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The Effectiveness of Using 3D Printing Technology in STEM Project-Based Learning Activities

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ABSTRACT

Engineering design process has been recognized as one of the crucial parts of science, technology, engineering, and mathematics (STEM) education. However, when focusing on engineering design process, STEM education at the Kindergarten-12 level often neglects the role of modeling in engineering design process. The characteristic of rapid prototyping of 3D printing technology could be utilized in supporting modeling during engineering design process. This study aims to explore the effectiveness of application of 3D printing technology to STEM project-based learning activities in developing students' understanding regarding engineering design process, particularly their understanding of modeling. This study employed a quasi-experimental pretest-posttest non-equivalent control group design. A series of knowledge structure analyses showed that in terms of knowledge structures for modeling in engineering design process, the experimental group explained better than the control group in terms of information processing strategies after the teaching experiment.

Keywords: engineering design, knowledge structure, modeling, STEM education

INTRODUCTION

Since the publication of *The Engineer of 2020*, the studies of engineering education are gradually focused more on the question of how to improve the engineering student retention rate or increase students' interest in science, technology, engineering, and mathematics field (Clough, 2004; Han, Capraro, Capraro, 2015). The National Science Foundation (NSF) also stated that in the past years, the completion rate for bachelor's degrees in engineering has decreased, by 5–7% (NSF, 2006). In light of this problem with the development of engineering talent, various scholars in engineering education, from countries such as Australia and New Zealand, have raised concerns about the problem of loss of engineering talent and the importance of giving more attention to this issue (Flower, 2014). One major reason why gifted students are less likely to choose engineering-related institutions, apart from the various stereotypes about engineers that the engineering field usually presents, as proposed by Nehdi (2002), may be their insufficient knowledge of these institutions, rendering them unwilling to enter an engineering-related field. Thus, assisting students in acquiring basic engineering literacy at the Kindergarten-12 (K-12) level is an important factor in addressing the lack of talent in engineering-related field (Brophy, Klein, Portsmore, & Rogers, 2008). In accordance with two reports by the National Science Board (NSB) and the President's Council of Advisors on Science and Technology (PCAST), Raju and Clayson (2010) pointed out that the US has put greater emphasis on nurturing new talent in the fields of science, technology, engineering, and mathematics (STEM). Nevertheless, STEM education usually focuses on science and mathematics and neglects the important roles of technology and engineering. Appropriate implementation of engineering education is a topic of great significance, especially at the K-12 level (Strimel & Grubbs, 2016).

In recent years, many researchers have engaged in discussions about engineering education at the K-12 level (Cohen, 2018; Sinatra et al., 2017; Song et al., 2016). The focus of these studies has tended to be on the engineering design process, and how it should be highlighted to advance STEM education. However, developing the

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Contribution of this paper to the literature

- This study explores the senior high school students' performances in knowledge structures for engineering design process.
- This study develops a STEM project-based learning activities that use 3D printing technology in developing senior high school students' knowledge structure for modeling in engineering design process.
- This study explores the effects of applying 3D printing technology in developing senior high school students' knowledge structure for modeling in engineering design process.

engineering design process is not an easy task. When studying the engineering design process of senior high school students, many scholars discovered that the students' performances in several areas, including defining questions, gathering data, and modeling, had yet to improve, and thus deemed it worthwhile to further reflect on how to improve the students' performance in these respects (Atman, Adams, Cardella, Turns, Mosborg, & Saleem, 2007; Wells, Lammi, Gero, Grubbs, Paretti, & Williams, 2016).

Regarding the modeling problems that senior high school students encounter during the engineering design process, it is possible that they simply lack modeling abilities and thus cannot assess the feasibility of their proposed ideas correctly (Atman et al., 2007). To tackle these modeling problems, Blikstein, Kabayadondo, Martin, and Fields (2017) suggested that the application of 3D printing could help students acquire procedural knowledge through modeling and help them learn how to solve such problems by applying scientific and design principles. Apart from using 3D printing technology to enhance learning related to modeling, this study also applies the principles of model-eliciting activities to develop STEM project-based learning activities (Kaiser & Sriraman, 2006). It is believed that integrating 3D printing into such STEM activities is effective in helping students carry out modeling and optimization properly during model construction. In this way, they can acquire comprehensive knowledge structures for engineering design.

This study was aimed primarily at helping students assess the feasibility of their ideas and attain more comprehensive knowledge structures for engineering design process, by assisting them in modeling through the use of 3D printing technology. The research questions were as follows: (1) what is the senior high school students' performances in knowledge structures for engineering design process, and (2) can STEM project-based learning activities that use 3D printing technology help develop students' knowledge structures for modeling in engineering design process?

