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The Integration of the Engineering Design Process in Biology-related STEM Activity: A Review of Thai Secondary Education

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ABSTRACTS

STEM education is an effective instructional approach to multidimensionally develop students. Although the engineering discipline (E) in STEM education is ambiguously represented and integrated in the field of biological concepts in secondary education, the engineering design process (EDP) is showing potential to clearly guide educators to incorporate the EDP in biological classes. Thus, this review paper proposes to offer ideas of integrating EDP into biology-related STEM lessons in the context of Thai secondary education. It also outlines benefits and challenges of EDP integration which may assist teachers during designing lessons. The gathered results of prior research suggest that the EDP has potential to provide experiences focused on multidisciplinary real-life circumstances via hands-on activities in order to investigate solutions to problems. The challenges are greater to integrate EDP into biological tasks than other disciplines because of the nature of the content. Due to the ambiguity of integration, professional development programs, the implementation of suitable life-science content, and biological inspiration would assist teachers in conducting high-quality biological STEM activities which incorporate EDP. Moreover, time constraints, teachers' negative attitudes, and a lack of resources should be addressed as barriers to consider before the implementation.

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1. INTRODUCTION

Nowadays, in the industrial sectors of workforce markets, there are shortages of professional workers having proficient STEM-oriented knowledge and competencies in the 21st century (Salzman, 2013). Accordingly, the implementation of STEM learning into education evidences a significant educational movement; for example, the launches of education policies and federal documents leading to the national reformation in education (Laforce *et al*., 2018). As a result of the reformation of the education system, there is an increase in universal interest in STEM integration. The objectives of integration for the four disciplines (science, technology, engineering, and mathematics) are the emphasis on students' understanding via investigation, the development of their understanding by applying STEM-oriented concepts, and encouragement of STEM-related interest resulting in an increase of students STEM involvement (Guzey *et al*., 2016). Nonetheless, in many country's including Thailand, there is an unequal representation of four disciplines in STEM-related curriculum; for instance, the learning area of mathematics and engineering are often underrepresented (English & King, 2015).

In STEM integrated-curriculum, engineering education is introduced contributing to the development of engineering-involved curriculum from kindergarten to K-12 education. To encourage learning, there is an incorporation of engineering principles, reasoning, and thinking procedures for classroom design (Kelley & Knowles, 2016). The engineering design process (EDP), particularly, is considered to be an important element of K-12 engineering education. It is the learning process purposing to resolve vague problematic situations by applying strategies and methodology of engineering practice (Householder & Hailey, 2012). However, the construction of a product is not the main purpose of EDP. Its major goal is the development of decision-making competencies helping students to examine possible solutions or artefacts for solving critical issues. Because of the implementation of engineering knowledge and skills via EDP, opportunities are created for students to learn and develop engineering literacy (Hynes et al., 2011). The lack of appropriate support for engineering design in high schools, nonetheless, results in a lack of clarity of teaching process, curriculum, and direction of engineering education in secondary schools (Householder & Hailey, 2012).

In addition, there are many difficulties in teaching and learning biology. First of all, due to the nature of biological learning, memorization of content is the regular learning methodology. The degree of abstract conceptualization and organization in biology, moreover, seems to be very challenging to students (Lazarowitz & Penso, 1992). Finally, learners confronted with the difficulty of overloaded biological content and interdisciplinary concepts of some biological topics become frustrated. Conversely, some interdisciplinary fields of biology; for instance, bioengineering and biotechnology, are regarded as subtopics appropriate to STEM integration (Çimer, 2012). Therefore, this review article aims to define and critically review the basal understanding of STEM integration and EDP, the integration of EDP into STEM-based biological activities including advantages and barriers of the integration, especially in the Thai context.

