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A Pedagogy in STEM Classrooms for Primary Students to Develop Knowledge of Electric Circuits and Problem-Solving Skills

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Abstract: This study trialed a pedagogy of "To Play and Learn, To Inquire, To STEM and Code". Supplementary with seven hands-on activity worksheets and 19 coding product templates and samples, the pedagogy was designed to expose students to the construction of electric circuits with Micro:bit in STEM classrooms for developing knowledge of electric circuits and problem-solving skills. The pedagogy was implemented as a 280-minute teaching in eight lessons for 23 selected Grade 5 classes, which involved 369 students from nine primary schools at Hong Kong. The results of pre-post-test validate the success of the pedagogy in students' statistically significant growth in all three topic-specific knowledge points. The results of questionnaire survey demonstrate the impact of the pedagogy on students' statistically significant growth in their awareness of and their confidence in applying the target problem-solving skills. The results of focus group interviews confirm that students were satisfied with the experiences and outcomes of the pedagogy in developing topic-specific knowledge and problem-solving skills. This study reveals that the pedagogy is well received by students; noticeably effective to enhance students' knowledge of electric circuits; and potential to promote their development of problem-solving skills. Future directions to extend the pedagogy for senior primary curriculum are discussed.

Keywords: coding, electric circuits, Micro:bit, pedagogy, primary schools, problem-solving, STEM education

1. Introduction and Background of Study

Science, Technology, Engineering and Mathematics (STEM) education and coding education are the two growing curriculum trends in school education in the digital era to nurture the young generation to be problem-solvers with a computer scientist mindset for the success in the digitalized society (Lee, Grover, Martin, Pillai, & Malyn-Smith, 2020; Priemer et al., 2019). Coding is advocated to be a pedagogy potential to foster students to develop capability to solve interdisciplinary problems using techniques from computing (García-Carrillo, Greca, & Fernández-Hawrylak, 2021; Li et al., 2020). This study addressed these trends to innovate a pedagogy which supported senior primary students to develop knowledge of electric circuits and problem-solving skills through STEM classroom activities on constructing electric circuits with Micro:bit.

"Electric Circuits" is a common learning topic in science-related subjects in primary school curriculum around the world; and in Hong Kong this learning topic is structured under the General Studies subject curriculum at senior primary grades (Curriculum Development Council, 2017; Fokides & Papoutsi, 2019). The scope of this learning topic covers knowledge points in three main areas: (i) about electronic components, electronic symbols, and closed circuit; (ii) about conductors, insulators, resistance, series circuit and parallel circuit; and (iii) about the application of electric circuits in daily life (Fokides & Papoutsi, 2019; Preston, Hubber, Bondurant-Scott, & Gunesekere, 2020). The prevailing way to teach this learning topic is to engage students in hands-on activities of constructing basic electric circuits, to enable students to experience and explore the use of electronic components and so to observe and understand the happenings and reasons of different phenomena of electric circuits (Cederqvist, 2022; Preston et al., 2020). STEM activities – which emphasize students' work on applying knowledge of the four disciplines in STEM domain for designing and making tangible artifacts to solve problems – become a popular lesson component for teaching this topic.

Problem-solving is the prime goal in the process of designing and making tangible artifacts in STEM activities; and therefore, researchers such as García-Carrillo et al. (2021) and Morado, Melo, and Jarman (2021) recognize that it is a natural fit for students from an early age as in primary schools to develop problem-solving skills through the engagement in STEM activities. When students design and make tangible artifacts in STEM domain, they are commonly required to demonstrate the practices of *sequencing* to order steps in a logical manner, *causal reasoning* to identify the relationship between a cause and its effect, *conditional reasoning* to identify the relationship between a decision and its condition, and *engineering systems thinking* to perceive how a component functions as part of a system (Cederqvist, 2022; Lee et al., 2020).

