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How High School Students Apply Knowledge in Engineering Design Projects*

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This study examined how students applied conceptual and procedural knowledge when engaged in an engineering design project. A mechanical toy design project was used as a context for exploring how science, technology, engineering, and mathematics (STEM) concepts taught in an engineering module facilitated student performance. Study data were collected from 103 high school student participants and analyzed using correlation, variance, and simultaneous regression analysis. The major finding of the study was that the students' STEM conceptual knowledge was the key to success in engineering design, especially at the synthesis and evaluation levels, and for their process ability to analyze, and evaluate during the project. Three recommendations are made to improve high school engineering instruction. To facilitate in-depth learning about the process of engineering design, multiple approaches should be employed to develop the students' application of STEM conceptual knowledge and process abilities. Teachers need to enhance students' science and mathematics knowledge to establish mathematical analysis and systems thinking. Students' spatial and sketching abilities need to be improved to better facilitate engineering design work.

Keywords: conceptual knowledge; procedural knowledge; engineering design; STEM

1. Introduction

Engineering design is an important part of technological problem solving and an integral element for the study of technology education [1–3]. As defined by the Accreditation Board for Engineering and Technology [4], engineering design 'is the process of devising a system, component, or process to meet desired needs. It is a decision-making process, in which basic science, mathematics, and engineering science are applied to convert resources optimally to meet these stated needs.' Engineering design includes the process of emphasizing problem factor analysis and understanding science, mathematics, engineering, and technology [2, 5], highlighting the importance of conceptual and procedural knowledge required for completing an engineering design. McCormick [6] noted that conceptual and procedural knowledge are required to solve technology problems. Conceptual knowledge includes understanding broad concepts and recognizing their application; procedural knowledge is knowledge relevant to design, problem solving, optimization, modeling, and strategic thinking, and is focused on crucial aspects of practice and implementation [7–9].

Procedural knowledge often develops during the design process, when students have the opportunity to think, reflect upon, and develop ideas, then test them in a practical context. When developing an engineering design, students must resolve problems for the practice of design and reflect on their thinking process to analyze, evaluate, and predict while applying concepts in various situations. In contrast, conceptual knowledge concerns understanding broad concepts and recognizing their application in various situations [6, 8]. In fact, procedural knowledge cannot be taught without conceptual knowledge. It is conceptual knowledge that enables the use of procedural knowledge [8]. In engineering design, science and mathematics, concepts constitute the majority of conceptual knowledge. Without the knowledge of these concepts, students will have difficulty proceeding both with design and the application of procedural knowledge.

Many models have been developed to describe how students think and act when working on a design project [10, 11]. Figure 1 presents the Assessment of Performance Unit (APU) model, which models the connection between thought and action through the interaction of mind and hands. This interaction is similar to the linkage between procedural and conceptual knowledge used in the engineering design process. Engineering design uses procedural knowledge, which occurs in the mind and is not easily observable [12]. Research needs to examine students' design processes to better understand how they think and apply conceptual knowledge to solve problems.

Traditionally, school curricula have chiefly been organized based on the concept that instruction should be separated into distinct subjects. Recently, the concept of integrating school subject areas has

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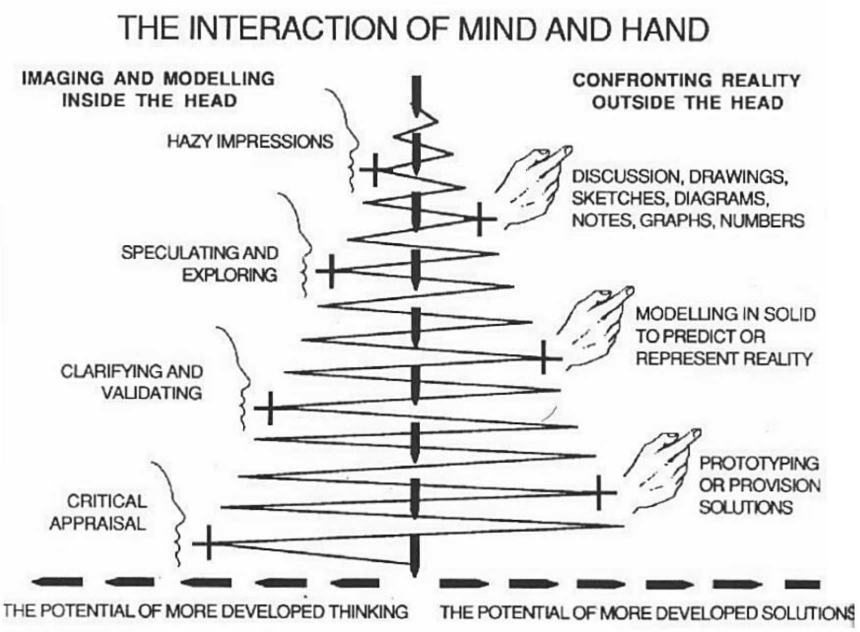


Fig. 1. The APU model of interaction between mind and hand.

gained significant attention as a plausible solution for developing a more relevant approach to teaching and learning [13, 14]. In particular, attention within the field science and technology education has been directed at integrating mathematics, science, engineering, and technology [3, 15–18]. For example, Roman [16] encouraged technology teachers to use an integrative approach to design, which incorporates mathematics and applied science in keeping with the crosscutting nature of engineering. Cotton [17] argued that mathematical theories should be applied to design for technology education, and that students should use mathematics to predict the outcomes of their designs. Lewis [19] urged that science and mathematics should be taught to help students make design predictions through a process of analytical design.