2. THE INTEGRATION OF STEM IN THE SCHOOL CURRICULUM

There are many elements to efficiently integrate STEM instruction to ensure learning. Firstly, the implementation of motivating contexts and relevant situations into the curriculum will encourage students to engage with the activities (Guzey *et al*., 2016). There are also other elements to be considered to create high-standard integrated STEM frameworks: an appropriateness between contents and grade levels, a student-centred learning approach, and the application of teamwork-focused and communication-focused tasks (Carlson &

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Sullivan, 2004; Fortus *et al*., 2004). Although the reformation of STEM-integrated curriculum supports educators to design STEM-based instruction, teachers are still faced with a variety of quality of curriculum material (Guzey *et al*., 2014). To overcome this issue, the more implementation of educators as curriculum designer tend to effectively develop STEM-integrated curriculum which correspond with the uniqueness of school contexts (Guzey *et al*., 2016). The learners' participation in "engineering design", integrating mathematics, science and technology can possibly generate meaningful STEM-integrated learning and assist them to solve real-world problems because students are engaged to connect cross-disciplinary lessons applying scientific and mathematical knowledge into engineering and technological contexts (Honey *et al*., 2014; Moore *et al*., 2014). Consequently, teachers as curriculum makers who integrate engineering design into the curriculum is one of the key factors to productively develop an integrated STEM education.

The integration of STEM education into the Thai education system is considered as new pedagogy and learning which tends to generate many challenges. To begin with, there is ambiguously diverse understandings and a lack of valid guidelines toward the integration of STEM into the classroom (Srikoom *et al*., 2017). Due to the recent introduction of engineering into Thai science and technology curriculum, the inadequate understanding of the engineering discipline possibly affects the quality of STEM integration. To overcome these problems, an increase in understanding of STEM integration and the implementation of engineering areas into the curriculum through in-depth investigations about design process and engineering design is essential in order to realize "how to create high-quality STEM-integrated education in Thai context" (Srikoom *et al*., 2018). In brief, the development of a greater understanding towards STEM-integrated curriculum and the engineering discipline through engineering design is crucial in order to result in effective STEM integration into the Thai curriculum.

3. ENGINEERING DESIGN PROCESS (EDP)

The "engineering design process" is an educational pedagogy which underpins various engineer-related practices. The study of engineering does not only result in artefacts but also applies "engineering design and habits" to guide students through the artefact construction. They also have to apply scientific and mathematic concepts to examine ill-defined problems based on real-life situations in order to develop solutions to address the issues. It means that the combination of problem-solving approaches and basic concepts is a key factor to solve real-world problems like engineers do (Jonassen *et al*., 2006; Moore *et al*., 2014). In a framework of K-12 education, EDP is regarded as one of the core ideas and practices for students since engineering education in K-12 enhances learners engineering experiences (Honey *et al*., 2014; Hynes *et al*., 2011). Hence, engineering education, particularly EDP, can play an essential role in K-12 education to support the cross-disciplinary knowledge and practices to resolve real-life issues and problems.

Although the EDP provides procedures for practitioners, there are a number of steps involved in integrating EDP into STEM lessons. A review of the steps in EDP are listed in Table 1. From the reviewed steps of EDP, it could be considered as an iterative and creative learning process, applying interdisciplinary concepts (science, math, technology) to address problems (Sneider, 2012). This means that EDP is not a sequential approach like scientific inquiry, but each step of EDP relies on what students can learn from the previous step (Moore *et al*., 2014). EDP, therefore, is not a rigid set of procedures, but is a flexible guiding to processes involved in STEM-oriented curricula or activities (Hynes *et al*., 2011). Therefore, the more

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implementation of EDP into STEM courses, the more comprehensive are student skills in how to design the most efficient processes based on EDP (Householder & Hailey, 2012).

