Eco-design learning framework on integrating life cycle assessment into engineering courses for sustainability competency enhancement

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ABSTRACT This empirical study aims to construct and evaluate an eco-design learning framework to help instructors design practical teaching in engineering curricula and enhance the sustainability competency of engineering undergraduates. The framework was designed into three phases, including introductory lecture, life cycle assessment (LCA) practice, and eco-design embedding. The formative reflection on the previous phase was analyzed to provide suggestions for the next phase of teaching settings, thereby forming an iterative mechanism. A structured design flowchart, technical documents, and LCA toolkit were provided as scaffolding for students to implement eco-design. The immediate feedback learning environment helped students overcome challenges in the eco-design practice. The experimental findings suggested that the participants had good learning initiative in the learning process, and the deep learning needs were synchronized with the three-phase curriculum. The curriculum improved participants' sustainability competency in terms of environmental consciousness and eco-design skills. Participants' overall reflection on the curriculum showed that the improvements were related to the teaching materials, curriculum settings, and learning environment involved in the eco-design learning framework. Also, the limitations and future research directions were discussed.

INDEX TERMS Engineering curriculum; Sustainability competency; Eco-design learning; Life cycle assessment; Teaching approach

I. INTRODUCTION

The industry’s demand for engineers and managers with sustainability competency is increasing. In colleges and universities, sustainability competency development has become one of the main goals of engineering curricula [1]. For improving the sustainability competency of engineering undergraduates, it is necessary to guide them to regard product sustainability as an essential part of the design process. An appropriate approach to integrating sustainability competency training into professional core curricula is essential to guide students to establish a direct link between design solutions and sustainability outcomes in engineering applications [2]. The learning environment construction and the design tool selection are two critical elements for developing a sustainability teaching approach to enhance students' environmental consciousness and design skills.

Design-based learning provides students with a learning environment with engineering context, customer-driven, and open-end, improving students’ conceptual understanding and problem-solving skills [3]. Different from the traditional lecture-based classrooms, the design-based learning environment encourages students to apply advanced design tools and structured design flowcharts to solve real-world challenges, discuss and reflect on the learning experiences and gains. Design-based learning is developed from two active learning approaches, problem-based learning and project-oriented learning [4]. It is widely used in engineering curricula and proved to be an effective practical teaching approach for professional skill enhancement [5]. Solving complex problems, such as product sustainability design, requires applying multidisciplinary principles and professional skills, which are best learned from doing. A well-constructed learning
framework guides students through the phases of definition, analysis, evaluation, and productization, which are highly related to sustainability competency. Eco-design methods are developed in response to sustainability policies adopted by national and international organizations and are widely disseminated in academic literature [6]. Eco-design is defined as integrating environmental factors into product development, aiming to reduce the adverse impact on the environment throughout the product life cycle [7]. Therefore, the eco-design learning framework seems to be a promising approach for improving individual sustainability competency.

Creating an eco-design learning framework in engineering curricula faces several technical challenges. Firstly, conventional eco-design principles are generalized, and practical teaching requires operational eco-design tools integrated with the existing design flowchart. Secondly, the examples in the current textbooks are abstract and fragmented, and it is urgent to absorb eco-design problems with multidisciplinary principles and engineering contexts. Practical eco-design tools and real engineering challenges are the key elements for constructing an efficient eco-design learning framework. Life cycle assessment (LCA) is a mature tool for eco-design and environmental sustainability. It is widely used to evaluate material/energy consumption and environmental pollution during product design and manufacturing [8]. The LCA is expected to become a potential learning tool supporting the eco-design learning framework. However, there is little literature on applying LCA in engineering curricula, especially the teaching researches that integrate the LCA with the existing structured design flowchart.

This study explores how to integrate existing LCA design tools to enhance the eco-design learning effect and support the sustainability competency development in engineering education. The purpose of this study is not only to examine an instructional design to highlight its significant effects, but also to explore a general eco-design learning framework suitable for engineering curricula. We follow the empirical research paradigm and propose practical solutions through iterative experimental design to respond to the real challenges faced by engineering education. Thus, it bridges the gap between educational theory and teaching practice. This paper explores the following research questions.

1. How to construct an eco-design learning framework for teaching sustainability competency?

2. How do participants view the sustainability practice teaching under the eco-design learning framework?

3. How does the eco-design learning framework strengthen environmental consciousness and eco-design skills?

The rest of this paper is structured as follows. Section 2 reviews the literature on sustainability teaching, design-based learning, and eco-design methods. Section 3 proposes an eco-design learning framework, including the teaching materials, measures, and procedures. Section 4 performs data analysis on learning effects. Section 5 discusses and answers the three research questions. Section 5 states the limitations. Section 7 draws the conclusions and points out the future research directions.

