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Mathematical Modeling from Metacognitive Perspective Theory: A Review on STEM Integration Practices

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Abstract

This study presents to identify mathematical modeling is the least elements focusing on current STEM integration practices. Through this study, a review of the existing practice of STEM integration curriculums, models, modules, and programmes was undertaken to confirm the issue. The database reviewed to confirm this issue is from Social Sciences Citation Index with keyword "Mathematical Modeling," "STEM curriculum," "STEM model," "STEM module" and "STEM program." As a result, these studies confirmed that mathematical modeling activities were the least focusing on existing STEM integration practices and the theory of metacognation and the theory of sosial interaction development could promote these abilities.

Keywords

STEM Integration and STEM Practices

1. Introduction

In many countries, the primary policy for the implementation of integrating STEM disciplines is created to enhance the interests and involvement of students in the career fields related to STEM disciplines (Freeman, Marginson, & Tytler, 2015; Kuenzi, 2008a; Merchant, Morimoto, & Khanbilvardi, 2014). According to the report by the Australian Council of Learned Academies (ACOLA) in 2013 (Rowe, 1991), more than 16 countries provide ideas and the implementation of STEM education to enhance students' interest in STEM-related career fields. These countries are Great Britain, United States of America, Canada, New Zealand, China, Japan and Singapore (Lacey, & Wright, 2010). The initial steps to enhance STEM integration base education taken for this country are due to decline in students' interest and involvement in the areas of STEM-related careers. Until nowadays, those countries still cannot fulfill the demand of industry's in STEM backgrounds (Roehig & Moore, 2011). Furthermore Roehig & Moore (Roehig & Moore, 2011) noticed the future careers which require abilities and qualifications at very high-level thinking in the field of STEM integration contribute to this issue.

As mathematical modeling involves activities such as describing natural phenomena or designing a component or a system by writing mathematical equation (Baumann, Keel, Elsworth, & Weston, (Eds.), 2010) was mentioned as a component to interconnecting STEM's discipline. Therefore, the ability on constructing a mathematical model in STEM integration focuses should be made, and these value-added had to focus on the existing standard STEM integration practicing. From the philosophical point of view curriculum, model and module of teaching and learning are usually developed based on one or by combination of some of the educational theories on what students should achieve and how they are going to achieve in their teaching and learning (Baumann, Keel, Elsworth, & Weston, (Eds.). 2010). In fact, many theories could explain how students think, act and set strategies for solving the problem (Hacker, Dunlosky, & Graesser, 2009).

To explain these phenomena, the ability to solve a problem in mathematical modeling is closely related to the cognitive activities that are applied while they are facing a problem solving (Chun & Eric, 2010) task. Therefore, good cognitive skills will lead a person to be more analytically minded while facing mathematical modeling problem solving (Sokolowski, 2015). Consequently, a lot of mathematical modeling activities should focus on cognitive aspects and this could help students exposure indirectly to STEM-related careers in real life. There some cognitive theory proposes the ability to set thinking strategy. Mathematical modeling is considered a challenging task and it involves high-level problem-solving abilities (Blum & Borromeo, 2009) and it is proved as an enjoyable task for students to develop their cognitive abilities. Therefore, implementing this task, could lead students to be more analytical as required in STEM careers industry (Tseng, Chang, Lou, & Chen, 2013). However, the difficulties of mathematical modeling activities are because students do not know how to regulate their cognitive ability. The cognitive development at this stage is placed under the zone of proximal development, where students need the elements of scaffolding as a means to assist metacognitive activities (Larkin, 2010; Louca & Zacharia, 2012; Papaleontiou Louca, 2008; Schraw, Crippen, & Hartley, 2006).

2. Background Problem

The less focusing element have been identified from the existing STEM curriculums, models, modules or programmes is the ability to make a correlation to all STEM disciplines. This could be due to carrying all STEM integration elements in a teaching and learning activities is something considered challenging to be done (Bowers, 2016; Valtorta, 2015; Berland, 2013). To improve these situations, an appropriate STEM integration task with the characteristics of crossing and balances all STEM disciplines and at the same time could expose students to STEM careers needs to be identified. The exposures of STEM integration elements at an early stage to students mainly on the actual STEM fields activities is crucial to attracting students' interest on adapting STEM careers for the future (Kitchel, 2015; Stotts, 2011; Honey, Pearson, Schweingruber, Education, Engineering, & Council, 2014; Valtorta, 2015).

