OPEN ACCESS
EURASIA Journal of Mathematics Science and Technology Education
ISSN: 1305-8223 (online) 1305-8215 (print)
2017 13(7):2941-2958
DOI 10.12973/eurasia.2017.00729a

Developing a Pre-engineering Curriculum for 3D Printing Skills for High School Technology Education

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Received 16 October 2016 ▪ Revised 7 December 2016 ▪ Accepted 8 December 2016

ABSTRACT

This study developed an integrated-STEM CO_2 dragster design course using 3D printing technology. After developing a pre-engineering curriculum, we conducted a teaching experiment to assess students' differences in creativity, race forecast accuracy, and learning performance. We compared student performance in both 3D printing and manual creation of dragsters. One hundred and eighty-two participants in five classes of Grade 10 participated in this study. The results of the teaching experiment showed that students who used a 3D printer significantly outperformed those students who made their dragsters by hand in terms of both the novelty and sophistication of their dragsters. The students in the 3D printing group were able to forecast the outcomes of the race significantly more accurately than those in the group who made theirs by hand were. No significant difference in learning performance was found in the two groups. Based on these experimental results, the development of the curriculum and hands-on activities and the teaching recommendations were revised. This research has an impact on offering an effective approach to the design and implementation of digital manufacturing and pre-engineering curricula in the future.

Keywords: 3D printing technology, dragster, engineering education, technology education

INTRODUCTION

Amidst fierce global competition, technological innovation is a method of maintaining national competitiveness. National economic growth is driven by enhancements to technological competency. Therefore, to promote national competitiveness and economic growth, engineering and technology education must be valued (Hernandez et al., 2014). In recent years, Taiwan's Ministry of Education has encouraged universities to launch departments focusing on new applications of technology. The subject matter dealt with by these departments is unfamiliar, even confusing, to high school students. In response, Taiwan's Ministry of Education has been redesigning high school curricula to include the applications of technology. We were commissioned to develop a pre-engineering curriculum for high school students by combining integrated science, technology, engineering, and

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State of the literature

- To foster engineering and technology professionals and enhance national competitiveness, many countries are investigating means to combine integrated STEM teaching with pre-engineering curricula. This can help increase students' willingness to choose these subjects.
- With the expiration of 3D printing patents, the popularity of such equipment is increasing in manufacturing, education, and other fields.
- Using 3D printing technology to develop a pre-engineering curriculum is a crucial step in technology curriculum development. However, there is a lack of studies in this area.

Contribution of this paper to the literature

- Introduced a 3D printing integrated-STEM pre-engineering curriculum verified through a teaching experiment.
- Compared the difference between a digital manufacturing course and a course involving handmade goods.
- Proposed a model for the design and development of future pre-engineering curricula using digital manufacturing.

mathematics (STEM) teaching with novel technology applications. This curriculum is intended to serve as a model for in-service teachers to use when developing their own curricula.

Technology education will largely focus on engineering implications, STEM integration, electromechanical integration, and investigating engineering and technology issues. Taiwan's high school students will be taught relevant courses. High schools will also organize engineering design activities and teach in a way that integrates interdisciplinary knowledge. This will foster students' high-level cognitive abilities, such as design, innovation, and critical thinking (National Academy for Educational Research, 2016).

To develop integrated STEM teaching and curricula, STEM knowledge should first be explored separately. Hands-on activities can be organized to integrate the knowledge, and engineering design procedures and handouts can be used to foster core competencies (Hernandez et al., 2014; Fan & Yu, 2015; Nam, Lee, & Paik, 2016). In the past, math and science education focused on imparting abstract theories rather than practical applications (Corum & Garofalo, 2015). Integrated STEM education can help students form associations between theory and reality. Moreover, course content that assists students in forming associations with their future career content motivates students to learn (Kwon, 2016) and facilitates the integration of STEM subjects.

In terms of new technologies, the prices of 3D printers are gradually declining due to patent expirations. They do not require a mold and designs can be produced rapidly, making them a perfect tool for realizing innovative ideas (Lipson & Kurman, 2013; Snyder et al., 2014). Taiwan's Executive Yuan vigorously supports the 3D printing industry and collaborates with the Ministry of Education to form policies that incorporate new technologies into STEM-oriented curricula in high schools. 3D printers have been listed as a priority item for subsidization in high schools (Executive Yuan, 2014). Against this background, we were commissioned to develop a STEM-oriented pre-engineering curriculum to serve as a model for the 2018 high school technology curriculum. The proposed curriculum adopts 3D printing technology and 3D digital modeling as tools to assist students in self-exploration and self-learning, ultimately fostering technology professionals who meet the national development standards.