II. LITERATURE REVIEW

A. SUSTAINABILITY TEACHING IN ENGINEERING CURRICULA

Integrating sustainability teaching into conventional engineering curricula has become a consensus in the educational community. In engineering education, sustainability teaching can be roughly divided into the following three categories. The first category is to develop a new engineering curriculum with environmental sustainability as the core. For example, Cao et al. developed a sustainability curriculum for fashion designers. The curriculum focused on the scientific concepts behind textile-related ecological issues and the "cradle to cradle" design model [9]. Gross et al. presented a green chemistry and sustainability curriculum for undergraduates [10]. The curriculum introduced the twelve principles of green chemistry, organized as three themes of energy, safety and pollution. The second category is an autonomous learning environment with sustainable development contents. Gennett et al. proposed an educational computer game called "Shortfall", which simulates a business environment for exploring alternative paths related to the sustainability principles [11]. Faludi and Menter introduced a self-guided online learning system, i.e., Autodesk Sustainability Workshop, which involves principles and practical skills related to eco-design, mechanical engineering, and construction science [12]. The third category is to extend the sustainability principles to conventional engineering curricula. Brundiers et al. proposed a functional and progressive learning model for sustainability education, integrated into the undergraduate curricula to cultivate students' problem solving and work collaboration skills [13]. Ramanujan et al. explored a guided discovery instruction approach, integrating environmental sustainability into the mechanical engineering curriculum. It was conducive to promoting undergraduates' understanding of the complex relationship between design solutions and the resulting environmental impact [2].

However, sustainability learning encountered difficulties in the practical teaching of engineering education. It is difficult for students to integrate sustainability principles into engineering practices, and they face challenges in environmental awareness and professional skills. The challenge lies in their environmental consciousness and professional skills [14]. Olsen et al. suggested that engineering students should consciously consider environmental sustainability in engineering designs. But the issues of schedule, cost and organization limit the
possibilities [15]. Thus, it is necessary to develop an efficient sustainability learning framework for improving the environmental consciousness and practical skills of engineering students.

B. DESIGN-BASED LEARNING

As a teaching approach, design-based learning (DBL) encourages students to reflect on the learning process while solving real design problems [3]. The DBL generally gives a design task with an engineering context. In the DBL environment, students' conceptual understanding and practical skills are improved through the iterative process of problem definition, performance analysis, solution evaluation [16]. The DBL is partly derived from problem-oriented and project-based teaching approaches [4,5]. The difference is that the DBL focuses on integrating the discipline knowledge of science and engineering into an actual design task to guide students to a solution. Scoping, generating, evaluating and creating is the core links of the DBL environment, stimulating students' structured thinking and learning reflection [17]. Precious researches demonstrated the DBL advantages in improving systematic thinking, multidisciplinary applications, and collaboration capabilities [18,19].

Wijnen et al. summarized the six characteristics of efficient design activities, including specialization, activation, cooperation, authenticity, creativity, integration, and multidisciplinary [20]. Puente et al. described the DBL characteristics from five dimensions, i.e., task feature, teacher's role, solution evaluation, engineering context, and design elements [21]. Baran and Uygun presented the eight DBL principles [22], such as the design of technology integrated artefact, engagement with theoretical knowledge, reflection on design experiences, applying design in authentic settings, collaboration within design teams, etc. These outcomes were summarized from various empirical researches, providing a theoretical basis for creating efficient design activities to address the challenges of sustainability teaching. However, few empirical studies applied these theoretical frameworks to cultivate the sustainability competency of engineering students. The development of relevant teaching materials, curriculum programs and learning environments may fill this gap.

C. ECO-DESIGN AND LIFE CYCLE ASSESSMENT

Eco-design aims to reduce the adverse impact of product life cycle on the environment. The eco-design is interdisciplinary. It integrates environmental factors into product development, broadening the design space for engineers while increasing the design difficulties [23]. Product design is the core content of conventional engineering curricula and the main research direction of engineering teachers. Embedding eco-design into traditional design and forming a structured design flowchart is a potential teaching approach. As a scaffold for eco-design learning, it seems to be a promising tool for teaching and learning. The eco-design practice may help simulate students' environmental consciousness and eco-design skills, thereby developing their sustainability competency. Scholars have made fruitful attempts. Turner proposed and tested an eco-design strategy based on advanced systematic inventive thinking and applied it to the technology education classroom [24]. Lambrechts et al. studied the role of engineers' sustainability competency in the building eco-design and suggested that the aspects of strategic management, action, diversification, interdisciplinary, communication are critical [25].

