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A Systematic Literature Review of Design Thinking Application in STEM Integration

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Abstract

To date, the emphasis on STEM integration in education is increasing since the way of thinking acquired through silo approach in traditional learning is not enough to understand and solve real-world problems. Design and design thinking have become increasingly important in STEM education as they are indispensable to creativity, problem solving and innovation. Nevertheless, little attention is given to this field. This study aims to identify the suitable teaching and learning approaches that apply design thinking for STEM integration among students by examining the available literatures. Providing students with the STEM skills can be acquired by adopting new approaches to teaching and learning across the STEM disciplines. For this systematic literature review, six databases were used which produced a total of 7209 articles. Identical articles were removed, and the data set was reduced by using three eligibility criteria in line with the research question, resulting in only 7 articles were chosen as samples for the study. The findings identified the suitable teaching and learning approaches that apply design thinking for STEM integration in education are focused on problem solving, designing activity and collaborative learning. The implications of the study allowed teachers and stakeholders to integrate STEM by applying design thinking through suitable approaches such as problem-focused teaching and learning, design learning and teamwork learning. The recommendation for future research is to conduct a study to see the effectiveness of problem-focused teaching and learning in applying design thinking for STEM integration.

Keywords

STEM Integration, Teaching and Learning Practices, Design Thinking

1. Introduction

In general, STEM education focuses on preparing students to become skilled workforce in scientifically and technologically advanced society. In line with that, producing competent students in the fields of Science, Technology, Engineering and Mathematics played a pivotal role in developing human capital to meet global need for workforce in STEM (English, 2016). By empowering STEM education, national economies and sustain leadership will be stimulated within this unpredictably changing and expanding globalized economy. STEM education is often associated with real world, innovative and exciting learning experience which require interdisciplinary approaches. According to the researchers, an interdisciplinary approach focuses on establishing explicit connections between relevant disciplines by juxtaposing and integrating two or more disciplines (Klein, 2004; Miller, 1981).

Instead of interdisciplinary approach, STEM integration can also be fulfilled through multidisciplinary approach. Wang et al. (2011), differentiate between interdisciplinary and multidisciplinary approaches. In multidisciplinary approaches, the particular concepts and skills of the subject are learned separately in each discipline. Students need to link the content from different subjects by themselves. Besides that, for an interdisciplinary approach, it starts with problems or real-world problems and emphasis on interdisciplinary content and skills such as critical thinking and problem-solving, instead of subject-specific content and skills. Satchwell & Loepp (2002), used interdisciplinary curricula and integrated curricula rather than multidisciplinary. Integrated STEM education is an approach that explores teaching and learning between/any two or more STEM subject areas, and/or between STEM subjects and one or more other school subjects (Sanders, 2009). On the other hand, integrated curriculum clearly assimilates concepts from more than one discipline and gives equal attention to two or more disciplines. Stohlmann et al. (2012), distinguish between content integration and context integration. According to them, content integration focuses on the merging of disciplines into one activity while context integration focuses on the content of one discipline and uses contexts from other disciplines to make content more relevant.

In an attempt to define integration, STEM mostly argues the need to create explicit relationships across STEM disciplines. The combination of some or all four disciplines of science, technology, engineering, and mathematics into one class, unit, or lesson based on the relationship between subjects and real-world problems (Moore et al., 2014) that incorporates the concept of STEM (Wang, Moore, Roehrig, & Park, 2011) is an effort to implement the STEM integration education. At the curriculum level, STEM integration has been described as integrating the concepts of science, technology, engineering, and mathematics in a way that reflects STEM professional practice to encourage students to pursue the STEM profession (Breiner et al., 2012). Cohesive STEM integration contains elements of scientific research disciplines namely students constructing their own questions and investigations, technological literacy in which students use instruments, engineering design to provide a systematic approach to problem solving, and mathematical solutions (Kelley & Knowles, 2016; Schnittka, 2016).