Trial-and-error remains a prevailing design approach in technology education classrooms [19]; we therefore need to encourage students to integrate their knowledge when working on designs. Knowledge integration involves the conceptual and procedural application of science, technology, engineering, and mathematics (STEM) knowledge. However, more research is needed to examine whether integration with different subjects, particularly STEM, can improve the student acquisition of technological concepts and processes. The integration of STEM knowledge can enhance convergent and divergent thinking because mathematics and science tend to focus on convergent thinking, whereas technology and engineering focus more on divergent thinking. Students can use mathematics and science concepts to solve technology problems, learn concepts more easily, and retain them better because engineering design provides real-world contexts for abstract concepts [18].

Engineering concerns the designed world. It uses the design process to produce workable solutions and create innovation. Technology, the output of engineering, includes processes, products, systems, and services to meet the needs of society [3]. Numerous curricula have been designed to infuse engineering content into technology education courses [20, 21]. This study incorporated engineering design work into a high school technology education course in which students could apply STEM to resolve a real-world problem. Engineering concepts are not applied in Taiwan's high school technology content standards, and so technology teachers are not inclined to include engineering in their curriculum. Therefore, an appropriate curriculum progression, especially in terms of knowledge integration, would be a general technology-based education at the junior high level, followed by high school-level engineering classes.

The STEM project was a collaborative effort among faculty from the College of Technology at National Taiwan Normal University, which pairs university faculty members with high school technology teachers to create engineering design modules. The STEM project was a pilot study focused on small numbers of high school students and teachers in Taiwan. The aim of the project was to facilitate better understanding among technology teachers as to how engineering concepts can be aligned with science and mathematics to create rigorous STEM content.

The aim of this study was to examine how high school students applied their conceptual and procedural knowledge when engaged in an engineering design project. The study examined how both kinds of knowledge were employed and measured their relationship against the success of final design projects. This information is important if technology teachers are to understand the difficulties that students usually face during the engineering design process. To provide systematic learning of engineering design, a STEM engineering module (STEMEM) was developed to facilitate student application of conceptual and procedural knowledge in learning engineering design skills.

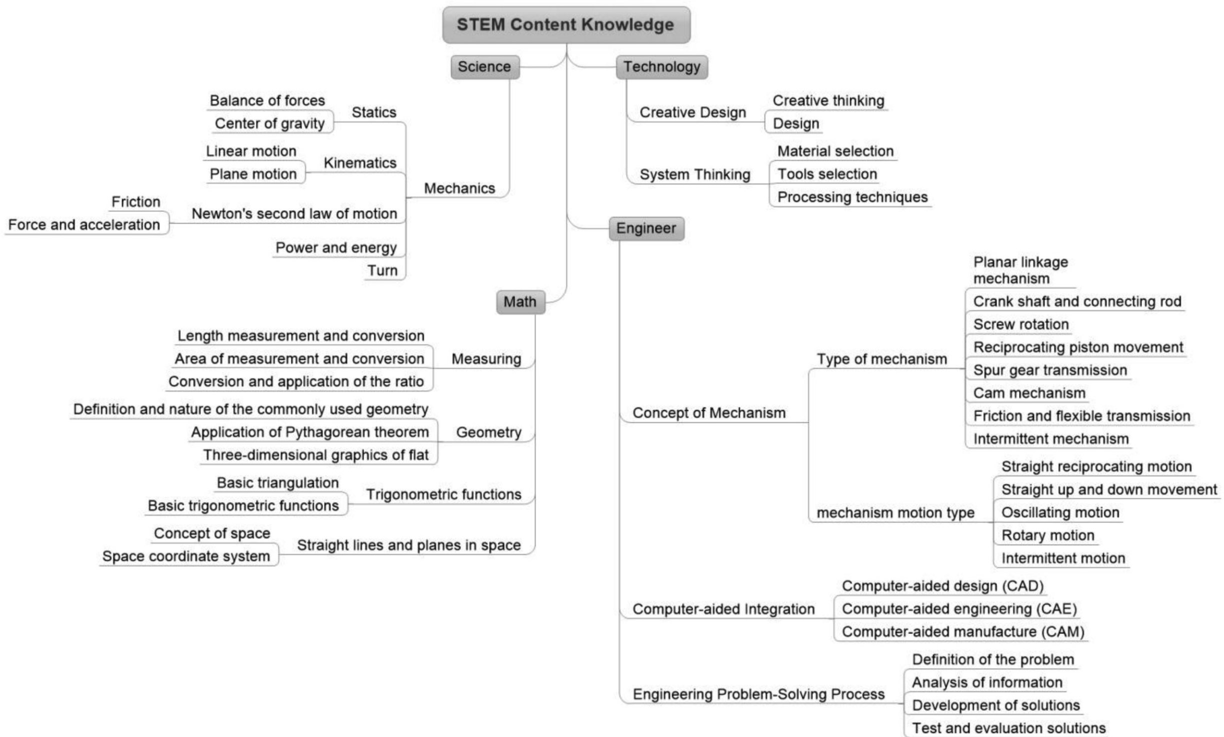
2. Development of the STEM engineering module