THEORETICAL BACKGROUND

Engineering Design Process in STEM Project-based Learning Activities

With the constant advance of technologies, education methods for students at the K-12 (kindergarten through 12th grade) level should differ from those applied when they enter higher education. To be precise, helping students gain a clear understanding of their future needs and directions, so that they can become valuable STEM talents, has become an important topic that has attracted much attention in recent years; thus, it has been deemed important to consider, in the process of advancing STEM education, which aspects of engineering content should be taught at the K-12 level (Brophy et al., 2008). For example, in the US, engineering standards set by the national and state governments focus primarily on such issues as materials, tools, machines, and engineering design (International Technology Education Association (ITEA), 2000/2002; Massachusetts Department of Education, 2016). The American Society for Engineering Education (ASEE) also proposed a major policy objective regarding engineering education at the K-12 level, suggesting that engineering education at that level should consist mainly of hands-on, interdisciplinary practice and emphasize the engineering's relevance to society (Douglas, Iversen, & Kalyandurg, 2004).

However, many scholars in the fields of science, mathematics, and technology education create engineering content based around the development of engineering design ability. Hence, instructional models based on engineering design process have become a prevalent means of meeting curriculum standards (Brophy et al, 2008). Design-based engineering activities can advance students' conceptual understanding of related knowledge and principles, as well as their self-guided inquiry skills (Crismond, 2001; Fleer, 2000; Kimmel et al., 2006; Kolodner et al., 2003; Linn, 2003; Zubrowski, 2002; Sadler, Barab, & Scott, 2007). Brophy et al. (2008) also agreed that for early K-12 level engineering education, hands-on activities should be organized to give students a basic understanding of material properties, spatial reasoning, physics, and mechanics, and to enhance number sense and general problem-solving abilities. Concerning advanced curricula for more senior levels, the focus should be on enhancing students' ability to construct conceptual prototypes for their ideas.

Scholars in technology education in the UK and Australia use engineering design activities to develop students' technological literacy and help them recognize its significance to society. Thus, the engineering design process is often regarded as the optimal means of organizing students' learning experience (Dillon & Howe, 2007; Johnsey, 1995). Aguirre-Munoz & Pantoya (2016) suggested that the engineering design process should be incorporated into meaningful contexts. This point of view is consistent with that of other scholars (Brotman & Moore, 2008; Clewell & Braddock, 2000; Reid & Skryabina, 2003), who also considered that if engineering education focused mainly on the engineering design process, and provided students with activities so that they could experiment with STEM, it would enhance their interest in studying disciplines such as science or mathematics in the future.

As these scholars have stated, engineering design should be a key part of K-12 level engineering education (Brophy et al., 2008; Brotman & Moore, 2008; Clewell & Braddock, 2000; Reid & Skryabina, 2003). Atman et al. (2007) took the same stance, agreeing that engineering design is a crucial and indispensable skill. To develop students' abilities in engineering design, Dutson, Todd, Magleby and Sorensen (1997) discussed how to use project-based courses to teach engineering design. They pointed out that if such courses were planned well, they could help senior high school students learn more about engineering design process and the field of engineering. Kist (2014) also used project-based courses to improve student engagement, showing that students were more inclined to learn when they were involved in project-based courses that integrated theory and practice. Thus, there is general recognition that using capstone engineering courses in teaching engineering design process, and including this design component in engineering courses, can help students to improve their practical engineering abilities (Dutson et al., 1997).

Role of Modeling in the Engineering Design Process

The literature reviewed above shows that to execute STEM learning programs successfully, it is important to include suitable project-based learning activities and integrate them into an engineering design process. Engineering design process is mainly oriented towards customer needs, not designers' imaginations, which presents students with many additional challenges. To fulfill customers' needs, they must learn to think from the customers' perspective and make critical assessments of how to solve problems in the most efficient way (Brophy et al., 2008).

When studying how engineering experts and students performed in terms of the engineering design process, Atman et al. (2007) divided the process into three steps: (1) problem scoping: identification of a need, problem definition, and gathering information, (2) developing alternative solutions: generating ideas, modeling, feasibility analysis, and evaluation, and (3) project realization: decision-making, communication, and implementation. In the study of Atman et al. (2007), it was found that, overall, engineering experts spent more time on a task than did students during every step, especially in phases such as problem scoping and the gathering of diverse information. This result showed that in terms of the engineering design process, the main differences between the performance of experts and students were manifest in two areas: problem scoping and gathering information.

Another important issue in students' engineering design process relates to modeling. Fostering modeling ability plays an essential role in engineering education, and the ways of creating and using representations during modeling are important. When students are learning to build a model, they often have to use different representations to express, test, correct, and communicate their ideas; this is why model development usually has to rely on representational fluency and the ability to translate between and within different representational forms. Modeling is thus useful for the development of a higher-order understanding of important concepts in engineering education (Lesh, Yoon, & Zawojewski, 2007; Moore, Miller, Lesh, Stohlmann, & Kim, 2013; Moss, Kotovsky, & Cagan, 2006; Streveler, Litzinger, Miller, & Steif, 2008). Additionally, Kaiser and Sriraman (2006) posited that modeling in the fields of science, mathematics, and engineering education could cover both theoretical and practical perspectives, mainly by applying contextual modeling to engineering design activities, encouraging students to apply relevant knowledge from different fields (such as science and mathematics) to problem-solve in a more constructive way.

