

Article

A Design-Based Learning Approach for Fostering Sustainability Competency in Engineering Education

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Abstract: This paper provides and illustrates a design-based learning (DBL) approach for fostering individual sustainability competency in engineering education. We performed two studies with engineering students in typical educational activities. The first study helped students perform a topic-specific design task in the practicum unit of a sensor technology course, which compared the performance of the DBL approach and conventional passive learning approach. The second study guided students to develop innovative projects for participating in the "Internet Plus" Innovation and Entrepreneurship Competition (IPIEC). To validate the proposed approach, stakeholder questionnaires and performance evaluations were implemented. The results show that the DBL approach was viable for sustainability competency teaching in terms of learning demand and teaching procedure. We found that students in the DBL group gave more prominence in the individual competencies, such as system-thinking, multidisciplinary applications, and collaboration. These findings suggest that applying the DBL approach to train sustainability competency in engineering education is beneficial for promoting students' abilities in dealing with challenges involved in sustainability practice.

Keywords: sustainability education; design-based learning; individual competency; engineering education

1. Introduction

The emerging academic field focused on sustainability has been engaged in the studies of pedagogies to foster practitioners' competencies for corporation sustainable development. Global leaders integrated 17 goals into the Sustainable development agenda: 2030 [1], such as poverty, education, sustainable economic growth, renewable consumption, production, etc. These goals are rooted in exploring solutions to extensive social challenges around the world. Maximizing the contribution of science, technology, and innovation is critical to achieving the sustainability goals. Considering the value-oriented, outcome-motivated nature of sustainability, previous literature [2–6] has established a link between sustainability education and transformative learning. Its basic idea is to motivate change that addresses complex problems involved in the sustainability goals [7]. Strategic and operational decisions are generally taken at the individual level or the team level of individuals. Thus, individual competency of practitioners is essential for achieving the sustainability goals. Wiek et al. [8] suggested a framework of key individual competencies for sustainability, including system-thinking, embracing diversity and interdisciplinarity, interpersonal competence, action competence, and strategic management. Wesselink et al. [9] linked these competencies to core tasks in business sustainable practices and figured out research directions for developing individual sustainability competency in both academic and business communities. Consequently, there is a call for studies on exploring practical pedagogical approaches to promoting students' sustainability competency in engineering education.

Design-based learning is a constructivist pedagogy that inspires students to solve real-life challenges and reflect on the learning process by applying design activities. It has proven to be an effective approach for acquiring engineering expertise [10]. Building on theories in constructivism, the integration of principles and skills required for complex problems (e.g., sustainable practices) can best be learned by doing. The transition towards more learner-centered curricula has become a worldwide trend in engineering education [11]. As a result, an increasing interest emerged in both problem-based learning and project-oriented learning [12,13]. The design-based learning was developed from the two active learning approaches, borrowing the principles of learner-centered pedagogy [14]. Similar to dealing with sustainability challenges involved in a design task, a well-designed design-based learning activity guides students through the stages of orientation, communication, implementation, and productization, which are highly relevant to the students' competencies. Therefore, the design-based learning seems to be a promising approach for developing ISC in engineering education.

In contrast to previous efforts, this paper focuses on proposing a design-based learning (DBL) approach to fostering students' sustainability competency, which includes not only teaching procedures, but also performance evaluations. We conducted two studies with engineering undergraduates by applying the proposed design-based learning (DBL) approach in two educational programs, a sensor technology course and an innovation project. This paper will explore three primary research questions, as follows.

- Is the DBL approach viable for fostering students' sustainability competency in existing educational programs?
- What are the stakeholders' perceptions of using the DBL approach for training individual competency?
- What are the effects of the DBL approach on the development of individual competency?

The paper is organized as follows. The second section gives a background on sustainability competency and DBL. The third section proposes the DBL approach, including materials, procedures, and measures. The fourth section outlines the findings. The fifth section discusses the three research questions based on results from our studies. The sixth section presents the conclusion and further research directions.

2. Background

2.1. Key Competencies in Sustainability

The business community is playing a pivotal role in sustainable development, as enterprises increasingly acknowledge the importance of responsible and sustainable practices to their legitimacy and competitiveness [15]. Enterprises voluntarily combine their economic benefits with environmental and social concerns when formulating business strategies [16]. Such voluntary action has the potential to enhance their business competitiveness. However, the problems like environmental protection, employment promotion, and industrial upgrading cannot be addressed in a unilateral way. That is, a company's sustainable development usually faces various challenges, where each problem should be analyzed in its specific context and time frame [17]. The complexity involved in sustainable practice further increases due to the often conflicting values and standpoints between multiple stakeholders, such as enterprises, governments, and non-governmental organizations [18].

In a company, practitioners (e.g., managers, engineers) address these complex problems in sustainability through innovative efforts. Hesselbarth and Schaltegger [19] called them "change agents", and they emphasized the importance of individual competencies for advancing the flexibility and adaptability of business operations to meet changing challenges in sustainable development. Over the past few years, ISC training has received increasing attention in both academic and business practices. A series of sustainability competencies [8,20] is summarized as system-thinking, embracing diversity and interdisciplinarity, action, interpersonal communication, strategic management, etc.

Considering that these competencies find their origins in educational literature, Wesselink et al. [9] empirically explore the abilities as to which of them facilitate practitioners to implement core tasks in a specific context and time frame. Lans et al. [21] identified the competency frame constituting the heart of sustainable entrepreneurship, and revealed the feasibility of developing these competencies in higher education. Hermann and Bossle [22] proposed a pedagogical frame based on bibliometric analysis to cultivate students' entrepreneurial competencies in business education.