We developed a STEMEM that served as a mechanism to explore whether STEM knowledge supports the construction of engineering design skills. The STEMEM focused on an engineering topic that was aligned with Taiwan's Technology Curriculum Content Standards. It helps high school students learn concepts from each of the four STEM disciplines and apply their knowledge to the design, construction, evaluation, and redesign of technological solutions. Two experts with more than 10 years of teaching experience in the field of technology education ensured the content validity of the STEMEM.

The design project for the STEMEM was to create a toy with a multifunctional mechanical structure. The creation of the toy was not only viewed as a culminating experience, in which students attempted to apply STEM knowledge, but also as a design experience. The content knowledge needed to complete the design project was predefined, which required the integration of STEM, as shown in Table 1.

The STEMEM included lesson plans, classroom-based and computer-based learning activities, assessment, and materials. The students were provided with a design brief that introduced the problem, specified any design constraints or limitations to the problem solution, and explained how the students' solutions would be evaluated. This design brief included details about how technology, science, and mathematics concepts are interrelated. The STEMEM was divided into three stages: design, analysis, and manufacturing. The design stage used computer-aided design to create a three-dimensional (3D) model of the toy (Fig. 2); the analysis stage included analyzing the mechanical structure with mathematical and scientific principles to make decisions (Fig. 3); finally, the manufacturing stage entailed selecting appropriate tools and materials to complete the toy design (Fig. 4).

Table 1. The STEM content knowledge



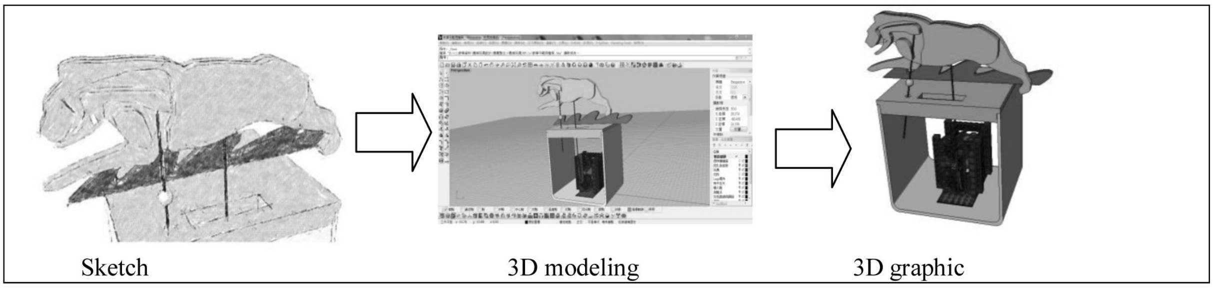


Fig. 2. Using CAD to design a 3D model.

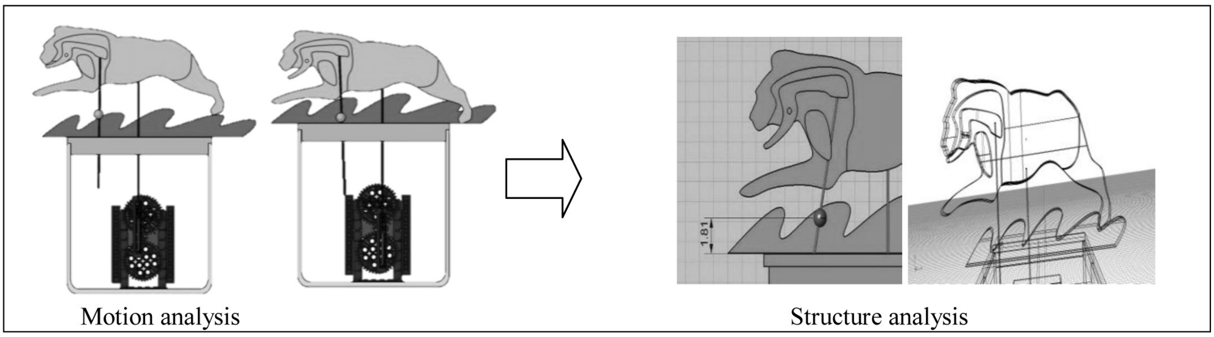


Fig. 3. Analysis of the mechanical structure.