Meanwhile, Velten (Velten, 2009), highlighted mathematics is a tool for science, technology, and engineering to describe and to relate the variables phenomena under investigation. It is beneficial to use the characteristic of mathematics to interconnecting every discipline in STEM disciplines. Therefore it is worth to using mathematical modeling as a task on STEM integration practices (Alder, 2001). Generally, mathematical modeling can be defined as interpretation, verification, correction and generalization to an eventual situation, phenomena or a system (Roehig & Moore, 2011). Lesh and Zawojewski (Lesh & Zawojewski, 2007) define mathematical modeling as a process of producing an excellent concept, an expression that can be modified and can be reused for controlling the actual situation. As a result, mathematical modeling can provide a space for students to develop the concept of interconnection on science, technology, engineering and mathematics in a way that is more meaningful and significant in the real situation (Kaiser & Stillman, 2011). Activities that involve mathematical modeling usually have been taught to engineering students at the tertiary level. Eventually, for the past several years, studied have found that the importance of the application of mathematical modeling for primary and secondary school students had a significant effect to developing the analytical thinking and problem-solving ability (Stohlmann, M. S., & Albarracín, L. (2016); Cardella, 2006; Lesh & Zawojewski, 2007). As consequences, the competency of STEM careers could be improved.

3. Research Problem Statement

It has been proved, mathematical modeling is said to be tough for primary and secondary school practises' (McKeachie, 1987). Students were said to have no knowledge and experience in these abilities, as well as the level of students' thinking was reported to be not at the level to build mathematical modeling (Stohlmann & Albarracín, 2016). They have never been exposed to such activity. This problem can be addressed by identifying the aspects of how students think and plan their thinking or better known as metacognition while they are doing problem-solving on mathematical modeling (Kelley & Knowles, 2016). According to Kaiser and Stillman (Stohlmann & Albarracín, 2016), the use of metacognitive skills is said to be not only useful but very suitable to improve the mathematical modeler's competency especially for someone who is new in this field.

The ability to analyze, synthesize and generate a new idea in a STEM task is highly emphasized by the community of STEM integration (McKeachie, 1987; Roehig & Moore, 2011). Tasks on mathematical modeling will involve students' cognitive activity (Thompson, 2009; Kelley & Knowles, 2016).

Meanwhile, the confirmation on constructing mathematical modeling by STEM practitioners is no clear pictures. This situation was due to the difficulty of building mathematical modeling, and it is highly dependent on the students' cognitive ability is said to be not at the level to develop mathematical modeling. The cognitive perspective phenomena on how a person's transfer their science knowledge to engineering applications in the form of a mathematical model are something interesting to be studied, and it sought to an explanation (Hacker, Dunlosky, & Graesser, 2009).

4. Research Objectives

The purpose of this study is to confirm that mathematical modeling is the element that less been focusing on STEM integration education for secondary school level. Furthermore, this study is to identify the specific cognitive theories to supporting for the mathematical modeling activities for STEM integrated practices.

5. Methodology

This study undertook a review on confirming that mathematical modeling and aspects of promoting of metacognition were the fewer elements focusing on existing STEM integration curriculums, model, module, and program. The primary database source taken for this study is from Social Sciences Citation Index with basic search as "STEM curriculum," "STEM model," "STEM module" and "STEM program." Two journals were identified actively reporting on STEM education, and they are Proceedings of IEEE (Jan.-Oct. 2016) and Advances in Engineering Education (Jun. 2016-Feb. 2013). From these two journals, 18 articles were found reported on STEM model and STEM module out of 149 articles stated on the STEM on general aspects. By using literature review, theory(ies) then were proposed to mobilizing cognitive aspect on facing problem on mathematical modeling.