STEM integration approach can be applied to solve global problems on energy, health and the environment (Bybee, 2010) population growth, environmental problems, agricultural productions and many more. It requires a global approach supported by in-depth research in science and technology to address this issue (Thomas & Watters, 2015). The traditional way of thinking is not enough to deeply understand the complex problems that can affect the environmental, social and economic domains (Davis & Stroink, 2016). Nevertheless, in reality, over the past few decades, there is vagueness in STEM education and how it is effectively in school (Breiner et al., 2012). STEM education remains as disconnected subjects (Breiner et al., 2012; Bybee, 2010; Hoachlander & Yanofsky, 2011; Sanders, 2009; Wang et al., 2011). Furthermore, STEM subjects are often taught separately from environmental education (Wals et al., 2014) as well as art, creativity, and design (Hoachlander & Yanofsky, 2011). Although design thinking is always associated with problem solving skills (Buchanan, 1992) and user-centered (Brown, 2008), however, it is given less emphasis in STEM education at the school level.

In recent times, design not only refers to the process applied to a physical object i.e., the manufacture of a product but it has been adapted and developed into a different new discipline: design thinking. The term, design thinking had been used for the first time by David Kelly (Brown, 2008) as a systematic approach to problem solving that starts from considering the customers and how to create a better picture for them (Liedtka & Ogilvie, 2011). Innovative, smart and effective design was behind the success of many commercial items that achieve human beings necessity, thus, assist in understanding how to facilitate innovation. Buchanan (2019) proposes using design to solve unusual and difficult challenges. Together with the teacher support, design thinking can be an appropriate way to positively foster students' integrated STEM learning experience (Chiu et al., 2021).

The process of integrating Science, Technology, Engineering and Mathematics in real world context is a challenge in producing a new generation that will drive national progress and create a society that can make the right decisions and actions in order to address global problems such as climate change, food shortages and biodiversity loss (UNESCO, 2018). The integration of the STEM disciplines through design is acknowledged as a progressively major area of research (McFadden & Roehrig, 2018). Design thinking can be considered as a promising approach to finding creative and sustainable solutions to environmental problems (Léger et al., 2020) as the design thinkers tend to use both creative and analytical modes of reasoning (Liedtka, 2014). In Education, design thinking can provide rich learning opportunities in a collaborative, effective and accessible environment (Brown, 2009) with positive effects of design thinking on learning, motivation, engagement, and creativity (Cassim, 2013; Rauth et al., 2010; Renard, 2014). Instead of that, design thinking can be used to address issues that students face in their everyday lives (Pruneau et al., 2019). Together with the teacher support, design thinking can be an appropriate way to positively foster students' integrated STEM learning experience (Chiu et al., 2021) besides can improve teacher-student relationships (IDEO, 2012).

Based on this context, the purpose of this study is to answer the research question that is how design thinking is being applied in integrated STEM education? The objective in this study is to identify teaching and learning approaches which is used to apply design thinking in integrated STEM education. According to Hacioglu & Donmez Usta (2020), finding solution in interdisciplinary manner can build up students curiosity and also promote active learning but there is little research on teaching and learning methods used to integrate STEM disciplines (Pearson, 2017). In this analysis, the combination of some or all four disciplines of science, technology, engineering, and mathematics into one class, unit, or lesson based on the relationship between subjects and real-world problems (Moore et al., 2014) that incorporates the concept of STEM (Wang, Moore, Roehrig, & Park, 2011) is the definition to the STEM integration education.

2. Design Thinking in STEM Integration

Based on the literature review, there are three definitions of design thinking. According to Brown (2008), design thinking is a discipline that uses designer sensitivity and methods to meet the needs of people with what is appropriate in terms of technology and business strategies that can be transformed into business opportunities. This definition placed design thinking as a process (method) and individual characteristics (sensitivity) and explicitly connects design with business. Lockwood (2010) defined design thinking is a process of human-centered innovation that emphasizes observation, collaboration, rapid learning, idea visualization, rapid prototyping and simultaneous business analysis. In contrast, Martin (2010), emphasizes the element of thinking, defining design thinking as a productive combination of analytical thinking and intuitive thinking.

