Group engagement in each EDP step	Rubrics for worksheet and group presentation	Likert scale (1–4)	Descriptive analysis

Research question	Aim	Instrument	Scale	Analytical techniques
Discussion	Triangulation of the result	Lesson videos	Each activity	Coding per activity and per group

To achieve a balance between individual and group perspectives, we first analyzed each student's perspective based on their responses to the self-assessment instruments, and then we considered the group perspectives through worksheets and their group presentation. The worksheets and presentation were scored by two science teachers based on rubrics adapted to our context from previous research that also investigated the teaching of engineering concepts (Hirsch et al., 2017). The addaptation included the change of the scale from 0 – 3 to 1 – 4 to recognized the effort of our students.

RESULTS AND DISCUSSION

In this section, the results of our analysis are presented. Evidence related to each research question is presented and discussed.

RQ 1: How well do the students engage overall in the STEM activities through the EDP steps?

The findings about the students' engagement are summarized in Figure 3. Interestingly, the students showed consistent responses related to their participation in the two activities over the semester. Most of the students (93.75%) stated that their engagement level was very high, while others stated their level of engagement was high. An open-ended item was included to provide data about students' reasons for their response. Group work could support student's engagement higher than lecture (Shernoff, et al, 2003). The results of the co-occurrence network analysis of their engagement with the wind and solar activities are provided in in Figures 4 and 5.