The integration of coding elements into STEM activities is suggested potential to support primary students to develop both domain-specific knowledge and problem-solving skills for their everyday success in the digital era (Fokides & Papoutsi, 2019; Lee et al., 2020). The pedagogy should address the component-related concern on giving students a hands-on experience in using and assembling the actual pieces of artifact components to construct tangible artifacts to solve real-life problems (Blackley & Howell, 2019; García-Carrillo et al., 2021); and the coding-related concern on allowing students to code microcontrollers in visual programming environments to control digital devices to solve real-life problems (Blackley & Howell, 2019; Li et al., 2020).

Micro:bit is a type of single-board microcontroller developed to promote coding among young generation (Cederqvist, 2022; Trilles & Granell, 2020). Micro:Bit is a pocket-sized computer composed of an LED light display, buttons, sensors and a series of input-output features. This tangible programming material is easy for young children to use; and becomes popular for the educational use in primary schools to foster students to develop competencies emphasized in the STEM domain in the digital era (Cederqvist, 2022; Morado et al., 2021). Micro:bit is recognized to be helpful for boosting young students' computational actions in the classroom activities which design and code tangible artifacts as programmable solutions for solving real-life problems, in which students are engaged in analyzing phenomena and contextualizing problems which need programmable solutions; as well as planning and sequencing the construction and coding of tangible artifacts in the programmable solutions (Cederqvist, 2022; Trilles & Granell, 2020).

For the design and implementation of STEM activities which engage primary students in building programmable artifacts for solving real-life problems, researchers suggest three main criteria for the pedagogical designs. First, students should be provided with enough chances to work on the selected programmable artifacts to explore domain-specific knowledge and stimulate their interest in coding (Blackley & Howell, 2019; Fokides & Papoutsi, 2019). Second, students should be provided with enough chances to analyze the problems and the conditions behind the solutions addressed by the selected programmable artifacts for a further thinking about technological solutions with programming materials for solving domain-specific problems in daily life contexts (Cederqvist, 2022; Preston et al., 2020). Third, students should be provided with enough chances to apply and consolidate domain-specific knowledge through building and coding tangible artifacts as programmable solutions for solving real-life problems (Blackley & Howell, 2019; Morado et al., 2021).

2. The Study

2.1 Research Design

This study trialed a pedagogy which supported students to develop both knowledge of electric circuits and problem-solving skills via a three-step pedagogy "To Play and Learn, To Inquire, To STEM and Code" together with seven hands-on activity worksheets and 19 coding product templates and samples (see Figure 1) in eight lessons lasting 280 minutes.

"To Play and Learn" step	"To Inquire" step	"To STEM and Code" step
(Guiding students to try and learn the connection of electronic components as well	(Guiding students to explore the conditions for controlling the smart light and think about the	(Guiding students to build an artifact of a traffic light system, involving coding with Micro:bit to reuse and remix codes from

as observe the operation of the smart light prototype)	reasons of different phenomena in controlling the smart light)	the smart light into the traffic light system for enabling automation features)