To develop students' modeling abilities, many programs make use of model-eliciting activities, which are not only available to freshmen. Furthermore, numerous senior high schools have designed model-eliciting activities that are primarily customer-oriented and based on open-ended questions (Diefes-Dux, Hjalmarson, Zawojewski, & Bowman, 2006). These learning activities typically provide students with a context for learning how to construct a pattern by themselves. When constructing a pattern, students must be able to describe, explain, or predict possible behavior in realistic situations. This type of model-eliciting activity can encourage each student within a team to participate actively in the problem-solving process and express, test, and refine their ways of thinking repeatedly according to the realistic situations presented to them (Doerr, Ärlebäck, & Costello Staniec, 2014; Lesh & Doerr, 2003).

Model-eliciting activities can be used to help students acquire important yet intricate concepts and develop their technical, teamworking, and project management skills (Bursic, Shuman, & Besterfield-Sacre, 2011; Kean, Miller, Self, Moore, Olds, & Hamilton, 2008; Ridgely & Self, 2011; Self & Widmann, 2010). Although Doerr et al. (2014) stated that single modeling tasks might have rather limited efficacy in developing students' modeling skills, such tasks are still valuable as a reference for the development of STEM project-based learning activities.

3D Printing and Modeling

In addition to using model-eliciting activities to construct a learning context for STEM project-based activities, it is also important to reflect on how to use other emerging technologies to help students build models, where Doerr et al. (2014) suggested that mere application of a single modeling task for the development of students' modeling abilities has limited effectiveness. In recent years, as Makerspaces and FabLabs have gained in popularity, using digital processing tools to assist students in learning has become a major subject (Blikstein et al., 2017). Among these tools, 3D printing is one of the most salient technologies. Many scholars have studied the benefits of 3D printing technologies for student learning. For example, Horowitz and Schuitz (2014) discussed the advantages of 3D printing with respect to producing concrete models, as well as the importance of these models in science education. Scalfani and Vaid (2014) also aimed to use 3D printing to teach students how to build chemical structures. In their study, they also discovered that 3D printing was effective for producing teaching aids to facilitate students' learning of chemistry. In addition to its application to science education, Brown and Burge (2014) used 3D printing to help female high school students acquire computing skills; it was also found that the technology could improve the students' degree of acceptance of computing. Kostakis and Niaros (2014) used mainly 3D technologies to aid interactive communication between students with and without visual disabilities, thereby strengthening their cooperation skills and creativity.

It should be noticed that relevant studies related to the application of 3D printing majorly focus on the use of 3D printing technology to assist students in acquiring knowledge of science or other subjects. Blikstein et al. (2017) advocated that 3D printing could help students acquire procedural knowledge through modeling, and by learning how to use scientific and design principles to solve immediate problems. However, relevant empirical research is still rare. Thus, this study aimed to explore was effective use of 3D printing to help students construct models and improve the modeling-related problem-solving capacity of senior high school students, as reported in previous studies (Atman et al., 2007; Wells et al., 2016). To this end, this study developed STEM project-based learning activities, primarily model-eliciting activities. Furthermore, to help students construct and optimize models properly; we integrated 3D printing technology into a STEM project-based learning activity that used bridges as its theme. In this way, the students could leverage the technology to construct and test a bridge model, and analyze the pros and cons of their design ideas accurately, especially in terms of the compressive strength and pulling tensions of bridge members, so that they could design better bridge structures.

METHODS

Research Design

This study was aimed primarily at helping students assess the feasibility of their ideas and attain more comprehensive knowledge structures for engineering design process, by assisting them in modeling through the use of 3D printing technology. To achieve the research purpose, a quasi-experimental "pretest-posttest non-equivalent control group design was utilized to carry out investigations (**Figure 1**). For the experimental group, the main research method was a STEM project-based bridging activity based on 3D printing; during the modeling process, the modeling principles proposed by Diefes-Dux et al. (2006) were applied. For the control group, 3D printing technology and modeling principles were not available; instead, a problem-solving process was used to guide students through the bridging activity. To eliminate the effect of prior differences in engineering design process and knowledge structures among the senior high school students, a pre-test questionnaire about engineering design process was administered; the content of the questionnaire is described later, in the "Data Collection and Analysis" section). By doing this, we could address prior differences in engineering design process and knowledge structures among the students.