Current studies mainly concentrated on the conceptualization of sustainability competency and the content of sustainability in business education. As promoters of technology research and development, engineers and business managers are equally important for achieving a corporation's sustainability. However, a research gap still exists in developing practicable pedagogies to foster students' ISCs in engineering education.

2.2. Design-Based Learning Pedagogy

Design-based learning (DBL) was initially proposed by Gijsselaers in 1996, based on a problem-oriented and project-based learning model [23]. Wijnen et al. [24] highlighted six characteristics of a well-designed DBL activity, including professionalization, activation, cooperation, authenticity, creativity, integration, and multidisciplinary. This work suggested directions for further developing and integrating the DBL within educational programs. Puente et al. [25] framed the DBL characteristics in five dimensions, thereby also improving its definition. Table 1 gives a summary of the DBL characteristics.

These characteristics of DBL were summarized from various empirical studies on DBL-similar practices in engineering education. Consequently, these defined characteristics were taken as a theoretical construct to create a DBL activity, and a few studies began to emerge. Swan et al. [26] explored a collaborative, design-based approach to improving the learning effects in core courses of an online program. Gómez Puente et al. [27] boosted teachers to use the DBL theoretical framework to create teaching activities and proposed an immersive learning model to enhance teachers' professionalism. Baran and Uygun [28] outlined eight DBL principles to foster the competency of translating technological, pedagogical, and content knowledge into action in teacher education contexts. Royalty [29] presented a design-based teaching framework and cataloged a series of relevant variables gathered from senior engineers and design-thinking teachers. Qattawi et al. [30] discussed the DBL implementation by combining engineering design theories with cooperative learning skills.

Existing research exhibits the potential benefits of DBL for promoting the competencies of system-thinking, multidisciplinary applications, and collaboration. However, it is still not enough to prove that the DBL is an appropriate and practical tool for teaching sustainability competency in engineering education. Firstly, it requires further measuring of the teaching effects on the ability to handle complex problems in sustainability. Secondly, there exist challenges in integrating DBL activities into traditional engineering courses, such as conflicts with existing instruction objectives and schedules. Furthermore, to the best of our knowledge, previous research on exploring practical DBL approaches to developing the sustainability competencies of engineering students is very little.

Table 1. Design-based learning (DBL) characteristics in five dimensions [25].

Dimensions	Characteristics	Examples
Project characteristics	Open-ended Authentic Hands-on Multidisciplinary	Project vaguely formulated, no unique solution is encouraged. Assignments represent real-life engineering problems. Prototype design, implementation, and testing. Integration of different disciplines.
Teacher’s role	Coaching on task and process	Ask students challenging questions; provide consultation in process; focus on heuristics to implement major tasks; give just-in-time teaching or use the lecture-by-demand strategy; stimulate students to self-evaluate and self-reflect; organize discussions to reflect on the process and explicate rationale for their technical design; provide formative feedback on mid-term deliverables.
Assessment	Formative assessment Summative assessment	Weekly reports or presentations; intermediate checkpoints based on intermediate deliverables; improvements in reports; prototypes; quality of experiments. Individual contribution to project group; final presentations; reports; portfolio assessment; peer and self-assessment; use of rubrics; involvement of industry representatives in evaluation.
Social context	Collaborative learning	Communication with real-life stakeholders; students manage processes as experts; teamwork and debates; peer-to-peer communication; shared laboratory resources; motivation through competitions; variation in design techniques and approaches.
Design elements	Explore problem statement Explore graphic representation Validate assumptions and constraints Build a normative model Explore issues of measurement	Framing of the design task can involve exploring a problem, issue, or artifact that needs to be analyzed, synthesized, or investigated. Contrast with a verbal description, a quantitative representation, or other alternative forms of representation. Test the designs to confirm that they fall within constraints as expected and that the assumptions they made about the design appear to hold true. Articulate what the desired, ideal outcome of their design ought to look like if they were not constrained or limited. Examine the way that quantitative information is gathered relating to some aspects of a design.

3. Methodology

Considering the benefits of design-based learning (DBL) and the lack of relevant research, the purpose of this study is to explore a teaching approach for the integration of DBL activities in engineering educational programs. Specifically, we present the three research questions outlined in Section 1. To answer these questions, we implemented two separate studies with engineering undergraduates in typical educational activities, which are a sensor technology course and an open-topic innovation project. Stakeholder questionnaires and performance evaluations are used to measure the DBL approach. The research sketch is shown in Figure 1.

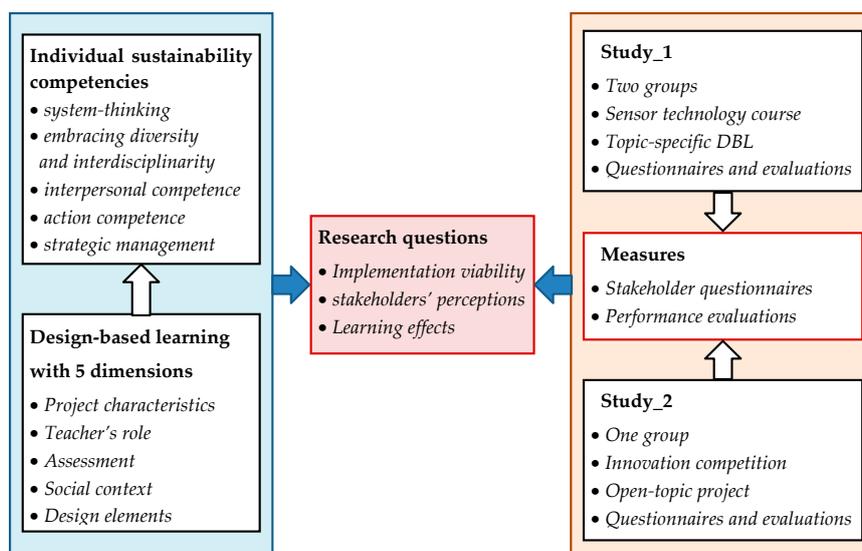


Figure 1. A sketch of the research content and implementation.

