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Teaching Sustainability Principles to Engineering Educators*

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This paper is to provide experimental evidence of designing and assessing a teacher training program for sustainability competency enhancement in higher education. Eighty-five engineering teachers participated in the program comprising three stages of fifteen days. The first stage focused on the content knowledge of eco-design and how to apply the life cycle assessment (LCA) methods and tools. The second stage aimed at using the four-step LCA method to a power battery eco-design problem. The third stage was to create a general structured eco-design teaching approach for realizing its expansion in various engineering fields. The findings suggested that the participants enhanced their sustainability awareness and eco-design skills, and improved in the four elements of technological pedagogical content knowledge (TPACK) through the program. The analysis on participants' reflective essays indicated that improvement mainly comes from the stages of LCA practice and eco-design integration. This study validates the importance of focusing teacher professional development on sustainability awareness and eco-design skill.

Keywords: sustainability competency; eco-design; life cycle assessment; teacher training; engineering education

1. Introduction

The industry is actively solving environmental sustainability issues by developing sustainable products and services. All stages in the product life cycle, including resource extraction, production, distribution, usage, and disposal are increasingly subject to socio-ecological considerations to ensure sustainability [1]. Eco-design refers to integrating the concepts of environmental sustainability into product development, aiming to reduce the adverse impact on the environment throughout the product life cycle [2]. The eco-design approaches are developed based on the environmental standards and laws adopted by international organizations and are widely applied in academic literature [3]. Consequently, the educational community is increasingly interested in embedding eco-design into engineering education for sustainability competency enhancement.

Eco-design learning is regarded as fundamental for students to enhance their sustainability awareness and to provide them with potential design tools to address real-world sustainability challenges. However, practical instruction about eco-design in engineering education faces challenges [4]. For example, engineering teachers are not capable of implementing the eco-design instruction because they lack the requisite engineering experience in environmental sustainability, or are not familiar with the use of eco-design tools. Currently, most teacher training programs are implemented in lecture-based workshops without an instant feedback mechanism. The literature [5] suggests that significant improvement depends on constructive feedback and engineering context.

At present, high-quality experimental studies on eco-design skill enhancement for engineering teachers are lacking. Many existing studies are descriptive and employ self-assessment based methods. The framework of technological pedagogical content knowledge (TPACK) is a useful tool for measuring teacher professional development and is often used to develop technology-enhanced teaching approaches [6]. However, there are few studies on the TPACK related to sustainability competency development. To fill this research gap, we implemented an experimental study on the teacher training program of enhancing sustainability competency related to eco-design. In the next section, we review the literature on sustainability competency development in engineering education and briefly illustrate the features of the teacher training program.

2. Related Literature

2.1 Sustainability Learning in Engineering Education

There is growing recognition of the importance of integrating environmental aspects in conventional

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engineering education for sustainability [7, 8]. Integration of environmental sustainability learning is roughly divided into three ways: (1) develop new engineering courses, e.g., product eco-design [9]; (2) integrate sustainability concepts into traditional engineering courses [10]; (3) introducing self-directed learning modules, e.g., Autodesk Sustainability Workshop [11]. Previous researches make sustainability learning more immersive, which is seen as a focus for sustainability education.

Eco-design learning focuses on providing design solutions with minimum adverse environmental impact from the perspective of the product life cycle. Product design is the essential contents of conventional engineering courses, and the research expertise of engineering teachers. Therefore, the implementation of product eco-design teaching makes it relatively easy for teachers and students to foster sustainability awareness and gain sustainability practices. Eco-design is interdisciplinary with integrating environmental sustainability elements into product development, which naturally broadens the design space for engineers [12]. Turner [13] proposed an eco-design strategy of advanced systematic inventive thinking, which provided a useful method to be used in the engineering education classroom for problem-solving in the sustainability context. Lambrechts et al. [14] revealed the key role of individual sustainability competencies in various stages and characteristics of eco-design building projects. Thus, sustainability awareness and eco-design skill have an inherently consistent and mutually reinforcing relationship.

2.2 An Eco-design Framework of Life Cycle Assessment

An appropriate eco-design framework has an important influence on eco-design training within sustainability education. However, the conventional eco-design guidelines are over general to be directly introduced into actual teaching practice for providing teachers and students with a practical design tool [2, 15]. The scholars [16, 17] employed the principle of life cycle engineering as a benchmark to develop engineering courses for environmental sustainability and product eco-design. Currently, the concept of life cycle assessment (LCA) has been embedded in the product development process and has become a research focus in engineering science [3]. Although LCA is not a mandatory standard, it was widely used to measure energy consumption and pollution emissions in product development and manufacturing processes [1]. Therefore, the LCA is an appropriate framework for creating an eco-design learning environment and performing eco-design instructions within engineering education.

There is little literature on empirical research on the LCA teaching [18, 19]. These researches suggested that conventional teaching approaches such as lecture-based instruction are not efficient at enhancing sustainability awareness and eco-design skill. This concern encourages the development of an innovative training approach to delivering sustainability in engineering education.