Engineering-oriented technology education

In the United States, over 50% of high schools offer prerequisite college courses. In the prerequisite framework, pre-engineering education is a pathway to engineering. This pathway is the gateway to technology in middle school (Moye, Dugger, & Starkweather, 2012). An important aspect of technology education in the United States is the inclusion of project-oriented activities in pre-engineering education. This enables students to connect with the technology and engineering domains, which they are likely to encounter throughout their careers. It also helps them to understand the associations between technology and other subjects, thereby enhancing their interest in STEM (New Hampshire Department of Education, 2008).

Engineering design is an important integral element of technology education (Kelley & Kellam, 2009). Engineering design is a complex decision-making and problem-solving process where STEM-related knowledge is applied to solve ill-structured problems. During the engineering design process, higher-order thinking abilities are indispensable for analyzing problems, predicting the feasibility of different solutions, evaluating results, and optimizing the solution. In brief, through the teaching of engineering design, technology education seeks to develop problem-solving capabilities and STEM literacy (International Technology Education Association, 2000).

The range of departments at Taiwan’s universities is diversifying. Therefore, it is imperative to guide high school students using exploratory curricula so that they understand the subjects offered for further study. In Taiwan, engineering and technology education is offered mainly at university, and only rarely in high schools. By contrast, high schools in the United States have long offered integrated STEM courses that focus on incorporating interdisciplinary integration and learning into real-world settings. These courses emphasize experience integration, self-exploration of knowledge, discovery, reflection, and student-centered learning behaviors (Lin, Lee, Chang, & Tsai, 2009). Therefore, it is important for us to develop engineering-oriented STEM teaching activities. We must explore the feasibility of such activities, and provide models on which teachers can base relevant curricula.

Engineering education and digital manufacturing

Students often experience difficulty in understanding abstract scientific concepts. This impedes their learning performance (Corum & Garofalo, 2015). For example, abstract concepts such as force and movement are difficult to observe directly. We can help students to learn these concepts by using visualizations (Verner & Merksamer, 2015). The educational value of 3D printing and digital modeling stems from the fact that it helps students to visualize dynamic virtual objects and produce visible and tangible models. This enables the students to perceive and experience multiple abstract concepts (Lipson & Kurman, 2013).

The popularization of 3D printers contributes to the reform and innovation of future industrial and manufacturing industries. It has gradually become simpler to operate consumer 3D printers. The development of 3D digital modeling applications has enabled these technologies to be incorporated into education by the development of hands-on courses that help students to combine theories and concepts concerning design, output, and revision rapidly (Eisenberg, 2013). With the advantages and features of 3D printing technologies, students are no longer required to rely solely on their imagination when learning scientific concepts. They are now able to engage in peer discussions and exploration during the printing process, thereby learning actively. It is easy to realize ideas for new products using 3D printing technologies. As the machines are now simple to use, the students can focus on creative endeavors.

CO_2 dragster design

Carbon dioxide (CO_2) dragsters are miniature racing cars that are propelled by a CO_2 cartridge. They are pierced to begin the release of the gas, and can typically race over a distance of 20 meters. Two hooks (eyelets or screw eyes) are fixed to the bottom of the car. These are linked to a string (usually a monofilament fishing line) to prevent the car from losing control during launch.

CO_2 dragsters are used in engineering curricula around the world, including in Australia, Europe, England, and the United States. The dragster is frequently used to demonstrate mechanical principles such as mass, force, acceleration, and aerodynamics. These scientific concepts influence the performance of the dragsters. Building a dragster is an engineering-oriented activity that allows students to take scientific concepts into account while participating in an engineering design process. The dragster is often built from pre-purchased balsa wood blanks, wheels, and axles.

3D printers can be used to create complex, multi-curved prototypes without the need for specialized printing procedures or pre-purchased materials. These features greatly reduce manufacturing requirements, reduce time and labor expenses, promote product innovation, and reduce development cycles (Lipson & Kurman, 2013). Using 3D printers in hands-on activities involving CO_2 dragsters can eliminate manufacturing-related limitations from the designs of prototypes. Moreover, a physical model provides students with a visible and tangible object to aid observation and learning.