The post-test evaluation took place 10 weeks after the experimental teaching program. Tsai and Huang (2002) compared the efficacy of different types of representational knowledge structure, such as concept maps, suggesting that flow-maps represented the optimal method to study knowledge structures. Thus, this study used an in-depth interview, flow-maps (Anderson & Demetrius, 1993) and the meta-listening technique (Tsai, 2001) to assess the overall performance of the students with respect to engineering design process and knowledge structures after delivery of the experimental teaching program (details about the flow-map method, meta-listening technique and core concept analyses are set out in the "Data Collection and Analysis" section). The efficacy of using 3D printing

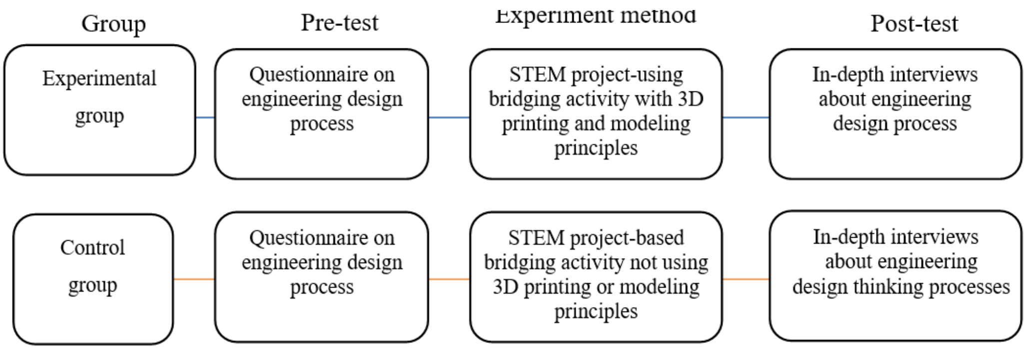

Figure 1. The research framework

technology in STEM project-based activities to develop senior high school students' engineering design process and knowledge structures was also evaluated.

Participants

The participants were 43 students coming from two 10th-grade classes chosen randomly from a senior high school in Taiwan. One of the classes (23 students) was chosen randomly to be the experimental group (STEM project-based hands-on activity with 3D printing technology) and the other (20 students) formed the control group same STEM activity but without the use of 3D printing). All the participants were male students.

There were two class sessions each week, giving a total classroom time of 50 min per week. As classes were conducted in a technology learning laboratory with an abundance of equipment and facilities; this setting satisfied the practical needs of the study and allowed the researchers to control relevant variables that might affect the teaching, such as an uneven distribution of participant characteristics, researcher bias, and bias related to the testing and implementation (Fraenkel, Wallen, & Hyun, 2012). This ensured the reliability and validity of the experimental results.

Implementation

The experimental teaching program ran from February to May 2016. The weekly curriculum was structured as follows: (1) week 1: pre-test, (2) week 2: introduction to STEM project-based bridge design activity, (3) week 3: 3D drawing software and printing techniques, (4) week 4: identification of a need, problem definition, and gathering of information, (5) week 5: generating ideas, modeling, feasibility analysis, and evaluation, (6) week 6: decision-making and communication, (7) weeks 7–8: implementation, (8) week 9: testing, reflection, and improvement, and (9) week 10: in-depth interview. The major difference between the experimental group and the control group was that, in the former, modeling principles were emphasized (Diefes-Dux et al., 2006) and 3D printing was used to build models; in contrast, students in the control group used only spaghetti for modeling.

Instrument

This study used two main research instruments, the first of which was a questionnaire about engineering design process designed to assess the status quo regarding the participants' knowledge structures pertaining to engineering design. The researchers posed the following question to the students: "Assume that you would like to design a ping pong ball launcher now. To what kind of engineering design process would you refer to achieve this? Please list your work steps in detail and explain what the main focus of each step is." The design of this question was largely based on a study by Cardella, Atman, Adams, and Turns (2002); furthermore, it used the engineering design process defined by Atman et al. (2007) to analyze and understand the participants' pre-experiment knowledge structures pertaining to the engineering design process. The other instrument took the form of interviews about engineering design process; these interviews were necessary for the flow-map method. The interview questions were designed mainly according to the suggestions of Tsai and Huang (2002) and Wu (2013). The questions included: (1) Could you tell me how would you use engineering design process to solve engineering problems? (2) Could you tell me more about the concepts you have just mentioned? (3) Could you explain to me the relationships among the concepts you have mentioned? and (4) Is there anything that you would like to add?

Data Collection and Analysis

To examine the engineering design process and knowledge structures of the senior high school students, we collected data through an in-depth interview and analyzed the students' knowledge structures using the flow-map