2.3 Sustainability Education in Teacher Development

The importance of embedding sustainability education in teacher development has been emphasized through calls from international bodies, curriculum resource releases, academic publications, and various research projects [20]. At the higher education level, some institutions conducted theoretical research and practical exploration in teacher sustainability education. For example, Hickey and Whitehouse [21] developed a multilevel classification model of lecturer practice in sustainability education, embedding sustainability awareness into lecturers' practice when planning programs, courses, learning activities, and assessments. Birdsall [22] found that many teachers' understanding of sustainability was limited to an environmental component and were not able to accurately assess their own understanding. Bürgener and Barth [23] proposed an open learning environment based on the living laboratories for sustainability learning in a transdisciplinary manner on real-world projects.

There is a challenge in promoting teachers' competency for embedding sustainability into engineering courses [2]. Firstly, many teachers lack engineer knowledge about environmental sciences and allocated resources for ecological analysis. Secondly, conventional courses lack training in eco-design methods and tools to support trade-off analysis between cost, performance, and environmental sustainability.

2.4 Teacher Professional Development in the TPACK Framework

The TPACK provides a framework for teachers to efficiently integrate technological contents into teaching activities [24]. As shown in Fig. 1, the TPACK comprises three basic elements and four elements of the cross-sections. Some scholars applied the TPACK framework to evaluate teachers' competency and teaching performance in higher education [25]. For example, Maor [26] explores using the TPACK model in two e-learning courses that enhanced students' ability to use technology in their learning and later in their professions. The findings showed that most students increased their understanding of the use of the

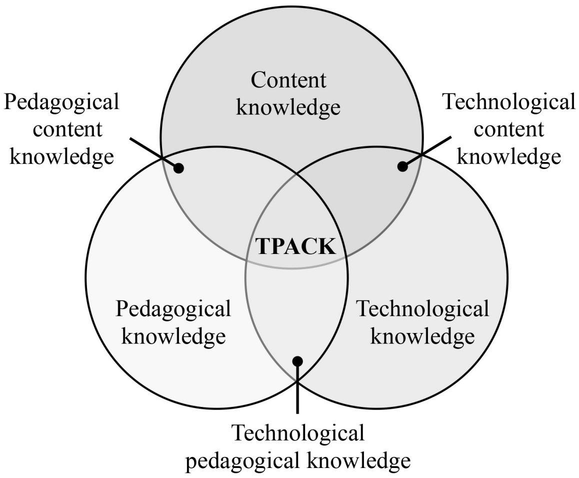

Fig. 1. TPACK framework.

different domains of TPACK and became digital pedagogues to implement the TPACK model in their classrooms. In a study that focused on environmental sustainability education, Álvarez-Otero et al. [27] proposed a pedagogical tool using the TPACK framework in geography education. The practices in secondary schools and universities demonstrated that the TPACK enhanced students' global understanding by integrating sustainable development goals and spatial data infrastructures.

The above researches indicate that (1) the TPACK framework is vital for the evaluation of teaching effects, (2) the discussion does not need to cover all TPACK elements, (3) the TPACK elements should be adjusted appropriately according to the course characteristics. In the eco-design learning context, the seven elements of TPACK are listed in Table 1. This paper focused on the four elements related to content knowledge because the content knowledge of eco-design is the basis for sustainability competency enhancement. A teacher training program was proposed to develop the teachers' competency of teaching eco-design (content knowledge) with the use of the LCA method (technological content knowledge) and appropriate teaching approach (pedagogical content knowledge) in the context (TPACK).

2.5 The Purpose of this Study

In this experimental study, a teacher training program was developed and performed for fostering teachers' competence in integrating sustainability into engineering courses through an eco-design task. We used objective tests and self-assessment surveys to evaluate teachers' sustainability awareness and eco-design skills, and investigated whether the program significantly improved teachers' competency in teaching sustainability. To further reveal the teachers' improvement sources, we also discussed the reflective essays submitted by teachers after the program. This study will provide a reference to develop teacher training courses for sustainability competency enhancement based on the TPACK framework.

The study focused on three research questions as follows. (1) What were the influences of the teacher training program on the participates' sustainability awareness and eco-design skill? (2) What were the influences of the teacher training program on the participates' competency in the four TPACK elements? (3) What were the participants' perceptions on their improvement through the teacher training program?

3. Methodology

3.1 Study Background and Participants

The teacher training program was part of *the Industry-University Cooperation Collaborative Education Project*, initiated by the Higher Education Authority. The program was organized by an enterprise for enhancing the sustainability competency of teachers and students in colleges and universities. More than one hundred teams submitted applications, and we selected eleven teams (including eighty-five teachers) based on two criteria. Firstly, they conducted practical explorations and accumulated experience in integrating sustainability learning into conventional engineering courses. Secondly, their institutions were to provide support in terms of workforce and funding for the program implementation. Of the 85 participants, 75 (88.2%) were male, and 10 (11.8%) were female. All

Table 1. The TPACK descriptions in the context of eco-design training

Elements	Descriptions
Content knowledge	Knowledge of product sustainability and eco-design practices
Pedagogical knowledge	General technological knowledge, e.g., design-based learning
Technological knowledge	General technological knowledge, e.g., life cycle assessment
Pedagogical content knowledge	Knowledge of teaching eco-design without the use of technologies
Technological content knowledge	Use of technologies for teaching eco-design
Technological pedagogical knowledge	Knowledge of applying technological tools to teach contents other than eco-design
TPACK	Knowledge of applying technological tools to teach eco-design for sustainability competency enhancement with the appropriate approaches

teachers had degrees in engineering disciplines (e.g., mechanical engineering, and electrical engineering), 45(52.9%) participants had a doctorate, and 40(47.1%) participants had a master's degree. Their average teaching experience in engineering was 3.9 years.

