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Development and Assessment of a 3D Printing Course for Technical High School Students*

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The purpose of this study is to use the 5E model (Engagement, Exploration, Explanation, Elaboration, Evaluation; 5E) to develop a 3D printing course for technical high schools, and to explore the impact of this model on students' learning effectiveness. This study invited five experts to conduct focus interviews to explore the development of student-centered 3D printing courses in the 5E model, and jointly developed a 5E 3D Printing Course and a learning effectiveness scale. In addition, 39 students majoring in mechanical engineering from a technical high school in southern Taiwan were selected as subjects to conduct experimental teaching, and the learning effectiveness of the students was investigated by questionnaire survey. This study proposed a 5E 3D printing course, including: (1) course objective planning, (2) machine elements and design application, (3) topic setting and revision, (4) mechanical parts drawing and combination simulation, (5) 3D printing practices, (6) presentation and sharing of results, and summarization of the key points of teaching at each stage. After 18 weeks of experimental teaching, significant positive feedback was obtained from most students, indicating that this course is conducive to the improvement of their learning effectiveness. According to the conclusions, the 5E 3D printing teaching model was developed, and the 6-stage curriculum planning and implementation suggestions were put forward for students and teachers, in order to provide a reference for teachers to participate in 3D printing courses in the future.

Keywords: 5E model; 3D printing course; high school students; education reform

1. Introduction

The maturing of 3D printing technology and the innovative development of material technology have brought a disruptive impact on global manufacturing production [1]. According to the Market Research Report of [2], the global 3D-printed medical equipment market will grow from USD 12.2238 billion in 2020 to USD 23.751.9 billion by the end of 2025. 3D printing breaks through the traditional manufacturing methods and provides a new, fast, low-cost, and high-performance flexible manufacturing model, which conforms to the current customer-oriented, diversified, and complicated market trend [3].

With COVID-19 having a significant impact on the global manufacturing and supply chain, global manufacturers have realized the importance of local production, especially for medical equipment and consumables. There is a huge gap in the market for medical supplies. Many companies have attempted to adopt 3D printing technology to make breathing valves, breathing filters, and face mask buckles to alleviate the shortage of supplies, which highlights the potential of 3D printing in response to the changing situation [4]. In the future, the manufacturing industry will inevitably introduce more 3D printing technology to assist in production, otherwise enterprises may lose their market competitiveness [5]. Therefore, talent cultivation in 3D printing technology is an important direction for the mechanical department of technical high schools.

With the rapid development of the technology industry, the demand for interdisciplinary professional talents has multiplied, and the technical and the vocational education organizations of all countries have been developing towards cultivating

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students' integration ability, teamwork spirit, and problem-solving ability [6]. Moreover, in recent years, ITEEA has proposed 5E learning by design to guide students to conduct interdisciplinary integrated learning, in order that students can deepen their learning step by step during practice and make practical products [7, 8]. Chung, Lin and Lou [9] pointed out that teachers should have clear tasks at each stage of practical teaching to help learners develop scientific inquiry abilities, and teachers should be guided to design diversified teaching activities to arouse learners' learning motivation, encourage them to explore, explain or clarify wrong concepts, extend the application of concepts, and evaluate students' learning effectiveness [10]. Therefore, the integration of 5E inquiry-based learning strategies into 3D printing course design and practical activity planning should guide students to construct 3D printing knowledge from exploration and acquire 3D printing skills from problem solving and practical application, which is feasible and worthy of further verification in terms of innovative 3D printing course teaching strategies.

Thus, this study integrated 5E inquiry-based learning strategies into a 3D printing course, developed a 5E 3D printing course, and guided students to understand the principles and application of 3D printing technology. Based on the cam mechanism application course of the mechanical department, the application of computer-aided drawing was planned in combination with the principle of machine components. In addition, students' DIY projects were planned to achieve the teaching objectives by identifying and solving problems and verifying the knowledge content. The objectives of this study include the following points:

(1) To develop the 5E 3D printing course for the mechanical department of technical high schools.
(2) To explore the learning effectiveness of students from the mechanical department of technical high schools in the 5E 3D printing course.
(3) To construct the 5E 3D printing teaching mode for the mechanical department of technical high schools.

2. Literature Review

2.1 3D Printing and its Educational Applications

3D printing, also known as Additive Manufacturing (AM), is a technology that employs layers of materials to produce three-dimensional finished products [11]. In the process of 3D printing, the model file should be provided first and the printing parameters should be set by slicing software before the file is transferred to the 3D printer platform for printing. The model file is in the STL format, which is a common format compatible with most models and slicing software. The model design can be completed with the assistance of stereoscopic drawing software or a scanner. 3D printing technology does not require mold development, tool replacement, or industrial fixtures, and the product design and parameter data can be directly used to produce new product samples or models [12]. 3D printing has been widely adopted in industrial, medical, and design industries, and its advantages are, as follows:

(1) It is easy to operate and maintain.
(2) Compared with other methods, 3D printing is relatively cheap.
(3) It is easy to keep the environment clean and tidy without the use of additional chemicals.
(4) The device is of moderate size and can be placed on a desk.
(5) The whole process is carried out inside the machine without the need for additional equipment.
(6) A variety of materials are available with engineering characteristics.
(7) The price of the equipment is relatively low, which helps to shorten the delivery time.

3D printing technology is widely used in medical treatment, photography, teaching, product design, and other fields, among which the application in teaching needs to be promoted most. Therefore, the cultivation of 3D printing professionals is the basis for the sustainable development of 3D printing technology. According to Mitrousias, Varitimidis, Hantes, Malizos, Arvanitis and Zibis [13], 3D printing models can be used to improve medical students' understanding of the stereoscopic anatomy of bones, and can be applied to the anatomy of complex parts of bones. 3D printing software has been used to make teaching aids to assist the teaching of anatomy and pathology with good results [14, 15]. The University of Toronto provides a 3D printing website to introduce 3D printing technology and online resources, in order that potential users can learn by themselves. Maker workshops are also launched to introduce 3D printers and free model design software [16, 17].