3.1. Participants and Educational Activities

3.1.1. Study_1 in a Sensor Technology Course

The participants in Study_1 were 129 full-time junior students majoring in mechanical engineering from four classes at an application-oriented university that provides undergraduate and continuing education programs covering engineering, natural science, economics, literature, etc. We implemented Study_1 in the required course of sensor technology, which is offered to undergraduates of various engineering majors, such as mechanical, electromechanical, electrical, etc. As one of the critical technologies in advanced information technology, sensor technology [31,32] has become a theoretical method and design tool that engineers must master. From the view of developing students' sustainability competencies, the reasons for selecting this course over others were (1) the presence of a practicum that is appropriate for integrating a DBL activity, (2) the requirement of the students to consider product performances from chip level to system level, and (3) multidisciplinary, covering micro-electromechanical systems, precision machinery, material engineering, data analysis, etc.

The sensor technology course contains two teaching units: Theory teaching (32 hours/8 weeks) and concentrated practicum (2 weeks). We proposed an image sensor design problem at the board level as the design task for this practicum. It comes from a real-world challenge [33] that requires students to explore a way to improve the imaging quality of the sensor under inevitable uncertainties. As shown in Figure 2, the image sensing module with an ultra-low-noise image sensor was developed for surveillance cameras under extremely low-light conditions. In this module, the image sensor and other components (e.g., codec, converter) were assembled on a printed circuit board (PCB), and the module can be fixed in a device through the mounting holes at the four corners. Due to the mismatch in the thermal expansion coefficients of the various materials, thermal deformation occurred on the sensor of this module under the combined action of self-heating and thermal environment. To acquire more image information under low-light conditions, the sensor with a large-format die was selected, resulting in an imaging quality of the module that was more susceptible to deformation. In addition, we provided students with the context of the design task, including the specifications, power dissipation test results of the components (e.g., sensor, converter, and codec), and material properties of the PCB. Note that the power dissipation and material properties (e.g., elastic modulus, expansion coefficient) were uncertain; hence, we provided the sample data.

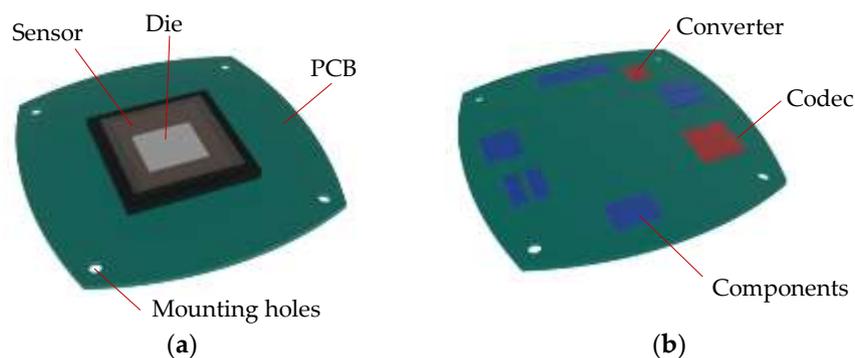


Figure 2. The image sensing module with an ultra-low-noise image sensor. (a) Top surface of the module; (b) bottom surface of the module.

The students were required to perform this task in random groups. Each group contained three members, and every eight groups shared one instructor. At the end of the practicum, each group needed to submit a design report, which should contain at least the following items: (1) Problem statement, (2) performance measurement, (3) normative model, (4) graphic representation, and (5) design validation. We defined these evaluation items based on the design elements listed in Table 1. The five items were evaluated on a five-point scale and given the same scoring weight.

3.1.2. Study_2 in an Innovation Competition

The activity in Study_2 refers to instructing students to participate in the 5th China College Students' "Internet Plus" Innovation and Entrepreneurship Competition (IPIEC) [34]. The participants in Study_2 were actively seeking our guidance, and the total enrollment was 78. These students were sophomores or juniors from the majors of mechanical engineering and electromechanical engineering. The instructor team in Study_2 included four members with expertise in electromechanical system design and manufacturing.

Having been held successfully four times since 2015, the IPIEC has gradually grown into the largest innovation and entrepreneurship award for university graduates in the world. Student members of participating projects must be currently registered graduates or graduates who graduated from university within the past five years. A three-level evaluation system is adopted: College preliminary, provincial rematch, and national final. Each project team needed to prepare a business plan and a five-minute presentation. According to the entrepreneurial stage and equity characteristics of the participating projects, the racing tracks of the IPIEC consist of a creative group, start-up group, growth group, and teacher–student co-creation group.

In the preliminary round for our university, there were a total of 1449 participating projects, of which the participants in Study_2 provided eight. These projects were registered in the creative group because its entry prerequisites emphasized good ideas, such as an innovative product prototype or original service model. After all, our purpose was to develop and measure the DBL approach for sustainability competency training, rather than to start a real business. From this perspective, the evaluation rules were very appropriate for verifying the teaching effect. The evaluation items of the creative group include five aspects, as listed in Table 2.

Table 2. The evaluation items of the Creative group in the “Internet Plus” Innovation and Entrepreneurship Competition (IPIEC).