Table 1: The comparison of previous research about the step of engineering design process

The reviewed data of EDP step / **Prior research**	1. Problem identification	2. Background research investigation	3. Idea generation and analysis and	4. Selection of the best solution	4. Prototype construction	5. Prototype testing and assessment	6. Communication and reflection	7. Redesigning and finalizing the design
Householder and Hailey (21	✓	✓	✓	✓	✓	✓	✓	✓
Hynes et al. (2011)	✓	✓	✓	✓	✓	✓	✓	✓
Fortus et al. (2004)	✓	✓		✓	✓	✓		✓
Wendell and Rogers (2013)	✓	✓		✓	✓	✓		✓
Capraro et al. (2013)	✓	✓	✓		✓	✓	✓	
English and King (2015)	✓		✓		✓	✓		✓
Cunningham (2009)	✓		✓		✓			✓

4. THE INTEGRATION OF EDP INTO BIOLOGICAL STEM-RELATED ACTIVITIES

Several learning activities focused on engineering design challenges are present in many areas of life science. Firstly, in the field of ecological crisis and ecosystems, “Loon nesting platform” lessons engage students to create nesting platforms in different features and locations. The challenges of “Butterfly puddles” enable learners to design and create mud paddles for slowing down evaporation rates (Guzey *et al*.,2016). There is also a task to extract DNA in remote areas with cost limits, so the task challenges students to design a better process for gaining more yield of DNA extraction by using engineering design (Aranda *et al*., 2018). To make a solution for preventing and examining cross-pollination of genetically modified plants (GM plants) into nature, the EDP is integrated in life science-related STEM lesson in topics of “GM plants” (Aranda *et al*., 2019). It seems that EDP can be implemented perfectly in interdisciplinary biological issue related to real-world situation.

In Thailand, there is scant research in this field. There is an application of EDP into modelling learning activities which focuses on construction of organ models in human body systems to foster students’ creative thinking (Tidma *et al*., 2015). To address agriculture and human health global issues, in addition, “hydroponic planting” is introduced to be a real-life challenge for supporting learners’ 21st century skills (Noiwong & Wongthong, 2020). “Yarn dyeing from natural colour” also integrates life science-related concepts through EDP and local wisdom for solving an ecological crisis (Ratchawet *et al*., 2019). In summary, the key features of EDP-focused learning activities in the biological field are implemented through real-world contexts, the integration of cross-disciplinary knowledge into engineering design, and the cultivation of high-level thinking abilities.

The biological disciplines utilize a smaller number of EDP-integrated STEM activities compared with other learning areas. There are many challenges in applying EDP into biological STEM lessons (Guzey *et al*., 2016). The abstract and complex level of biological content provides few opportunities to integrate EDP in life-science learning fields (Lazarowitz & Penso, 1992). In other words, there is a narrow range of suitably meaningful problems in biology to implement EDP (Guzey *et al*., 2014; Moore *et al*., 2014). Similarly, "human biology", "genetic engineering", and "neuroengineering" are some impactful fields which are available to learning projects through engineering design tasks (Guzey *et al*., 2014; Guzey *et al.,* 2016; Roehrig *et al*., 2012). Due to the lack of connection between the life-science discipline and engineering practices in stand-alone biology courses, the area of "biosystem engineering" should be implemented to bridge the biological content and engineering design because they enhance the interaction between them. The examples of related fields in "biosystem engineering" are biomedicine, bioprocessing, agriculture, environmental science, and sustainable building systems. The introduction of biological inspiration by way of the design steps of EDP is a recent approach for integration. These activities apply biological inspiration from animal body and movement to design and construct bio-inspired vehicles (Bilici *et al*., 2021). Thus, the cross-disciplinary concepts in biology or "biosystem engineering" and biological inspiration have potential to effectively implement EDP STEM-based curricular activities.