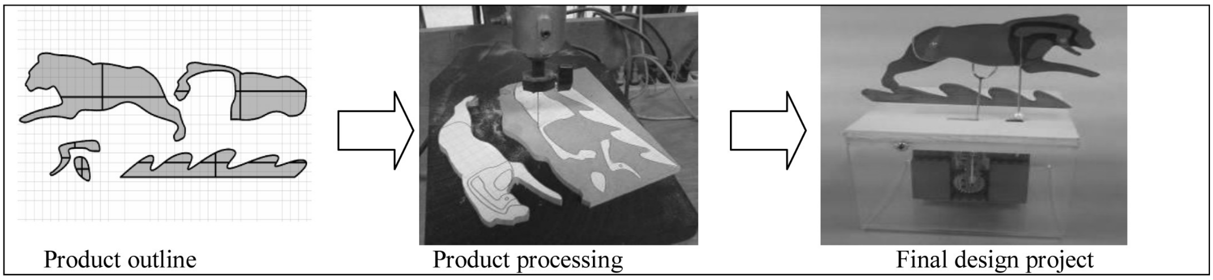


Fig. 4. Manufacturing process.

An important component of the STEMEM was computer simulation in the analysis stage. Simulation in educational settings is a widely employed technique to teach certain types of complex concepts [22]. Computer simulation enables students to enter values for a system of variables relevant to their engineering design. For this reason, it and has features in common with STEM because it emphasizes engineering design processes and the implementation of science knowledge and mathematical analysis. Selected snapshots of the simulation page are shown in Fig. 5. This figure also indicates possible student test choices, including structure, function, and material type.

3. Methods

3.1 *Setting and participants*

The study was conducted in three tenth-grade technology classes with a total sample group of 103 students. One teacher taught all the participants at a public high school in Taipei during the 2011–2012 school year. The high school served approximately 2400 students in grades 10–12. The school was chosen because teachers had greater flexibility in curriculum construction compared with most public schools in the area. The participating teacher had a master's degree in technology education and 10 years of experience, and was certified to teach technology education at the secondary level. Although this was the first time the teacher had taught the STEMEM unit, he had taught a mechanical structures unit during the previous school year. Otherwise, he had no former experience using any STEM-based curriculum.

3.2 *Procedure*

In the preparation of the toy design, students completed a semester of lectures and hands-on training in both engineering and metal fabrication