Items	Weights	Descriptions
Innovation	40%	Highlight the value of original ideas and discourage imitation; emphasize the use of Internet technologies, methods, and thinking to seek breakthroughs and innovations in sales, technology, production, logistics, information, manpower, and management; encourage the combination of the project and the transfer of scientific and technological achievements from colleges.
Team	30%	Investigate team members' educational background, values, areas of expertise, division of labor, and business complementarity; the company's organizational structure and staffing arrangements; business consultants, major investors, and shareholdings; a resource base for ensuring the implementation of proposed solutions.
Business Model	25%	Emphasize the integrity and feasibility of the business model; evaluate the rationality of this derivation of profitability; possibility in the areas of opportunity identification and utilization, competition and cooperation, technology foundation, product or service design, funding, and personnel requirements; investigate the degree of industry investigation and research, discourage literature investigation, and emphasize field investigation and practical operation experience.
Society and Environment	5%	Anticipate the employment that the project may bring, and the impact on the society and environment.

3.2. Procedures

3.2.1. Implementation of the Sensor Design Task

The sensor technology course was scheduled for a two-week practicum after eight weeks of theory teaching. Before the practicum, the instructors delivered the task statement (see Section 3.1.1)

to students for background reading. The instructor guided the students to focus on outcomes as they performed the task. Specifically, we divided the implementation procedure into three phases: Exploration, formulation, and productization. The timeline is shown in Figure 3.

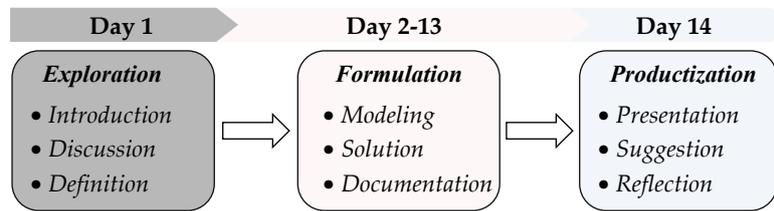


Figure 3. Timeline of the sensor design task in Study_1.

The outcome exploration refers to converting a real-world challenge into an easy-to-understand problem for computers. For example, the challenge of this task is to improve the imaging quality of the sensor under inevitable uncertainties, and the anticipated outcomes are mathematical models of the imaging quality and uncertain parameters. The exploration phase consisted of three steps: introduction, discussion, and summary. For aiding students to integrate concepts from earlier courses, the contents of introduction covered: (1) the description of the image sensor design task, (2) the flowchart of thermal–mechanical coupling analysis based on the finite element method (FEM) [35], and (3) the concepts in uncertainty modeling and reliability analysis, including the statistical moments, six-sigma principle, and safety factor [36]. The contents had been used many times in a similar practicum offered to students majoring in mechanical engineering, which were compiled by a teaching team with expertise in FEM and structural reliability analysis. After the two-hour introduction, the instructors organized the group discussion. To guarantee outcomes, we encouraged students to use a structured expression; that is, to first express the opinion in one sentence, then provide evidence to support the opinion, and finally give a practical suggestion. At the summary step, each group needed to state the outcomes of their discussion, including current doubts, anticipated difficulties, and different views and consensus on the performing strategy of the task. In the end, each group was required to submit an action plan outline covering the labor division and timeline to enable completion of the task within two weeks.

The outcome of the formulation was defined as building a normative model, which can be solved by existing tools to obtain a design solution. The instructors took a series of measures to train the students' sustainability competencies during task implementation. (1) In system-thinking, the instructor guided the students to create a systematic design framework consisting of controllable variables, uncontrollable parameters, objectives, and constraints. When members proposed different design objectives, the discussion was encouraged on the topics of transforming some objectives into constraints, or introducing weights for integrating different objectives into the one. (2) In embracing diversity and interdisciplinarity, we encouraged the use of existing tools and concepts taught in other courses, such as the FEM solvers [35], optimization toolkit [37], and statistical analysis tools [38]. We emphasized the establishment of data interfaces between existing tools for efficient integration. (3) In interpersonal competence, the instructors suggested each member provide a quantified consequence of the work undertaken for embedding the personal efforts into the team outcomes. Quantifying outcomes has proven to be an effective way to strengthen the openness and trust in cooperation. Clarifying everyone's contribution to an overall goal could help to reach consensus in communication. (4) In action competence, each group was required to report the current progress and conduct self-assessment based on the submitted action plan at the end of each day. We used QQ group [39] as an online group-chat tool for students' feedback in task implementation. QQ group is a free cellphone application, which is useful for team communication and sharing files. In this manner, the instructors viewed the students' daily reports and text conversations about the task, and gave just-in-time teaching to motivate students to take further actions.

Productization refers to embedding the solution into practice. To provide students with a productive experience, they were required to not only answer challenging questions from a practitioner, but also, finally, to convince the practitioner that their solutions can work in practical engineering. We invited an engineering expert with expertise in design and manufacture to participate in the final phase of the practicum. Since this class was four hours in length, this allows adequate time for communication. This process enabled face-to-face interaction between the theoretical researchers and engineering expert, and hence provided an opportunity to embed the concept that productization brings value to design deeply into students' cognition. For example, a solution to enhancing sensor robustness through controlling the power consumption fluctuation may be of no value for device providers, but is instructive for integrated circuit designers. The students needed to respond to the expert's comments one by one and to improve the design solution in the final design report.

3.2.2. Preparation for the IPIEC

To evaluate the effectiveness of the DBL for teaching sustainability competency in engineering education, we utilized mentorship of students to participate in the IPIEC as a case study. In this process, we purposefully selected a specific innovation field and racing track to train students' sustainability competencies. Firstly, since the instructors were specialized in the design and manufacture of electromechanical systems, the selected innovation field was advanced manufacturing [40], including smart factories, intelligent hardware, internet of things, environmental protection, etc. Secondly, the racing track was selected for the creative group because its rules place more emphasis on the individual competencies demonstrated by an innovative project. Thus, the results of the competition may verify our students' competence for all participants.