To sum up, 3D printing technology is widely used in medical teaching and maker courses in universities [18]. In order to meet the needs of connecting industry and technology in technical high schools, this study integrated the professional knowledge required by mechanical parts processing and mechanical drawing, integrated 3D printing technology into the course of thematic production, and developed students' 3D printing knowledge through the development of innovative works.

2.2 *Connotations and Educational Applications of 5E*

In 1960, the Science Curriculum Improvement Study (SCIS) proposed a basic teaching model and a set of teaching procedures for science education, including three steps: exploration, invention, and discovery. Bybee [7] proposed the 5E Learning Cycle Mode (including engagement, exploration, explanation, elaboration, and evaluation). The teaching model was designed with the spirit of inquiry as the core, which focuses on students' ability to gradually develop a conceptual understanding over time, improves the way of imparting knowledge, and deepens the connection between the acquired knowledge and learning experience. The five processes are, as follows:

(1) Engagement: It refers to designing activities based on students' learning interest, makes students actively participate in teaching activities, connects students' experience with course content, elicits the direction of the topic by asking questions, defining questions, and presenting contradictory results.
(2) Exploration: Students participate in activities and are given enough time and opportunities to explore and construct common and concrete experiences through hands-on operation.
(3) Explanation: The teacher first asks students to give explanations, and based on their ideas, elaborates and confirms the explanations by verbal description, videos, or other teaching media, in order that the students can truly understand the knowledge. Then, the teacher guides the students to the next stage of the teaching process.
(4) Elaboration: Teachers attach importance to student interactions and create a learning environment that encourages students to discuss and cooperate, share ideas, and give feedback, in order to build a personal understanding of knowledge. Furthermore, teachers pay attention to whether students can apply the explanations to new situations or problems, in order to extend to the conceptual understanding of generalization, and then, acquire higher-level knowledge.
(5) Evaluation: Teachers encourage students to assess their own understanding and ability, and use evaluations to determine whether students have achieved the teaching objectives previously established.

The 5E inquiry teaching mode is widely employed in teaching, and many scholars have pointed out that the 5E inquiry teaching mode mainly focuses on the design of guided inquiry activities. In this mode, teachers only provide materials and questions for students, and students solve problems according to their own designed procedures under the guidance of teachers [19–21]. Moreover, the emphasis of the 5E inquiry-based teaching model begins from psychological, cognitive ability. Students are guided to discover phenomena and explore problems through systematic experiments or activities to arouse their interest in learning new knowledge. Using existing resources to understand new concepts and construct new knowledge can deepen their learning level and enhance their learning effectiveness through hands-on operation and exploring and solving problems [22].

By summarizing the above research results, we can gain an in-depth understanding of how to apply 5E inquiry teaching strategies into the curriculum design and the development of teaching materials. This can help students to learn and explore the complex knowledge of various subjects, and effectively help them overcome problems, thus, generating conceptual change and construction knowledge [23–25].

Therefore, in the course development and design of this study, the 5E (engagement, exploration, explanation, elaboration, and evaluation) inquiry teaching mode was selected to design learning activities, in order that students could experience the experimental operation activities. Through inquiry-based teaching activities, it is hoped that students can be motivated to discover and solve problems, and thus, cultivate their ability to explore and solve problems independently.

3. Research Design

Based on the purpose of this study and literature review, the 5E 3D printing course for the mechanical department of technical high schools was developed, and the influence on students' learning effectiveness was discussed. Relevant research methods and tools are described, as follows.

3.1 *Research Structure*

The structure of this study is shown in Fig. 1. Firstly, the literature on the 5E teaching model, project development, and 3D printing course is discussed and reviewed as a reference for teaching design and course content planning in integrating the 5E teaching model into the 3D printing project development course. Then, the research design is carried out according to the research purpose, including course implementation planning, teaching strategies, and the development of relevant research tools to confirm the effectiveness of the teaching model.

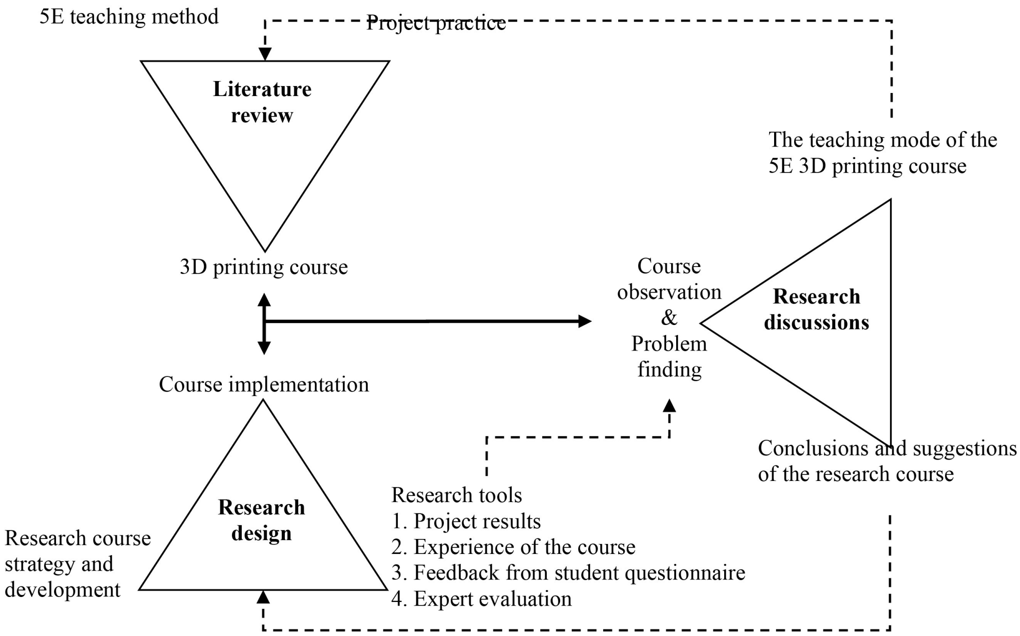


Fig. 1. Research structure.