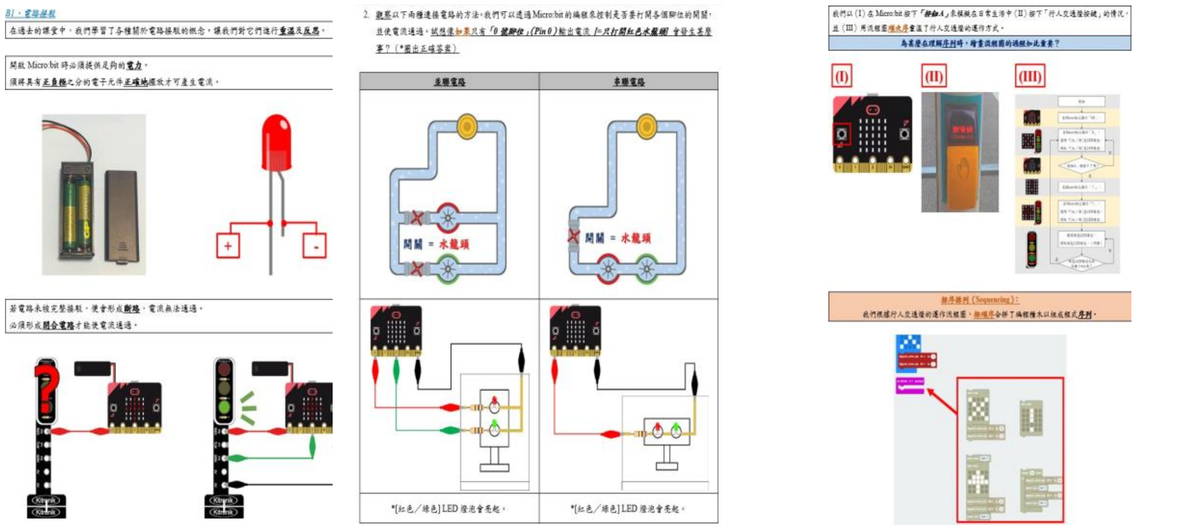

Figure 1. Samples of hands-on activity worksheets in the “To Play and Learn, To Inquire, To STEM and Code” steps in STEM classrooms.

Students coded with Micro:bit in topic-specific hands-on activities for learning the fundamentals for constructing basic electric circuits (i.e., knowledge of electronic components, electronic symbols, and closed circuit); the elements for altering closed circuits construction (i.e., knowledge of conductors, insulators, resistance, series circuit and parallel circuit); and so the application of knowledge of electric circuits for designing and making STEM artifacts. The three-step pedagogy first exposed students to “play” a smart light prototype and “learn” to distinguish between closed and open circuits; differentiate conductors and insulators; and connect electronic components for constructing basic electric circuits. It then arranged students to try to adjust the smart light to “inquire” about the concepts of electric current in electric circuits – specifically, to think about and generalize the conditions of controlling the smart light, and so to abstract the computational ways of controlling smart electrical devices. It finally exposed students to apply the learned knowledge to build a “STEM” artifact of a traffic light system, of which students were arranged to “code” with Micro:bit to reuse and remix codes from the smart light into a traffic light system for enabling features of automating the smart electrical device.

The pedagogy covered four elements of problem-solving skills – namely, sequencing, causal reasoning, conditional reasoning, and engineering systems thinking. Figure 2 illustrates how the hands-on activities under the designed pedagogy supported students to develop knowledge of electric circuits and problem-solving skills. Students first developed an understanding that the proper *sequencing* of *constructing a closed circuit* must start with turning off all switches of the *electronic components* to avoid the risk of electrical injury caused by *electric current* passing through the body. Students then tried to connect various objects of *conductors and insulators* in the smart light prototype; and observed the status of bulb-lighting in the electric circuits with different ways of connecting the electronic components, for their *causal reasoning* of the relationship between *the choice of electronic components and the status of bulb-lighting* when operating the smart light prototype. Students then tried to connect a resistor in the smart light prototype; and observed the change of brightness of bulb-lighting in the electric circuits when adjusting the smart light prototype, for their *conditional reasoning* of the relationship between *the use of resistor and the flow of electric current* when operating the smart light prototype. Students finally add the *microcontroller* Micro:bit as a *part of the system* of the smart light prototype for demonstrating the skill of *engineering systems thinking*.

[1] Students first developed the knowledge of *basic electronic components* and the skill of *sequencing*; then the knowledge of *conductors and insulators* and the skill of *causal reasoning*.	[2] Students then developed the knowledge of *resistance in series circuit and parallel circuit* and the skill of *conditional reasoning*.	[3] Students finally applied the knowledge of *electronic components and circuit connections* and the skill of *engineering systems thinking*.