The DBL activity ran a full semester with eighteen weeks. The teaching procedure adopted a framework similar to that of Study_1. The flowchart and outcomes are shown in Figure 4. Differently from the topic-specific task in Study_1, the participating teams needed to choose their entrepreneurial projects. Considering that the participants in Study_2 were engineering undergraduates, they first were exposed to an online business course describing entrepreneurial strategy and sustainability as well as change management. The first and most crucial step in entrepreneurship is to clarify the market boundary through data analysis, that is, the opportunities and challenges of the industry. The primary reading material was a practical handbook [41], which addresses how to achieve business value from data analysis. The students were required to collect the primary data from interviews with practitioners and literature surveys. The outcomes included unmet user core demands and corresponding target market capacity. QQ group was used as an online communication tool where the discussion was carried out and all material was submitted.

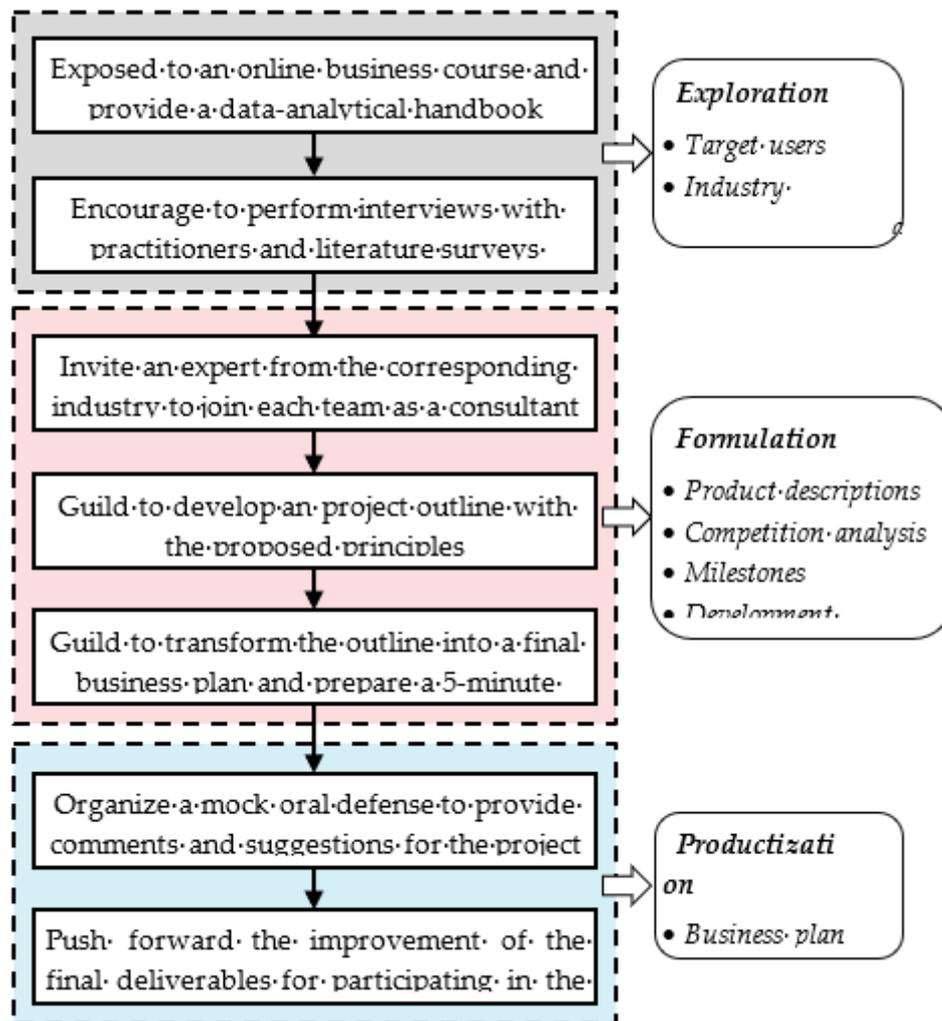


Figure 4. The flowchart and outcomes of the DBL in Study_2.

In the next formulation phase, the project team needed to create a product prototype or service process to address the industry challenge. For the defined entrepreneurial theme, we invited an expert from the corresponding industry to join each project team as a consultant. Under the guidance of mentors and consultants, the students developed a project outline. The description of the project outline is detailed in Table 3. Included in the project outline were the project theme, target users, industry challenges, product descriptions, competition analysis, milestones, and development planning. The project outline is the essential project management tool used to capture the clear deliverables and timeline. As they developed and updated the project outline, the instructor and consultant followed three guiding principles: Autonomy, authenticity, and visualization. (1) Autonomy principle: The instructor and consultant motivated students to autonomously develop the project outline through a lecture-by-demand strategy, challenging questions, online questionnaires, and formative feedbacks. The students learned from updating the project outline and reflecting on lessons to reinforce just-in-time action awareness and strategic management skills. (2) Authenticity principle: The proposed innovation points should focus on users' real needs, rather than pursuing so-called sophisticated technologies and leading advantages. We emphasized that practical efforts to support sustainable development are solving problems in engineering practice, not talking about the concepts of sustainability. (3) Visualization principle: We asked the students to use more graphics and diagrams in the project outline to avoid large paragraphs of text. The students gained excellent communication

skills and expression habits by creating logical, beautiful pictures and charts, and their understanding of the project was further improved.

Table 3. The description of the project outline in Study_2.