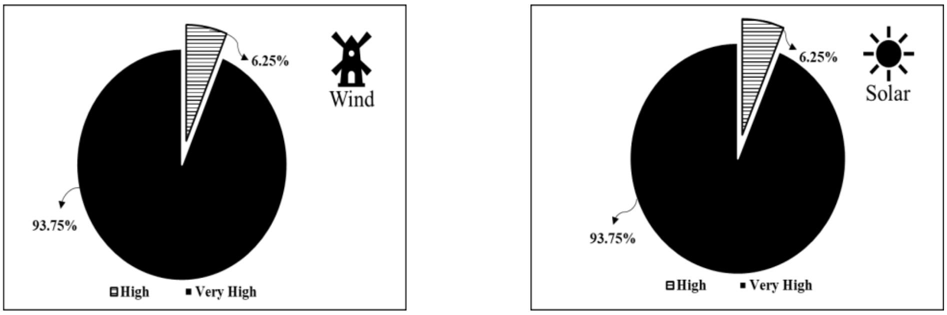

Figure 3. Students' Engagement with the Activities

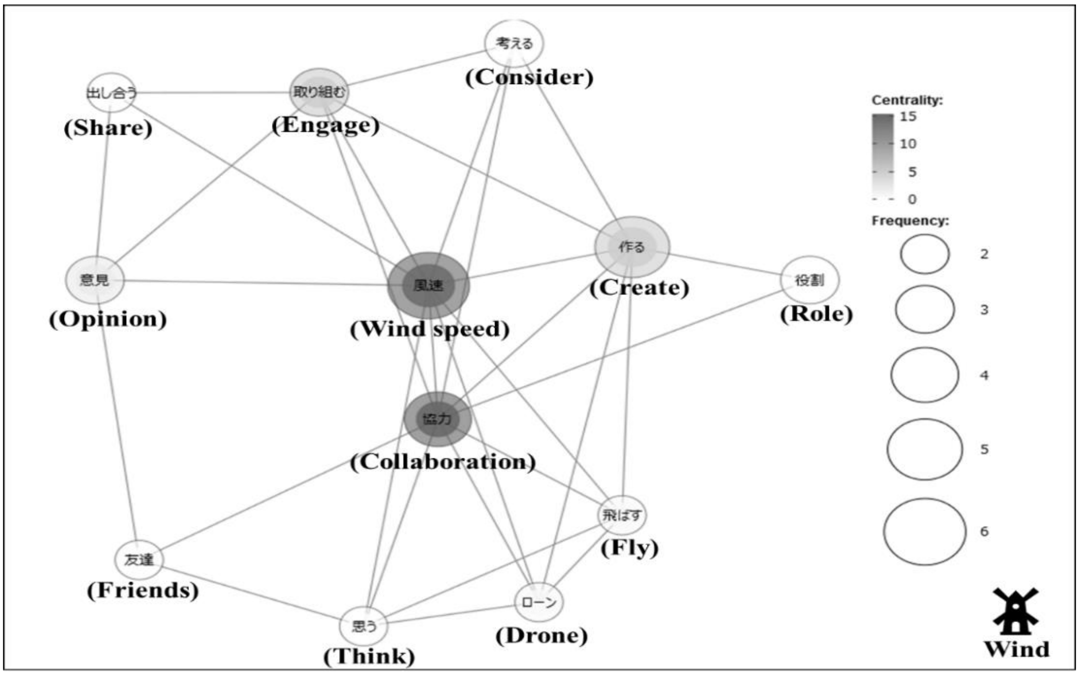

Figure 4. Reasons for Students’ Engagement in the Wind Activity

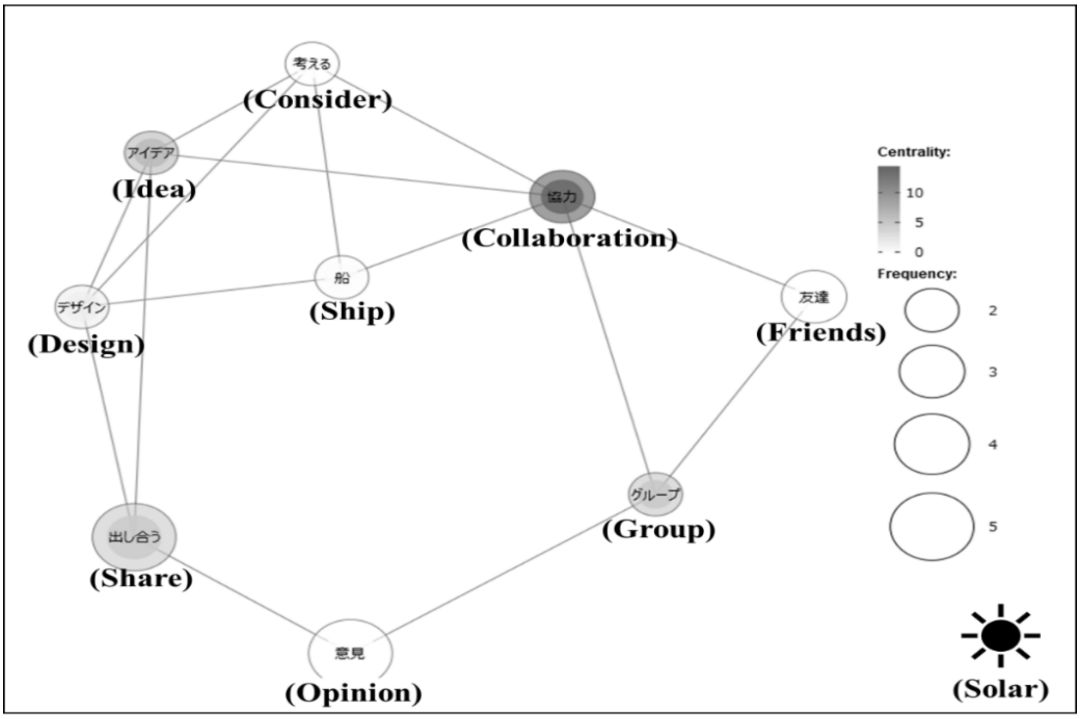

Figure 5. Reasons for Students’ Engagement in The Solar Activity

Table 2. Samples of Students' Responses to Their Engagement

Students' Responses	
D13 (Wind power activity)	*それぞれ意見を出し合ったり、お互いの得意なこと、知識を生かして、* *グループ全体で取り組むことができたから。* To share our opinions, what each other's good at, use our knowledge, we as a group can finish our project well.
A3 (Solar boat activity)	*たくさんのアイデアを総合して考えられた。協力すればいいものも作れる。* I have many ideas about the project. By working together with my group, we bring the ideas into the real boat.