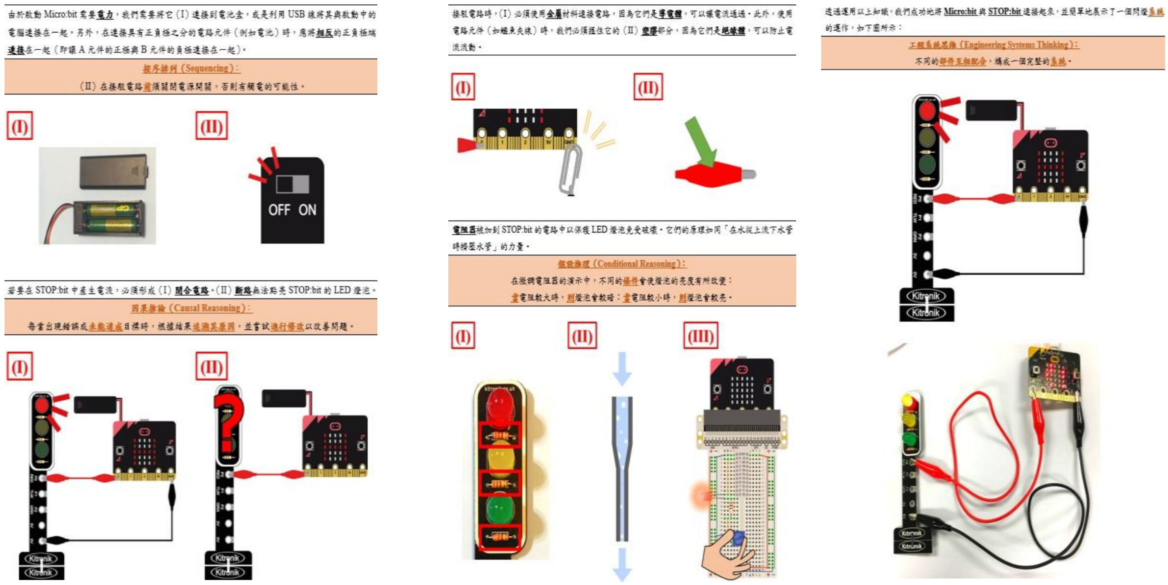

Figure 2. A sample task of hands-on activities in STEM classrooms for developing students' knowledge of electric circuits and problem-solving skills.

2.2 Research Methodology

There was a total of 369 students from 23 Grade 5 classes in nine primary schools at Hong Kong participated in this study (see Table 1). The General Studies teachers of the nine participating classes implemented the pedagogy on a class-specific manner. A three-hour training workshop was arranged for the participating teachers before the trial teaching for preparing them to integrate the rationale of learning through coding in local General Studies curriculum; implement the "To Play and Learn, To Inquire, To STEM and Code" pedagogy in STEM classrooms; and use the seven hands-on activity worksheets and the 19 coding product templates and samples in topic-specific lessons. This study evaluated the pedagogy via three methods for addressing two research questions: (1) How did the students achieve in developing knowledge of electric circuits under the pedagogy? (2) How did the students perceive the pedagogy for developing knowledge of electric circuits and problem-solving skills?

Table 1. *Profile of Students Participated in This Study*

	School 1	School 2	School 3	School 4	School 5	School 6	School 7	School 8	School 9
No. of students	61	62	33	48	18	32	31	25	59
No. of classes	4	4	2	2	1	2	2	1	5
Boys : Girls	30:31	31:31	18:15	26:22	6:12	19:13	16:15	16:9	36:23
Mean age (years)	9.98	9.98	9.71	9.81	10.65	10.20	9.81	9.91	10.12

First, pre-post-tests were conducted at the beginning and the end of the pedagogy. It investigated students' achievement in knowledge of electric circuits. The test papers contained eight questions: two on electronic components, electronic symbols, and closed circuit; five on conductors, insulators, resistance, series circuit and parallel circuit; and one on design of an electronic alarm with the application of knowledge about electric circuits. The pre- and post-test scores of students were compared statistically with the assistance of SPSS software. The Cronbach's alpha reliability coefficients for the pre-test and post-test are 0.74 and 0.75 respectively.

Second, pre-post-surveys were conducted at the beginning and the end of the pedagogy. It investigated students' perception of the pedagogy for developing knowledge of electric circuits and problem-solving skills. The questionnaire contained seven 5-point Likert scale questions on problem-solving. The mean rating for each question and the corresponding standard deviation were then calculated. The Cronbach's alpha reliability coefficients for the pre-survey and post-survey are 0.93 and 0.95 respectively.