Prior to the implementation of the course, students' knowledge of existing professional subjects was evaluated, their understanding of the cam mechanism was analyzed, and the course design was adjusted according to the principles of the machine elements and the course objectives of the cam mechanism. Moreover, in accordance with the teaching objective of Project Practice, cooperative learning and inquiry-based 5E teaching were adopted to help students build their knowledge framework and enhance their learning motivation, and guide students to become the subjects in learning. Finally, according to the teacher's curriculum schedule, students' learning experience, and the results of the project practice, this study cooperated with experts to evaluate the effectiveness of the curriculum, and then, discussed the advantages and disadvantages of the curriculum design, which can be used as reference to improve the curriculum.

3.2 Case Study Method

This study employed the case study method to investigate the planning focus of the 5E 3D printing course and its impact on students' learning effectiveness. The case study method is a germplasm-oriented research method, which is a special strategy for collecting, organizing, and analyzing data, and has the characteristics of particularity, description, inspiration, induction, exploration, and interpretation. Case studies usually combine multiple data collection methods, such as archival data, interviews, questionnaires, and field observations [26]. Therefore, this study adopted the case study method to collect and analyze the data of curriculum planning, teachers' teaching reflections, students' on-site reactions, students' feedback, practical works, questionnaire survey, and student interviews. By determining the problems in curriculum planning and implementation, the curriculum design could be revised and students' learning effectiveness of 3D printing courses could be improved.

3.3 Learning Effectiveness of 5E 3D Printing Course

In terms of student learning effectiveness, the combination of qualitative research and quantitative research was used for experimental teaching research [27]. The research subjects and tools are described, as follows:

(1) Research Subjects.

This study selected 39 third-year mechanical students from a technical high school in southern Taiwan as the research subjects. All participants had learned the cam mechanism in second-year Machine Elements Principles, and thus, had sufficient knowledge to participate in this case study. This study divided students into nine groups with four to five students in each group. The duration of the 3D printing course was 18 weeks, at three hours per week, and the impact on students' learning effectiveness was explored through the 5E teaching method.

(2) Quantitative research tool.

In quantitative analysis, a questionnaire survey was used to investigate the subjects, and single sample t-test was adopted to analyze the influence of this course on the learning effectiveness of the subjects. This study developed the 5E 3D Printing Learning Effectiveness Questionnaire, which contained 14 questions. A total of 93 subjects were selected by purposive sampling for pre-test, and the questionnaire was collected for items analysis. After deleting the inappropriate items, the principal component analysis method and Varimax were employed for the orthogonal rotation axis to extract the factors. The factor load of each item in the questionnaire was between 0.76 and 0.91. The total Cronbach's α was 0.89, which indicated that the scale had good reliability.

(3) Qualitative research tool.

In terms of qualitative analysis, this study used the document analysis method to analyze the learning effectiveness of students in the 5E 3D printing course. This study collected students' study sheets, learning experiences, written reports, and group projects as the basis for qualitative analysis of students' learning process. The text data coding principles for the nine groups of students are described, as follows; for example, in S0203, S stands for student text, 02 for Group 2, and 03 for Student 3.

To cope with the variability and difficulty of on-site teaching observations and text data collection in the learning process of students, this study adopted triangulation correction. (1) At least two of the teachers and the research team participated in the teaching field observation, (2) qualitative questionnaire analysis was adopted for assistance, (3) text data collection of study sheets, learning experiences, written reports, and group projects were conducted to establish the validity of the research data and research results. Furthermore, this paper discusses the change of abstract concepts and knowledge construction of 3D drawing and 3D printing in 5E inquiry-based teaching to confirm the change in students' learning process.

3.4 *Development and Design of 5E 3D Printing Course*

Regarding the 5E 3D printing course development, we invited five experts with more than 13 years of experience from engineering education, 3D printing, machining, and other relevant fields to participate. The three university professors and two technical high school mechanics teachers participated in the curriculum planning. The curriculum design integrating the 5E inquiry teaching method and 3D printing, as shown in Table 1, is described, as follows.

(1) Course objective planning.

This study integrated the meaning of engagement in 5E and created attractive teaching themes to motivate students to understand the meaning and objectives of the project production course. In addition, teachers explained the knowledge and technology related to the mechanical major, including machine elements and computer aided drawing. This course mainly combined 3D printing technology and teaching to assist students in producing works. During the course, the importance of teamwork was emphasized, the cooperative learning method was adopted, the students were instructed to work as a group, the work was assigned, and the group leaders were selected.

(2) Machine elements and design application.

The meanings of exploration and explanation in 5E were integrated, and the cam mechanism of machine elements was introduced through a teaching video. When the application of the mechanism in daily life was explored and analyzed, it was hoped to inspire the motivation of students to innovate their designs and practices. In addition, grouped students were encouraged to collect relevant materials and videos to discuss the direction and topic of the group's finished product design. Teachers were present to observe, guide, and assist in management. Finally, each group was invited to present an example or video using the teaching broadcast system, and explain their design and the principles of the mechanism through oral presentation.

(3) Topic setting and revision.

The connotation of explanation was continuously integrated. Student groups were asked to set a design topic, and determine the components needed for the mechanism. Students were encouraged to present their hand-drawn sketch designs of their mechanism, and explain the topic and the components used in the mechanism design, as well as their functions. Furthermore, teachers and students communicated about the mechanism design. Finally, the teacher guided the students in each group to revise their topic according to the feasibility of their mechanism design, and their final designs served as the basis for planning and scheduling the subsequent computer-aided drawing and 3D printing manufacturing.

(4) Mechanical parts drawing and combination simulation.

This study elaborated and integrated the connotations of 5E, and required each group of students to complete a 3D pattern presentation according to their hand-drawn design sketches. The computer-aided mechanical drawing technology of SolidWorks was used for students to show what they had learned, in order to further complete the mechanism combination drawing. During the process, students were assisted to discuss the size errors of their simulated combinations, as well as the shape corrections for their mechanisms.

(5) 3D printing practice.

This step continued to elaborate the 5E designs and applied 10 3D printers in the teaching field. The teacher helped students to understand the principles, operation steps, and precautions of 3D printing. Then, the teacher assigned one 3D printer to each group and assisted the students to print their mechanical components. In the process, the teacher helped students to set software, eliminated printing problems, guided students to think about the order and location of components, encouraged students to observe the printing status, and helped them to adjust printing parameters and eliminate errors in case of problems. Finally, the students in each group were required to record their group discussions and manufacturing process problems and solutions during printing, which were included in their results reports.