The most attractive aspects of CO_2 dragster design activities for students are the fun of speed racing and the creation of beautiful, fast-moving cars. Such design activities are not currently available in Taiwan's high school curricula. In this study, we aimed to develop an

Table 1. Detailed contents of the 3D Printing and Handmade courses

Week	Content	Engineering design	3D Printing group	Handmade group
01	Knowledge review – Principles of CO_2 dragster operation	--	(1) Show videos of CO_2 dragster races. (2) Explain course content and teaching objectives. (3) Explain the scientific principles of CO_2 dragsters.	
02-03	Knowledge review – Teaching material package of the CO_2 dragster	--	(1) Use modular material package to help students gain a preliminary understanding of CO_2 dragsters. (2) Students designed the dragster and used additional materials to achieve a car weight exceeding 120 g. They also compared each other's dragster designs.	
04	Knowledge review – Racing and curriculum reflection	Confirm requirements	(1) Race and record results. (2) Discuss the commonalities of outstanding work. (3) Establish associations between design principles and speed. (4) Introduce 3D printing. (5) Show 3D-printed CO_2 dragsters. (6) Explain course and evaluation criteria and divide students into groups of 3 or 4.	(1) Race and record results. (2) Discuss the commonalities of outstanding work. (3) Establish associations between design principles and speed. (4) Introduce modeling using polyurethane blocks. (5) Show handmade CO_2 dragsters. (6) Explain course and evaluation criteria and divide students into groups of 3 or 4.
05	Knowledge imparting – Defining problems (wind resistance, weight, friction, etc.)	Define problems Gather information Generate ideas	(1) Discuss design concepts. (2) Teach 123D Design (including three-view drawings). (3) Students paste their design concepts onto handouts. (4) Students illustrate a draft of their design concept.	(1) Discuss design concepts. (2) Teach manual illustration of three-view drawings. (3) Students paste their design concepts onto handout. (4) Students illustrate a draft of their design concept.
06	Design & 3D modeling – Analyzing conditions and three-view drawings	Establish 3D model Analyze feasibility	(1) Review 3D modeling applications. (2) Convert design concept drafts into 3D models. (3) Teachers and students discuss feasibility of design.	(1) Demonstrate the application of three-view drawings in the processing of polyurethane blocks. (2) Teach the operation of machinery and hand tools. (3) Teachers and students discuss feasibility of design.
07	Evaluation – Selecting the best design from each group	Evaluate Decide Communicate	(1) Complete 3D modeling, and then evaluate and revise the designs. (2) Students engage in group discussions and nominate the best 3D-printed design.	(1) Complete handmade polyurethane models, and then evaluate and revise the models. (2) Students engage in group discussions and nominate the best model.
08	Testing – Racing, reviewing, and curriculum reflection & feedback	Decide Communicate Realize	(1) Race and record performance. (2) Discuss the commonalities of outstanding work. (3) Exhibit special designs. (4) Engage in curriculum reflection and feedback. (5) Interview students.	

NOTE: Underlined items are activities that differ between the two courses.

engineering-oriented CO_2 dragster activity that encourages students to apply engineering design procedures and STEM knowledge. The activity involves contest and reward systems that demonstrate the applicability of 3D printing technologies to teachers, schools, and relevant educational institutions, thus promoting the use of 3D printing in education.

METHODOLOGY

We developed a course to teach the design of CO_2 dragsters using 3D printers coupled with free 3D digital modeling software. This course serves as a project-oriented, hands-on curriculum for students to experience interdisciplinary engineering design within specific technology settings. The study is in two parts. First, we developed the course, which involves integrated STEM knowledge, execution of engineering design procedures, 3D digital modeling, and using 3D printers to create a hands-on CO_2 dragster. In the second part, we compare the performance of two hands-on CO_2 dragster courses, specifically, "Handmade" and "3D Printing," to determine the differences between students' product creativity, prediction accuracy, and learning efficiency.

Curriculum development and implementation

The engineering design procedure proposed by Atman et al. (2007) was adopted to develop the Handmade and 3D Printing teaching activities. Both teaching activities lasted eight weeks, with two 50-minute classes per week for a total of 800 minutes. The course content delivered to the Handmade and 3D Printing groups is shown in Table 1.

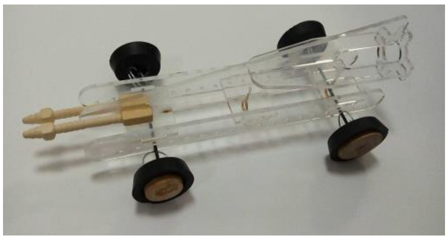
The courses were developed collaboratively with the authors and three in-service technology teachers. The planning of the course content involved preparing teaching materials, planning and forming lessons, preparing required materials, and arranging equipment and implementation procedures. The teaching steps for the Handmade and 3D Printing groups were:

1) Week One: Videos of 3D CO_2 dragster races were shown to students to stimulate their interest in the activity. The goals of the hands-on activities were disclosed and handouts were provided. The handouts were used to review the students' acquisition of knowledge in other subjects, such as the concepts of Newton's three laws of motion and pneumatics, and the definitions of additive manufacturing and engineering surveying.
2) Weeks Two and Three: Modular materials were given to help students gain a preliminary understanding of CO_2 dragster structures. Materials consisted of laser-cut cars equipped with 8-gram CO_2 cartridges for propulsion. Regulations state that cars must be over 120 grams in weight. Therefore, students were required to test different materials and design different car bodies to control the weight (Figure 1).
3) Week Four: Students participated in racing activities, reviewed their performance using the handouts, and provided feedback concerning the activities. In this week, the five classes were divided into two groups, namely, the 3D Printing group and the Handmade group. During the introduction to the subsequent four weeks of the course, both groups were shown actual examples of car bodies and were informed of the dimensions, limitations, and rules. The Handmade group would be constructing the dragsters manually using polyurethane blocks. Polyurethane blocks

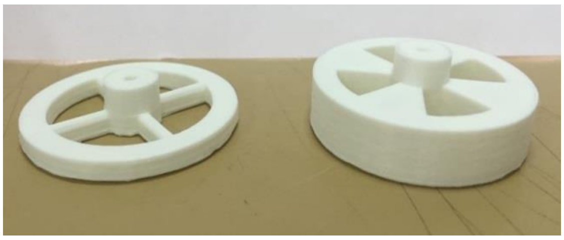
were used instead of balsa blocks because they are more affordable in Taiwan. Polyurethane blocks are also commonly used for model construction in university industrial design departments in Taiwan. They are readily available and easy to model.

4) Week Five: Students in the 3D Printing group were trained in modeling 3D objects and illustrating three-view drawings using the free 123D Design application. Students in the Handmade group practiced illustrating three-view drawings using a pen and block paper. Both groups were instructed to collect data and illustrate their design concepts on the handout.
5) Week Six: Students used the collected CO_2 dragster data and knowledge acquired in the STEM course to complete their CO_2 dragster designs. Students in the 3D Printing group used 123D Design to build their digital models. Students in the Handmade group used a variety of machinery, including a drill, band saw, grinder, and wire saw, to model CO_2 dragsters from 250 mm (L) × 70 mm (W) × 70 mm (H) polyurethane blocks.
6) Week Seven: Students in the 3D Printing group were divided into sub-groups. Each group nominated their best 3D Design and printed the selected model using Makerbot Replicator Fifth Generation using polylactide material. Students in the Handmade group completed the modeling of their dragster. The students were then divided into sub-groups. Each group nominated their best design to participate in the 20-meter race.
7) Week Eight: Students collaboratively assembled the dragsters. They then participated in a design presentation and a dragster race. Students reviewed their performance, provided feedback on the activity, and formulated a course summary on the handout. During the race, a Pitsco race system was used to record manual trigger times and dragster movement times.

Once the preliminary framework for the proposed course was complete, seven in-service technology teachers were invited to participate in a two-day (six hours per day) workshop to (a) learn about the course content, (b) physically construct laser-cut cars and design 3D-printed CO_2 dragsters, (c) participate in the dragster race, and (d) provide suggestions regarding the feasibility of the course plans and hands-on activities for students. The activities that these teachers participated in are shown in Figure 2. The teachers' feedback was used to revise the course and then conduct a teaching experiment. One of the suggestions was that handouts should be completed during the hands-on activities and that space should be reserved at the end of the handout for students to forecast race outcomes. Before the race, students forecasted race outcomes based on the knowledge they had acquired during the seven-week course. This enabled the researchers to determine whether the students truly understood the concepts and were able to apply their knowledge effectively.

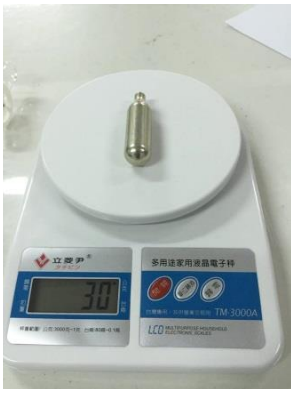


(a) Acrylic laser-cut CO_2 dragsters assembled with additional materials



(b) 3D-printed polylactide wheels

(c) 67g acrylic dragster body



(d) 30g CO_2 cartridge

(e) 5g iron wheel axle

Figure 1. Laser-cut CO_2 dragster materials

(a) Teachers assembling the laser-cut modular dragsters

(b) Two teachers' dragster competition

Figure 2. In-service technology teachers participating in the CO_2 dragster design workshop