3.2 The Proposed Teacher Training Program

The teacher training program was composed of three stages: introductory lecture, LCA practice, and eco-design integration. The introductory lecture aimed to explain knowledge related to design for environmental sustainability and provide the basic concepts of environmental engineering, eco-design, and LCA. The LCA practice trained participants in performing LCA analysis for a power battery product by applying the four-step method [28]. The eco-design integration used the battery example and contexts to develop a structured eco-design framework integrated with conventional product development.

3.2.1 Introductory Lectures (The First Stage)

From the perspective of the TPACK framework, the focus of the first stage was mostly on the content knowledge of eco-design and how to apply the LCA methods and tools. Besides, the lecture covered the pedagogical principles applicable to eco-design instructions. The first stage was limited to twelve hours (three four-hour lectures) over three days. The lecture-based courses were organized around the following concepts: (1) the environmental standards and laws related to product development and manufacturing, (2) the life cycle thinking and how to embed it into the product development process, (3) the basic principles involved in LCA methods and tools.

In the 3-day course, the basic course materials (see Table 2) were provided to participants for understanding the content knowledge about environmental sustainability and the general eco-design methods implementing in their engineering courses. For example, the environmental impact of raw material production was introduced for using relevant data sources to count the energy consumption and pollutant emissions in the production process of raw materials. For the development of pedagogical content knowledge, participants received a series of papers [29] on energy consumption and pollution emission at various stages of battery production, use, and recycling. These materials helped them understand the LCA-based eco-design approach. Table 2 lists the teaching content and time allocation in the first stage.

3.2.2 LCA Practice (The Second Stage)

The second stage was mostly focused on using the four-step method to practice the LCA process, integrating content knowledge, pedagogy, and technology. The advanced course materials (see Table 3) were expected to improve participants' competency in the content knowledge and technological content knowledge. The LCA practice started after the first stage and lasted for eight days (eight hours per day). The participants performed an LCA task on an actual power battery product under the guidance of environmental experts and senior designers. The purpose of the

Table 2. Teaching contents and time allocation in the first stage

Learning contents	Activity	Hours
Environmental management – Life cycle assessment – Principles and framework (ISO14040)	Lecture	2
Environmental management – Life cycle assessment – Goal and scope definition and inventory analysis (ISO14041)	Lecture	2
Environmental management – Life cycle assessment – Life cycle impact assessment (ISO14042)	Lecture	2
Tests on sustainability awareness, eco-design skill, and TPACK (see Section 3.3.2)	Test	2
The Greenhouse gases, Regulated Emissions, and Energy use in Transportation model (GREET-2012)	Lecture	2
The commerce life cycle assessment software for fact-based sustainability (SimaPro)	Lecture	2

Table 3. Advanced course materials provided in the second stage.

Category	Course materials
The technical documentations for content knowledge enhancement	The structure and working principle of a battery cell
	The structure and manufacturing process of the battery pack
	The 3D model of the battery pack
	Product bill of Materials
The LCA technology for technological pedagogical knowledge enhancement	The algorithm of the energy consumption
	The algorithm of the pollution emission
	The equivalent methods for different functional units
	The data analysis methods, such as sensitivity analysis

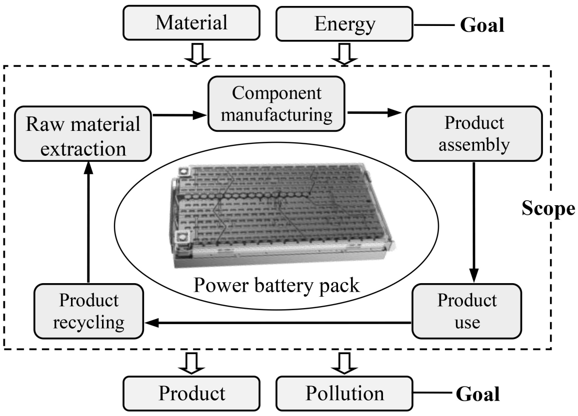

Fig. 2. Goal and scope of the battery LCA.

practice course was not only to deepen the participants' understanding of sustainability and eco-design concepts, but also to emphasize the teaching approach to applying the structured LCA framework. The four steps of LCA include (1) goal and scope definition, (2) inventory analysis, (3) environmental impact assessment, and (4) interpretation of results. In the context of the power battery, the goal referred to the environmental impact (i.e., the energy consumption and pollution emission) per functional unit (i.e., energy storage unit / kWh). The scope was defined as the environmental impact factors during the "cradle to cradle" life cycle with the stages of raw material extraction, component manufacturing, product assembly, use, and recycling. The inventory analysis involved the data collection and the environmental impact analysis at each stage of the battery life cycle. The environmental impact assessment used the inventories to classify and characterize various impact factors in the life cycle.