(6) Presentation and sharing of achievements.

This step integrated the evaluation connotations of 5E. At the end of the semester, each group presented the design principle and purpose of their works, the finished mechanism, the design drawings of parts, the problems encountered, and the solutions applied, as well as their feelings and experiences regarding the work assignments and course content. This study invited three mechanical teachers to offer comments and suggestions on the finished products, presentations, and written data from each group.

3.5 Teaching Focus and Process of 5E 3D Printing Project Course

The teaching focus and process planning of the 5E 3D printing course involved students and teachers, as shown in Fig. 2, and the student-centered activity design was emphasized. By completing the tasks of each stage, mechanical design knowledge and its principles were constructed, the knowledge of computer aided drawing was reviewed, 3D printing skills were acquired, and the finished products were produced. The teacher played the role of guidance, and eliminated students' technical difficulties in learning. The key teaching points implemented in this course are mainly based on the course objective and the 5E inquiry teaching mode, including (1) course objective planning, (2) machine elements and design application, (3) topic setting and revision, (4) mechanical parts drawing and combination simulation, (5) 3D printing practices, (6) presentation and sharing of results.

4. Results

According to the purpose of this study and the implementation results of the research design, the

Table 1. Summary of 3D printing course design

5E 3D printing course	5E	The content implications of incorporating the 5E model into the course
(1) Curriculum objective planning	Engagement	Plan "Appreciation of Excellent Works of National Project Competition" to arouse students' learning motivation and participation in the 3D printing course and take in the course themes and learning objectives.
(2) Machine elements and design application	Exploration, Explanation	Design "cam mechanism design and manufacture" theme and exploratory questions to guide students in learning data collection and attaining group discussion ability and connect their life experience and preparatory knowledge.
(3) Topic setting and revision	Explanation	Guide students to discuss from different perspectives, explore the core of the "cam mechanism" theme, and continuously revise the theme direction for them to learn how to focus on the core of the problem.
(4) Mechanical parts drawing and combination simulation	Elaboration	Plan opportunities for students to put "SolidWorks software" into practice, present innovative design ideas of institutional components through 3D graphics, and learn the ability to concretize ideas.
(5) 3D printing practice	Elaboration	Plan the practical application of 3D printing technology to assist students in realizing innovative ideas and repeatedly practice and improve the quality of works in the implementation process.
(6) Presentation and sharing of results	Evaluation	Implement multiple evaluations, publication of planning results, physical demonstrations, and peer reviews to achieve creative experience sharing and peer communication and check students' learning effectiveness.

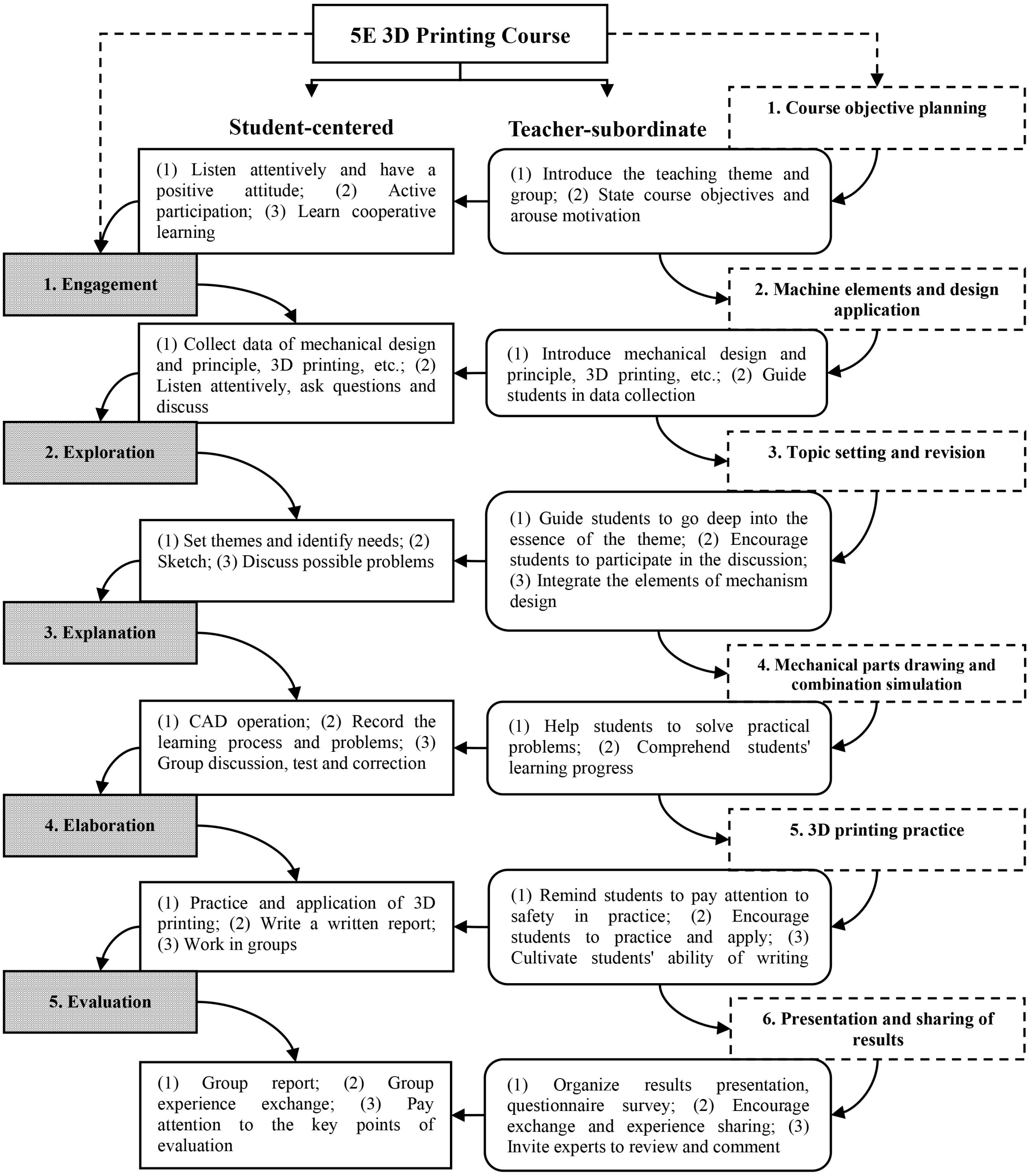


Fig. 2. Teaching process and key points of 5E 3D printing.

analysis of students' learning effectiveness of the 5E 3D printing course is based on the analysis of students' learning process and learning effectiveness, which are described as follows.