The eco-design framework suitable for practical classrooms plays an essential role in the sustainability competency development of engineering undergraduates. However, the existing eco-design guidelines are too general to be employed as a learning scaffold in practical classrooms [7,26]. The LCA is widely used to calculate energy consumption and pollution emissions in product manufacturing and use processes [8]. In the industrial community, the LCA concept gradually penetrated product development. In the academic community, advanced design theory integrated with the LCA became a research hotspot [6]. In the educational community, scholars developed environmental sustainability and eco-design curricula based on the LCA principles [27,28]. Therefore, the LCA may be a potential learning tool for creating an eco-design learning framework.

III. METHODOLOGY

A. RESEARCH DESIGN

We performed empirical research on the eco-design learning framework in a real classroom. The curriculum was designed into three phases, i.e., introductory lectures, LCA practice, and eco-design embedding. Problem definition, curriculum setting, and reflection analysis were conducted for each phase. The findings of the previous phase provided suggestions for the next phase. Thus, the empirical research was a sequential iterative process, as shown in Figure 1.

Before performing the experiment, a literature review was conducted to discover the issues of sustainability teaching in engineering education. For addressing the issues, we further reviewed the literature on the DBL and eco-design methods. In the first phase, environmental regulations, eco-design guidelines and LCA tools were introduced to build the participants' concepts. The issue of using the LCA tools to practice eco-design on an actual product emerged. Thus, the second phase focused on guiding participants to use the LCA tools to analyze the impact of a product life cycle on the environment. The issue of how to integrate the LCA into the conventional design was found. To this end, the focus of the third phase was to establish a structured product design flowchart embedded with the LCA tools. The researchers collected research data by environmental consciousness test,
eco-design skill test, formative reflection, and overall reflection.

| Literature review and previous experience analysis |
|--------------------------------------------------|
| Pre-test of sustainability consciousness and eco-design skill |
| Issue: how to create an eco-design learning environment in an engineering curriculum |
| Phase_1: introductory lectures / 3 days |
| Issue: how to use the LCA tools to practice eco-design on a real product |
| Phase_2: LCA practice / 8 days |
| Issue: how to integrate the LCA into the conventional design flowchart |
| Phase_3: eco-design embedded / 4 days |
| Post-test of sustainability consciousness and eco-design skill |
| Write an essay of overall reflection on the curriculum |

FIGURE 1. The implementation procedure of the empirical research

B. CURRICULUM AND PARTICIPANTS IN THE EXPERIMENT

The curriculum of Computer-Aided Analysis was selected to implement the empirical research. It is a core curriculum for undergraduates majoring in mechanical engineering, civil engineering, etc. The goal of the curriculum is to cultivate students' design skills based on numerical simulation. The course contains two teaching modules of theory and practice. The theory teaching toke lectures combined with example analysis as the primary teaching approach. In the practice teaching module, we carried out the empirical research on the eco-design learning framework.

The participants were junior undergraduates majoring in mechanical engineering. 154 participants contained 126 males (81.8%) and 28 females (18.2%) and came from four teaching classes. The participants' average age was 20.7 years, and the standard deviation is 0.62 years. The instructor team consisted of four full-time teachers and two engineering experts. The teachers had a doctorate in mechanical engineering, with an average teaching experience of 5.2 years. The experts came from the new energy field and were long engaged in smart product development. After explaining the research context, we obtained the informed consent of each participant in written form.

C. TEACHING MATERIALS

Teaching materials consist of three parts, i.e., a structured design flowchart, related technical documents, and an LCA toolkit. The structured design flowchart was developed by embedding the LCA into a conventional design, as shown in Figure 2. Conventional structural design formulates the optimization model, including defining design objective and constraint definition, performance function creation, and design variable selection. The objectives and constraints are determined by customer needs, characterized by performance functions based on discipline theory and simulation tools. The curriculum of Computer-Aided Analysis is to guide students to use the finite element method (FEM) to simulate structural performance. The LCA can evaluate the impact of the product life cycle on the environment and is also a structural performance analysis tool. Thus, the LCA has a similar role to the FEM in the design flowchart. The structured design flowchart embedded with the LCA was provided as teaching material.