(Groups are named A–D; students are numbered 1–16)

The words that the students used most frequently and that were central in their understanding of their engagement can be seen clearly. Figure 4 shows that students used the words "wind speed" and "collaboration" most frequently to explain their engagement with the wind activity. Moreover, in Figure 5, the words "collaboration," "group," and "share" are central(sources). This analysis shows that students' engagement was consistently related to their relationship with their peers during the STEM activities. To clarify how students used these central words, examples of complete sentences from two students' responses are provided in Table 2. Furthermore, Figure 5 showed that the dynamic group work greatly influenced students' engagement in the STEM activities. The opportunity to work in groups allowed students to share their ideas, opinions, and designs.

This result is in line with previous research, which found that through their engagement in EDP, students enhanced their communication and collaboration skills (Krajcik & Delen, 2017). These results show that engineering design tasks completed in small groups taught students science concepts and allowed them to engage in productive thinking (Guzey, 2020). Thus, the EDP activity successfully engaged the students and allowed them to be actively involved in the activity.

Question Research 2: How well do individual students engage in the STEM activities through the EDP steps?

After the students had finished the wind and solar activities, they answered questions designed to measure quantitatively the implementation of the EDP and identify which steps of the EDP were difficult. The first part of the self-assessment instrument was a dichotomous item where the students were asked whether they accomplished each EDP step during the project. Descriptive statistics were performed, and the results are provided in Figure 6.

To keep the analysis focused, 70% was the cut-off to determine whether a particular step was well understood. From the result, it can be observed that in the wind activity, the Learn, Plan, and Decide steps were not well understood with average scores of 37.5%, 56.25%, 56.25% scores, respectively. In contrast with the scores for the wind activity, the average score for the Test step in the solar activity was low at 43.75%. Although both of activities designed to be equal, the hands-on activity in solar project observed harder for the students. The fluctuation results were found based on the data in Figure 6. Therefore, these individual perspectives need to be triangulate with the group result in the following section.

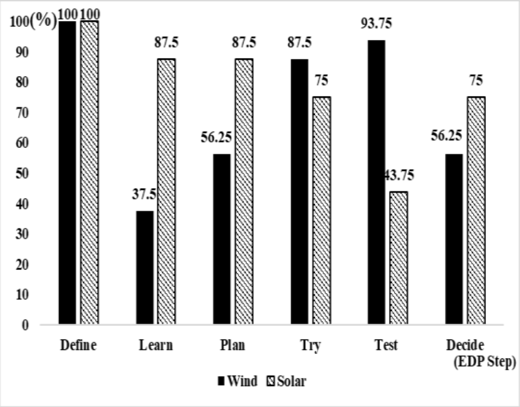

Figure 6. Individual Engagement

Research Question 3: How well do the groups engage in the STEM activities through the EDP steps?

During all the activities, each group recorded their work on group worksheets and presented the results of their classroom discussions. We scored each group's worksheets and presentations for each step of the EDP using rubrics (Table 3) that were adapted from other researchers (Hirsch et al., 2017). Based on Figure 7, the students had difficulties with the Learn, Try, and Test steps.

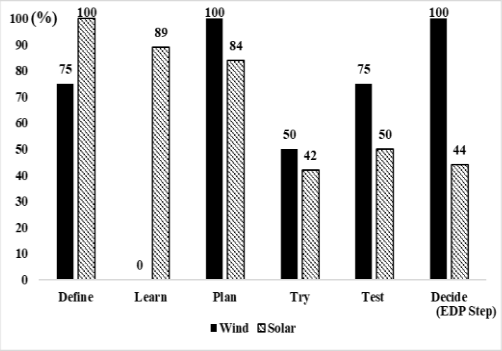

Figure 7. Group Engagement

Since we found some inconsistencies, triangulation was conducted with data from our lesson videos. This process is valuable to clarify the lesson situation and students' activities (Molbæk & Kristensen, 2019; Santagata & Angelici, 2010). The triangulation allowed us to understand the different levels of difficulty that were experienced by students in each activity, particularly the hands-on challenge of building their design. In the wind project (Video-3 to 6), all four groups of students successfully designed their solution. The hands-on element in this project involved designing an anemometer, which was not complicated for ninth-grade students. This project also had an outdoor activity for two meetings (100 minutes), during which the students measured wind speed and drone activity.