Experiment

Participants

Five classes of 182 Grade 10 high school students (94 males and 88 females) that had no significant differences in their last average grades in life science and technology participated in the study. The mean grades and standard deviations for the five classes were 81.58 (8.32), 80.50 (8.98), 85.38 (5.20), 81.46 (8.06), and 79.64 (13.77). Several students had prior experience

(a) Teachers instructing students on 3D digital modeling

(b) Adhering the three-view drawing onto polyurethane blocks

(c) Students in the 3D Printing group collaborating to assemble their dragster

(d) Race forecast discussion

(e) The starting line of the race

(f) The finishing line of the race

Figure 3. Activities from the teaching experiment

with 3D printing and 3D modeling, but no students had prior experience of constructing CO_2 dragsters.

Experimental design and procedure

A quasi-experiment design was developed. Three classes with a total of 108 students were randomly selected to be in the 3D Printing group (57 males and 51 females), and two classes with 74 students were selected to be in the Handmade group (38 males and 36 females). The students' learning performance, creativity, and forecast accuracy were compared throughout the course. The activities conducted during the teaching experiment are shown in Figure 3. This experiment was coordinated by three in-service technology teachers. One teacher was responsible for teaching, another assisted with the hands-on activities and helped resolve students' problems, and the other served as a field observer and documented the activities.

The revised creative product semantic scale

A revised version of the Creative Product Semantic Scale (CPSS) developed by Besemer and Treffinger (1981) was adopted as a rubric to evaluate seven variables in three dimensions of the students' work (Chang, 2003). The three dimensions were *novelty*, *functionality*, and *sophistication*. In the novelty dimension, we assessed *form* (originality of the overall car form design), *material* (originality in the selection of materials), and *structure* (originality in the design of the car body and wheels). In the functionality dimension, we considered the *durability* (whether the car lost parts and sustained damage) and *usability* (whether the car could complete the task) of the students' work. These were evaluated based on the race outcomes. In the sophistication dimension, we evaluated *consistency* (whether the appearance of the car was consistent) and *attractiveness* (whether the overall appearance of the car was attractive). The seven variables were scored on a five-point Likert scale, with 1 being a low score and 5 being a high score. To validate the scale, three in-service technology teachers were invited to evaluate 36 creative handmade wooden stationery holders using the scale. The results of Kendall's W test (Kendall & Smith, 1939) indicated that the dimensions of novelty, functionality, and sophistication had significant reliabilities of 0.72, 0.85, and 0.76, respectively ($p < 0.01$).

Race forecasts

Before the race, which occurred in the eighth week of the course, all students were requested to draw on the STEM-related knowledge acquired in the previous seven weeks, group discussion outcomes, and their engineering design experience to forecast which CO_2 dragsters in each class would be the fastest. This process was used to evaluate students' performance in learning engineering concepts.

The race

Each race involved two dragsters. To make the races more fun, students could nominate the participating dragsters randomly. The dragsters were placed on the starting line and a member of each group was selected to trigger the CO_2 cartridge manually. The time required to trigger the CO_2 cartridges and the movement time of the dragsters were recorded. Thus, the race time was equal to the student's response time plus the travel time of the dragster.

The densities of polylactide and polyurethane differ. The 3D-printed dragsters were far heavier than those produced with polyurethane blocks, causing the 3D-printed dragsters to be slower than the handmade dragsters. Therefore, the races were only a course activity and the outcomes were not considered an indicator of the students' learning performance.

Learning performance

The students' learning performance was measured using a handout. This handout included questions concerning STEM knowledge, engineering drawing exercises, course activity, data collection content, design drafts, group discussion outcomes, forecast and analysis results, performance records, correction and improvement discussion outcomes, and reflections and feedback on the curriculum. Three in-service technology teachers were invited to evaluate the handouts and give each a score from 0 to 100. The mean scores obtained by the students represented their learning performance.

RESULTS

Score of the revised CPSS

The three teachers used the revised CPSS to score the creativity of the students' cars. The mean scores of the seven variables in three dimensions are shown in Table 2.

In terms of novelty, sophistication, and functionality, analysis of variance (ANOVA) results showed a significant difference between novelty ($F_{(1,180)}$ = 13.61, $p < 0.01$, $\eta_p^2 = 0.07$, f = 0.06)) and sophistication ($F_{(1,180)}$ = 21.25, $p < 0.01$, $\eta_p^2 = 0.11$, f = 0.08) between the 3D Printing group and the Handmade group. The mean scores for novelty (M = 3.00, *SD* = 0.55) and sophistication (M = 3.08, *SD* = 0.72) in the 3D Printing group were significantly higher than those for novelty (M = 2.70, *SD* = 0.52) and sophistication (M = 2.61, *SD* = 0.63) in the Handmade group. The mean scores for functionality did not differ significantly between the two groups ($F_{(1,180)}$ = 0.23, $p = 0.63$, $\eta_p^2 < 0.01$, f = 0.03).