6. Data Analysis

Table 1 shows an analysis of articles review related to the STEM integration obtained from the database journal indexed by the Social Sciences Citation Index (SSCI) by Thomson Reuters. The primary objective of this analysis is to identify the fewer elements of mathematical modeling were stressed in STEM integrations practicing which were believed to have the ability to make connections to all disciplines through authentic activities.

From this review, a total of 149 journals were found reported on STEM

Table 1. Articles analysis of the missing elements for STEM integration.

Index Board	Journal name	Publisher	Number of STEM Article	Type of STEM practices	Less/missing elements
Social Sciences Citation Index—Thomson Reuters	Proceedings of the IEEE	Institute of Electrical and Electronics Engineers (IEEE)	**7/121** (Jan.-Oct. 2016)	More on exploration and application of scientific concepts in real situations.	Less or no mathematical modeling involve.
	Advances in Engineering Education	American Society for Engineering Education	**9/28** (Feb. 2013-Jun. 2016)	engineering design using science, technology, and engineering for university level.	Less/no mathematical modeling
Total articles			**16/149**	-	-

integration practices and some international journals actively reporting on STEM integration practices from February 2013 till October 2016. The Proceedings of Institute Electrical and Electronics Engineers (IEEE) and Journal of Advances in Engineering Education which are indexed by the Social Sciences Citation Index (SSCI) Thomson Reuters are found as two journals that are actively reporting on STEM integration education. It is found that the Proceedings of IEEE has published 121 articles related to STEM education. It is found that 7 of them are related to STEM modules and STEM teaching and learning models for school level. The Journal of Advances in Engineering Education has published 28 articles related to STEM education, and 9 of the articles are related to STEM model and modules training for university and college level.

As a result 18 out of 149 articles from the journals indexed by SSCI discussing STEM model and module integration and most of the articles were reported on STEM program which only focuses on the exploration of the concept of physics, chemistry and biology and the application of these concepts to solve problems in real situations. Through these activities, the students have to make an investigation on the phenomenon or situations being studied and have to use measuring tools such as a digital timer, measuring tape, weighing, voltmeter, etc. From this review, it is found that most of the practices reported on existing STEM integration programmes were less likely less focusing on relating all STEM element and the ability to make correlation on the variables being studied using mathematical relationship or in the form of a mathematical model. This evidence proved that the element of mathematical modeling is least emphasized. However, based on this review a few articles were found reporting on STEM integration with mathematical modeling that been implemented at the university level.

7. Discussion

The most common articles were reporting on STEM model and only one article on STEM curriculum (Egarievwe, 2015). The selected articles also focusing study on high schools and tertiary STEM integration model such as a study by Lin, Zhu & Ro (Egarievwe, 2015); Egarievwe (Mosina, Chebanov, & Belkharraz, 2012); Mosina et al. (Khan & Davis, 2016). The other two articles focusing on k-12 STEM model were reported byKhan & Davis (Sundaram, 2015) and Sundaram (Hamilton, Lesh, Lester, & Brilleslyper, 2008).

Most the objectives of the models were for enhancing student's interest on STEM element learning, performance, and skills, but there is one study by Hamilton et al. (Holzman, 1996) which gives focus on complex design or other task settings with underlying science and technology. Khan & Davis (Sundaram, 2015) studied on "Adopt-a-Professor"—A Model For Collaboration in STE between K-12 and Higher Education to strengthen K-12 student learning outcomes in all subject. Through these studied, the enhancing learning skills with a special focus on STEM fields were given but there were no mathematics element were found. In other hand, Lin, Zhu & Ro (Egarievwe, 2015) studying a dynamic project-based STEM Curriculum Model for a small humanities high School. The purposes of these study is to enhance students performances in international assessments on PISA.