Third, focus group interviews were conducted at the end of the pedagogy. It investigated students' perception of the pedagogy. There were 27 students randomly selected from the nine participating schools, with each focus group consisting of two to four students. The student respondents were asked to discuss the support from the pedagogy for developing knowledge of electric circuits and problem-solving skills, the level of enjoyment in and satisfaction with the pedagogy in STEM classrooms, and the challenges in and suggestions on the pedagogy in STEM classrooms. All the interview content was transcribed and systematically summarized.

3. Results and Discussion

3.1 Students' Achievement in Developing Knowledge of Electric Circuits under the Pedagogy

From the pre-post-tests results as shown in Table 2, the pedagogy effectively supported students to attain a noticeable gain in the knowledge specific for the topic of "Electric Circuits" in Grade 5 General Studies curriculum. The students had a statistically significant increase in the post-test scores for the question items on all three types of topic-specific knowledge points. The students were found to greatly enhance their knowledge about electronic components, electronic symbols, and closed circuit; and their capability of designing an electronic alarm with the application of knowledge about electric circuits.

Table 2. *Students' Achievement Before and After the Pedagogy on "Electric Circuits" (N =369)*

Question items			**Pre-test scores**	**Post-test scores**	**t-test**
Areas	**No. of items**	**Max. scores**	**Mean (SD)**	**Mean (SD)**	
(1) Electronic Components, Electronic Symbols, and Closed Circuit	2	5	3.13 (1.48)	4.08 (1.28)	11.65***
(2) Conductors, Insulators, Resistance, Series Circuit and Parallel Circuit	5	9	5.36 (1.85)	5.66 (1.72)	2.78*
(3) Design of an Electronic Alarm with the Application of Knowledge about Electric Circuits	1	4	0.36 (0.70)	0.59 (0.84)	5.21***
Total	**8**	***18***	***8.86 (3.15)***	***10.33 (2.92)***	***8.68****

$^*p < 0.05$ $^{***}p < 0.001$

Figure 3 gives an example that a student made great improvements in completing a test question before and after the pedagogy: (i) from no recognition (in pre-test) to a correct matching (in post-test) of electronic symbols with three target electronic components; (ii) from the correct identification of only one target conductor (in pre-test) to all three conductors and three insulators (in post-test); and (iii) keeping the correct understanding (from pre-test to post-test) of how the change in resistance influences the flow of electric current and the brightness of bulb-lighting in an electric circuit