ANOVA was then used to compare the two groups in terms of each of the seven finer-grained variables. There were significant differences between the two groups for form ($F_{(1,180)}$ = 18.59, $p < 0.01$, $\eta_p^2 = 0.09$, f = 0.33), structure ($F_{(1,180)}$ = 17.75, $p < 0.01$, $\eta_p^2 = 0.09$, f = 0.32), consistency ($F_{(1,180)}$ = 23.16, $p < 0.01$, $\eta_p^2 = 0.11$, f = 0.38), and attractiveness ($F_{(1,180)}$ = 5.00, p = 0.03, $\eta_p^2 = 0.03$, f = 0.17). The mean scores for form (M = 3.21, *SD* = 0.76), structure (M = 2.87, *SD* = 0.83), consistency (M = 3.29, *SD* = 1.10), and attractiveness (M = 2.87, *SD* = 0.85) in the 3D Printing group were significantly higher than those for form (M = 2.69, *SD* = 0.82), structure (M = 2.38, *SD* = 0.67), consistency (M = 2.62, *SD* = 0.58), and attractiveness (M = 2.59, *SD* = 0.79) in the Handmade group. There were no significant differences in the mean scores for material, durability, and usability between the two groups ($F_{(1,180)}$ = 1.53, $p = 0.22$, $\eta_p^2 < 0.01$, f = 0.10; $F_{(1,180)}$ = 0.38, $p = 0.54$, $\eta_p^2 < 0.01$, f = 0.05; $F_{(1,180)}$ = 0.01, $p = 0.91$, $\eta_p^2 < 0.01$, f < 0.01, respectively).

Table 2. Mean and standard deviation scores of the revised CPSS for the two different groups

Dimensions/Variables	3D Printing	Handmade
	M(SD)	M(SD)
Novelty	3.00(0.55)	2.70(0.52)
Material	2.91(0.56)	3.01(0.48)
Form	3.21(0.76)	2.69(0.82)
Structure	2.87(0.83)	2.38(0.67)
Functionality	4.02(0.55)	4.05(0.50)
Durability	3.55(0.75)	3.62(0.71)
Usability	4.50(0.50)	4.50(0.56)
Sophistication	3.08(0.72)	2.61(0.63)
Consistence	3.29(1.10)	2.62(0.58)
Attractiveness	2.87(0.85)	2.59(0.79)

Table 3. Race time means and standard deviations (ms) for both groups

Group/Class	Trigger response time	Dragster travel time	Overall time
	M(SD)	M(SD)	M(SD)
3D Printing	261 (214)	2109 (461)	2370 (535)
Handmade	193 (057)	1174 (128)	1367 (154)

Forecast accuracy analysis

ANOVA results show differences in the accuracy of the forecasts for second and third places between the two groups. The accuracy of the 3D Printing group (M = 67%, *SD* = 47%) was significantly higher than that of the Handmade group (M = 30%, *SD* = 46%) ($F_{(1,180)} = 27.33$, $p < 0.01$, $\eta_p^2 = 0.13$, f = 0.40). In terms of first-place forecasts, the 3D Printing group (M = 33%, *SD* = 47%) was also significantly more accurate than the Handmade group (M = 19%, *SD* = 39%) ($F_{(1.180)} = 4.65$, $p = 0.03$, $\eta_p^2 = 0.03$, f = 0.16).

Race outcomes

The race outcomes of the 3D Printing and Handmade groups are shown in Table 3. The manual trigger response times were similar for both groups ($F_{(1,58)} = 2.29$, $p = 0.14$, $\eta_p^2 = 0.04$, f = 0.22). In terms of travel times and overall times, the 3D-printed polylactide dragsters were heavier than the handmade dragsters. Therefore, the two groups could not be directly compared.

Learning performance

The mean score of the 3D Printing group (M = 86.56, *SD* = 5.20) was higher than that of the Handmade group (M = 84.90, *SD* = 8.58). However, ANOVA results did not show a significant difference between the two groups ($F_{(1,180)} = 2.64$, $p = 0.10$, $\eta_p^2 = 0.01$, f = 0.05).