Example of timeline	Deliverables	Descriptions
Week 1	Project theme	A short sentence to accurately summarize the project.
Week 2	Target users	Product usage scenarios; features of the target user; current market capacity and trends.
Week 3–5	Industry challenge	No more than three unmet user core demands.
Week 6–7	Product descriptions	A picture to describe the core functions of the proposed product; a flowchart to state the service process or business model.
Week 8–10	Competition analysis	List of potential competitors; innovation points; advantages and limitations; feasibility to outperform competitors.
Week 11–14	Certification and Cooperation	Intellectual Property Registration; expert recommendation letter; official certification of innovation; signing development agreements with enterprises.
Week 15	Development planning	A product development plan; a marketing plan; a financing plan.

In the final productization phase, each student team transformed the project outline into a final business plan and prepared a five-minute presentation as a deliverable for participating in the IPIEC. We organized a mock oral defense, and the committee members included all instructors and consultants. The consultants who failed to arrive at the site participated in the meeting via video link. Afterward, the students supplemented materials and analysis to integrate the comments and suggestions into the business plan and improve their presentation. Consequently, they developed eight innovative projects for the IPIEC through the DBL approach. These projects involved various fields, such as fitness assistance, home medical, smart home, intelligent building, agricultural processing, and environmental management. Table 4 provides a feature summary of the participating projects.

Table 4. The feature summary of the participating projects.

Project themes	Fields	Features
Smart Yoga mat	Fitness assistance	Monitoring of exercise posture and balance as well as physical signs; real-time feedback; periodic exercise effect analysis; artificial-intelligence-based tutorial.
Diving headband		Underwater inertial navigation; vital signs monitoring; self-organizing network; bone conduction speech interaction.
Portable ventilator	Home medical	Comfortable and stable air pressure; four-level noise reduction; undisturbed airflow; automatic start and stop; sleep quality report.
Medical-bed motion sensor		Patient motion sensing; high sensitivity; low false alarm rate; small size; low power dissipation; high reliability.
Home health monitoring system	Smart home	Monitoring of physiological characteristics; fall alarm; work in power outages and network-less environments.
Comfort monitoring system	Intelligent building	Multi-source heterogeneous data analysis; data-driven comfort assessment; optimized design of comfort sensor; customized monitoring system solution.
Bamboo mat automated production line	Agricultural processing	Automatic loading and unloading; automatic glue drying device; pollution treatment process; energy-saving design.
Road dust monitoring robot	Environmental management	Mapping and path planning in complex environments; measurement of various environmental parameters; large sampling area; high weighing accuracy.

3.3. Measures

3.3.1. Stakeholder Questionnaires

At least three major stakeholder groups are related to the pedagogical research, that is, students, instructors, and practitioners. We utilized three questionnaires to gain insight into measuring the proposed DBL approach. The specific information of these questionnaires is listed in Table 5.

The first questionnaire asked the students in Study_1 and Study_2 questions, including their experience in learning sustainability competency, self-perceived importance of this learning, and their perception of the DBL approach. The second questionnaire was delivered to 35 practitioners for investigating their background and attitudes towards training sustainability competency. These practitioners covered a variety of occupations, and included engineers, patent agents, project managers, sales, and business owners. We provided them with the design reports submitted by two groups. The students in Group_1 were the participants in Study_1. The students in Group_2 were the previous students (Group_2) in a similar course with the passive learning approach [42]. Note that we randomly selected the current and previous reports, and the sample size for both groups was 40. The two groups of design reports were delivered to the practitioners for blind evaluation. Based on the provided reports, these practitioners intuitively judged whether they would be willing to work with these students in the further.

The first two questionnaires contained six closed-ended questions with the same scale of “Yes” or “No”. Unlike these questionnaires, the third questionnaire contained two open-ended questions about the gains and challenges of integrating the sustainability competency teaching into engineering education from the instructors’ perspective. Six instructors responded to the third questionnaire, and all of them were involved in Study_1.

Table 5. The feature summary of the participating projects.

Stakeholders	Questions
Questionnaire_1: Students	(1) Do you have experience in learning sustainability competency? (2) Do you agree that it is important to learn sustainability competency? (3) Do you expect to embed the DBL activities into other engineering courses?
Questionnaire_2: Practitioners	(4) Do you have experience in learning sustainability competency? (5) Do you have a plan to participate in a course related to sustainability competency in the future? (6) Are you willing to work with this student after reviewing their submitted design report?
Questionnaire_3: Instructors	(7) What did you gain from teaching sustainability competency? (8) What are the challenges for you to teach sustainability competency?

3.3.2. Performance Evaluations

Two performance evaluations were performed based on the submitted design reports in Study_1 and the deliverables in Study_2. To compare the proposed DBL approach with the passive learning approach [42], the design reports of the two groups were blindly evaluated based on the same scoring criteria as described in Section 3.1.1. Group_1 was the DBL group in Study_1, while Group_2 contained 100 random samples of previous students in a similar course with the lecture-based approach. The graders include not only the instructor, but also the invited expert in Study_1. The instructor and expert respectively gave the grades for each report, and the final grade was the average of the two.

For another evaluation of Study_2, the results were naturally generated from the three-level evaluation system of the IPIEC, as mentioned in Section 3.1.2. From the IPIEC’s evaluation items, as listed in Table 2, it can be found that students’ entrepreneurship is a key element to ensure their outstanding performance in this competition. The literature [22] pointed out that there are commonalities between the competencies of entrepreneurship and sustainability, such as system-thinking, complex problem-solving, and interdisciplinarity. Therefore, it makes sense to use the IPIEC results to measure the sustainability competencies of students in our DBL group.

4. Results

4.1. Questionnaire Results

In Questionnaire_1, We received 123 responses for Study_1 (response rate: 95.3%) and 78 responses for Study_2 (response rate: 100%). We observed that most students had no experience in learning sustainability competency. Only three respondents in Study_1 and two respondents in Study_2 reported having prior experience from elective business courses or off-campus internships. Most respondents agreed that it is important to learn sustainability competency, and the proportions were 107/123 in Study_1 and 78/78 in Study_2. Students' ratings on the willingness of extending the DBL to other courses showed that 81 respondents (65.8%) in Study_1 and 62 respondents (79.5) in Study_2 answered "Yes".