Design thinking is widely used in business, especially in product design where innovative products are designed to meet the public needs and to ease innovation. In addition, certain design thinking attributes such as prototypes and trial and error approaches have been considered as the main methods for generating new ideas and innovating (Deserti & Rizzo, 2014; Martin, 2009). Moreover, the design thinking process is the application of an integrative approach that allows the development of a deeper contextual understanding of the problem and identification of relevant views (Gruber et al., 2015; Nedergaard & Gyrd-Jones, 2013). Throughout the design thinking process, designer instinct plays a crucial role, experimentation that involves users happens swiftly, various solutions are created, and failure is accepted as learning opportunity (Liedtka & Ogilvie, 2011).

In STEM integration, students are involved in design challenges that give rise to the ability to do research and the research is done whenever needed during the design process. Johns & Mentzer (2016) found that there is a correlation between activities for both engineering design and scientific research, which is seen in activities such as planning and conducting research, analyzing and interpreting data, making arguments as well as obtaining, evaluating, and presenting information. This activity shows that scientific research can be included in the steps of the design process, that is during activities such as data search and analysis.

From our point of view on the design thinking, as stated by Pruneau et al. (2019), design thinking is a thorough process of problem solving that focuses on understanding the goals, experiences and constraints of the people affected by a given problem. As it compares to traditional scientific investigation, design thinking concerns itself as much with the problem as it does with the solution. Based on user input and practical needs, design thinking gives significant contribution (Léger et al., 2020) that will lead to constructing physical product (King & English, 2016; Kolodner et al., 2003). Design activities have great potential to foster young students' development of STEM knowledge, but greater attention is needed in enhancing young students' learning through design.

3. Methodology

Systematic literature review typically involved detailed and comprehensive search strategies for the purpose of gaining transparency on a particular topic by identifying, evaluating, and synthesizing all relevant studies (Uman, 2011). Data sources were obtained through electronic search databases. For this systematic literature review, six databases were used namely SCOPUS, Science Direct, ERIC, Taylor & Francis, Web of Science and Springer. The databases were browsed using a combination search terms: "Design Thinking Application AND STEM", resulting in a total of 7209 (n = 7209) articles as shown in **Table 1**. Identical articles were removed, and the data set was reduced using the eligibility criteria. There were three article eligibility criteria were included in this literature review. First, the study must be published in scientific journals (magazines and newspapers excluded) in English and peer reviewed between 2016 and 2020. Second, the study must involve teaching and learning in the field of STEM and finally, the study must clearly show the application of design thinking. After using the eligibility criteria, only 7 articles were chosen as the samples for the study.

The analysis was carried out in two steps. The first step was case analysis (Miles & Huberman, 1994), that is, each article was analysed and summarised separately in a table, which was categorized as shown in **Table 2**. Second, cross-case analysis was performed (Miles & Huberman, 1994). The application of design thinking extracted from all articles was rearranged and the same elements were grouped, leading to 4 different categories as shown in **Table 3**. The classification of teaching and learning practice criteria for each category was made based on the categories by Thibaut et al. (2018). Next, the proposed teaching and learning practices of design thinking were constructed by focusing on the most used instructional categories for design thinking in the systematic review articles.

Table 1. Preliminary search results.

Search terms	Database	Numbers of articles	Search limitations
Design Thinking Application AND STEM	SCOPUS	107	1. The study must be published in scientific journals, in English and peer reviewed between 2016 and 2020. 2. The study must involve teaching and learning in the field of STEM. 3. The study must clearly show the application of design thinking.
	Web of Science	48	
	Taylor & Francis	6849	
	Science Direct	132	
	ERIC	21	
	Springer	52	
	Total number of articles	7209	

Table 2. Within case analysis.