FIGURE 2. An LCA-embedded structured design flowchart

A balancing vehicle was introduced as an engineering example for eco-design teaching. As shown in Figure 3, the vehicle life cycle includes five stages: raw material extraction, component manufacturing, product assembly, use, and recycling. The vehicle technical documents were provided as teaching materials, including performance parameters, manufacturing processes, three-dimensional models, and bills of materials. The impact of the balancing vehicle from "cradle to cradle" on the environment was analyzed by the LCA toolkit. The LCA analysis steps are 1) definition of goal and scope, 2) inventory analysis, 3) environmental impact assessment, and 4) interpretation of results. The goal is the
energy consumption and pollution emissions caused by an energy storage unit (kWh). The scope covers the five stages of the vehicle life cycle. The inventory analysis refers to the data collection on the consumption and pollution at various stages. Environmental impact assessment uses the inventory to classify and characterize the consumption and pollution in the life cycle. The interpretation of the results employs sensitivity and correlation analysis to extract variables that have a significant impact on the environment, providing evidence for design modelling. To facilitate students to master the LCA method, we provided an LCA toolkit, including the consumption and pollution algorithm, the unit normalization approach, and sensitivity/correlation analysis codes.

The eco-design skill test included twenty close-ended questions and four open-ended questions. The instrument was developed based on Bloom's framework, and its reliability was verified [30]. The questions were slightly modified according to the context of the balancing vehicle design. The scoring standard for closed questions is 5 points for correct answers, 2 points for no answers, and 1 point for incorrect answers. The distinction between no answer and wrong answer was to prevent participants from guessing, thereby ensuring validity. The scores for open-ended questions ranged from 1 point for no answer to 5 points for a complete answer. To reduce subjectivity, each answer sheet was scored by two researchers separately, and the average score was taken as the final score. The close-ended and open-ended questions account for 60% and 40% of the test scores, respectively.

3) FORMATIVE REFLECTION
During the curriculum, participants can submit their reflections through online documents at any time. To guide students to submit feedback actively, we provided formative reflection guidelines regarding experience, needs, and expectations. After each curriculum, the teachers urged participants in reflecting on learning contents, teaching approaches, and group collaboration. Also, the participants were encouraged to communicate with teachers through face-to-face, instant messaging, or email. At the end of each phase, the researchers summarized the feedback from the online documentation and direct communication. The researchers coded the raw data into different themes. These themes were designed for the curriculum iteration, including feedback on the curriculum content, teaching approach, and learning challenges.

4) OVERALL REFLECTION
Participants were required to submit a 600-word report to reflect on their learning experience at the end of the curriculum. The contents included the eco-design methods and tools learned, the beneficial or interesting curriculum, the challenges encountered and the ways to overcome them, and how to embed the LCA into conventional design. By analyzing the overall reflections, we determined the participants' views on the eco-design learning framework, and the correlation between the curriculum and the participants' improvements. Researchers conducted semantic analysis on curriculum reflection, and the coding themes were designed to respond to the research questions, including teaching materials, curriculum setting, and learning environment.

D. DATA COLLECTION
Environmental consciousness test, eco-design skill test, formative reflection, and overall reflection were employed to collect qualitative and quantitative data. This research tested participants' environmental consciousness and eco-design skills before and after the experiment. The test results were regarded as the data of pre-test and post-test. After each phase, the researchers analyze students' formative reflections. At the end of the curriculum, participants were asked to submit a reflection report on the curriculum.

1) ENVIRONMENTAL CONSCIOUSNESS TEST
The environmental consciousness test is a self-reported questionnaire. The test items are modified from the questionnaire proposed by Gericke et al., measuring the individual sustainability consciousness from three dimensions of environment, society and economy [29]. In the product eco-design context, we selected twelve items in the environmental dimension to establish the questionnaire of the environmental consciousness test. Participants answered the items on a five-point scale, i.e., 1 point (completely disagree) to 5 points (completely agree).

2) ECO-DESIGN SKILL TEST

FIGURE 3. An example of balancing vehicle for eco-design teaching
apply a four-step method for the LCA analysis on the balancing vehicle. The eco-design embedding trained participants to embed the LCA into the conventional design flowchart and implement structural optimization design of the balancing vehicle satisfying environmental sustainability.

1) PHASE_1: INTRODUCTORY LECTURE
Before Phase_1, we performed the eco-design skill pre-test on each participant. The average score of the pre-test was 2.12 points, indicating that their eco-design skills were at a low level. 8 participants (5.2%) did not answer any question in the pre-test. The unanswered sheets were scored as 1.2 points because no answer was scored as 2 points for the close-ended questions. 65 participants (42.2%) did not provide answers to the five closed questions about the LCA concepts and tools. 31 participants (20.1%) did not give any answers to the four open-ended questions. The results showed that participants lacked the necessary background knowledge of product eco-design, and they knew little about design tools.

The Phase_1 curriculum was defined as an introductory lecture, focusing on the eco-design principles and how to use LCA methods and tools. The eco-design principles were organized as 1) environmental standards and regulations related to product development and manufacturing, 2) life cycle thinking and how to embed it in the product development, 3) The basic principles of LCA methods and tools. Relevant materials were provided to participants for understanding the environmental sustainability knowledge and general eco-design methods. The Phase_1 curriculum lasted for three days (four hours per day). The materials and schedule are presented in Figure 4.