In Questionnaire_2, 32 respondents provided valid responses (response rate: 91.4%). More than half of the respondents (20/32) reported having no experience in learning sustainability competency. Almost all respondents (31/32) stated that they had plans to attend a course related to sustainability competency. Figure 5 shows the ratio of answering "yes" to Question (6) for each respondent based on the design reports from Group_1 and Group_2. The ratio means are 71.4%. Thus, the results show the practitioners favored working together with the students in Study_1.

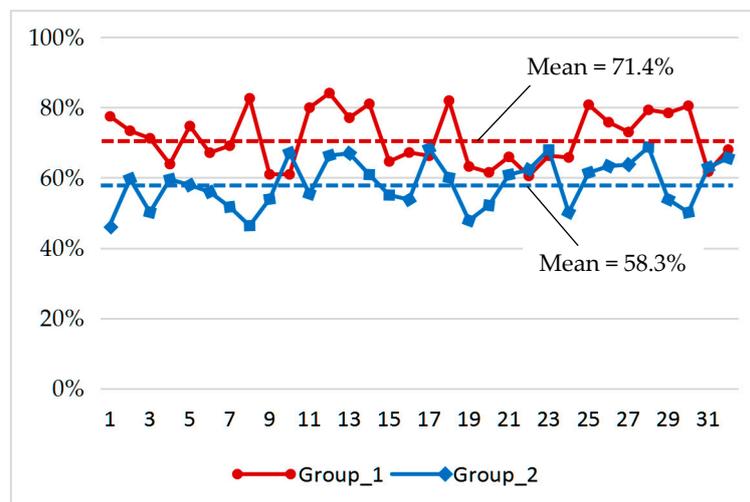


Figure 5. The ratio of answering "yes" for each respondent on the third question in Questionnaire_2.

Striking in Questionnaire_3 was the perceived overlap between the six respondents. The overlap of gains in teaching sustainability competency was found in two aspects. Four out of six respondents reported that performing the DBL approach in the course provided an opportunity to build the relationships between the school and corporations. These relationships can bring potential benefits for developing and reforming engineering curricula as well as placing students in internships and jobs. Five out of six respondents mentioned another gain, that teaching sustainability competency with the DBL approach also improved their own competencies. For example, through various perspectives on the design task exhibited in the discussions between the students and invited practitioners, the instructors perceived that their competencies of system-thinking and embracing diversity were improved to some extent. The overlap of challenges reported by the respondents was threefold. Firstly, all respondents noticed that a small number of students were still less engaged in the DBL activity, although the well-designed course had intrinsically motivated most students. Secondly, four out of six respondents mentioned possible obstacles to promoting DBL teaching, in that not all faculty believe in its benefits and are willing to change, since classroom learning through a traditional lecture mode based on passive learning techniques is still the norm. Thirdly, half of the respondents mentioned a significant concern about identifying corporations who are interested and have budgets for school–enterprise cooperation.

4.2. Evaluation Results

Figure 6 details the mean of students' scores for Group_1 and Group_2 in Study_1. We verified these mean values by statistical hypothesis testing at the significance level of $\alpha = 5\%$ [43]. The results showed that the mean total score (3.76) of Group_1 was significantly higher than that (3.03) of Group_2 ($p < 0.01$). By comparing the mean scores of the two groups in the five evaluation terms, we found that Group_1 had significant advantages ($p < 0.01$) in terms of (1) problem statement, (2) performance measurement, (3) normative modeling, and (4) graphic representation. A significant difference was not found in (5) design validation ($p < 0.36$).

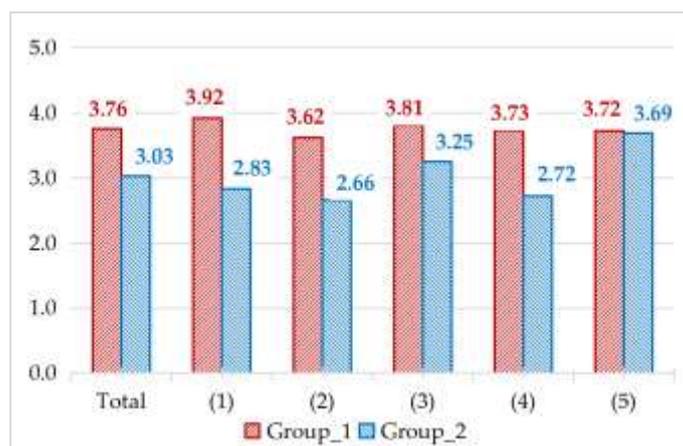


Figure 6. The mean of students' scores for the two groups in Study_1.

Since the evaluation results of Study_2 were generated from the evaluation system of the IPIEC, we present the system backgrounds in the college preliminary and provincial rematch. A total of 120 universities, 88,496 projects, and 215,827 students signed up to participate in the preliminary round of Hunan province. For our university, there were 1449 competing projects, including our eight projects in Study_2, as shown in Table 4. A total of 19 projects won from the preliminary round in our university and were approved for the provincial rematch. The organizing committee of the IPIEC organized experts to blindly review the deliverables of the 915 projects recommended by the universities for the first round of the provincial rematch. As a result, 341 projects were approved for the second round. For the eight projects in Study_2, five out of eight projects entered the first round, then four out of five projects entered the second round, and, finally, the four projects won the third prizes. These projects were the Smart Yoga mat, portable ventilator, home health monitoring system, and bamboo mat automated production line.