In the second stage, the participants learned how to extract information from relevant literature and technical documents for identifying the goal and scope of the battery LCA, as shown in Fig. 2. The second stage focused on normalizing benchmarks for the assessment of energy consumption and pollution emission at various stages. For example, the pollution emissions per kilometer of an electric vehicle were equivalent to those per unit energy (kWh) of the battery. It was conducive to enhancing the participants' pedagogical content knowledge. We selected practical tools from industrial sectors for guiding participants to implement the LCA, such as the GREET models, calculation formula of consumption and emission, and LCA software. These elements were likely to deepen their content knowledge and technological content knowledge. Over the eight days, the participants had the opportunity to work on the battery material composition lists, consumption and emission inventories, sensitivity analysis to environmental impact factors, and technical roadmap for the battery eco-design. The participants gained support and feedback from peers and experts in the group activities. They learned to use the LCA method and tools for eco-design, thereby promoting their technological content knowledge. Besides, the participants experienced the design-based learning enhancement, which is a promising teaching approach in engineering education [30]. The design-based learning environment contained the basic elements of content, pedagogy, and technology, thereby strengthening participants' TPACK. Table 4 summarizes the teaching content and time allocation in the second stage.

3.2.3 Eco-Design Integration (The Third Stage)

The third stage focused on the content knowledge of organically integrating eco-design concepts into the conventional product design framework, and

Table 4 Teaching contents and time allocation in the second stage

Learning contents	Activity	Hours
Technical documentations of the battery cell and battery pack (see Table 3)	Lecture	6
The definition of the LCA goal and scope	Group exercises and discussions	2
Compilation of the battery material inventory	Group exercises and discussions	8
Compilation of the energy consumption and pollution emission inventory for the battery raw material extraction	Group exercises and discussions	8
Compilation of the energy consumption and pollution emission inventory for the battery component manufacturing	Group exercises and discussions	8
Compilation of the energy consumption and pollution emission inventory for the battery assembly	Group exercises and discussions	8
Compilation of the energy consumption and pollution emission inventory for the battery usage	Group exercises and discussions	8
Compilation of the energy consumption and pollution emission inventory for the battery recycling	Group exercises and discussions	8
The environmental impact assessment based on the inventories	Lecture and group discussions	4
Tests on sustainability awareness, eco-design skill, and TPACK (see Section 3.3.2)	Test	2

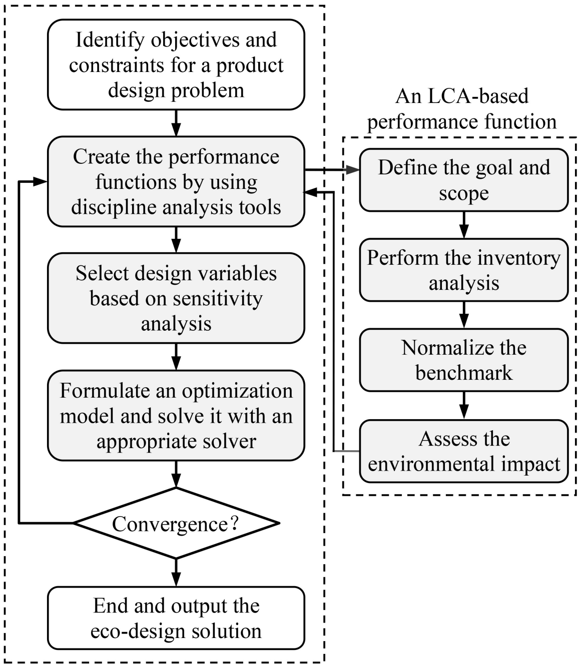

Fig. 3. A general structured eco-design framework.

the technological content knowledge of structured eco-design teaching method. The course also covered the extension of LCA training to the reliability assessment of product sustainability, multidisciplinary modeling involving sustainability, and other engineering fields. The stage of eco-design integration was carried out in a combination of lectures and discussions, and lasted four days (eight hours per day). The task was to discuss the LCA findings for the power battery and explore appropriate approaches for embedding eco-design concepts into conventional engineering courses. The course contents included three aspects: (1) feasibility analysis of the eco-design proposals, such as reducing the aluminum-plastic ratio of the battery package; (2) creating similar design-based learning environments by referring to the battery design task, such as laptops, sensor networks, and wind power systems; (3) expanding life cycle thinking in teaching for other engineering fields, such as reliability analysis, multidisciplinary modeling, and material development. On the last two days of the third stage, each teacher team shared a lecture (30 minutes) to deliver their engineering course with integrating eco-design and achieved peer feedback.

The course took the power battery as an example to establish a link between the eco-design and conventional product development, thereby creating a general structured eco-design framework, as shown in Fig. 3. For example, the battery LCA showed that the energy consumption of the aluminum extraction accounts for the largest proportion of all battery materials. Therefore, the aluminum-plastic ratio should be considered as the performance function for the product design optimization model. The environmental sustainability-oriented design methodology developed the participants' content knowledge. The course also included the content of establishing an eco-design learning environment, which helped participants develop appropriate teaching approaches and materials in their courses. The learning environment was improved from the existing approach [30] and conformed to the five-dimensional framework. It strengthened the participants' technological content knowledge. In the expansion of eco-design instruction, we guided participants to package the LCA into a performance function with parameterized inputs and outputs, then embed it into the original discipline analysis framework. As a result, their engineering course achieved sustainability-oriented improvements. Table 5 lists the course contents and time allocation in the third stage.