![FIGURE 4. The implementation procedure in the introductory lecture](image)

The analysis of the participants' formative reflection showed that 103 participants (66.9%) expressed an interest in environmental sustainability and ecological design. 93 participants (60.4%) said that LCA was a useful eco-design tool. 112 participants (72.7%) reported their concerns about completing a product eco-design on their own. 58 participants (37.7%) expected to use the LCA tools to solve a specific engineering problem. These findings suggested that the next phase should introduce a product design with engineering context and provide scaffolding to help participants practice eco-design. Establishing an immediate feedback learning environment may be the key to guiding participants to overcome learning challenges.

2) PHASE_2: LCA PRACTICE
Based on the suggestions of the Phase_1 outcomes, Phase_1 instructed participants to implement LCA for an actual problem in group collaboration. The problem was given as a balancing vehicle design, which was a challenge from the real world. A balancing vehicle is a typical smart product and familiar to participants. Compared with individual completion, group collaboration helps to reduce the learning burden of participants and gain peer support. Compared with individual completion, group collaboration was conducive to reducing the learning burden and achieving peer support. The scaffolding with the structured flowchart, technical documents, and practical algorithms was proposed to help participants overcome the challenges in LCA practice.

The structured LCA flowchart consists of four steps: 1) definition of goal and scope, 2) inventory analysis, 3) environmental impact assessment, and 4) interpretation of results. The technical documents of the balancing vehicle were provided to support students in defining the goal and scope, including performance parameters, manufacturing processes, three-dimensional models, and bills of materials. The consumption and pollution algorithms help participants perform inventory analysis and environmental impact assessment, such as the GREET model [31]. The normalization algorithm is given to achieve the equivalence between different measurement units, such as 1MMBtu = 293 kW·h. The data analysis methods for sensitivity and correlation were programmed as standard input/output functions to interpret results. The above documents, algorithms, and tools provide scaffolding for students to implement LCA analysis of the balancing vehicle. Group collaboration to practice LCA was the primary teaching approach at Phase_2. Teachers and engineering experts provided constructive feedback through individual guidance and concentrated teaching. Participants received peer support and suggestions in group collaboration. The scaffolding, expert guidance, and peer support were the core elements of...
the eco-design learning framework, which may help participants apply the LCA to perform the vehicle eco-design.

Phase_2 lasted for eight days (eight hours per day), and the implementation procedure was summarized in Figure 5.

The formative reflections in Phase_2 showed that 125 participants (81.2%) expressed an excellent sense of gain. 132 participants (85.7%) reported high levels of participation. 104 participants (67.5%) agreed that the scaffolding was sufficient to support them in LCA practice. 81 participants (52.6%) reported that the instructor guidance and peer support helped them overcome challenges. Forty-five participants (29.2%) expressed their confusion about using the LCA to obtain the eco-design solution. These findings pointed the way for the curriculum in the next phase. The immediate feedback learning environment was necessary for the professional skill enhancement. A structured eco-design flowchart embedded with the LCA analysis is what participants expected to learn.

3) PHASE_3: ECO-DESIGN EMBEDDING
The Phase_2 curriculum solved the issue of the LCA engineering application. The conclusion is that the practical scaffolding and the learning environment seem to be beneficial to enhance students' sense of gain and participation and enable them to master the LCA method. However, the LCA only assesses the impact on the environment during the product life cycle. How to train participants to apply the LCA outcomes in the conventional design for an eco-design solution was the issue to be addressed in Phase_3.

Phase_3 focused on integrating the eco-design concepts into conventional design and establishing a general structured eco-design flowchart, and finally obtaining the eco-design solution of the balancing vehicle. The curriculum contents included three aspects. 1) how to define the design objectives and constraints, 2) how to formulate the performance function based on the FEM and LCA, 3) how to create the structural design optimization model, 4) how to use existing algorithms to solve the optimization model. Defining goals and constraints was an open-end issue, determined by group discussion and expert suggestions. The FEM was the main content of the theory teaching module of Computer-Aided Analysis, and the LCA analysis was the Phase_2 learning outcome. The phase taught participants to program the LCA into a standard input/output function so for embedding it in the optimization model. The optimization modelling was realized by the commercial numerical analysis software (i.e., MATLAB), which provides algorithms [32], such as the quasi-Newton method, genetic algorithm, etc. The curriculum guided participants to operate the tool, avoided teaching complex algorithm principles and programming skills, thereby reducing the difficulty of learning. During the phase, participants still carried out the eco-design practice of the balancing vehicle in group collaboration. The immediate feedback learning environment with instructor guidance and peer support helped participants overcome challenges in design practice. The curriculum of eco-design embedding lasted four days. Figure 6 shows the specific implementation procedure.
The formative reflection shows that 98 participants (63.6%) had a keen interest in eco-design learning. 84 participants (54.5%) claimed that the eco-design was similar to conventional product design. 71 participants (46.1%) reported the plan of applying eco-design in the graduation project. 59 participants (38.3%) expected to introduce eco-design concepts in similar engineering curricula. The findings suggested that the eco-design teaching can be regarded as the content extension of Computer-Aided Analysis. Both LCA and FEM are numerical simulation technologies in essence, suitable for similar teaching and learning approaches. The key is to provide the general structured design flowchart and immediate feedback learning environment.