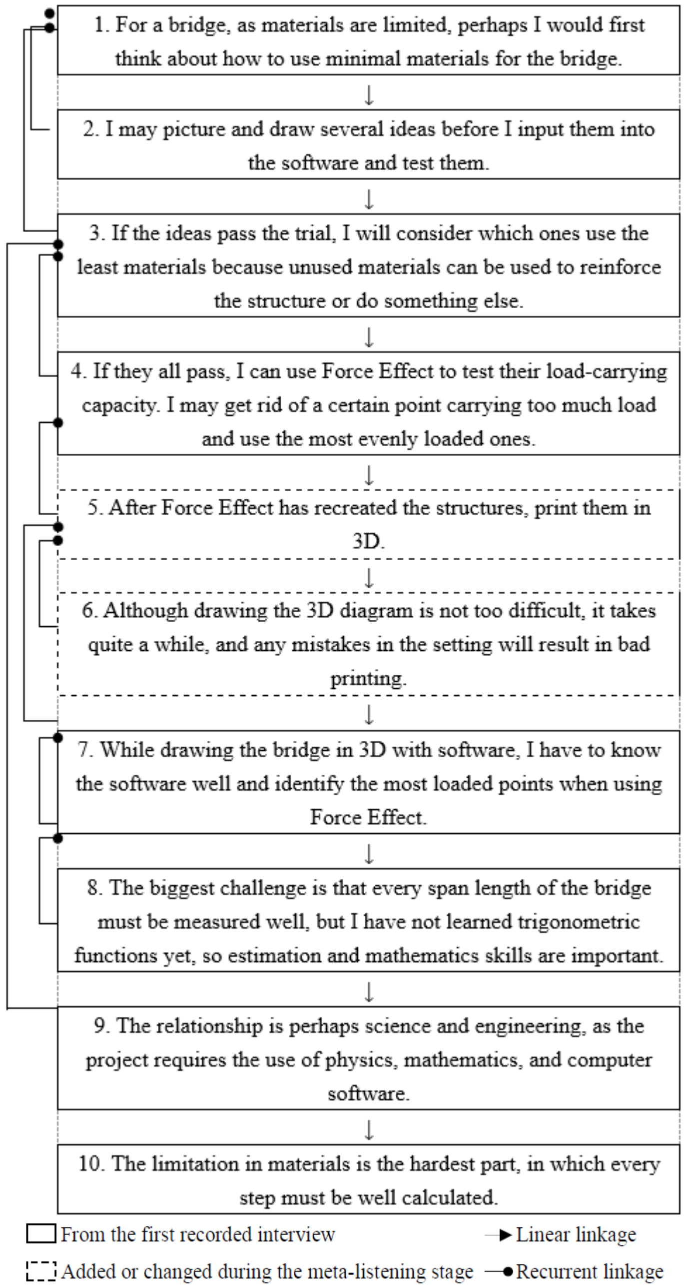

Figure 2. Example flow-map for an interviewee

method (Anderson & Demetrius, 1993) and meta-listening technique (Tsai, 2001). We arranged the concepts apparent in the participants' discourse into a flow-map (**Figure 2**). Each flow-map represents an individual student's knowledge structure regarding engineering design. Tape-recorded audio transcripts were transcribed and phrases or descriptions irrelevant to the concepts of interest were omitted. The concepts delineated by the students were then drafted into a flow-map in the sequence in which they were mentioned. If the students added any other concepts during application of the meta-listening technique, these new concepts were inserted in sequence. If they changed their description of any concepts during the meta-listening stage, the original statements were amended accordingly. After the main concepts were listed, they were interconnected by arrows, in chronological order. If a concept mentioned by the interviewee was related to a previous concept, the two ideas were connected by a "recurrent linkage."

To effectively analyze students' knowledge (content and organization) and information processing patterns with respect to engineering design process and knowledge structures, , this study probed every concept included in the flow-maps using content analysis. We used the five aspects proposed by Tsai and Huang (2002): "extent," "correctness," "integration," "availability", and "information processing strategies"—as an analytical framework

Table 1. Analytical framework of knowledge structures

Aspect	Variables included in the flow-maps
Extent	Initial and final number of linear linkages
Correctness	Proportion of incorrect conceptions
Integration	Initial and final number of recurrent linkages, initial and final complexity of linear concepts
Availability	Number of changes in linear concepts and recurrent linkages, and changes in the complexity of linear concepts
Information processing strategies	Defining, describing, comparing or contrasting, inferring and explaining

Source: Tsai & Huang, 2002

Table 2. Results of independent-samples *t*-test comparing the knowledge structures of the experimental group and control group (*N* = 40)

	Experimental group (*N* = 20)		Control group (*N*= 20)		*t-value*	*Cohen's d*
Knowledge structure element	*M*	*SD*	*M*	*SD*		
Extent						
Initial no. of linear linkages	6.75	1.83	7.30	2.39	-0.82	-0.26
Final no. of linear linkages	6.85	1.95	7.30	2.39	-0.65	-0.21
Correctness						
No. of incorrect conceptions	0.00	0.00	0.00	0.00	N/A	N/A
Integration						
Initial no. of recurrent linkages	5.75	1.83	6.30	2.39	-0.82	-0.26
Final no. of recurrent linkages	5.85	1.95	6.30	2.39	-0.65	-0.21
Initial complexity of linear concepts	0.46	0.02	0.46	0.01	-0.37	< 0.01
Final complexity of linear concepts	0.46	0.02	0.46	0.01	-0.37	< 0.01
Availability						
Change in linear concepts	0.10	0.45	0.00	0.00	1.00	0.31
Change in recurrent concepts	0.10	0.45	0.00	0.00	1.00	0.31
Change in complexity of linear concepts	0.00	0.00	0.00	0.00	1.00	<0.01
Information processing strategies						
Define	0.55	0.51	0.60	0.94	-0.21	-0.07
Describe	4.90	1.68	5.30	2.13	-0.66	-0.21
Compare and contrast	0.55	0.51	0.55	0.60	0.00	< 0.01
Infer	0.55	0.83	0.60	0.88	-0.19	-0.06
Explain	0.30	0.47	0.25	0.44	0.35	0.11