5. Discussions

In this section, the three research questions presented in the introduction section are discussed based on results from our studies.

- Is the DBL approach viable for fostering students' sustainability competency in existing educational programs?

The questionnaires show that students participating in two studies had little experience in training sustainability competency through educational programs or self-study. Although they lacked experience, the students agreed on the importance of learning sustainability competency within undergraduate courses. Furthermore, our questionnaires for practitioners found similar knowledge gaps. The practitioners reported a high likelihood of taking sustainability competency courses in the future. These findings indicate the need for undergraduates and practitioners to foster sustainability competency with practical pedagogy.

On the other hand, we applied the DBL approach to the two typical educational activities in engineering education: The topic-specific course with a strict timeline in Study_1 and the open-topic project with a loose deadline in Study_2. The results show the practicability of the DBL approach in the existing educational program. Therefore, the viability of the DBL approach is verified for training sustainability competency in terms of learning demand and teaching procedures in engineering education.

- What are the stakeholders' perceptions of using the DBL approach for training individual competency?

The questionnaires show that more than half of the students in the two studies developed positive attitudes towards the DBL approach. A higher percentage of students in Study_2 were in favor of extending the DBL approach into other engineering courses. The reason may be that the students in Study_2 were active learners, while the students in Study_1 were passively involved in the educational activities. Active learners may prefer the DBL approach and be more aware of its advantages in developing individual competencies. We also found the potential benefits of the DBL approach in enhancing student employment. The questionnaires show that the practitioners were more willing to work with the students in Study_1 because of better individual competencies exhibited in their submitted design reports. Furthermore, although several gains from applying the DBL to teach sustainability competency occurred, the instructors reported challenges from students, teachers, and corporations.

- What are the effects of the DBL approach for the development of individual competency?

The previous studies [8,9] created the sustainability competency frame and established a direct link between the competency development and core tasks in sustainable business practices. Our findings in Study_1 extend the previous studies by showing the advantages of the DBL approach for enhancing students' sustainability competency. Through comparing the outcomes of students in the DBL group (Group_1) to those in the group of conventional lecture-based approach (Group_2), we found that students in Group_1 gave more prominence in problem statements, performance measurements, normative modeling, and graphic representations. The differences in the mean scores of the four evaluation items were 38.5%, 36.1%, 17.2%, and 37.1%, respectively. It shows that the DBL approach was more beneficial in fostering students' sustainability competency. For example, exploring problem statements and issues of measurement requires students to think systematically about real-world challenges and to formulate action strategies by embracing diversity and interdisciplinarity. Logical graphic representation and normative modeling have proven to be an efficient communication tool in engineering practice.

Our findings in Study_2 qualitatively show the contribution of the DBL approach to developing students' sustainability competency. Promotion in the IPIEC involving tens of thousands of competitors was a challenging task, which required participants with strong sustainability competencies. Through the DBL activities, our students developed several competitive entries covering the fields of smart hardware, intelligent building, and advanced manufacturing. The implementation of this open-topic task consisted of identifying industry challenges, defining innovative products, building collaboration, and developing sustainable plans. The results of the IPIEC showed that such experiences had contributed to students' sustainability competency, such as system-thinking, complex problem-solving, and interdisciplinarity.

6. Conclusions

When dealing with the challenges involved in corporate sustainability practice, business decisions are made at the individual level or at the team level of individuals. The academic community increasingly acknowledges the importance of practitioners' sustainability competency. This paper presents a DBL approach for fostering students' sustainability competency in engineering education.

This pedagogy was tested in two typical educational activities: A topic-specific design task with a strict timeline and an open-topic project in an innovation competition. We performed two studies to evaluate the viability and stakeholders' perceptions of the proposed approach, and also compared its performance to a conventional passive learning approach.

In answer to the first outlined research question, the DBL approach was found to be viable for teaching sustainability competency in terms of learning demand and teaching procedure in engineering education. The findings of our questionnaires answered the second research question about the stakeholders' perceptions of using the DBL approach for training sustainability competency. It shows that students and practitioners both agreed on the importance of integrating ISC training into an educational program, and were in favor of the proposed approach. In addition, we summarized the perceived overlaps between instructors about the gains and challenges in teaching ISC with the DBL approach. Finally, we found that the DBL approach was more beneficial in fostering students' sustainability competency compared to the lecture-based approach. In the process of performing the design task and developing innovative projects, students guided by our approach gave more prominence in system-thinking, embracing diversity and interdisciplinarity, interpersonal competence, action competence, and strategic management.

However, using this approach for teaching sustainability competency may face challenges from three aspects. Firstly, the type and level of students' motivation for participating in a DBL activity may have a moderating effect on the effectiveness. For example, passive students were less engaged, resulting in a low level of gain. Secondly, the feasibility of incorporating the DBL approach for teaching sustainability competency in engineering education is significantly affected by teacher resources. It could be challenging to organize enough teachers every semester to run the practicum unit in all engineering courses similarly to that of sensor technology.

The limitations of this research are relatively clear. This study focuses on the specific mechanical engineering domain in undergraduate education, though it does not explore the effects of the proposed DBL approach in other engineering or educational fields, such as electrical engineering or continuing education. Therefore, the practicability of this approach to these domains cannot be confirmed without further research. This study also involved limited samples with the data analysis at a course level. Despite the presence of the qualitative analysis at an institutional level, a quantitative analysis could provide more insight into the features of using the proposed approach for training sustainability competency.

In the future, we will apply the discussed DBL approach to other engineering courses, such as electrical engineering and civil engineering. In addition, extending this approach to continuing education will be considered. Furthermore, we could conduct additional studies for each element of this proposed pedagogy. More efforts should be made to develop teaching materials and performance measuring tools.

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