The three-phase experimental procedure is summarized as follows. In the proposed eco-design learning framework, the introductory lecture, LCA practice and eco-design embedding were not three independent teaching phases, but iterative. By analyzing the participants' formative reflections, the findings of the previous phase provided the basis for the curriculum settings in the next phase. Therefore, the eco-design learning framework may have better performance on students' sustainability competency improvement than conventional design-based learning.

IV. DATA ANALYSIS

This research performed the pre-test and post-test on participants' environmental consciousness and eco-design skill. The effect size () was used to assess the significance of the difference between the test results. means significant difference [33]. At the end of the curriculum, participants submitted an overall reflection report. Through semantic analysis, the qualitative data in the reflections was coded into different themes for understanding participants' views on the eco-design learning framework. The coding themes responded to the research questions, thus highlighting meaningful findings and future research directions. Two researchers implemented coding to ensure inner-coder reliability.

A. RESULTS OF THE ENVIRONMENTAL CONSCIOUSNESS TESTS

The environmental consciousness test results are listed in Table I. The average score of participants increased from 2.89 points in the pre-test to 3.52 points in the post-test, an increase of 21.8%. presented a large effect factor. The pairwise comparison suggested that the participants' environmental consciousness was significantly improved through the eco-design learning curriculum.

Participants came from four actual teaching classes. Data analysis was carried out separately for the four teaching classes, and the results were roughly the same as the overall analysis results. The environmental consciousness of each teaching class was improved by 20.2%, 22.1%, 23.5%, and 21.3%, respectively.

| Measure                  | Overall sample | Class_1 sample | Class_2 sample | Class_3 sample | Class_4 sample |
|--------------------------|----------------|----------------|----------------|----------------|----------------|
| Mean of pre-test scores  | 2.89           | 2.77           | 2.98           | 3.01           | 2.77           |
| Mean of post-test scores | 3.52           | 3.48           | 3.59           | 3.73           | 3.24           |
| Increase (%)             | 21.8%          | 25.6%          | 20.6%          | 24.1%          | 16.7%          |
| P-value                  | <0.05          | <0.05          | <0.05          | <0.05          | <0.05          |
| Effect size              | 0.18           | 0.19           | 0.17           | 0.19           | 0.17           |

B. RESULTS OF THE ECO-DESIGN SKILL TESTS

The eco-design skill test results are listed in Table 2. The average score of participants increased from 2.12 points in the pre-test to 3.58 points in the post-test, an increase of 68.9%. presents a large effect factor. The pairwise comparison shows that participants' eco-design skill was significantly improved through the eco-design learning curriculum.

The eco-design skill test contained four open-end questions. In the pre-test, 31 participants (20.1%) submitted completely blank answer sheets. In the post-test, the proportion decreased to 1.9%, and only three participants submitted blank answer sheets. The score statistics of open-end questions indicated that the average scores of the pre-test and post-test were 1.69 and 3.65, an increase of 116%. It further demonstrated the significant improvement of participants' eco-design skills.
### TABLE II

**THE COMPARISON OF ECO-DESIGN SKILL TEST RESULTS**

| Measure                     | All questions | Open-end questions |
|-----------------------------|---------------|--------------------|
| Mean of pre-test scores     | 2.12          | 1.69               |
| Mean of post-test scores    | 3.58          | 3.65               |
| Increase                    | 68.9%         | 116%               |
| Effect size \( \frac{2}{\pi l_p} \) | <0.05         | <0.05              |
| Effect size \( \frac{2}{\pi l_p} \) | 0.55          | 0.59               |

### C. Results of the overall reflection

151 (98.1%) participants mentioned improvement in their overall reflection reports. The improvements were related to the three coding themes of teaching materials, curriculum settings, and learning environment. In terms of teaching materials, 105 (68.2%) participants mentioned the structured design flowchart, 97 (63.0%) mentioned the technical documents, and 122 (79.2%) mentioned the LCA toolkit. In terms of curriculum settings, the number of participants who reported their improvements related to the three phases were 33 (21.4%), 109 (70.8), and 98 (63.6%), respectively. In terms of learning environment, 85 (55.2%) participants emphasized the help of instructor guidance, and 95 (61.7%) mentioned peer support. Table 4 lists the statistical results of the overall reflection and examples extracted from participants' statements.