Category	Researcher (Year)	Application
Design thinking	(Hébert & Jenson, 2020)	Researchers are studying student learning through project: designing and constructing of e-textiles (wearable hats) using the LilyPad Arduino, along with sensors and LEDs at a school in Ontario, Canada. Planning and design elements such as "picking which cap" and "coming up with the idea" were reportedly the easiest parts of making a wearable for students. Researchers also found that enormous amount of facilitator and research labor was required to help students in completing their wearable designs project.
	(English, 2018)	Focusing on shoe design tasks, students build their learning from the initial problem components that collect and analyse data on shoe types, sizes, fabrics and more. Students build their learning by collecting and analysing data. While conducting this assignment, students gain more knowledge about processed and natural materials from the science curriculum and also general information about shoe designers and manufacturers. Students need to design their own shoes in small groups. Learning processes and outcomes described how student learning evolved from the application of knowledge and the use of a sequence of design strategies such as initial design, redesign, and reconstruction to an informed planning. From the design task, it is shown that students tend to express a desired shoe rather than a problem to be solved, but they still able to identify the features of the shoe they intended to create thus setting constraints to address, such as the appropriate selection of materials and shoe style. They becoming more informed designers as they increased their achievements by doing iterative designing and reconstructing. The majority of students displayed style features on both designs, together with different perspectives including 3-D, and 2-D top and side views, even though they were not instructed to do so. The inclusion of materials and their placement, together with measurements, was seen on their sketches especially for the initial design. Students' inclusion of measurements decreased on their redesign sketches, which could be due partially to time constraints and/or fatigue. Nevertheless, students displayed increased satisfaction with their redesigns, suggesting that they had targeted the weaknesses of their initial designs in redesigning to better meet their aims.
	(Juškevičienė et al., 2020)	Researchers used two integrated activity applications based on FabLab integration and physical computing. FabLab is an example of a fabrication laboratory. It uses digital fabrication tools such as 3D printers for 21st century skills, hands-on, design thinking and project-based learning. Physical computing uses technology to create installations that interact with participants, for example, connecting the physical world and creating interfaces between interactive objects and humans. It is also used to create prototypes. Researchers proposed the design thinking approach as a path for educators to work on redesigning activities to move toward more comprehensive STEAM learning and for educational foundations, they consider problem and project-based approaches.

Continued

	(Léger et al., 2020)	The study used two groups of civil engineering students by comparing their findings to solve the same environmental problems. One group used a conventional-based approach, and another group used a more innovative design thinking approach. This study shows that students who used a design thinking approach are more competent in finding solutions that are creative and appropriate to the needs of users as they used more time talking to the affected community in the early stages of their problem-solving process. The design thinking group likely gained deeper insight into the needs of the people. They also showed more tendency towards innovation and adaptability. Finally, they also demonstrated competencies in collaboration and communication. Moreover, finding from this study also suggest that future engineers should be taught design thinking as an alternative strategy for solving problems by comparing view of the overall problem-solving experience in both groups.
	(King & English, 2016)	Researchers plan engineering activities in the context of real-world problems and contextualize students' STEM conceptual learning. Therefore, this study examines the learning that occurs in the training of fifth grade students in completing engineering activities using repetitive engineering design models through student design sketches from eight focus groups. As a result, they concluded that, first, the design sketch afforded opportunities for the integration of science, technology and mathematics concepts. Second, students' design sketches enabled them to conceptualise an optical instrument that was translated into a working model albeit with some modifications. Third, the redesign process enabled students to improve physical characteristics of the model. Furthermore, the study identified the importance of the first drawing or first 'design sketch' stage for students actively applying their STEM ideas to the design.
	(English et al., 2016)	A longitudinal study for 3 years on grade six students by solving engineering-based problems involving integrated STEM learning about earthquakes in government and independent school. Students use STEM discipline knowledge and engineering design process to plan, make sketches and after that, a building designed to withstand earthquake damage is built, taking obstacles into account. During testing, students need to redesign to build a better structure. Using the design process framework, researchers report students' abilities in designing, making annotated sketches, and transforming them into 3D models. The decline in annotations from the first to second design could be due in part to time limits as well as student fatigue. The government school students appeared to have a better understanding of how to make their structure strong, with over half of the students making the relatively advanced observation about the importance of stability, rigidity, and balance in contrast to the independent school students, who generally attributed performance to the quantity or quality of materials. The outcome revealed students' application of design processes and STEM disciplinary knowledge as they worked the problem. Students identified the problem goal and constraints, debated ideas on their designs and subsequent constructions, sketched and interpreted their designs, transformed their designs into constructions, tested their first structure, and redesigned and tested their second.
	(Hacioglu & Donmez Usta, 2020)	Students are given digital game design challenges that reflect real life problems based on design-based science learning by applying knowledge and skills in every field of STEM. During this design challenge, students worked as scientists and engineers. They conduct research and scientific research processes in science disciplines, understand engineering design processes in engineering disciplines, establish mathematical relationships in mathematical disciplines, learn how to make coding in technology disciplines, and apply these knowledge and skills to their proposed solutions to design challenges. They design digital games by encoding and presenting the knowledge and skills of science gained from the inquiry process.