Noticeably, there is an adoption of EDP as an additional activity at the end of an instruction. Even though this strategy allows learners to find the solutions towards EDP-integrated challenges and interact with engineering experiences, the lessons might be reduced to just handcraft activities which lack the integration of scientific conceptions (Guzey *et al*., 2016). Furthermore, although there are four areas of science disciplines; physical science, biological science, earth and space science, and technology in the revised version of Thai curriculum 2018, "science and engineering practice" which are key characteristics of STEM education still are implemented in unbalanced, inconsistent, and ambiguous ways. Consequently, the recent introduction of technology in the revised Thai learning curriculum probably assists learners comprehend the features and development of engineering discipline because the technological implementation in particular engineering areas is a normal emphasis in many STEM programs (Bilici *et al*., 2021).

In order to efficiently integrate STEM content into activities by using EDP, there are diverse learning methodology which underpin constructivist theory (Fan *et al*., 2020). Firstly, project-based learning stresses the significance of learners navigating problems via the procedures of inquiry thinking, cognitive construction, and problem-solving competencies through the approach of "learning by doing" (Thomas, 2000). Project-based learning methods can provide meaningful themes, problem declarations, and constraints to overcome traditional learning approaches (Kertil & Gurel, 2016). The application of scientific and mathematical understanding in project-based learning tends to improve students' designing performance and advocates research-related experience during learning approaches (Burghardt & Hacker, 2004). Hence, using EDP through project-based learning approaches can navigate learners to discover the engineering field.

Secondly, problem-based learning is a student-centred learning methodology which promotes the application of broad academic knowledge to improve students' abilities in solving ill-defined and open-ended issues focused on real-life situations (Jones, 2006; White, 2014; Yadav *et al*., 2011). Therefore, students have to define standards and design ideation and synthesize new knowledge to resolve the authentic problems (Dixon & Brown, 2012). To conclude, there is an exploration of real-world issues by implementing EDP into the problem-based learning.

Finally, inquiry-based learning can utilize an engineering design approach to provoke learners' interest towards conceptual understanding, and integrate the sequence of inquiry-related experiments for new conceptual construction (Fan *et al*., 2020). Inquiry-based

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approaches also present more flexibility in problematic circumstances to engage students. It allows students to experience cross-disciplinary learning areas with consideration of open-ended issues (Ghaemi & Mirsaeed, 2017). To remove students' regular misconceptions, there is a focus to connect scientific inquiry with engineering design practices which frame inquiry procedures and practices as the major emphasis of inquiry-based activities (Fan *et al*., 2020). Consequently, inquiry-oriented learning can be adopted as a framework to implement STEM activities via EDP.

5. BENEFITS OF EDP INTEGRATION INTO STEM ACTIVITY

The integration of EDP into STEM activity positively impact on the students' and their learning environment. The significant challenges in engineering design activities stimulate learners' involvement in their learning activities (Guzey, Moore, & Harwell, 2016). They, nevertheless, might not participate in the tasks if they feel that the challenges are irrelevant and uninteresting for them (Aschbacher *et al*., 2010; Moll *et al*., 1992). This means that the correlation between meaningful engineering design tasks and learners' interests positively influences problem-solving competencies and participation throughout the activities (Committee on Public Understanding of Engineering Messages, 2008).

Communication and collaboration also enhances task accomplishment and the learning environment because of the learning process of EDP. Teachers should group students based on variety of competencies to assist capacity within a team to solve engineering design challenges (Alfonseca *et al*., 2006; Ropohl, 1997). However, a diversity within a team may inhibit communication and collaboration as students may work individually based on their expertise, which restricts the process of EDP (Householder & Hailey, 2012). Thereby, EDP seems to encourage more participation and collaboration of students during the activities.

Another advantage of EDP implementation is the development of creativity. The ill-defined problems do not have single perfect single solutions but numerous solutions through creative thinking approaches (Guzey *et al*., 2016). Although the instruction of systematic approaches encourages creative thinking, less-structured learning methods also foster that because it allows learners to discuss and brainstorm various alternative ideas (Barak, 2004). It can be seen that the EDP implementation positively impacts on students' creativity.