### TABLE III

**THE STATISTICAL RESULTS OF THE OVERALL REFLECTION AND STATEMENT EXAMPLES**

| Theme               | Improvement resource | Number (%) | Examples extracted from the reflections                                                                 |
|---------------------|----------------------|------------|--------------------------------------------------------------------------------------------------------|
| Teaching materials  | structured design    | 105 (68.2%)| I smoothly completed the structural optimization design of the balancing vehicle step by step following the design flowchart. |
|                     | flowchart             |            | The technical documents of the balancing vehicle were comprehensive, which saved me the time of looking up information. |
|                     | technical documents   | 97 (63.0%) | The LCA toolkit was easy to use, and I can directly observe the analysis results of the energy consumption and pollution emissions. |
|                     | LCA toolkit           | 122 (79.2%)|                                                                                                        |
| Curriculum settings | Introductory lecture | 33 (21.4%) | The content of environmental sustainability was closely related to product design and helped me understand the basic concepts. |
|                     | LCA practice          | 109 (70.8%)| The design of the balancing vehicle is interesting, and the LCA analysis seems not as complicated as thought. |
|                     | Eco-design embedding  | 98 (63.6%) | I felt that it was similar to a conventional design, and it was enough to address the LCA analysis into a general performance function. |
| Learning environment | Instructor guidance   | 85 (55.2%) | I am not familiar with some concepts in the inventory analysis, and the teacher answered immediately. |
|                     | Peer support          | 95 (61.7%) | We divided the work according to the design flowchart, and we discussed solutions together when encountering difficulties |

### V. DISCUSSION

#### A. HOW TO CONSTRUCT AN ECO-DESIGN LEARNING FRAMEWORK FOR TEACHING SUSTAINABILITY COMPETENCY?

The eco-design learning framework was designed into three phases: introductory lecture, LCA practice, and eco-design embedding. The formative reflection analysis was performed after each phase, and the findings provided a basis for the curriculum settings in the next phase, forming the iteration mechanism. The structured design flowchart, related technical documents, and LCA toolkit were proposed as teaching materials for scaffolding to guild students to implement eco-design. The immediate feedback learning environment was a vital element of the eco-design learning framework, emphasizing constructive feedback and peer support in group collaboration.

The LCA method was selected as the eco-design learning tool, establishing a direct link between environmental impact and product design. The LCA toolkit is similar to the finite element analysis software, essentially a numerical simulation technique. The two played a similar role in the proposed structured eco-design flowchart, used to evaluate structural performance and establish standard input and output functions. Therefore, the eco-design teaching can be regarded as an improvement of the original engineering curriculum, rather than a subversion. This study integrated eco-design into the engineering curriculum to realize the practical teaching of individual sustainability competency development, providing an example for sustainability integration in engineering education.

#### B. HOW DO PARTICIPANTS VIEW THE SUSTAINABILITY PRACTICE TEACHING UNDER THE ECO-DESIGN LEARNING FRAMEWORK?
We observed participants' experience, needs and expectations of the eco-design learning through the formative reflections. In Phase_1, 66.9% of participants were interested in environmental sustainability and eco-design, indicating that they expected to understand the complex relationship between environmental impact and product design. 60.4% of participants agreed that the LCA method is a useful eco-design tool, and 37.7% of participants expressed their expectations for performing eco-design on a real product design. It shows that participants had a positive attitude towards integrating sustainability teaching in engineering curricula.

In Phase_2, 81.2% of participants reported that the LCA practice brought them a good sense of gain. 85.7% of participants reported that they actively participated in group collaboration to complete the LCA task. 67.5% of participants agreed that the scaffolding provided sufficient support for conducting LCA analysis. 52.6% of participants believed that the learning environment with instructor guidance and peer support helped them overcome learning challenges. 29.2% of participants further thought about guidance and peer support helped them overcome learning challenges. The immediate feedback, scaffolding contained in the learning environment significantly improved participants' learning motivation.

In Phase_3, 63.6% of participants expressed a strong interest in the product eco-design. 46.1% of participants had the plan of performing eco-design in their graduation project. 38.3% of participants expected to introduce the LCA concepts in other engineering curricula. It indicates that participants realized the sustainability competency enhancement in terms of consciousness and skill, reflecting their positive attitudes towards considering environmental factors in future product design.