4.1 Analysis of Learning Process of 5E 3D Printing Course

The 3D printing course of this study took 5E as the main structure, and planned the 5E 3D printing course teaching mode with the students as the main body. The following is a summary of the students' learning sheets, learning experiences, written reports, and works. The performance and transformation of the students' learning process were analyzed and summarized, as follows:

(1) Course objective planning: planning attractive curriculum topics, arousing students' learning motivation.

During the course, teachers guided students to browse the excellent works of a project competition in Taiwan, in order to increase students' involvement and motivation, and explained the purpose, course content, and course evaluation method of the 3D printing course. Finally, the students were divided into nine groups according to their number, and the teacher assigned tasks.

It was found that there was a large gap in the professional knowledge and skills of some students, which made them feel uneasy, and some students were left out of their group activities. Therefore, when teaching, the teacher should encourage the students to take the opportunity to review their previous knowledge with the group, and emphasize mutual learning, group discussion, teacher-student interaction, and extended learning, in order that the students can feel comfortable when learning. In terms of 5E, students understood the innovative application of 3D printing and improved their motivation to participate in learning by appreciating the excellent works of the competition. Moreover, students enhanced their 3D printing practical skills during the hands-on manufacturing process.

Students' learning experience:

S0201: I learned that 3D printing should also be combined with computer-aided mechanical drawing. Although I have learned computer drawing before, I didn't learn it well. I hope I can learn it well this time.

S0502: Thanks to the help of my teachers and classmates, I was able to review and become proficient in computer-aided mechanical drawing.

(2) Machine elements and design application: cultivating students' ability to collect data, linking real life experiences and applications.

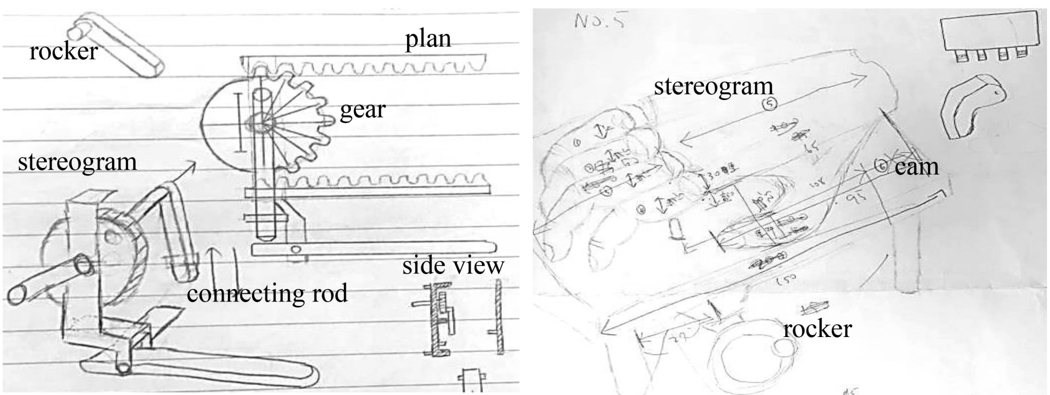
Focusing on the design and manufacture of cam mechanisms, the teacher introduced to students the works of Kazuaki Harada, a Japanese mechanical device artist, and used online resources to arouse students' motivation for design and creation. Students were encouraged to collect resources and videos from the internet, and after group discussion, they drew their parts and mechanism combination sketches by hand, as shown in Fig. 3.

During this course, the teacher encouraged students to focus on the discussions and designs of their applications in daily life, asked students to explain the results of their discussions, and designed and provided learning sheets to increase participation in the discussion. While A4 paper was provided for students discussions, sketches, and revisions, the students thought that it was inconvenient for group discussion, and a whiteboard was provided for discussion. Furthermore, in the teaching process of the 3D printing course, teachers employed guided teaching – such as appreciation of cam mechanism works, network data collection – and discussion according to students' learning status to reduce students' learning obstacles. Through teachers' guidance and cooperative learning among peers, students learned knowledge and skills in data collection, group discussion, creative thinking, hand-drawn design sketches, and innovative applications of 3D printing.

Students' Learning sheet:

S0104: We hope to put what we have learned into practice and design an automatic money-dividing saving pot that can be used in daily life, as shown in Fig. 3(a).

S0501: After group discussion, we decided to apply the characteristics of the cam mechanism to design a finger metronome



(a) automatic money-dividing saving pot (b) finger metronome

Fig. 3. Examples of hand-drawn design sketches from students.

that can simulate the rhythm generated by finger beating, as shown in Fig. 3(b).

S0801: The learning sheet helps us to focus on the main points of the discussion and engage the passive students in the discussion.

(3) Topic setting and revision: guiding students to explore the topic in-depth and focus on problem solving.

In this study, each group presented a 15-minute brief report on their topic, including the principle of the mechanism's hand-sketched design, followed by five minutes of classmate questions and discussions, and then, the teachers provided design suggestions as a reference for each group's topic and mechanism's revision.

It was found that, after the presentation of each group, the questions and discussions among peers were enthusiastic, and students were willing to give design recognition and innovative suggestions. In order that the students could focus on the key points and feasibility of the mechanism design, the teacher made the final summary. In addition, there were significant differences in student presentation skills among the groups, with some groups unable to fully describe the project topic or mechanism design concept. Therefore, a tutorial course on presentation editing skills was added to help students establish presentation points and classroom standards. In terms of 5E, after several instances of 3D printing theme exploration and discussion, most student groups took themselves as the main body. They explored, thought, and solved problems with their own ability and gradually clarified the core of the cam mechanism design problem, from which they obtained ideas to solve problems. Further, students were also able to integrate group members' opinions, sort out ideas, and focus on the direction and feasibility of solving the 3D printing theme.