Note: The number of students in the experimental group was reduced to 20 because three students were unable to take part in the interview

for the flow-maps, to examine the students' engineering design process and knowledge structures. This framework, together with the flow-map method, allowed us obtain the various qualitative and quantitative data shown in **Table 1**.

For content analysis, the researchers and Teacher A analyzed and coded the concepts mentioned in eight flow-maps, which were chosen randomly from among the maps made during all of the interviews and were based on the same mapping rules. Ultimately, the analytical results of the researchers and Teacher A were compared to obtain the inter-coder reliability for flow map analyses. The overall results showed that in these flow-maps, the inter-coder reliability for flow map analyses were above 0.8 both before and after teaching, illustrating the high reliability of the scorers and the trustworthiness of the results of this study (Wu, 2013).

RESULTS

Students' Knowledge Structures Regarding the Engineering Design Process

After the experimental and control groups had participated in the STEM project-based learning activity, the flow-map method and meta-listening technique were used to create flow-maps for 40 students. These maps were then analyzed in terms of the extent, correctness, integration and availability of the concepts, as well as the information processing strategies, based on Tsai & Huang (2002). As shown in **Table 2**, the two groups showed no significant difference any of these aspects (independent-samples *t*-test). However, this analysis did not take into consideration the students' prior knowledge. Thus, a more in-depth analysis is included below, to assess the utility of applying 3D printing to STEM project-based learning activities for developing engineering design process and knowledge structures in students.

Table 3. Analysis of the numbers of concepts used in the engineering design process of the experimental and control groups

	Experimental group (*n* = 20) *M/SD*	Control group (*n* = 20) *M/SD*	*t*-value	*p*
Pre-test	1.65/0.99	3.65/1.04	-6.24*	< 0.01
Post-test	4.00/1.81	5.70/1.56	-3.82*	< 0.01

Note. $^{*}p < 0.05$

Table 4. Summary of test results: within-group regression coefficient of homogeneity

Engineering design process	*SS*	*df*	*MS*	*F*
Number of concepts	9.53	1	9.53	3.73

Table 5. Summary of ANCOVA of the number of concepts used during the engineering design process

Source of variance	*SS*	*df*	*MS*	*F*	η^2
Within groups	31.48	1	31.48	11.47*	0.24
Between groups (error)	101.57	37	2.75		
Adjusted total	137.1	39			

Note. $^{*}p < 0.05$

Effects of 3D Printing on Development of Students' Knowledge structures for the Engineering Design Process

With regard to Atman et al. (2007), a comprehensive engineering design knowledge structure should consist of 10 important concepts. A comparison of the numbers of concepts produced by the experimental and control groups before and after the experimental teaching program is presented in **Table 3**. It is clear that both before and after teaching, the control group performed better than the experimental group in terms of the number of concepts pertaining to engineering design process and knowledge structures, and differences in numbers of concepts were statistically significant (independent-samples *t*-test: $t = -6.24$, $p < 0.01$ and $t = -3.82$, $p < 0.01$, respectively). This analysis was done to assess the effects of different teaching methods on the students' engineering design process and knowledge structures. Analysis of covariance (ANCOVA) was used for exploring the effects of applying 3D printing technology and modeling principles in STEM project.

As shown in **Table 4**, the within-group regression coefficient of homogeneity ($F = 3.73$) was not statistically significant. Thus, as the assumption of homogeneity within groups was not violated, a further ANCOVA could be carried out. According to the ANCOVA results (**Table 5**), the between-group effect was significant ($F_{(1, 37)} = 11.47$, $p = 0.003$) and the effect size was 0.24, which is 'large' according to Cohen (1988). In other words, there was a significant difference between the two groups in the mean numbers of concepts used during engineering design process and the control group (adjusted $M = 6.11$) performed better than the experimental group. To further explore the possible reasons for this finding, the actual performances of the two groups, in the form of flow-maps, were analyzed further.

In-Depth Exploration of Students' Knowledge structures for Modeling in Engineering Design Process

To gain further understanding of the students' performance in terms of engineering design process and knowledge structures, a content analysis was done, focusing on the flow-maps, to investigate: (1) the deficiencies present in the students' engineering design process and knowledge structures before and after the experimental teaching, and what should be improved, and (2) whether the students could give a further explanation of how each concept in the engineering design process works.