4. Findings

There are four different categories which are applied in design thinking as shown in **Table 3**. Based on Thibaut et al. (2018), for the problem-focused category, it emphasis on engaging and motivating the use of real world problem. These include problem-based learning, project-based learning, problem-solving, and

Table 3. Cross-case analysis.

Category	Teaching and learning practices	Design Thinking
Focus on problems	1. Problem-based learning, 2. Project-based learning, 3. Problem solving, 4. Real world problems/authentic problems.	(Hébert & Jenson, 2020), (English, 2018), (Juškevičienė et al., 2020), (Léger et al., 2020), (King & English, 2016), (English et al., 2016), (Hacioglu & Donmez Usta, 2020)
Inquiry	1. Planning and conducting investigations, 2. Collect, analyse and interpret data, 3. Scientific inquiry.	(Hacioglu & Donmez Usta, 2020)
Design	1. Learning through design, 2. Design-based learning, 3. Develop and use models, 4. Engineering design.	(Hébert & Jenson, 2020), (English, 2018), (Léger et al., 2020), (King & English, 2016), (English et al., 2016), (Hacioglu & Donmez Usta, 2020)
Teamwork	1. Collaborative learning, 2. Teamwork, 3. Cooperative learning, 4. Work with peers.	(English, 2018), (Léger et al., 2020), (King & English, 2016), (English et al., 2016), (Hacioglu & Donmez Usta, 2020)

real-world problem, or authentic problem. These approaches required the same procedure in order to achieve desired outcome. Firstly, problematic situation is introduced as the organizing centre and context for learning (Asghar et al., 2012; Bybee, 2010) to trigger student prior knowledge and concatenate significantly with new knowledge and experiences (Asghar et al., 2012). Furthermore, instruction should be motivating and engaging context involving latest events and/or issues. So, meaningful learning is encouraged by connecting the information and skills to be learned to personal experiences (Selcen Guzey et al., 2016). Lastly, the problems should be authentic, open-ended, and ill-structured real-world problems (Burrows et al., 2014; Edy Hafizan et al., 2017; Satchwell & Loepp, 2002). Although these approaches can be grouped as student centred, advocate the active learning and support the use of real-world problem, but, there is specific differences between these approaches (Asghar et al., 2012).

In addition, the other categories of teaching and learning practices used are inquiry, design and teamwork. The inquiry category includes planning and conducting investigations, collecting, analysing, and interpreting data and scientific inquiry. Inquiry learning involving questioning (Wells, 2016), initiating prior knowledge to gain new ideas, design, carry out investigation and discover new concepts with appropriate amount of guidance (Satchwell & Loepp, 2002). Additionally, design category contains learning through design, design-based learning, developing, and applying models and engineering designs. Engineering design activities can enhance students' knowledge of science, technology and mathematics, as they connecting between factual content knowledge, abstract knowledge and application (Riskowski et al., 2009).