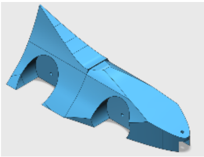
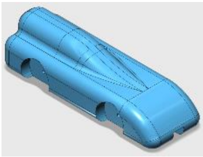
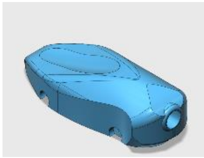
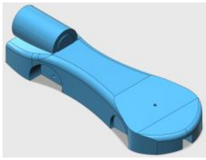
DISCUSSION AND CONCLUSIONS

The mean scores of the revised CPSS were similar for both groups for the material variable with respect to novelty, as were the variables of durability and usability in the functionality dimension. In terms of the material, only a few students considered using different materials to reinforce the car structure. These included using spacers or casings to improve the stability of the car body. In terms of durability and usability, only a few dragsters lost parts or sustained damage during the race. All dragsters were able to cross the finish line successfully. Therefore, the two groups performed similarly.

The mean scores of the revised CPSS for form, structure, consistency, and attractiveness attained by the 3D Printing group were significantly higher than those in the Handmade group. Both groups of students styled their cars at a beginner level due to a lack of experience in sketching and drafting three-view drawings. However, students in the 3D Printing group were able to alter the styles of their car continuously using the 3D digital modeling software. The students in the Handmade group struggled to formulate design drafts and convert their drafts into three-view drawings. Therefore, the dragster designs created by the students in the Handmade group were much simpler than those created by the students in the 3D Printing group. In addition, students in the Handmade group relied on manual processing techniques to model their designs. In contrast, 3D printing and modeling can be used to create designs that are difficult to achieve manually, facilitating the realization of innovative ideas (Snyder et al., 2014). Hence, the scores of the 3D Printing group were significantly higher than those of the Handmade group.

A previous study suggested that 3D printing allows students to visualize dynamic virtual objects and produce visible and tangible models. This enables students to perceive and experience abstract concepts in a number of ways (Lipson & Kurman, 2013). Moreover, 3D printing technologies have simplified product realization. The competency of machine operation is no longer an issue, opening new opportunities for students to maximize their creativity (Eisenberg, 2013). Thus, the mean consistency and attractiveness scores on the revised CPSS attained by students in the 3D Printing group were significantly higher than those attained by students in the Handmade group. The structural integrity of the models created by students in the Handmade group was significantly weaker than for those created by students in the 3D Printing group. This reduced integrity was associated with the low precision of manual processing. The lack of technical skill increased the likelihood of car body asymmetry, skew holes, enlarged holes, or car axes that were not parallel. The 3D Printing group used machinery to replace manual processing, resulting in accurate models with increased integrity. Examples of the models produced by the two groups are shown in Table 4.

Table 4. Examples of models created by the 3D Printing and Handmade groups

Groups	Students' works			
3D Printing (printed models)				
3D Printing (digital models)				
Handmade (polyurethane models)				

The race forecast outcomes were used to compare how well the two groups of students had learned engineering concepts. The 3D Printing group forecast the first-, second-, and third-place percentages more accurately than the Handmade group. Corum and Garofalo (2015) investigated the effects of using digital manufacturing equipment and simple 3D modeling applications to improve the learning performance of Grade 5 students. Their findings indicated that the use of digital manufacturing technologies reinforces students' understanding of science. Students in the 3D Printing group learned engineering concepts through repeated 3D modeling, group discussions, and corrections. This enabled them to apply their knowledge more flexibly and make accurate forecasts. By contrast, those in the Handmade group spent an increased amount of time in production and less time in group discussions and design corrections. This reduced the effectiveness of learning engineering concepts. It is also possible that 3D printers are excellent teaching tools that help students with design, output, and revision (Eisenberg, 2013), eliminating problems in processing accuracy. Both the lower level of creativity in the car designs and the lack of processing skills, resulting in issues such as uneven car axes and unstable structures, affected the race performance of dragsters made by the Handmade group.

The 3D-printed models were heavier than the polyurethane models, meaning that their race performance could not be compared directly. In addition to car design, every detail must be taken into consideration to enhance race performance. Among these details, assembly quality is the most important. High school students had neither the time nor the experience to account for every detail. Therefore, they were unable to understand fully the impact of each detail on performance. Our activity enabled students to understand that, in engineering design and manufacturing, favorable designs rely on quality production and assembly. For Taiwan's students, whose main focus is to further their education, the time they spend on such activities is extremely limited. The use of 3D printers and digital processing equipment can enhance product accuracy, reduce manual processing errors, and foster students' manual techniques and concepts. This helps them to realize that attention should be placed on a number of details during assembly to produce desirable end products.