First, in terms of the deficiencies in the students' engineering design process and knowledge structures (**Table 6**), before the experiment both groups showed relatively weak performance in terms of expressing the concepts of modeling, feasibility analysis, evaluation, decision-making, and communication. At the same time, the experimental group were poorer in terms of gathering information. According to χ^2 test, the control group participants were better able to expressing concepts about gathering information ($\chi^2 = 11.61$, $p < 0.01$), implementation ($\chi^2 = 22.56$, $p < 0.01$), and redesign ($\chi^2 = 15.00$, $p < 0.01$) than were the experimental group participants.

Table 6. Analysis of concept expression regarding the engineering design process

	Group	1.1	1.2	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4
Pre-test	Experimental group (n=20)	9 (45%)	0 (0%)	19 (95%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	3 (15%)	2 (10%)
	Control group (n=20)	11 (55%)	9 (45%)	20 (100%)	0 (0%)	1 (0%)	0 (0%)	0 (0%)	0 (0%)	18 (90%)	14 (70%)
	χ^2	0.90	11.61*	1.03	N/A	1.03	N/A	N/A	N/A	22.56*	15.00*
	p	0.34	<0.01	0.31	N/A	0.31	N/A	N/A	N/A	<0.01	<0.01
Post-test	Experimental group (n=20)	9 (45%)	8 (40%)	12 (60%)	11 (55%)	8 (40%)	12 (60%)	1 (5%)	3 (15%)	9 (45%)	7 (35%)
	Control group (n=20)	13 (65%)	17 (85%)	17 (85%)	11 (55%)	8 (40%)	18 (90%)	2 (10%)	3 (15%)	17 (85%)	8 (40%)
	χ^2	1.62	8.64*	3.14	N/A	N/A	4.80*	0.36	N/A	7.03*	0.11
	p	0.20	<0.01	0.08	N/A	N/A	0.03	0.55	N/A	0.01	0.74

Note 1. *p < 0.05.

Note 2. N/A indicates that the χ^2 test could not be performed.

Note 3. 1.1 problem definition, 1.2 gathering information, 2.1 generating ideas, 2.2 modeling, 2.3 feasibility analysis, 2.4 evaluation, 3.1 decision-making, 3.2 communication, 3.3 implementation, 3.4 redesign

Table 7. Analysis of explanations of concepts relevant to the engineering design process

Team	1.1	1.2	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4
Experimental group (n = 15)	1 (5%)	0 (0%)	5 (25%)	10 (50%)	8 (40%)	9 (45%)	0 (0%)	3 (15%)	7 (35%)	0 (0%)
Control group (n = 13)	4 (20%)	12 (60%)	9 (45%)	11 (55%)	8 (40%)	5 (25%)	0 (0%)	3 (15%)	8 (40%)	4 (20%)
χ^2	2.06	17.14*	1.76	0.10	N/A	1.76	N/A	N/A	0.11	4.44
p	0.15	<0.01	0.19	0.75	N/A	0.19	N/A	N/A	0.74	0.04

Note 1. *p < 0.05, **p < 0.01.

Note 2. N/A indicates that the χ^2 test could not be performed.

Note 3. 1.1 problem definition, 1.2 gathering information, 2.1 generating ideas, 2.2 modeling, 2.3 feasibility analysis, 2.4 evaluation, 3.1 decision-making, 3.2 communication, 3.3 implementation, 3.4 redesign

After the experimental teaching program, both groups demonstrated great improvements in concept expression pertaining to modeling, feasibility analysis, evaluation, decision-making, and communication (and especially for the first two aspects). Their conceptual understanding regarding decision-making and communication could still be further improved, which should be a main focus for future modifications to STEM project-based learning activities that use 3D printing technology. As shown by χ^2 test, the control group performed better in terms of gathering information (χ^2 = 8.64, p < 0.01), feasibility analysis (χ^2 = 4.80, p = 0.03), and implementation (χ^2 = 7.03, p = 0.01) than the experimental group.

Second, regarding the students' ability to provide further explanations of the mechanism underlying each concept in the engineering design process (**Table 7**), both groups were weak in terms of elaborating on the concepts of decision-making, communication, and redesign. This should be a focus for future STEM project-based learning activities that aim to develop the engineering design process and knowledge structures of senior high school students. The experimental group remained relatively weak, after the teaching program, in terms of elaborating on the concept of gathering information. This should also be taken into account in future refinements of STEM project-based learning activities that make use of 3D printing technology.