3.3 Research Design

3.3.1 Procedure

The program first tests participants' sustainability awareness, eco-design skill, and TPACK competency. The test results were considered as the pre-test data. The post-test data came from the three similar tests at the end of the program. Besides, the

Table 5. Teaching contents and time allocation in the third stage

Learning contents	**Activity**	**Hours**
Feasibility analysis of the ecological design proposal for the power battery	Expert guidance and group discussion	4
To create eco-design-based learning environments by referring to the battery design task	Group discussions	4
Expanding life cycle thinking in the teaching of other engineering fields	Group discussions	4
Lecture preparation to teach their engineering course with integrating eco-design	Group exercises and discussions	4
Lectures provided by the participants to teach their engineering course with integrating eco-design for gaining peer feedback and engaging in reflection	Lectures and discussions	12
Tests on sustainability awareness, eco-design skill, and TPACK (see Section 3.3.2)	Test	2
The reflective essay on their eco-design learning experiences (see Section 3.3.2)	Self-report	2

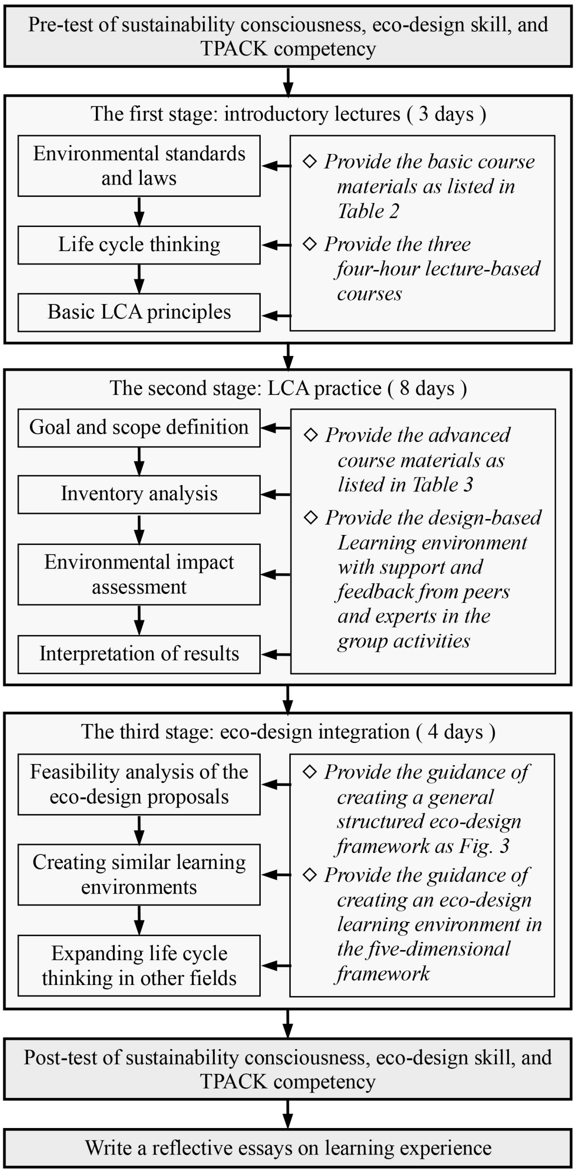

Fig. 4. The procedure of the experimental study.

participants were required to submit a reflective essay within two days after the program. Fig. 4 presents the procedure of the experimental study.

3.3.2 Measures

Three tests of sustainability awareness, eco-design skill, and TPACK competency were adopted as instruments. Also, we investigated the contribution of each stage in the program to the participants' improvement through their reflective essays.

(1) Sustainability awareness test

A sustainability awareness test was a self-reported questionnaire. The test items were modified from the questionnaire proposed by Gericke et al. [31], which can measure individuals' sustainability awareness in the dimensions of environment, society, and economics. Considering the context of product eco-design, we selected twenty items from the environmental and economic dimensions to construct our questionnaire (see Appendix A). We then revised three items by changing the water consumption to energy consumption. The participants responded to the items on a five-point scale, i.e., 1 point for totally disagree $\sim$ 5 points for totally agree. The overall consistency values were measured by Cronbach's alpha (α_c), i.e., 0.64 and 0.72 for the pre-and post-test.

(2) Eco-design skill test

The eco-design skill test involved twenty closed-ended questions and four open-ended questions [4]. The instrument was developed based on Bloom's framework, and its reliability was verified. The questions were slightly modified according to the context of the power battery, as listed in Appendix B. The scoring criteria for closed-ended questions were 5 points for a correct answer, 2 points for no answers, and 1 point for an incorrect answer. The reason for choosing the criteria of distinguishing no answer and an incorrect answer was to prevent participants from guessing, thereby improving the validity. The score of open-ended questions ranged from 1 point for no answer to 5 points for a complete answer. For reducing the subjectivity, each answer sheet was scored by two researchers separately and the average score was taken as the test result. The closed-ended and open-ended questions accounted for 60% and 40% of the test scores. The α_c values for the two tests were 0.60 and 0.70, respectively.

(3) TPACK test

The instrument was developed by Scott and Nimon [32], validated with a sample of 1299 college teachers. We used it to evaluate the four TPACK elements of content knowledge, pedagogical content knowledge, technological content knowledge, and TPACK. For the TPACK elements in the context, we specified the eco-design concepts and LCA skills as the content and technology, respectively. Thus, several items were modified, as listed in Appendix C. Each item was scored on a 5-point scale, i.e., 1 point for totally disagree $\sim$ 5 points for totally agree. The overall consistency for the pre- and post-test was verified by $\alpha_c = 0.69$ and $\alpha_c = 0.60$, respectively.