The teachers' roles in the implementation of engineering design experience in a classroom different to the traditional teaching methodology (Hammer & Schifter, 2001). In other words, the roles of teacher shift from lecturers to facilitators who support learners becoming problem solvers (Householder & Hailey, 2012). The discretion and creativity of teachers are also critical attributes in selecting the appropriate level of problem complexity in order to avoid learners' frustration (Hafiz & Ayop, 2019). Therefore, the role of the teacher in EDP implementation shifts from lecturers in the traditional classroom to facilitators.

6. LIMITATIONS OF EDP INTEGRATION INTO STEM ACTIVITY

Multiple barriers obstruct the implementation of EDP into STEM-related lessons. To begin with, if teachers believe that the engineering learning area is an additional workload in the science curriculum then they may have negative attitudes toward this approach. The encouragement of cooperation among stakeholders related to STEM education are likely to provide support for educators in advising the best practice of STEM integration into curriculum (Moore *et al*., 2014). A professional development program for teachers in engineering integration is considered necessary in order to develop the knowledge, skills, and teaching pedagogies for constructing high-standard engineering design activities; however, there is little of this training available. So the provision of effective professional development

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should focus on how to implement engineering into instructional planning (Guzey et al., 2014).

Another challenge in applying engineering design is time constraints to conduct the activities because students need plenty of time to communicate and discuss when designing solutions to problems (Capraro *et al.*, 2013; Guzey *et al.,* 2016). Specially, the step of "redesigning" is skipped because of time limitation but the neglect of this step might influence students missing the opportunities to experience the iterative design thinking (Guzey *et al.*, 2014). To efficiently conduct EDP-based activities, learners should have a chance to participate in every step of the learning process.

Finally, the resources and facilities requirements for conducting engineering design activities is another limitation for STEM integration. Although efficient EDP activities require facilities and equipment such as media centre, laboratory, or free space for artefact creation, the inequity of resources still exists in many education settings (Capraro *et al.*, 2013; Householder & Hailey, 2012; Moore *et al.*, 2014). To overcome these barriers, the transformation of existing working spaces and workshops into engineering design studios, and the request for community support via online networks in EDP resources can narrow the gap of these issues (Householder & Hailey, 2012). Accordingly, the negative perception towards engineering design, time limitations, and the shortage of EDP-related facilities and resources obstruct the accomplishment of STEM-integrated EDP activities.

7. CONCLUSION

The EDP is an effective tool to promote high-standard integrated STEM activities for secondary learners (Hafiz & Ayop, 2019). The EDP has the potential to be incorporated into scientific lessons because of the similarities with the scientific thinking approach (Eekels & Roozenburg, 1991). Although there is broad integration of EDP into STEM activities, most EDP tasks motivate learners through authentic contexts related to real-word situations in areas of physical and technological science because of their nature. In contrast, the EDP implemented in life-science disciplines is less common because it is more difficult to apply appropriate biological concepts in EDP (Guzey & Harwell, 2016). Hence, to effectively integrate EDP in biology learning areas, Thai teachers need to carefully choose appropriate concepts for integration; for example, "biosystem engineering" concepts related to bioprocessing, biomedicine, agriculture and environmental science. The adoption of bio-inspiration during lessons also assist teachers to create high-quality biological EDP-based activities (Bilici *et al.*, 2021). Moreover, the development of positive perceptions towards STEM and EDP by teachers through professional development programs are likely generate the high-quality EDP-integrated biological STEM activities. The integration of constructivist learning approaches also positively impacts on EDP-integrated STEM lessons (Fan *et al.*, 2020). Time constraint considerations and accessible engineering design resources are also significant determinants of high-standard EDP (Householder & Hailey, 2012).

Accordingly, to design and integrate EDP into biology STEM tasks, the more investigation into appropriate life-science content and constructivist learning methods, effective professional development programs, and more consideration of barriers before implementation should be more stressed in further studies to narrow the gaps of EDP-integrated biology STEM activities.

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