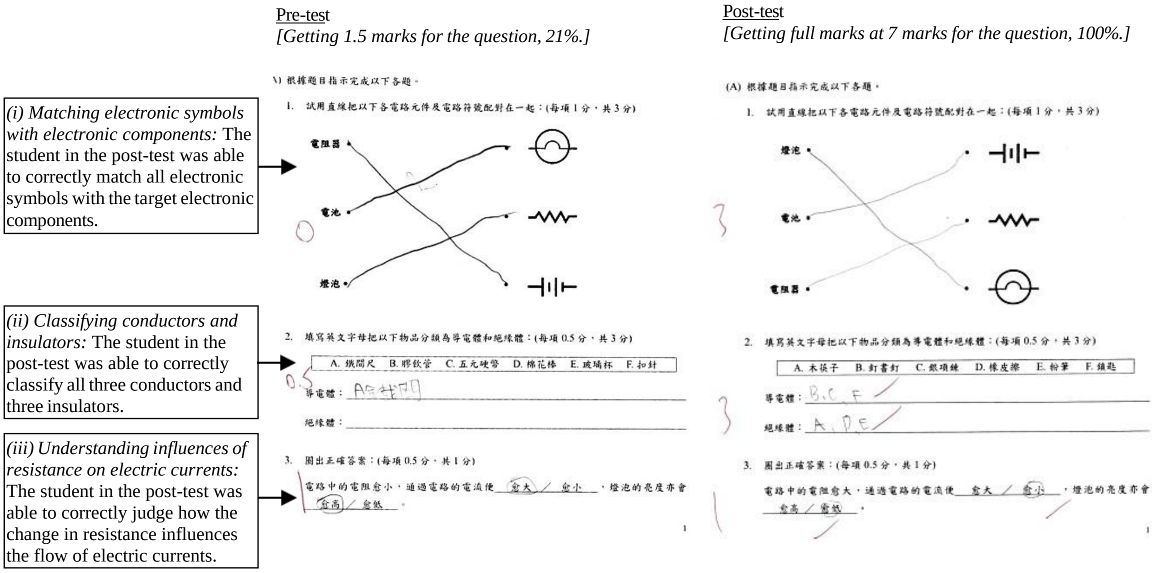

Figure 3. An example of the improvements made by a student in completing a test question before and after the pedagogy on "Electric Circuits".

3.2 Students' Perception of the Pedagogy for Developing Knowledge of Electric Circuits and Problem-Solving Skills

From the questionnaire survey results as shown in Table 3, the students positively perceived the pedagogy for developing knowledge of electric circuits and problem-solving skills. The students demonstrated a positive perception persistently that the pedagogy promoted them to repeat attempts for solving problems successfully. It is noteworthy that the students had a statistically significant increase in the level of confidence in their capability of all four elements of problem-solving skills. This shows that the pedagogy, from students' perspectives, can help with the development of problem-solving skills. Such finding serves a good indicator that the pedagogy is a pleasing and promising way for students to develop problem-solving skills.

Table 3. *Students' Questionnaire Survey Results on the Pedagogy on "Electric Circuits" (N =369)*

In the process of learning STEM …	***Pre-survey***		***Post-survey***		**t-*test***
	Mean (1-5) #	***(SD)***	***Mean (1-5)*** #	***(SD)***	
I can design and create things in the correct order.	3.52	(1.11)	3.78	(1.15)	3.79***
I can solve a problem with repeated attempts until success.	3.62	(1.13)	3.77	(1.11)	2.24*
I can form a system through the interaction between devices.	3.50	(1.15)	3.74	(1.16)	3.40***
I can set different conditions (If… then…) to get desirable results.	3.44	(1.13)	3.70	(1.11)	3.87***
My overall problem-solving skills are improved.	3.53	(1.19)	3.70	(1.23)	2.32*
I can apply the problem-solving skills learned from STEM to other academic subjects.	3.42	(1.14)	3.68	(1.18)	2.67**
I can explain what cause the change and I can expect the result.	3.40	(1.12)	3.66	(1.14)	3.78***

#Note: 1 = "strongly disagree"; 2 = "disagree"; 3 = "neutral"; 4 = "agree"; 5 = "strongly agree".
**p < 0.05 **p < 0.01 ***p < 0.001*

From the focus group interviews results as shown in Table 4, students' positive perception of the pedagogy in STEM classrooms were further confirmed.

Table 4. *Students' Focus Group Interview Feedback on the Pedagogy on "Electric Circuits" (N = 27)*

Major interview feedback
Help in the development of knowledge of electric circuits and problem-solving skills
• Many students were able to differentiate the various types of electronic components and electric circuits, to draw circuit diagrams, and to connect electric circuits for building the target STEM artifacts.
• Many students realized the necessity to think carefully about the casual relationship between the use of different types of electronic components, to correctly connect the given electronic components for a workable electric circuit.
Enjoyment in and satisfaction with the pedagogy
• Many students liked and enjoyed the STEM activities with coding tasks very much because they can do the hands-on practice of constructing various electric circuits.
• Many students felt the experience of building STEM artifacts interesting and useful; and were highly satisfied with the effectiveness of the approach of learning by doing in the STEM activities.
Challenges in and recommendations for the pedagogy in STEM classrooms
• Some students were not familiar with coding with Micro:bit at the beginning and found challenging to complete the coding tasks in the STEM activities within the limited class time.
• Some students recommended to extend the teaching scope of the pedagogy to introduce more different types of sensors for building STEM artifacts to solve problems in daily life.