Since the teacher did not specify some aspects of the Learn step, students had the perspective that they were designing the solution but not learning specific science concepts. In the Solar project (Videos 7 to 12), the solar boat project involved more complicated hands-on activities, and the use of solar panels provided a deeper understanding of the mechanism of the sun as the source of energy. Therefore, students' engagement in the Learn step was better.

However, one group did not successfully build their boat. This affected their perception of the Test step. From the analysis of each EDP step, it appeared that failure in a hands-on activity, such as designing the solar-powered boat, could influence students' engagement. Therefore, when the students failed to design their engagement tend to decrease. The fluctuation of students' engagement influence by their success in hands-on activity.

Table 3. Rubrics for EDP Worksheet and Presentation

EDP Step	Score
Define	1 Did not included the client, problem and its criteria
	2 Poorly stated the client, problem and its criteria
	3 Adequately stated the client, problem and its criteria
	4 Clearly stated the client, problem and its criteria
Learn	1 Did not mentioned science concept in their project
	2 Poorly stated science concept in their project
	3 Adequately stated science concept in their project
	4 Clearly stated science concept in their project
Plan	1 Did not included the design
	2 Poorly included the design
	3 Adequately included the design that matched with criteria
	4 Clearly included the design that matched with criteria
Try	1 Did not try the design
	2 Poorly tried the design
	3 Adequately tried the design that matched with criteria
	4 Clearly tried the design that matched with criteria
Test	1 Did not explained how to test the design
	2 Poorly explained how to test the design
	3 Adequately explained how to test the design that match with criteria
	4 Clearly explained how to test the design that match with criteria
Decide	1 Did not made the decision and the needed instrument
	2 Made decisions that not based on the test results
	3 Made decisions that loosely based on the test results
	4 Made valid decisions based on the test result and gave related possible improvement

Learning from failure, or in other words, persistence in problem-solving activities, is an essential skill for students. Perseverance has been identified as a critical factor in personal success in the twenty-first century (Sengupta-Irving & Agarwal, 2017; SRI International, 2013). Nurturing perseverance in problem-solving could be a future target in the implementation of STEM education.

Another factor that influenced the

poor result in the Learn step was the allocation of time. Previous research shows that EDP for elementary school students requires adequate time allocation (King & English, 2016). Additional time allocated to the Try and Test steps might be helpful for students. According to both the individual and group results, the students showed positive attitudes toward the EDP steps, especially after becoming familiar with the steps. A comparison of the EDP steps with the routine steps in Japan science classrooms reveals some similarities and differences. In Japan, a science lesson plan for JHS usually comprises three main steps: introduction, learn (experiments and discussion), and conclusion (Keirinkan, 2016; Otaka, 2012). Consistent with previous research (Wieselmann et al., 2019), our results showed that by increasing their opportunities to engage in hands-on activities, students became more familiar with the EDP. Our finding suggests that more time needs to be allocated for STEM activities to facilitate students' ability to design their solution.

CONCLUSION

As integrated STEM activities through EDP steps are implemented in JHS, the exploration of students' engagement is essential. The results showed that during two STEM activities, student engagement was very high, including engagement associated with the topic of the STEM activity, the design activity itself, and students' relationships with their peers. Within the EDP steps, engagement was also influenced by the difficulty of the hands-on activity. Therefore, scaffolding from the teacher is essential.

Integrating STEM education especially the engineering component in an elective science class is valuable for students to achieve essential skills for their future such as design and collaboration. By the process of introducing STEM activity, the student engagement is growing in the hands-on activity. For further research, the deeper exploration by gender is needed to understand more the characteristics of engagement based on gender.

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