Students' mid-term written report and learning experience:

S0102: Through the presentation, we can get to know the creative ideas of other groups. With this, we can be stimulated to provide more creative designs.

S0304: Suggestions from students and teachers can pinpoint our blind spots and improve the feasibility of our design. I am looking forward to the production of the work.

(4) Mechanical parts drawing and combination simulation: emphasis on students' application of what they have learned, the combination and application of theory and practice.

This unit required students to use SolidWorks to draw their parts plan and stereogram of the mechanism designed by each group, as shown in Fig. 4, and try to combine and modify the original design size of each part. Students learned to use SolidWorks to present the hand-drawn sketch of their mechanism in the form of a stereogram.

It was found that the participation rate in the discussion and drawing of each group was high, and the students helped each other and learned from each other in the computer-aided mechanical drawing. The teacher provided assistance to reduce the size errors between the drawing and the stereogram to facilitate the assembly of parts. Moreover, most students experienced learning for application in this stage. They integrated the results they had explored, their drawing concepts, cam mechanism-related professional knowledge, and computer drawing skills they learned in the past and practically applied them to the innovative design and implementation of 3D printing projects.

Students' Learning sheet:

S0102: We used the gear, scraper, circuit and crank design, as shown in Fig. 4(a), and drew all parts using the computer-aided drawing skills we learned. It feels good to put what we've learned into practice.

S0501: The practice of computer-aided drawing made me understand the technical gap between me and my classmates. Thanks to the help of other students and teachers, the mechanism assembly drawing was completed as scheduled, as shown in Fig. 4(b).

(5) 3D printing practice: new technology was incorporated into curriculum planning to assist students in learning and innovative application.

The teacher explained the principles and application of 3D printing, the placement and sequence skills for parts, and guided the students to learn the printing parameter settings of the slicing software Cura, as well as the methods of operation, and the safety and maintenance precautions of 3D printers.

It was found that the students were excited about printing their 3D products; however, the long printing time made some groups with more mechanical parts feel anxious. During the course, the groups that had completed their project helped the groups that had not yet completed their parts. This facilitated col-

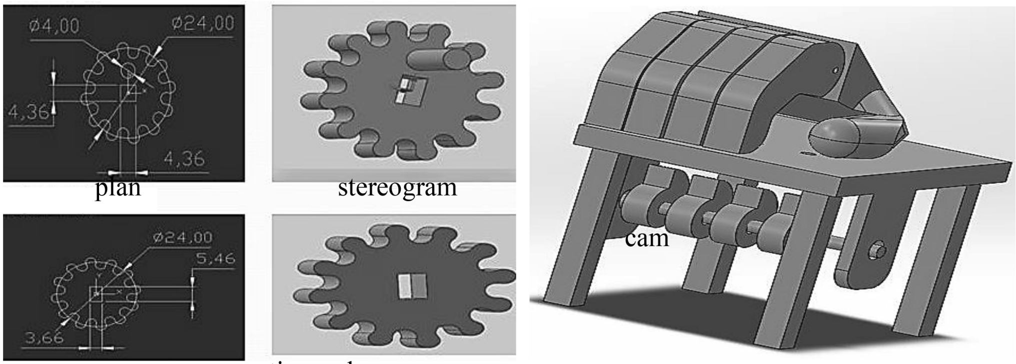


Fig. 4. Examples of computer-aided drawings of students.

laborative learning among the groups, which accelerated the project progress of each group and enabled the students to complete their products within the course schedule. Finally, with the teacher's assistance and advice, the students worked together to complete their presentations and written reports. In terms of 5E, students applied 3D printing technology to produce works with innovative ideas and modified, optimized, and refined the physical works to achieve refined 3D printing conceptual models. Hence, the practical application of students' 3D printing course knowledge is deepened, while the connection and application of cross-domain knowledge and ability are strengthened.

Students' Learning sheet:

S0503: Our team designed more parts, which gave us more opportunities to operate the 3D printer. However, the time spent increased as well. We should consider simplifying the design without affecting the function.

S0601: Although 3D printing is very convenient, different parts have different parameter settings, resulting in printing failure. We reviewed the reasons for the failure and learned how to set the printing parameters.

S0702: We found that the printing failed because there was too little space inside the part for the 3D printing to form the support material. The limitations of 3D printing need to be considered in the design.

(6) Presentation of results: experience sharing and peer communication, multiple evaluations to examine students' learning effectiveness.

The presentation of course results was carried out two weeks before the end of the semester. Each group had 20 minutes, then teachers collected students' experiences, reports, and written data, and two mechanical teachers were invited to participate in the evaluation and give the final scores to students.

It was observed that most of the groups expressed satisfaction with the application of 3D printing technology in the course, as shown in Fig. 5, and were willing to share their feelings with their classmates in their report. In addition, the presentation performance of most groups was significantly better than that at the mid-term subject evaluation, and most groups had good reporting time control and report expression. Furthermore, most students shared their innovative design ideas about the work themes and exchanged practical experience in cam design problem solving and mechanism function verification through discussion, implementation, and publication of results. In this way, students could constantly strengthen the links between different concepts (e.g., 2D drawing, 3D design, and 3D printing products) and the blind spots of the problem-solving process to improve their learning effectiveness and strengthen the improvement of practical skills.

Students' final written report and group project work:

S0101: We innovated and applied the professional knowledge learned from the gear unit of Machine Elements and added the function of automatic money classification to the money box, as shown in Fig. 5(a). The Arduino electronic circuit was mainly used to make the mechanism operate automatically and become a mechatronic mechanical device. With the gear, connecting rod and scraper, the coins can be layered according to the face value of the coins.