(4) Reflective essays on learning experience

Participants were required to submit a 500-word essay for reflecting on their learning experience at the end of this program. The content included the eco-design methods and tools learned, the most helpful or interesting courses, the challenges encountered and the means to overcome them, and how to integrate the eco-design into their engineering courses for students' sustainability competency enhancement. By analyzing the reflective essays, we determined the participants' perceptions on the teacher training program and the relationship between participants' improvement and the courses implemented in the program.

3.4 Data Analysis

We employed the repeated-measures and pairwise comparisons of the pre-and post-test on the sustainability awareness, eco-design skill, and TPACK to investigate the performance of the teacher training program. The effect size, i.e., partial eta squared (η_p^2), was calculated for each analysis to measure the significance of differences between the two test results. A value of $\eta_p^2 \geq 0.14$ denotes a large effect size [33].

The analysis of reflective essays was carried out in the following steps. Firstly, we searched for the improvement-related instances mentioned by the participants, including sustainability awareness, eco-design skills, and teaching approaches for sustainability competency enhancement. Secondly, we determined the sources of the improvements, and categorized them based on the four TPACK elements. Thirdly, two researchers coded the reflective essays to verify the inter-coder reliability. The consistency between the two code results was measured by Cohen's Kappa (κ_c). $\kappa_c \geq 0.6$ was considered acceptable consistency. The researchers discussed the inconsistent codes until achieving a consensus.

4. Findings

4.1 Test Results of Sustainability Awareness and Eco-Design Skill

The findings of the sustainability awareness test scores are listed in Table 6. The pairwise comparisons indicate a significant improvement through the teacher training program, and the mean score increases from 2.97 in the pre-test to 3.50 in the post-test. $\eta_p^2 = 0.18$ means a large effect size.

Similar to the sustainability awareness test, the pairwise comparisons show a significant improvement in the eco-design skill test. The mean score increases from 2.36 in the pre-test to 3.59 in the post-test. Correspondingly, the $\eta_p^2 = 0.18$ value is 0.55.

52.9% (45/85) of participants have a doctorate, and this proportion is higher than the university average. Considering high-educated teachers might have better understanding and motivation, we analyzed the results, excluding the scores of the participants with a doctorate. The results of the remaining forty participants are listed in Table 7, which also suggest significant improvements in sustainability awareness and eco-design skill. The η_p^2 values of 0.18 and 0.55 present large effect sizes.

4.2 TPACK Test Results

The analysis results of the TPACK test scores are shown in Table 8. It suggests that the participants achieved significant improvements through the teacher training program in the four elements of content knowledge, pedagogical content knowl-

Table 6. The test scores comparison for all participants

Measure	**Pre-test mean (standard deviation)**	**Post-test mean (standard deviation)**	**F-value**	**P-value**	**Effect size (η_p^2)**
Sustainability awareness	2.97 (0.52)	3.50 (0.62)	36.40	<0.05	0.18
Eco-design skill	2.36 (0.48)	3.59 (0.62)	208.18	<0.05	0.55

Table 7. The test scores comparison for the participants without a doctorate

Measure	**Pre-test mean (standard deviation)**	**Post-test mean (standard deviation)**	**F-value**	**P-value**	**Effect size (η_p^2)**
Sustainability awareness	3.02 (0.50)	3.58 (0.60)	22.39	<0.05	0.20
Eco-design skill	2.38 (0.46)	3.61 (0.61)	117.33	<0.05	0.57

Table 8. The test scores comparison of TPACK for all participants

TPACK Elements	**Pre-test mean (standard deviation)**	**Post-test mean (standard deviation)**	**F-value**	**P-value**	**Effect size (η_p^2)**
Content knowledge	3.00 (0.62)	3.82 (0.68)	69.06	<0.05	0.29
Pedagogical content knowledge	2.54 (0.65)	3.53 (0.65)	102.60	<0.05	0.38
Technological content knowledge	2.45 (0.55)	3.60 (0.65)	155.14	<0.05	0.48
TPACK	2.63 (0.67)	3.67 (0.65)	106.01	<0.05	0.39
Overall	2.66 (0.45)	3.66 (0.44)	216.85	<0.05	0.56

edge, technological content knowledge, and TPACK. The η_p^2 values for the four elements all exceed 0.14, indicating large effects.

We also analyzed the TPACK test scores excluding participants with a doctorate, and the results are presented in Table 9. Significant improvements with $\eta_p^2 > 0.14$ were found in the four TPACK elements, consistent with those of the full sample analysis.

4.3 Reflective Essay Analysis

The Cohen's kappa (κ_c) was employed to measure the improvements mentioned in participants' reflective essays. The result of $\kappa_c = 0.89$ indicates the participants' consistent perception on their improvements. 85.9% (73/85) of the essays said that the improvements were related to practicing and teaching the LCA-based eco-design. Therefore, we divided the possible improvement sources into three categories to facilitate statistics: the LCA practice stage only, the eco-design integration stage only, and both of them. Table 10 lists the statistical results of the sources and instances extracted from the essays. The percentages of participants reporting their improvement attributable to the three categories were 18.9%, 21.2%, and 45.9%, respectively. The κ_c values were correspondingly 0.81, 0.84, and 0.79. The findings suggest that the two main improvement sources were the stages of LCA practice and eco-design integration.