From theory point of view, two theories were identified as a guide to activate mathematical modeling activities on STEM practices. The theories were theory of metacognition (Vygotsky, L. (1978)) and the theory of social development (1978) (John H. Flavell. (1963); Piaget, J. (1950)). In fact, several theories present in real situations on how students think when they face a problem on learning which can be reflected in mathematical modeling task. The classical theory is the theory of cognitive development by Jean Piaget, which explains the cognitive development of humans through three stages: schematics, adaptation and sensorimotor (Polya, 1945). Meanwhile, Gorge Polya around 1945-1957 presented the model of problem-solving through three processes. involving understanding the problem, plan for a solution, implement the plan and review the result (Polya, 1945). But the metacognitive theory introduced by Flavell in 1979 explained metacognitive aspects which consist of three main elements, metacognitive knowledge, metacognitive experience and metacognitive strategies (Vygotsky, 1978) & (Hiltz & Turoff, 1993) was considered suitable theory due to the proposing of thinking about knowledge, skills and strategies. Another additional suitable theory is the theory of cognitive development from the social aspects introduced by Lev Vygotsky (Piaget, 1950). This theory mentions that students cognitive development from the social aspect which explains students ability and maturity on specific cognitive can be developed to a higher level if space or support are given to the development on a certain maturity level (Larkin, 2010).

A conceptual framework for this study is then proposed to illustrate on hypothetical elements base on the selected theories. The theoretical framework of STEM integration from the mathematical modeling practises as shown in **Figure**

1 is built with three intersection circles. The first circle is containing the metacognitive theory elements (metacognitive knowledge, processes, skills, and strategies), the second circle containing the theory of social development (socially mediated interaction—promoting communication and scaffolding media). The third circle comprises teaching element which is considered essential to creating a community of inquiry for educational purposes. This is because an appropriate cognitive and social presence, and ultimately, the establishment of a critical community of inquiry, is dependent upon the presence of a teacher. This is particularly true if an integration discipline curriculum or advance learning outcome is the primary means of an educational experience. In fact, when integration education based specific approaches fail, it is usually because there has not been responsible teaching presence and appropriate leadership and direction had been practiced (Daniels, 2008).

Therefore from all central themes collected in each of the intersection areas, STEM integration scaffolding on knowledge, processes and skills, STEM integration setting climate, STEM integration teaching content and, the intersection of the three circles as indicate number 4, then STEM integration practice experiences were expected could be quiring. From these new meanings, a guideline of STEM integration in the form of ways and techniques to sets strategy and action to perform mathematical modeling task could be useful for STEM integration practitioners.

A worthwhile STEM integration experience is embedded within a Community of Inquiry that is composed of metacognitive (Vygotsky, 1978) elements, social development elements by Vygotsky (Kozulin, Gindis, Ageyev, & Miller, 2003; Hadi, 2015; Piaget, 1950) and teaching elements as shown in **Figure 1**. The selected theories could guide this exploration in the STEM integration practitioner. These two theories are proposed based on the following principles so that the practice can be carried out.

There were many theories explained how learning occurs from the cognitive perspective, but the theory of metacognitive by Flavell was found as an appropriate theory to be proposed in this study. Flavell's theory can explain how a student thinks about his thinking, planning strategies and implementing actions precisely in solving problems on mathematical modeling, rather than the theory introduced by Piaget (Polya, 1945; Proust, 2013). The theory of cognitive development Piaget (Polya, 1945) only described aspects of cognitive development ages stages, whereby the best level of learning is at the specific age level of thinking development. Thus this theory does not fulfill the requirement of this study which is any STEM practitioners could do mathematical modeling activities with the appropriate guidance of metacognitive and social development aspect.

The problem-solving model by Polys (Proust, 2013) is seen lack of information for this study. It is only described problem from three aspects. 1. understand the problem and devise a solution and execute the plan. Compare with metacognitive