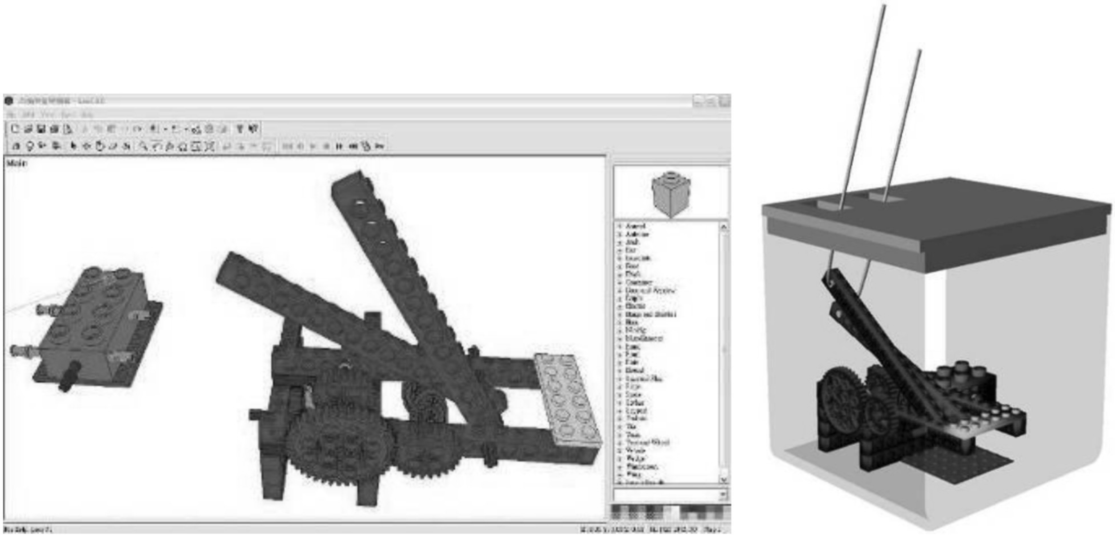


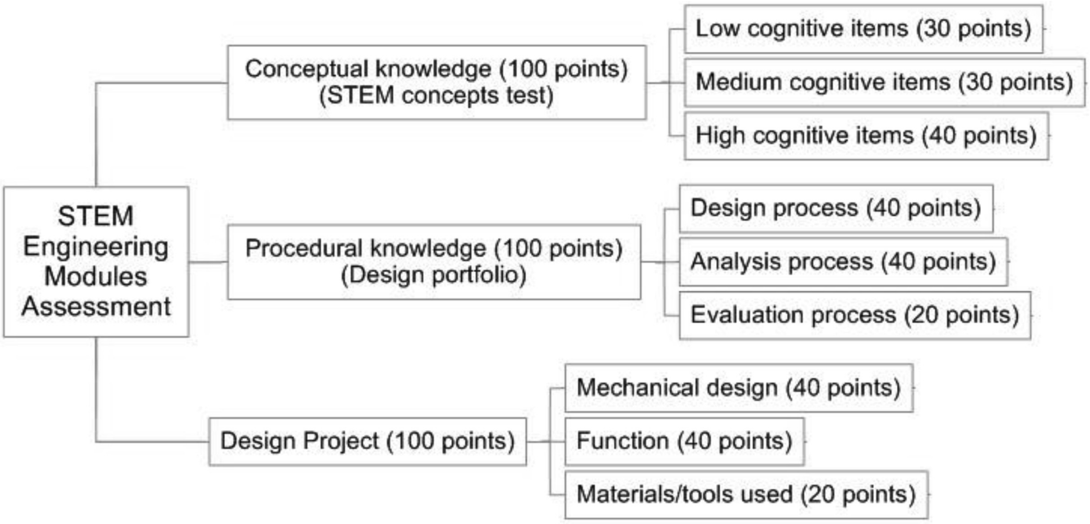
Fig. 5. Mechanical simulation and design.

processes. Concepts taught included motion, magnetism, making an electric motor with Lego, power, forces, electricity, and air pressure, as well as woodwork, welding, machining, the use of mechanical fasteners, cutting, and bending metals. As Lewis [1] argued, science and mathematics should be taught to help students to make design predictions through the process of design. Lectures helped students understand how to use science to elucidate phenomena, and to use mathematics to model and describe them. They also learned to use engineering design for practical purposes. Participants were asked to complete the STEMEM following the sequence of design stage, analysis stage, and manufacturing stage. In the manufacturing stage, the students were provided with Lego parts and materials, such as wood, metal, plastic, and other available resources in the technology classroom.

3.3 *Student assessments*

Three students' learning assessments, including their STEM concepts test, design portfolio, and toy design, were collected. Table 2 presents the structure of the students' learning assessment. The students' understandings of STEM concepts were tested after completion of the toy design. The test was based on STEM concepts taught in class. The test included multiple-choice and open-ended questions that assessed various levels of comprehension using low, medium, and high cognitive items. Multiple-choice questions were low cognitive items (i.e., knowledge and the comprehension levels of

Table 2. Structure of the student's learning assessments



Bloom's taxonomy) and medium demand items (i.e., application and analysis levels of Bloom's taxonomy); the open-ended questions were all high demand items (i.e., synthesis and evaluation levels of Bloom's taxonomy). The STEM concept test was used to assess the students' understanding of their own conceptual knowledge.

In addition, student learning was evaluated through an examination of each student's engineering design process. Participants were required to complete a design portfolio describing their use of design, analysis, and evaluation during the creation of the toy. Each portfolio was assessed and scored by the participating teacher using a 100-point rubric for ten items generated by the research team. A rubric can define the criteria for assessment and the qualities to be assessed, and is frequently used as a key element in assessment plans for technology education with an engineering design focus [23]. The assessment items in this rubric included four items in the design process, four items in the analysis process, and two items in the evaluation process; the last examined student performances in terms of procedural knowledge.

Finally, the students' design project (toy design) was assessed for mechanical design, function, and materials/tools used. The data collected and used in this study support the idea that the application and integration of STEM knowledge allows students to better reflect on their design. Students have the opportunity to analyze, evaluate, and predict while applying knowledge concepts to their project.

4. Findings

4.1 Descriptive statistics of student conceptual knowledge, procedural knowledge, and design projects

As presented in Table 3, skewness and kurtosis values demonstrate few extreme scores for each item. Overall, students' conceptual knowledge performance was acceptable (*M* = 61.09), demonstrating good performance for medium (MCI), and low (LCI) cognitive items, whereas performance of high cognitive items (HCI) was poor. Procedural knowledge performance (*M* = 54.33) indicated the need for further improvement, specifically in analysis and evaluation processes, both of which presented low scores. In addition, performance for design project achieved was good (*M* = 72.82).

4.2 The relationship between design project, and conceptual and procedural knowledge

To determine the relationship between design projects and conceptual and procedural knowledge, this study conducted a correlation analysis on scores attained for conceptual knowledge, procedural knowledge, and the design project. As presented in Table 4, the correlation between design project and conceptual knowledge (r = 0.26, p = 0.009), and the correlation between design project

Table 3. Descriptive statistics of the study variables (N =103)