The students asserted the help in the development of knowledge of electric circuits and problem-solving skills. Almost all of the student respondents considered that the pedagogy helped them to develop knowledge of electric circuits and problem-solving skills. For the development of topic-specific knowledge, the student respondents reflected that after the pedagogy they were able to recognize electronic symbols for comprehending and drawing circuit diagrams, and to identify different types of electronic components and connection methods for constructing varying closed circuits. Four student respondents further indicated that apart from learning about the rationale behind the operation of traffic lights, they were also stimulated by the pedagogy to explore the internal structures of common electrical devices in daily life. For the development of problem-solving skills, the student respondents indicated that the pedagogy helped them to go through the problem-solving process. Nearly one-third of the student respondents noted that they understood more about each of the four elements of problem-solving skills, especially the ones of sequencing and causal reasoning. Five student respondents noted that after the pedagogy they had more confidence in tackling challenging problems successfully through iterative trials and errors. One of these student respondents further illustrated that the impact of the pedagogy on stimulating interest and effort of thinking about the internal structure and operation model of various electrical devices in daily life. Another student respondent pointed out that the logical thinking built through the pedagogy can be extended to the learning process in other subjects, such as mathematical calculation in the mathematics subject.

The students expressed their high level of enjoyment in and satisfaction with the designed pedagogy for learning the topic of "Electric Circuits" in STEM classrooms. Almost all of the student respondents appreciated that the pedagogy brought them a happy and interesting experience in learning the target topic. The student respondents indicated that they liked the hands-on activities and became more engaging and attentive in General Studies lessons, comparing with subject lessons taught through the traditional teaching mode. Five of these student respondents further expressed their great sense of achievement after the successful completion of coding tasks and the correct connection of operable electric circuits in hands-on activities. More than four-fifths of the student respondents valued that the hands-on activities in the pedagogy exposed them to the real-life experience in handling electric circuits. Nine of these student respondents further indicated that such learning experience not only enabled them to deepen their understanding of the topic-specific knowledge, but also stimulated them to extend learning and thinking after class about the topic-related knowledge outside traditional textbook coverage for solving problems in daily life.

The students indicated challenges in and made suggestions on the pedagogy for General Studies lessons in STEM classrooms. Around one-fifth of the student respondents expressed their challenges when coding with Micro:bit at the beginning; and therefore had difficulties in completing the coding tasks in the STEM activities within the limited class time. More than half of the student respondents recommended the pedagogy to include more hands-on tasks on designing other STEM artifacts, such as automatic cars, electric switches, mini fans, mini air-conditioners, fire alarm, intruder alarms, etc. Three of these student respondents further suggested that more types of sensors for building STEM artifacts can be introduced in the hands-on tasks, to expand the learning scope among students in this subject topic. Three student respondents further expected for introducing hands-on tasks with different levels of difficulty to cater for the learning diversity among students. One student respondent suggested on extending the use of pedagogy in Grade 5 General Studies lessons themed in other subject topics such as reflections and refractions of light rays.

4. Conclusion and Future Work

This study innovated a pedagogy in STEM classrooms for developing knowledge of electric circuits and problem-solving skills among Grade 5 students at Hong Kong. The pedagogy "To Play and Learn, To Inquire, To STEM and Code", supplementary with seven hands-on activity worksheets and 19 coding product templates and samples, was implemented in an eight-lesson trial teaching for 23 Grade 5 classes from nine Hong Kong primary schools, involving a total of 369 students. From the pre-post-tests, the pedagogy can effectively support the students to develop knowledge of electric circuits. From the questionnaire survey and focus group interviews, the students positively perceived their learning experiences and outcomes gained from the pedagogy, and significantly enhanced their awareness and confidence in applying problem-solving skills.

The pedagogy in this study was recommended to be promising for expansion with the concerns on the diversity of hands-on activities and the introduction to other subject topics. Future work will explore the potential suggestions collected from this study to further enhance the design and widen the implementation of the pedagogy, to expose students to a more appealing and helpful process in learning senior primary General Studies curriculum. The research design of the future work will try to arrange a control group for the trial teaching, in view of the limitation in this study that there was no control group involved in the evaluation of the effectiveness of the pedagogy.

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