In addition, the participants' learning needs were in-depth during the three phases. After Phase_1, participants expected to implement LCA analysis for a real product design. After Phase_2, participants expected to embed the LCA into the conventional design flowchart. After Phase_3, participants expected to get more opportunities to practice eco-design. The iteration of the three-phase curriculum promoted the learning need deepening. It is consistent with the literature on design-based research [34,35].

VI. LIMITATIONS
The first limitation is that the framework is difficult to be directly extended to the engineering curriculum without a practical teaching module. Because the courses selected for this experiment include theoretical and practical teaching modules. The practical teaching shares the learning outcomes in the theory teaching module, such as the conventional structured design. If the original curriculum lacks the content of a structured design flowchart, applying the eco-design learning framework may lead to a heavy learning burden. Another limitation is that participants may not fully represent engineering students because the experiment was in a real classroom learning scenario. All participants came from the same university majoring in mechanical engineering. Without further research, we cannot confirm whether the participant experience and expectations are representative.

C. HOW THE ECO-DESIGN LEARNING FRAMEWORK STRENGTHENS CONSCIOUSNESS AWARENESS AND ECO-DESIGN SKILLS?
The environmental consciousness test results supported that the eco-design learning framework significantly strengthened participants' environmental consciousness. The average score of the post-test increased by 21.8% compared with the pre-test. The analysis results of the four classes were similar to the overall analysis, excluding the possible sample difference. The eco-design skills test results suggested that participants were significantly improved through eco-design learning. The average score increased by 68.9%, and the average score of the four open-end questions increased by 116%. The eco-design learning framework enhanced the participants' sustainability competency in terms of consciousness and skill. The fact that the majority of participants reported their improvements in the overall reflection also supported the conclusions. Besides, the findings verify the conclusions of previous literature. Environmental consciousness and eco-design skill complement each other and are the key to individual sustainability competency development [36,37].

The teaching materials, curriculum settings, and learning environment in the eco-design learning framework supported the participants' improvements. In terms of teaching material, the technical documents helped participants establish prior knowledge of product eco-design, and the LCA toolkits helped participants understand the complex relationship between environmental impact and design solutions. The structured design flowchart guided participants to integrate the newly learned eco-design concepts into the familiar design flowchart. The teaching materials provided scaffolding for participants to practice eco-design. In terms of curriculum setting, from life cycle thinking to LCA application to product eco-design, the eco-design learning was deepened in practical teaching, gradually prompting participants' eco-design skills. Applying LCA to evaluate consumption and emissions and making design decisions was conductive to foster their environmental consciousness. In terms of learning environment, participants implemented design optimization on the actual design problem and explored various solutions to minimize the environmental impact resulted from the product life cycle. When encountering challenges, participants received instructor guidance and peer support. The immediate feedback learning environment helped improve participants' sense of gain and participation, thereby realizing active learning. The findings are consistent with the conclusions of existing literature [38,39].
findings apply to engineering undergraduates in other majors and regions.

VI. CONCLUSIONS
This empirical study proposes and examines an eco-design learning framework, which helps teachers build an efficient practice learning environment for engineering curricula and enhance the sustainability competency of engineering undergraduates. The contribution of this work is to provide experimental evidence for embedding eco-design learning into conventional engineering curricula in response to concerns about sustainability teaching in engineering education. The proposed framework follows the general paradigm of students' professional skill development, focusing on teaching materials, curriculum settings and learning environment. The teaching materials, including a structured design flowchart, related technical documents, and LCA toolkits were provided as scaffolding for students to implement eco-design. The iterative three-phase curriculum drove students' learning needs deeper. The immediate feedback learning environment helped students overcome the challenges in the eco-design procedure.

The experimental evidence suggests the following conclusions. Firstly, participants had a positive attitude towards integrating sustainability teaching into conventional engineering curricula and were interested in the product structural optimization involving eco-design. Secondly, the elements of engineering application, immediate feedback, scaffolding in the eco-design learning environment enhanced participants' participation and sense of gain, thereby achieving active learning. Thirdly, the eco-design learning framework significantly improved participants' environmental consciousness and eco-design skills, strengthening their sustainability competency. The teaching materials, curriculum settings and learning environment in the proposed framework played an essential role in supporting the improvements. In short, the eco-design learning framework provides an efficient teaching approach for integrating sustainability competency development in undergraduate engineering curricula. Also, it is essential to implement sustainability teaching in other engineering education such as graduate education and vocational education. Extending eco-design learning to these fields and building an effective learning environment are our future research directions.

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