S0501: We used the disk-shaped cam and

(a) automatic money-dividing saving pot (b) finger metronome

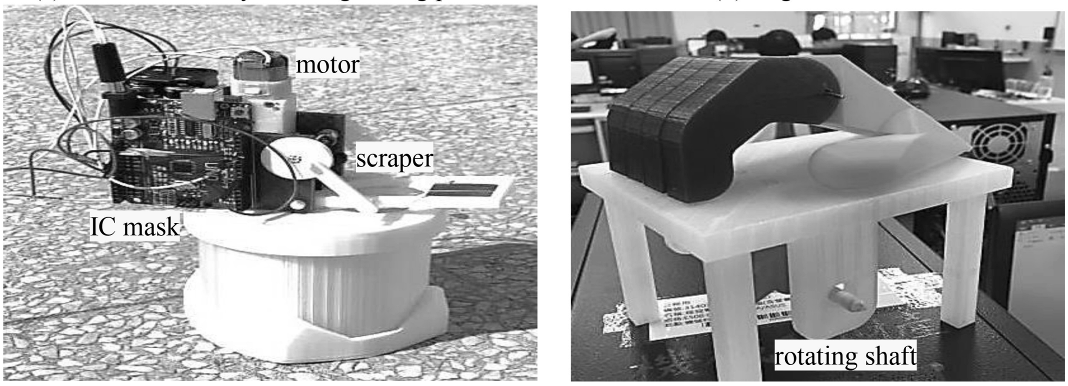


Fig. 5. 3D printed product example of students.

placed the cams of the same shape in different positions so that the four fingers could make different reciprocating linear motions at different times, as shown in Fig. 5(b). Since the linked parts and drive shaft are not suitable for 3D printing, we replaced them with iron wire and bamboo chopsticks, which successfully solved the problems encountered in production.

4.2 Analysis of Students' Learning Effectiveness

The statistical analysis results of the questionnaire survey on the learning effectiveness of 39 mechanical students in technical high schools after an 18-week 5E 3D printing course are shown in Table 2, and described, as follows.

After the 5E 3D printing course, the one-sample t-test was selected (test value was 3). Most students gave a positive evaluation of this course, with an overall mean of 3.94, a standard deviation of 0.61, and a t-value of 13.27, indicating a significant positive difference. The average score of each item is between 3.33 and 4.33. Furthermore, the one-sample t-test analysis was carried out with a test value of 3.5. Most of the students believed that this course was helpful to improve their application of professional knowledge, such as mechanical drawing and design, 3D printing, and SolidWorks, as

Table 2. Analysis of students' learning effectiveness

No.	Item	Average mean	Standard deviation	t	Significance
1	This course improved the application of my professional knowledge of mechanical design and principle.	3.97	0.91	3.81	0.000
2	This course improved the application of my professional knowledge of mechanical drawing and design.	4.31	0.66	7.70	0.000
3	This course improved the application of my 3D printing professional knowledge.	4.33	0.86	7.86	0.000
4	This course improved the application of my SolidWorks professional skills.	4.19	0.82	5.48	0.000
5	This course improved my PowerPoint presentation ability.	3.61	0.90	1.01	0.318
6	This course improved my Microsoft Word writing ability.	3.61	0.96	1.96	0.058
7	This course improved my oral expression ability.	3.33	0.95	–2.18	0.036
8	This course cultivated my interdisciplinary integration ability.	3.81	0.92	2.78	0.008
9	This course improved my teamwork ability.	4.08	0.80	4.10	0.000
10	This course improved my abilities in independent thinking and problem solving.	3.97	0.81	5.51	0.000
11	This course improved my innovative thinking ability.	3.97	0.91	3.99	0.000
12	This course promoted my active learning of professional knowledge.	3.97	0.91	4.19	0.000
13	This course improved my practical design and production ability.	3.97	0.77	4.43	0.000
14	This course improved my understanding of previous professional courses.	3.97	0.84	4.19	0.000
	The general dimensions of students' learning effectiveness.	**3.94**	**0.61**	**13.27**	**0.00**

Test value = 3.5.

well as to improve their teamwork ability. The mean value was higher than 4, and the t-value ranged from 4.10 to 7.86, which shows positive significant difference. The analysis results correspond with the "5E 3D printing course" objectives, integrating students' preparatory knowledge of mechanical drawing and SolidWorks into the new knowledge of 3D printing for application and learning the attitude and experience accumulation in teamwork.

Moreover, this course was conducive to improving students' application of their professional knowledge in mechanical design and principles, as well as students' abilities in cross-disciplinary integration, independent thinking and problem solving, innovative thinking, ability to actively learn professional knowledge, and ability of design and production. Students' impressions and understanding of previous professional courses were positive, and the scores ranged from 3.81 to 4. Furthermore, the results show that the "5E 3D printing course" can provide students with more experience in integrating and applying interdisciplinary knowledge, independent thinking, problem-solving, and innovative thinking. It can also cultivate students'integrated thinking and ability.

Among them, in the aspect of improving students' PowerPoint presentation ability and Microsoft Word writing ability, the score is 3.61, which is not significantly different. In terms of improving students' oral expression ability, the score is only 3.33, and the t-value is –2.18, which is a significant negative difference, indicating that this 5E 3D printing course has no significant effect on improving this ability. In the case when these three abilities are important improvement indicators of this course, they should be included in future course planning.

5. Discussion

The teaching activities of this study were developed according to the 5E model. The teaching plans were designed according to the teaching objectives of mechanical design and principles, the knowledge connotations of mechanical drawing and design, the skills of the 3D printing practice course, and cooperative learning strategies.

The relevant, comprehensive discussion is explained as follows:

5.1 Integrated Planning and Implementation Recognition of "5E 3D Printing Course"

The "5E 3D printing course" takes students as the main body and teachers as the guide to carry out 6-stage course activity planning to guide students in actively exploring, learning, experimenting, discussing, generating cognitive conflicts, and constructing knowledge.

Furthermore, the activities and tasks of teachers and students in each stage were planned, and their feasibility and effectiveness were confirmed, in order to guide the students to actively engage, be willing to explore, learn to explain, be innovative, and complete the evaluation [20, 22]. In this manner, students were guided to learn the concepts of mechanical design and principles, and master their 3D printing ability through the implementation of projects, group discussions, problem solving, hands-on practice and innovation, verification of results, and the completion of projects.