In summary, the students in the 3D Printing group were able to make highly precise models. The course allowed students to maximize their creativity and create attractive models that met engineering standards. The forecast results showed that students in the 3D Printing group outperformed those in the Handmade group in terms of mastering and flexibly utilizing STEM knowledge. However, a number of challenges remain. Based on the experiment results, the following suggestions were proposed:

1) Reinforce students' graphic and spatial concepts: Although students were able to understand the concepts of three-view drawings, they found it difficult to produce three-view drawings of their car structures. Students' visuospatial ability, or the skill to perceive relationships between objects in space, is a key predictor of success in STEM curricula (Snyder et al., 2014). STEM can often be overly abstract. Teaching plans should include more lessons on reinforcing 3D modeling and 3D printing to foster students' spatial visualization concepts (Verner & Merksamer, 2015).

2) Use integrated teaching: Through integrated STEM teaching, relevant courses can be combined with technology courses to achieve integrated teaching and knowledge application (Hernandez et al., 2014; Fan & Yu, 2015; Nam et al., 2016). Interdisciplinary knowledge integration in the fields of technology and engineering can enhance design, innovation, and critical thinking (National Academy for Educational Research, 2016). In addition, integrated teaching methods leave more time for students to engage in project design, contemplation, and production, as well as more time for them to complete their work.

3) Encourage students to use creativity to solve problems: When students find that their ideas conflict with model weight or size during the 3D modeling process, they often sacrifice their creative ideas for performance by simplifying their designs. It is important to encourage students to achieve a balance between creativity and performance in engineering design.

4) Guide students in performing tests and revisions: Students can test and revise their models after assembly. Tests involve traveling in straight lines, travel fluency, and part stability. Repeated testing and revision is an integral process in engineering design (Atman et al., 2007; Fan & Yu, 2015). However, few students undertake this process. Teachers should actively guide students in testing and revising their work.

5) Reinforce collaborative learning between students: Students tend to seek help from teachers without discussing the issues amongst themselves. Teachers should encourage collaborative learning between students as learning is most effective when students are actively involved in sharing ideas and working cooperatively to complete tasks (Zakaria &


(a) Before triggering

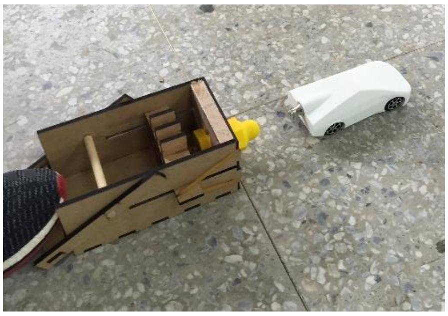

(b) After triggering

Figure 4. Our self-developed foot trigger

Iksan, 2007). Moreover, creativity can be encouraged through raising questions, communicating, and engaging in discussions and deep contemplation.

6) Use self-developed equipment: The precision trigger instruments, race tracks, and timer systems are relatively costly. To promote the CO_2 dragster course, a trigger and timer could be self-designed and self-developed as part of the race activity. The foot trigger device developed in this study is shown in Figure 4. A laser-cut pressure plate was used as the base of the trigger, and the trigger device was produced using a 3D printer. Races were largely conducted on the floor. The foot trigger was conceived based on ergonomics, so that students did not need to bend down to trigger the timer. The research team is currently exploring the possibility of incorporating a timer into the foot trigger. The device will be shared with in-service teachers once it is developed. This will help to promote the proposed course and race activity.

LIMITATIONS OF THE STUDY AND DIRECTIONS FOR FUTURE RESEARCH

There were limitations of this study and suggestions for future research. Some outcomes of the study were derived from informal observation and discussions among teachers and researchers. Formal observation or interview data on the actual implementation process of the dragster design pre-engineering curriculum may provide more insight into students' thoughts about the curriculum and 3D printing technology and help researchers to understand students' behaviors in the engineering design process. Moreover, it is important to understand students' attitudes about pre-engineering curricula by integrating an attitude scale and formal observation or interview data. The results of the teaching experiment were used to review and revise the course content. This revised course needs to be offered extensively in high school curricula in order to confirm these findings on a broader scale. Workshops with hands-on activities are needed to help in-service teachers understand the course content and incorporate it into their curricula. We hope that the proposed course will be used in the 2018 curriculum. The model development and verification processes adopted in this study can serve as a reference for future course design and development.

ACKNOWLEDGEMENTS

The author gratefully acknowledge the financial support provided by the Taiwan Ministry of Science and Technology under Project MOST 104-2511-S-003-040-MY3.

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