Items	M	SD	Skewness	Kurtosis
Conceptual knowledge	61.09	12.66	–0.31	0.55
LCI (30 points)	20.45	5.21	–0.35	–0.38
MCI (30 points)	25.34	6.54	–1.31	1.46
HCI (40 points)	15.30	8.22	0.24	–0.58
Procedural knowledge	54.33	24.85	0.36	–1.08
Design process (40 points)	26.33	11.35	–0.53	–0.51
Analysis process (40 points)	18.56	13.36	0.66	–1.34
Evaluation process (20 points)	9.44	6.08	0.73	–0.98
Design project	72.82	15.60	0.05	–0.91
Mechanical design (40 points)	27.57	7.41	0.42	–0.73
Function (40 points)	30.91	6.82	0.07	–1.23
Materials/tools used (20 points)	14.33	3.98	–0.23	–0.46

Table 4. Correlations between students' conceptual knowledge, procedural knowledge, and the design project

Items	1	2	3	4	5	6	7	8	9
1. Conceptual knowledge	–	0.47**	0.64**	0.73**	0.12	0.04	0.12	0.14	0.26**
2. LCI		–	0.08	0.02	0.12	0.14	0.07	0.05	0.11
3. MCI			–	0.14	0.02	–0.12	0.12	0.05	0.05
4. HCI				–	0.09	0.07	0.05	0.15	0.29**
5. Procedural knowledge					–	0.71**	0.89**	0.79**	0.53**
6. Design process						–	0.36**	0.25**	0.14
7. Analysis process							–	0.80**	0.57**
8. Evaluation process								–	0.64**
9. Design project									–

**p < 0.01 (two-tailed).

and procedural knowledge ($r = 0.53$, $p = 0.00$) were significant. A further examination of sub-items showed that the correlation between design project and student performance in the HCI of conceptual knowledge was significant ($r = 0.29$, $p = 0.00$). The correlation between design project and the analysis and evaluation processes for procedural knowledge was also significant ($r = 0.57$, $p = 0.00$; $r = 0.64$, $p = 0.00$). Overall, this statistical analysis indicates that crucial issues (i.e., whether students possessed HCI knowledge) and crucial factors (i.e., analysis and evaluation performance) can influence a student's design project performance.

To ascertain the importance of HCI knowledge to the design project, students were divided into groups according to design project performance: (1) the high project performance group (HPPG) consisted of the top 27% of students according to their scores; (2) the low project performance group (LPPG) consisted of the bottom 27% of students according to their scores; and (3) the middle project performance group (MPPG) comprised the remaining 46% of students. Subsequently, a single-factor analysis of variance (ANOVA) was performed to determine differences between the student performance groups in terms of conceptual and procedural knowledge. Results of the ANOVA analysis (see Table 5) indicated that HPPG student performance of LCI and MCI items was superior to that of MPPG and LPPG students, but was not significant. However, HPPG students' HCI performance was significantly higher than that of LPPG students ($F(2,100) = 3.40$, $p < 0.05$), suggesting that HCI significantly influenced design project performance. When a detailed analysis was conducted on procedural knowledge performance, the results showed that the performance of the HPPG students in the analysis ($F(2,100) = 34.85$, $p < 0.01$) and evaluation ($F(2,100) = 59.03$, $p < 0.01$) processes was superior to that of the MPPG and LPPG students, achieving significance. In other words, students with superior performances in the design project performed better in the analysis and evaluation processes, thereby demonstrating significant differences between the HPPG students and the MPPG and LPPG students.

4.3 Factors that influence high school students' design projects

This study used a regression model to analyze the explanatory power of each independent variable and to elucidate factors that influence design project performance. The findings indicated that the six independent variables measured (LCI, MCI, HCI, design process, analysis process, and evaluation process) accounted for 69% of the variation observed in design project performance (see Table 6). Additionally, results of the model testing indicated that the regression effect was statistically significant ($F(6, 96) = 14.29$, $p = 0.00$; see Table 7).

A post hoc test was subsequently performed on each independent variable. The coefficient estimation (see Table 8) showed that the evaluation process had the best explanatory power (β-value = 0.43), which suggests that better performance in the evaluation process will equate to better performance in the design project. Furthermore, HCI ranked second in explanatory power (β-value = 0.23), demonstrating that better performance by high school students in HCI resulted in superior design project performance. Based on the results of the t-test, although the analysis process achieved a high β-value (0.24), it was not statistically signifi-

Table 5. Results of the ANOVA analysis regarding the conceptual and procedural knowledge of the students with differing project performance groups

	LPPG ($N = 28$)		**MPPG ($N = 47$)**		HPPG ($N = 28$)				
Items	***M***	***SD***	***M***	***SD***	***M***	***SD***	***F***	η^2	**Scheffe**
Conceptual knowledge	57.64	11.20	60.38	14.60	65.71	9.04	3.10*	0.06	c>a
LCI	19.93	5.90	20.43	4.95	21.00	5.03	0.29	0.01	
MCI	25.00	6.38	24.89	7.19	26.43	5.59	0.53	0.10	
HCI	12.71	7.39	15.06	8.39	18.29	8.03	3.40*	0.06	c>a
Procedural knowledge	34.57	10.62	53.53	19.85	75.43	26.08	29.63**	0.37	b>a, c>a, c>b
Design process	21.71	9.46	28.09	11.17	28.00	12.41	3.33*	0.06	b>a
Analysis process	8.29	1.51	17.19	11.67	31.14	12.76	34.85**	0.41	b>a, c>a, c>b
Evaluation process	4.57	1.79	8.26	4.04	16.29	5.75	59.03**	0.54	b>a, c>a, c>b

Note 1: $*p < 0.05$; $**p < 0.01$.
Note 2: a represents LPPG, b represents MPPG, and c represents HPPG.