DISCUSSION

In this study, we applied the modeling principles of Diefes-Dux et al. (2006), as well as 3D printing technology, to STEM project-based learning activities to ascertain the benefits of such activities on the engineering design process and knowledge structures of senior high school students. After delivering the experimental teaching program, we conducted in-depth interviews with the experimental and control groups, and produced a flow map for each student using the flow-map method and meta-listening technique. From the results of the flow-map analysis, it is clear that the experimental group had a slightly weaker performance than the control group in all aspects except for the ability to explain as part of processing information strategies, in which the experimental group explained better than the control group (0.30 > 0.25; **Table 2**). The general weaker performance of the experimental group may be caused mainly by a pre-existing disparity between the two groups' engineering design process and knowledge structures. For example, there was a significant difference in the numbers of concepts produced by the two groups regarding the engineering design process (t = -6.24, p < 0.01). Nevertheless, according to the flow-map analysis (**Table 2**), the disparity was largely diminished after 10 weeks of experimental teaching.

The experimental group was even better than the control group at explaining concepts, which was categorized as an information processing strategy. This result shows that the use of modeling principles and 3D printing technology could help students develop a higher-order understanding of important concepts (Lesh et al., 2007; Moore et al., 2013; Moss et al., 2006; Streveler et al., 2008). However, as the difference between the two groups was not statistically significant, the actual efficacy of this teaching method needs to be investigated further.

With regard to the analysis of the number of concepts relating to the engineering design process, as shown by both the results of the independent-samples *t*-test (**Table 3**) and the ANCOVA (**Table 5**), the experimental group, who engaged with modeling principles and 3D printing, did not produce a higher number of concepts than the control group; in fact, the control group showed better performance ($F_{(1, 37)} = 11.47$, $p = 0.003$). We suggest two possible reasons for this result, the first being that the focus of the modeling principles and 3D printing was to help the students develop a higher-order understanding of important concepts (Moore et al., 2013) instead of helping them attain more comprehensive engineering design process. Thus, such students may only perform better in terms of modeling but with no clear improvement in terms of the overall engineering design process. A second possible reason was that, as Doerr et al. (2014) pointed out, a single modeling task may have limited effectiveness for improving students' modeling abilities. Due to the time constraint related to the experimental teaching program used in this study, it was not feasible to arrange two project-based learning activities within a single semester to help the students acquire more comprehensive modeling abilities. Thus, in future, it would be valuable to discuss how the design of STEM project-based learning activities could be adjusted to allow students to participate in multiple modeling tasks.

Despite the poorer performance of the experimental group in terms of the number of concepts produced during the engineering design process, deeper analysis of the flow-maps showed that, based on the analytical results shown in **Tables 6** and **7**, the experimental group had largely improved in terms of modeling and feasibility analysis, especially in terms of elaborating on concepts related to feasibility analysis. Indeed, there were nine (45%) students in the experimental group who provided a deeper explanation of this concept, but only five in the control group. Although the difference was not significant on χ^2 test, it was noticeable that the modeling principles and 3D printing technology helped the students to develop a higher-order understanding of important concepts (Moore et al., 2013). It is believed that the outcomes would have been clearer if multiple modeling tasks had been used to develop students' modeling skills (Doerr et al., 2014).

Finally, in terms of the limitations of this study, the pre-tests were carried out by means of a questionnaire because two rounds of in-depth interviews might have encroached on the students' learning or reduced their willingness to provide answers during the second interview. The analyses were thus based on qualitative data extrapolated from written descriptions. However, this method could be problematic because the students might not be able to convey all of their engineering design process and knowledge structures through writing alone. At the same time, some students might present their thoughts in a briefer, summarized manner because of the greater effort involved in writing. Although we asked the students to express their ideas as fully as possible before they completed the questionnaire, this limitation may still have affected the results.

CONCLUSIONS AND IMPLICATIONS

This study focused on exploring the engineering design process and knowledge structures of senior high school students, as well as the efficacy of modeling principles and 3D printing for developing these abilities. Regarding research question (1)—"What is the status quo regarding senior high school students' knowledge structures for engineering design process?"—the results showed that before the experimental teaching program, on encountering engineering problems the students were more inclined to directly searching for solutions, implement ideas, and improve the problem. However, students seldom considered steps such as information-gathering, modeling, analyzing feasibility, decision-making, or communication. After the experimental teaching program, although students improved in terms of modeling and feasibility analysis, students still thought little about decision-making and communication. Thus, related studies in the future should amend the content of project-based learning activities so that, in the face of engineering problems, students can give the customers' needs greater consideration and communicate well with other people. This is an important topic that should be highlighted.

For research question (2)—"Can STEM project-based learning activities that use 3D printing technology help develop students' knowledge structures for engineering design process?" —the results showed that, although the application of 3D printing to the STEM project-based hands-on activities used in this study did not increase the overall number of concepts used relevant to engineering design process, the use of modeling principles and 3D printing did indeed assist the students in terms of elaborating on the concepts of modeling and feasibility analysis. However, the improvement was not statistically significant, so future studies should consider looking deeper into the effects of multiple modeling tasks on students' modeling abilities (Doerr et al., 2014); this is likely to be an important topic in engineering design process and knowledge structures in the future.

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