Collaborative learning, teamwork, cooperative learning, and working with peers are elements in the category of teamwork. Teamwork skills can be strengthened by giving multiple chances and an ample of time for the student to take part in teamwork activities (Selcen Guzey et al., 2016). In addition, there are also categories of lesson study, cognitive map and flow experience which was only mentioned in one of the reviewed articles respectively.

From **Table 3**, it is found that teaching and learning practices for design thinking that can be developed from the literature review are the problem-focused, followed by design learning, teamwork, and inquiry.

5. Discussion

Based on the reviewed articles, to apply design thinking, most of the researchers used problem-focused learning as an approach. A problem occurs when there is dissimilarity between the current reality and a desired goal (Jonassen, 2000). Problems that have an unclear/ill-defined/undetermined self; with solutions that have an unclear/ill-defined/undetermined self is called as "wicked problems" (Jonassen, 2000; Ritchey, 2013). Wicked problem cannot be successfully treated with traditional linear, analytical approaches (Rittel & Webber, 1973).

Problem posing and framing, generating ideas and sketching designs, constructing and testing, reflecting on design products, and subsequently redesigning are the important tools in cultivating STEM learning (English, 2018). Problem-solving activities include describing the current and goal states, evaluating one's resources (e.g., physical, cognitive), recognizing additional resource needs (e.g., information), identifying constraints, and exploring underlying expectation that influence reasoning (Grohs et al., 2018) and problem-solving involves cyclical interaction between cognition and action.

Design thinking can be cultivated through engineering design challenges. The findings from Léger et al. (2020) study can be applied to technical education in general, offering insights on design thinking as an alternative approach to solving environmental problems, as well as other problems related to civil engineering. The results of this study showed that engineering students who used design thinking to solve environmental problems found it difficult to gather user input during the problem-solving process. However, the same students also revealed that they found solutions that are more diverse, more imaginative and more appropriate, which is derived from the concerns and needs of consumers. Thus, students who use design thinking to solve a given environmental problem showed more creativity in their approach to problem solving, such as their tendency to use different thinking, open-mindedness, and adaptability.

Recently, modelling this through engineering design in education has become of interest more to the international community as a way of connecting STEM disciplines (Lucas & Hanson, 2014). Through engineering design, engineers required to intertwine the STEM concepts through the designing and building process such that conceptual cohesion is reached (Walkington et al., 2014). According to Edy Hafizan et al. (2017) and Selcen Guzey et al. (2016), students in engineering design challenges, instead of learning about engineering design processes and engineering practices, also deepen their understanding of disciplinary core ideas. Five comprehensive core design processes (including problem, idea generation, design and construction, design evaluation, redesign), were used as a framework by English & King (2015). Moreover, sketching design can contribute to integration of STEM and to conceptualise (King & English, 2016). Most of the reviewed articles for design thinking are using problem focus learning integrated with design learning such as Hacioglu & Donmez Usta (2020), Hébert & Jenson (2020), Léger et al. (2020), English (2018), English & King (2015) and King & English (2016).

6. Conclusion

Design learning with the integration of STEM discipline is gaining attention (McFadden & Roehrig, 2018). Design challenges must be related to real life, have more than one solution, have criteria and limitations that will direct students to the target knowledge and skill, and be testable or assessable (Moore et al., 2014). The results of a systematic literature review found that teaching and learning approaches to apply design thinking for STEM integration are problem-focused, followed by design learning and then, teamwork approach. The practical implication of the study is, it provides information to teachers and stakeholders on how to apply design thinking in integrating STEM which is through problem-focused teaching and learning approaches, design learning and teamwork. The recommendation for future research is to conduct a study to see the effectiveness of problem-focused teaching and learning in applying design thinking for STEM integration.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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