Table 6. Summary of simultaneous regression analysis

Model	***R***	***R* square**	**Adjusted *R* square**	**Std. error of the estimate**	**Durbin-Watson**
1	0.69	0.47	0.44	11.68	1.40

Table 7. Summary of regression ANOVA

Model	Sum of squares	Degree of freedom	Mean square	*F*
1 Regression	11705.24	6	1950.87	14.29**
Residual Error	13106.25	96	136.52	
Total	24811.50			

Note. $^{**}p < 0.01$.

Table 8. Summary of regression coefficients

	Unstandardized coefficients		Standardized coefficients		Collinearity statistics	
Model	***B***	***SE***	β	***t***	**Tolerance**	**VIF**
1(Constant)	51.99	7.00		7.43*		
LCI	0.23	0.23	0.08	1.02	0.97	1.03
MCI	–0.13	0.19	–0.05	–0.69	0.91	1.10
HCI	0.44	0.15	0.23	3.00*	0.94	1.07
Design process	–0.11	0.11	–0.08	–0.97	–0.33	0.11
Analysis process	0.28	0.16	0.24	1.78	–0.03	0.59
Evaluation process	1.11	0.33	0.43	3.37*	0.46	1.76

Note. $^{*}p < 0.05$.

cant ($t = 1.78, p = 0.08$, n.s.), which could have been the result of a collinearity problem among analysis outcomes that introduced bias into the parameter estimations.

5. Discussion and conclusions

This study developed a STEMEM to examine how high school students applied conceptual and procedural knowledge when undertaking an engineering design project. The results showed that engineering design success depends on a student's high cognitive conceptual knowledge (i.e., his/her ability to synthesize and evaluate) and process ability to analyze and evaluate during the project. Responses received from students during the project regarding the HCI indicated that students neglected or could not comprehensively express conceptual knowledge of the following: mechanical fixation methods (i.e., the design of frame), motor and mechanism linkage methods (i.e., power transmission, and the linkage and relative position arrangements among different mechanisms (i.e., spatial arrangement or configuration). In addition, based on the overall performance of the design portfolio and toy design, the challenges that students commonly encountered included the following: transmission of speed or velocity between the motor and mechanisms, the control of the direction and angle of the toy's movement, fixation of the frame, relative positions of power and mechanisms, relative position of mechanisms and toys, and the fine adjustments of interference between the mechanisms. These problems primarily require students to apply substantial conceptual/procedural knowledge, relevant mathematics and scientific concepts, and spatial and sketching skills.

5.1 The roles of conceptual and procedural knowledge in engineering design

The results of this study indicated that students' conceptual knowledge and procedural knowledge were reflected in their design projects. HPPG students had better performances than MPPG and LPPG students in HCI, the analysis process, and evaluation process. Furthermore, these three variables, in contrast to the other variables, had higher and significant correlations with design project performance, indicating that students with better performances in high cognitive conceptual knowledge, analysis, and evaluation processes produce superior design project performances. However, the present study also found that student performance in solving engineering problems was also affected by the level or extent of their learning experiences. In addition to cultivating students' conceptual knowledge, they should be given concrete and mandatory guidance and much practice (i.e., discussions, sketching, recording problems, and data analyses) during a process of recurrent exploration and model development testing as presented in the APU model. This will enable them to establish engineering-related procedural and logical thinking abilities based on concrete operational experiences, which in turn further facilitates the integration of relevant conceptual knowledge into the design.

Based on Piaget's theory of cognitive development, although high school students have entered the formal operational stage, they should be able to apply symbols and words related to abstract concepts, for problem processing and to perform abstract thinking, reasoning, and judgment without requiring dependency on actual operations [24]. However, numerous studies have indicated that high school students do not typically apply their knowledge, as Piaget proposed, as the formal operational method in thinking processes [25]. Students may adopt the formal operational thinking process in a certain field with which they are familiar, but employ the concrete operational thinking process in unfamiliar fields. In other words, students are typically able to think using the formal operational method for topics that they are familiar with, whereas the thinking process for topics they are less acquainted with becomes substantially more concrete [26].

This theory is further reflected in the results of studies related to engineering education. An individual's problem solving, designing, and manufacturing abilities do not develop inherently with age, but rather, with nurture and the accumulation of appropriate instruction and experience [27, 28]. Consequently, although many students can select precise types of mechanisms and propose feasible combinations during toy design, the perceptions they propose remain stationary at the first phase of the APU model, i.e., as a hazy impression. In addition, without adequate knowledge and experience, students cannot adopt the formal operational method necessary for detailing and processing mechanical designs, and to engage in procedural thinking.