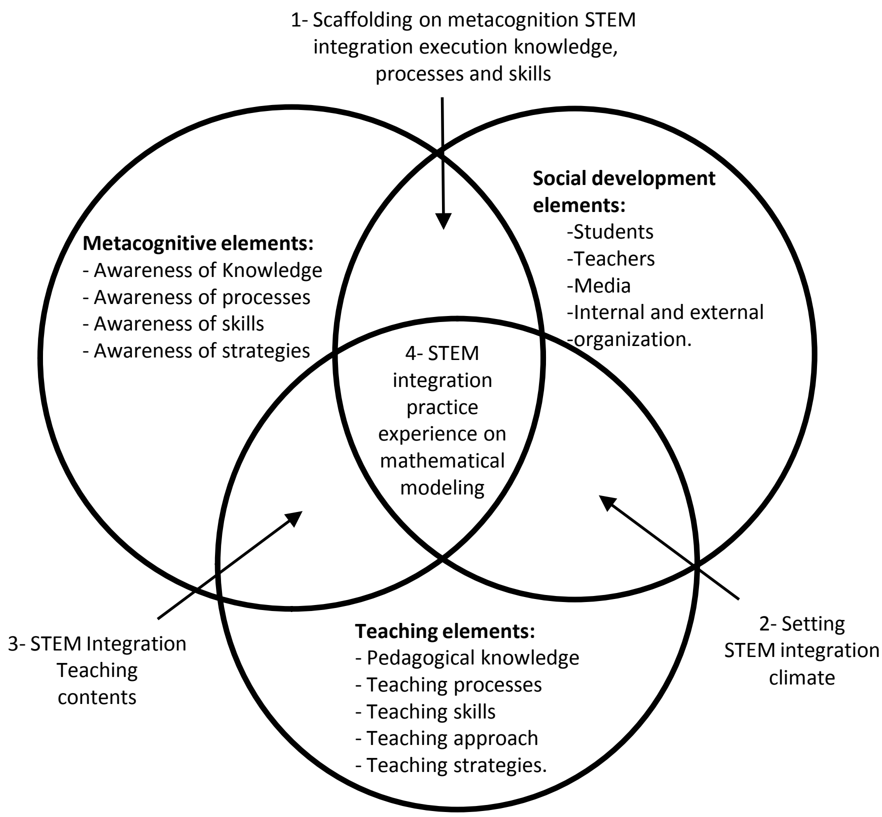

Figure 1. The Theoretical framework on Metacognition of STEM integration from mathematical modeling perspectives.

theory by Flavell which indicates more detailed and informative on the aspects of the thinking about thinking. It could provide hypothesis about how someone plans his thinking in building mathematical modeling which includes how someone is thinking about his or her thoughts from the aspect of knowledge of the problems, the experience, situations faced and on what action should be taken to achieve the objective.

8. Conclusion

In line with current global developments in the demand of thinking skills amongst labors for the future, the Malaysia Ministry of Education (MOE) has begun to implement cross-curriculum education policy in schools. This policy can be seen from the implementation done through the combination of teaching and learning elements of science, technology, and engineering in the pure science like physics, chemistry, biology, mathematics and additional mathematics for school and university level. However, since 2017 the implementation of STEM education has been done entirely through the Primary School Standard Curriculum (KSSR) and Secondary School Standard Curriculum (KSSM) (Mohamad, Lilia, Zanaton, Edy, & Raifana, 2015). Initially, the implementation of STEM integrated education is done through programs conducted outside the formal classes. Through this program, students will be exposed to a combination of several disciplines in STEM learning by using discovery and project-based inquiry activities (Kozulin, Gindis, Ageyev, & Miller, 2003).

Although only relatively few articles were found with data that were congruent with pre-set guidelines, it could be concluded that the focusing on ability students to make interrelation across disciplines was less focusing. Concerning previous studies, mathematical modeling had the potential to integrate STEM elements in a task and at the same time enhance students' ability on problem-solving. Even though these activities were considered as a difficult task, STEM integration programmes using mathematical modeling still could be implemented by promoting students metacognitive and student social interaction development. The importance of this study in the STEM integration education could be described concerning implementation and approach should be used in carrying out the teaching and learning of STEM integration. Implementation of mathematical modeling for STEM integration programmes is considered very important in ordered to construct not only concrete and meaningful problem solving but with a comprehensive and coherent way. The construction of meaningful, comprehensive and coherent learning on mathematical modeling could be viewed from constructivist, self-excessive and social development interaction learning practice (Baumann, Keel, Elsworth, & Weston, (Eds.), 2010). The philosophy (Reynolds, Hopkins, Potter, & Chapman, 2002), paradigm (Hiltz & Turoff, 1993), theory (Chun & Eric, 2010) or framework impact have been shown as necessary in the world of science, mathematics and engineering education.

Conflicts of Interest

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

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