Next, we categorized the participants' improvements into the four TPACK elements, and the analysis results are presented in Table 11. The reliability was verified by the values of $\kappa_c > 0.6$ for the four elements, i.e., 0.89, 0.83, 0.77, and 0.70, respectively. (1) In content knowledge and technological content knowledge, the improvements were mentioned in 30.6% and 24.7% of the essays. These improvements were related to the content-knowledge of eco-design and using the LCA method. (2) In pedagogical content knowledge, the participants reported their improvements in 55.3% of the essays, including the teaching goals of eco-design skill and the teaching approach of

Table 9. The test scores comparison of TPACK for the participants without a doctorate

TPACK Elements	Pre-test mean (standard deviation)	Post-test mean (standard deviation)	F-value	P-value	Effect size (η_p^2)
Content knowledge	3.05 (0.58)	3.83 (0.75)	30.16	<0.05	0.26
Pedagogical content knowledge	2.46 (0.50)	3.53 (0.66)	75.78	<0.05	0.46
Technological content knowledge	2.46 (0.52)	3.63 (0.58)	100.29	<0.05	0.53
TPACK	2.56 (0.65)	3.71 (0.64)	71.18	<0.05	0.45
Overall	2.63 (0.45)	3.67 (0.41)	153.33	<0.05	0.64

Table 10. Percentages of participants reporting their improvement sources

Source of improvement	Number (%)	Instances extracted from the essays
LCA practice	16 (18.9%)	The program has fundamentally changed my understanding of teaching sustainability. Now, I focus on cultivating students' life cycle thinking.
Eco-design integration	18 (21.2%)	I realized that the purpose of eco-design is not only to complete the LCA analysis of the product, but to embed it in our engineering curriculum.
LCA practice and eco-design integration	39 (45.9%)	My experience has taught me that eco-design is not only a concept, but also an engineering technology. It allows me to adjust the teaching method and understand the importance of sustainability.

Table 11. Percentages of participants' improvement in the TPACK framework

Source of improvement	Number (%)	Instances extracted from the essays
Content knowledge	26 (30.6%)	I learned about the relationship between environmental sustainability and eco-design, the LCA principles and the method of constructing an LCA learning environment.
Pedagogical content knowledge	21 (24.7%)	The biggest challenge is to establish a general functional unit. The LCA stages may involve different functional units, and they must be normalized into the same metric.
Technological content knowledge	47 (55.3%)	I often encounter problems when compiling an inventory of energy consumption and pollution emission. But through discussions with colleagues, my problem can be resolved.
TPACK	39 (45.9%)	Before the program, I taught the sustainability concepts in a direct way, which did not simulate students' desire to learn. Now, I learned that engineering skills are taught through a design-based learning environment and a general structured eco-design framework.

design-based learning. (3) 45.9% of the essays mentioned the improvements in TPACK, involving developing students' sustainability competency using the four-step LCA method to implement eco-design. Moreover, the participants reported the advantages of the design-based learning environment, which combined pedagogy and technology for teaching eco-design skills and provided instant feedback from peers and experts.

5. Discussions

This section discusses the three research questions outlined at the end of Section 2.

5.1 What were the Influences of the Teacher Training Program on the Participates' Sustainability Awareness and Eco-Design Skill?

The test results of the sustainability awareness and eco-design skill suggested the participants' significant improvements through the teacher training program. After excluding the participants' scores with a doctorate, the findings were similar to those of the full sample. This shows that the proposed program is conducive to enhancing the engineering teachers' sustainability competency in awareness and skills. The fact that most participants mentioned improvements in their reflective essays also supports the above conclusion. Moreover, our findings are in line with previous studies, which suggested sustainability awareness and eco-design skill was inherently consistent and mutually reinforcing [12].

Two essential features of the program are a real-context eco-design environment and a structured eco-design learning framework, which may be the potential reasons for the benefits. According to the discussions in Section 2.3, the lack of engineering knowledge and eco-design skills hinders the teachers' sustainability competency development. The basic materials of general concepts and advanced materials based on the real context were provided to the participants, which helped them build prior knowledge of environmental sustainability and deepen their understanding of eco-design concepts. The structured LCA framework provided participants with a scaffold to implement eco-design for the actual design problem. The participants applied the four-step LCA method to evaluate the energy consumption and pollution emissions during the product life cycle, thereby reflecting the reasons behind the eco-design decisions. The reflection might prompt them to select materials and processes with a lower impact on the environment and observe corresponding outcomes. In comparison, the common eco-design guidelines may be over general for a real-world challenge and cannot guide novices to obtain a feasible design solution step by step [2, 15]. This might explain the significant improvements in the participants' sustainability awareness and eco-design skill.

In the program, the participants gained support and feedback from peers and experts when using the LCA method to implement eco-design. They implemented an iterative design and explored various solutions in which the structure, material, process, and usage together affect the environment. The experience may prompt them to consider environmental factors in product design spontaneously. The findings seem to support the previous study [34] that suggested an instant feedback learning environment could enable students to learn continually until reaching a certain level of achievement or organizing their knowledge in a meaningful way.