After 18 weeks of experimental teaching and case study analysis, this study innovatively integrated 5E inquiry-based teaching into a 3D printing course. As most students gave positive feedback [3, 28], it showed that students felt a sense of achievement when combining theory with practice, practicing professional knowledge and manufacturing technology, using data collection, cooperative learning, mechanism design, production and verification, and 3D printing to complete the project [29]. This study planned an engaging course topic that motivated and engaged students to develop their knowledge of mechanical principles and their SolidWorks computer-aided mechanical drawing skills. Furthermore, this course linked the course content with students' life experiences and guided students to conduct in-depth exploration while focusing on problem solving. Students discovered problems, overcame difficulties, and continued to progress until the work was completed [6, 7]. According to course feedback, most students were satisfied with their ability to combine theory with practice when applying their knowledge, and they believed that the important factors for the success of the project are group cooperation, course participation, peer communication and teachers' assistance, as it could cultivate their correct learning attitude of active learning, communication and sharing.

In addition, most of the students affirmed the inclusion of emerging technology in the curriculum planning, and were excited about the ability to learn and use 3D printing to show their creativity [30]. They also believed that cooperative learning among peers was a good learning experience. Most students were sure that cooperative learning could improve their 5E task execution ability, problem solving ability, and cooperation and communication ability [23].

5.2 Implementation Results and Findings for the "5E 3D Printing Course"

(1) The 5E 3D printing course includes six key implementation points, which can guide stu-

dents to combine theory with practice to produce actual works.

After experimental teaching and analysis, most of the students gave positive feedback to the machine elements in the course, and believed that the practice of using 3D printing to materialize text and pictures gave them a sense of achievement. This study integrated 3D printing technology into the course, and according to the six key implementation points, students were guided to integrate the knowledge learned in senior one and senior two classes in the mechanism design project, in order to achieve integrated application. For example, by combining their professional knowledge of machine elements and the professional technology of CAD (SolidWorks) in the production process of 3D printing, students can develop their problem-solving ability through verification and application. Moreover, the operation of 3D printing equipment can cultivate students' quality of factory safety and hygiene, while printing failures, and their solutions, can encourage of students to learn independently and face the problems they encounter. In the process of assembly, students can be encouraged to discuss and improve their designs, which will allow them to obtain the knowledge and ability of project production [3, 20].

(2) Most mechanical students in technical high schools showed significant positive recognition in learning effectiveness after the 5E 3D printing course.

After 18 weeks of 5E 3D printing course teaching, most of the students thought that it was helpful to improve their professional knowledge related to machine elements, including the principles and designs of machine parts, mechanical drawings and design, 3D printing, and SolidWorks computer-aided mechanical three-dimensional drawing. In addition, 3D printing can help students to understand the function, size, and 3D printing process of cam, including connecting rods and gears in the mechanism design. Although designing a mechanism is difficult, students' confidence in their knowledge of mechanism design can be built up in the process of cooperative learning, discussion, and division of labor [12].

(3) The teaching mode of the 5E 3D printing course is student-centered and teachers are learning facilitators, which can strengthen the students' integrated knowledge learning and cooperation among peers.

The teaching mode of the 5E 3D printing course constructed in this study mainly focused on 3D printing teaching activities. Teachers employed 5E to teach and assist, but did not interfere with students' production of actual works. Through computer-aided drawing and design and 3D printing practices, students learned about machine elements and design, as well as the practical application of 3D printing. After the experimental teaching, most of the students have high recognition for the innovative teaching of the 5E 3D printing course, which can improve the quality of communication and discussion between students and their peers, and between teachers and students [23]. This result illustrates that the teaching activities developed in this study have the value of continuous growth.

5.3 Suggestions and Restrictions on the Implementation of the "5E 3D Printing Course"

(1) Increase the number of 3D printing courses.

The results of this study show that the duration of printing a 3D mechanism design is long, and improper printing parameter settings and machine operation may lead to a failure to print the parts. Moreover, after printing, the mechanism may not work because of improper part size. It is suggested that in course design, the number of courses in this stage should be increased to improve the possibility of students producing the finished products on time and in the correct size. The time limit of the course directly affects the data collection and research planning of this study. Thus, conclusions should not be over-inferred.

(2) Strengthen students' knowledge and experience before the implementation of each stage of the course.

The results of this study illustrate that students differ in their professional knowledge and skills, as well as in their ability and experience to present presentations and written data; therefore, in student-centered inquiry teaching, teachers should be responsible for guiding and assisting. It is suggested that explanations and demonstrations should be carried out before each stage is implemented, in order to strengthen the link between students' prior knowledge and technology memory. Further, the objects of this study are mainly technical high school mechanical students. Therefore, most students have a certain degree of cognition in the basic preparatory knowledge related to 3D printing. In the future, cautious application of the results of this study should be explored when promoting 3D printing courses in other departments.

(3) Set up the course assessment of 3D printing operation and safety instructions.

To make the 3D printing process in the course run more smoothly, assessments of machine operation, use, and maintenance can reduce the number of students' printing failures, and the possibility of delaying the course due to equipment maintenance. During course implementation, teachers can first explain the matters that need extra attention and provide instructions for the 3D printing of single parts, and then, let each group operate the printer. Teachers should help students to understand the size and proper position of parts, in order that students can successfully complete 3D printing. Learning 3D printing equipment and printing finished works takes time. Thus, the number of 3D printing equipment is another limitation in implementing this study, which indirectly affects the presentation of research results. It is recommended that at least 2 groups share one 3D printer (preferably 1 printer for each group) so that teachers can guide the student groups in solving practical problems.

6. Conclusion

In response to the diversified and complex customer-oriented market and the trend of cross-field professional and practical talent demand, this study innovatively adopted 5E inquiry-based teaching in the "3D Printing course" of technical high school mechanical departments. Key research results include the development and integration of the 6-stage 3D printing project courses and activities of 5E inquiry-based teaching. Through the experimental teaching, research observation, qualitative, and quantitative analysis, the positive responses of most students and teachers were obtained. It shows that the course objectives advocated in this study – combining 5E inquiry-based teaching strategies in the 3D printing practical course and cultivating professionals with interdisciplinary knowledge integration and application of emerging science and technology – are verified. Furthermore, 5E inquiry-based teaching emphasizes the interaction between individuals and the learning environment as well as between peers. This emphasis is feasible for improving students' communication, coordination, and teamwork ability and meets the needs of future industrial talents, worthy of further promotion.

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