5.2 The roles of science and mathematics in engineering design

When compared with MPPG and LPPG students, HPPG students were more willing to independently design a unique and complex mechanism instead of employing or following the simple demonstrations provided by teachers. More specifically, the HPPG students adopted perspectives from mathematics and scientific principles to comprehensively identify problems when mechanisms did not operate properly, and to determine possible solutions (e.g., adjust the gear ratio to change rotating speed, conduct fine adjustments on relative positions of each part, or adjust the extent of the up and down movement of the rocker arm). Not surprisingly, we found that the MPPG and LPPG students still preferred a trial-and-error process, which they usually used in the technology education classroom. In technology education, students usually perform their design without using mathematical prediction analysis. This is why many studies often question whether students can solve an ill-defined problem without learning a systematic problem-solving method through the application of the engineering design process [29].

In instances of a lack of detailed planning and design, LPPG students encountering problems could only propose indefinite or vague ideas for improvements, and identify viable solutions using a repetitive and unsystematic trial-and-error method. In addition, when they could not solve problems using science and mathematics knowledge, they disregarded their initial design ideas and adopted simpler mechanical designs. According to Zuga [30], cognitive processes are useless without the content knowledge upon which to operate. Specifically, when students are able to practically apply their science and mathematics knowledge, they are able to explicitly pursue their initial design ideas and solve problems encountered during the process. In other words, when these students perceived exactly how they wanted their toys to work, they were able to create mechanical designs and make corrections according to their preferred methods. In contrast, when students could not apply science and mathematics knowledge in a practical process, they lost confidence in their own design and doubted whether they could make the product successfully.

In general, during the initial stage of design planning, students, whether HPPG or LPPG, could not account for, or predict, problems that they might encounter in the manufacturing stage. This means that students could not think expansively regarding problem-related issues beforehand, but could only identify various minor problems in design after manufacturing. This required them to constantly adjust their original designs. Thus, a student's ability to apply science and mathematics in analysis and evaluation processes is the key factor influencing the success of the final design.

5.3 The roles of spatial and sketching skills in engineering design

This study also found that student application of conceptual and procedural knowledge during the engineering design process was affected by a student's spatial and sketching skills. Spatial skill refers to pictorial and operational thinking abilities [24]. During the mechanical design process, students may be limited in answering the questions presented in the HCI, or in performing the analysis and evaluation processes, due to their lack of spatial ability. This can hinder their ability to provide concrete or detailed responses (e.g., difficulty using illustrations and words to clearly describe the relative positions between mechanisms). According to Wai et al. [31], the spatial skill of students is a crucial factor that influences their learning performances within STEM domains. In addition, as observed by Welch et al. [32], novice design students, regardless of whether they were taught sketching skills, preferred creating a physical model when designing rather than sketching. The present study found that students were often restricted by a lack of relevant sketching skills, rendering them unable to demonstrate formulated solutions through design sketches. However, students could employ additional communication skills to mitigate their inability to produce sketches, subsequently presenting their ideas through solid or 3D modeling. This may explain why some students in this study achieved an acceptable level of performance in toy design, despite their poor performance in the conceptual knowledge test and design portfolio.

5.4 Conclusions

The major finding of this study is that successful engineering design depends on students' STEM conceptual knowledge, especially at the synthesis and evaluation levels, as well as their process ability to perform analysis and evaluation during the project design phase. This supports the findings of several previous studies reporting that conceptual and procedural knowledge are mutually supportive in the engineering design. Therefore, to facilitate better high school engineering instruction, three recommendations are made.

First, multiple approaches should be employed when teaching STEM and engineering design to develop students' application of STEM conceptual knowledge and process abilities, and to facilitate in-depth understanding of the process of engineering design. The purpose of high school education is not only to cultivate students as engineers, but also to help students of varying abilities and learning aptitudes accomplish an engineering design project. This is an issue that must be examined in detail when promoting engineering education.

Second, this study found that most students still preferred using the trial-and-error method to search for feasible solutions, thus neglecting how mathematical concepts can be applied in problem solving. Although this may originate from students' lack of knowledge in engineering design and mechanics, trial-and-error is the most practised and intuitive method of solving problems. Mativo et al. [33] asserted that during short or brief learning activities, outcomes obtained from processes of trial-and-error could be substantially superior to those obtained by solving engineering problems. However, teachers need to guide students from using unsystematic trial-and-error approaches to making significant attempts based on scientific and mathematical knowledge, which can lead students to develop their abilities in mathematical analysis and system thinking.

Third, this study found that students were often limited by a lack of relevant spatial and sketching skills. Teachers need to foster those skills so students can demonstrate their formulated solutions through design sketches.

In summary, students' cognitive developmental progress, practical experiences, spatial concepts, logical thinking abilities, and even sketching skills, may all be crucial factors influencing their overall engineering design ability. The relationships among these factors are focus areas worthy of in-depth investigations in future studies.

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