5.2 What were the Influences of the Teacher Training Program on the Participates' Competency on the Four TPACK Elements?

The TPACK test results indicated participants' significant improvements in the four TPACK elements by analyzing the full sample and the partial sample. The content knowledge refers to participants' understanding of product sustainability and eco-design practices. Thus, the test results of sustainability awareness and eco-design skill can explain and measure participants' improvements in the element of content knowledge. The objective tests are essential for evaluating the program performance because previous literature relies heavily on self-assessment instruments [35].

The technological content knowledge is related to the content knowledge of eco-design skills combined with the structured LCA method. The LCA task on the power battery product was employed in the second stage. The participants experienced eight days for the hands-on eco-design task with advanced materials (see Table 3). In the third stage, the participants practiced integrating eco-design concepts into the conventional product design framework and provided a lecture to teach their engineering course with integrating eco-design. These activities seemingly explained the significant improvement in the participants' understanding of the structured LCA method, and thus the enhancement in their technological content knowledge.

The pedagogical content knowledge focuses on teaching eco-design without using technologies. Building an instant feedback learning environment is a critical non-technical teaching approach in the program. The environment provides learners with just-in-time informative and constructive feedback, thus enhancing expertise and facilitate understanding through the conscious and unconscious process

[5]. Instant feedbacks were employed in the stages of LCA practice and eco-design integration, which seemingly explained participants' improvement in the element of pedagogical content knowledge. In the third stage, each teaching team delivered their engineering course, which was a non-technological teaching approach in a technological context. It may also contribute to the improvement.

The TPACK refers to using technologies to teach eco-design for fostering sustainability competency with appropriate approaches. The improvement in the element of TPACK might be explained by the course contents in the second and third stages. The contents covered the advanced materials and discussions of teaching approaches. For example, the participants were instructed to develop their eco-design teaching frameworks by referring to the battery design task. They were further guided to expanding life cycle thinking into the teaching of other engineering fields, such as packaging the LCA process into a parameterized function for embedding it into the original discipline analysis framework. Therefore, the structured teaching framework was used to encourage participants to actively engage in the learning process for their sustainability competency enhancement. It is a typical learner-centered teaching style [36], contributing to the participants' TPACK improvement.

5.3 5.3. What were the Participants' Perceptions on their Improvement throughout the Teacher Training Program?

The analysis of the reflective essays shows that the participants developed a consistent perception on their improvements through the teacher training program. They reported the two primary improvement sources were the stages of LCA practice and eco-design integration (see Table 10). The former created the design-based learning environment based on a real eco-design problem. The latter emphasized the learner-centered teaching style. Our findings lend support to previous studies that found the combination of advanced pedagogies promotes learner motivation and high-order thinking by encouraging them to reorganize knowledge between multidisciplinary concepts [37].

The findings also implied the participants' positive attitudes towards the competency enhancement in the four TPACK elements (see Table 11). The third stage focused on guiding participants to create their structured LCA analysis and teaching frameworks, which was the expansion and application of the eco-design skills learned in the second stage. Most participants reflected on the challenges encountered and the ways to overcome them during the learning experience. It implies that a high percentage of participants had a strong learning motivation for the courses. Most participants' reflective essays mentioned the intention to integrate the eco-design in their engineering courses and apply the advanced pedagogies learned. The findings seem to reflect previous literature [38] that suggested the benefits of design-based learning in teachers' TPACK competency through combing pedagogy and technology for teaching engineering abilities.

6. Limitations

The limitation of the experimental study lies in the flaws in the participants' representation for engineering teachers in education level, All participants had a master's degree or above, and 52.9% (45/85) of them had a doctorate. The highly educated participants might have a better understanding and a stronger desire to learn. However, the situation of well-prepared sustainability education and the availability of highly educated teachers does not fully represent all colleges and universities, especially local colleges and vocational colleges. Thus, we cannot confirm the performance of the teacher training program for all engineering teachers without implementing further investigation.

7. Conclusions

This experimental study proposes and performs a teacher training program for engineering teachers' sustainability competency enhancement at the higher education level. The contribution of this study is to provide experimental evidence of a practicable teacher training program in sustainability competency, responding to the sustainability concern of high-quality teacher professional development in sustainability competency. The proposed program follows the general paradigm of teacher professional development by focusing on content knowledge and pedagogy. The eco-design learning environment was provided with peer collaboration and feedback for eco-design practice and teaching. The participants were encouraged to implement product eco-design in an engineering context for practicing the content knowledge and structured teaching framework.

The experimental evidence suggested as follows. Firstly, the program significantly improves the participants' sustainability awareness and eco-design skill. Secondly, the participants' competency in the four TPACK elements was also considerably enhanced. Thirdly, the participants' self-reflection on the learning experience further demonstrates the correlation between their improvements and the program's features. The analysis results combined the objective tests and self-evaluations. Thus, it is more reliable than those relying entirely on self-assessment instruments. In conclusion, the proposed program can develop engineering teachers' competency to perform sustainability education by integrating eco-design into conventional engineering courses. Moreover, it is also vital to develop sustainability competencies in non-engineering education, which is our future research direction.

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Appendices

Appendices A–C to this article can be found online at:
https://1drv.ms/b/s!AmCJ9up6V-Szay3KwFN9JHKXGVY

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