Exploring the Impact of Generative AI for Sustainable Design Education: Developing and Evaluating an AI-Assisted Pedagogical Model

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Abstract

Generative Artificial Intelligence (AI) is increasingly reshaping design education by facilitating design workflow and enhancing students' creativity. However, its application in sustainable design education remains underexplored. This research develops an AI-assisted pedagogical model to examine how generative AI tools can support students' learning and practice in sustainable design. The model incorporates the EcoDesign Strategy Wheel within the Double Diamond design framework, with generative AI tools providing support during critical stages of the design process. A five-week project-based course involving 24 undergraduate students was conducted to generate quantitative and qualitative insights into the effectiveness of the teaching model and students' learning experiences. The results suggest that generative AI tools can effectively support various aspects of sustainable design practice, including research, concept generation, material selection, energy use, and distribution consideration. This study further reveals that generative AI helps students rapidly acquire complex interdisciplinary knowledge and develop systems thinking in sustainable design. However, it also poses challenges such as excessive reliance and limited understanding of local cultural contexts. This study provides theoretical and practical support for applying generative AI in sustainable design education, contributing to broader discussions on AI-driven pedagogical innovation.

1 Introduction

Human society is currently confronting a series of interconnected environmental and social challenges that threaten the sustainability of our planet. Factors such as rapid population growth, urbanization, and unsustainable consumption patterns are causing pollution and resource depletion, which call for urgent global sustainable actions [1, 2]. Designers are increasingly recognized as key agents in creating sustainable solutions that address these challenges [3, 4]. It is due to the fact that around 80% of the environmental impact of a product is defined at the early design stages of the product development process [5]. Sustainability-related design variables are therefore important to be identified by designers to guide development towards more sustainable solutions [6]. Sustainable design education plays a critical role in equipping future designers with the knowledge and skills needed to contribute effectively to sustainable development [7]. However, while sustainable design theory has expanded to encompass environmental, economic, and social dimensions, its translation into design education remains inconsistent [8]. Therefore, design education must integrate sustainability at scale by embedding theory and practice throughout the curriculum to adequately prepare future designers to address complex sustainability challenges [9].

Generative AI is opening up new possibilities in the field of design by reshaping design processes and workflows. Leveraging large language models, advanced natural language processing, and sophisticated machine learning techniques [10], AI technologies can autonomously generate diverse types of content, including text, images, and videos [11]. Designers are increasingly harnessing AI's capacity to generate diverse outputs, which serve both as sources of inspiration and as final design solutions [12]. This integration not only improves efficiency but also expands the space for creative exploration [13, 14]. In design education, a great number of practitioners have noticed the potential of artificial intelligence technologies and integrated generative AI into teaching programs for educational innovation [15]. A considerable number of studies have employed generative AI to support students in creative thinking, interdisciplinary collaboration, problem-solving, context analysis, and idea generation [16]. However, studies that specifically explore the use of AI tools to foster students' sustainable design capabilities remain limited [17].

In this context, this study develops an AI-assisted sustainable design education model, which is implemented in undergraduate professional courses at university. Furthermore, a mixed-methods approach, combining quantitative and qualitative analysis, is employed to assess the model's effectiveness in enhancing students' sustainable design capabilities and to examine students' learning experience within an AI-supported educational environment. We address the following research goals:

RQ1: How can an AI-incorporated sustainable design education model be developed and applied to a project-based design curriculum?

RQ2: How effective is this pedagogical model when applied in practice?

RQ3: What is the impact of AI tools on sustainable design learning and practice, and what potential implications might they hold for the future of sustainable design education?

The structure of the paper is as follows: Section 2 presents the results of the literature review. Section 3 delineates the theoretical framework and the development of the AI-assisted sustainable design education model, describes how the model is integrated into the design course, and explains the approach used to evaluate this model in real classroom settings. Section 4 outlines the findings of the practical implementation. Section 5 presents the discussion based on the results, and Section 6 concludes the study.

2 Literature Review

2.1 Research on Sustainable Design Theory

Sustainable design has been an area of research that has developed significantly over the last 30 years. In 1987, the Brundtland Report defined sustainable development as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [18]. After that, sustainable design was recognized as an area of major importance in the journey towards more responsible and sustainable production and consumption models [19]. While early efforts in sustainable design focused on minimizing environmental impacts throughout the product life cycle, the field of sustainable design has since evolved to address all three dimensions of sustainability: environmental, economic, and social [20–22]. Ecodesign, a sub-discipline within sustainable design, is defined as the integration of environmental aspects into product design and development, with the aim of reducing adverse environmental impacts throughout a product's lifecycle [23]. In the early level of ecodesign practices, the primary emphasis was on the redesign of individual qualities of a product, such as materials or components [24]. As the concept of sustainable design has continued to evolve, ecodesign solutions have progressively developed into products, services, or systems that not only consider environmental aspects, but social and economic factors as well [25].

Many qualitative and quantitative ecodesign tools have been developed to assist in the consideration of sustainable strategies throughout a product's life cycle. Some examples include EcoDesign Strategy Wheel [26], Ten Golden Rules [27], Environmental Effect Analysis (EEA) [28], MECO Matrix [29], Environmental Quality Function Deployment [30], and Life Cycle Assessment (LCA) [31]. These tools are considered as rational methods or procedures aiming to integrate the environment into the design of a system (product, services, industrial site) [32]. They have been increasingly applied in the design industry and generally considered to be helpful in supporting ecodesign activities [33]. Studies indicate that designers are largely satisfied with their functionality [34]. However, despite these advantages, the practical use of these ecodesign tools in industry remains limited and their integration within design education is still insufficient [33].

2.2 Education for Sustainable Development

On 25 September 2015, the UN General Assembly proposed 17 Sustainable Development Goals (SDGs), highlighting the urgency of addressing key systemic barriers to sustainable development such as inequality, unsustainable consumption patterns and environmental degradation [35]. According to UNESCO, the UN organization specializing in education, education represents an essential strategy in the pursuit of the SDGs. In 2017, UNESCO released *Education for Sustainable Development Goals: Learning Objectives*, which indicates that educational institutions should actively promote well-established approaches to empower learners to make responsible decisions and take responsible actions for economic viability, environmental integrity, and a just society for both current and future generations [36]. Within this context, different universities and higher education institutions have increasingly embraced the principles of sustainability and are equipping students with the knowledge, skills, and values needed for a sustainable future [37–39]. Given the significant impact of design on sustainability, particularly during the early stages of design development where key decisions can greatly influence environmental outcomes, design education must actively respond to this call. To support this shift, ecodesign knowledge and practices should be systematically integrated into design education programs, fostering future designers' sustainable awareness and equipping them with core competencies required for sustainability [40–42].

A number of studies have examined how sustainable design can be integrated into design education through various pedagogical methods [8–9, 43–44]. However, the incorporation of sustainability principles into the curricular frameworks across various design education programs remains insufficient [45, 46]. To begin with, compared to disciplines such as engineering, environmental science and business studies, design education remains underdeveloped due to the lack of curriculum — especially required curriculum — thereby limiting its capacity to achieve current sustainable design objectives [9]. Additionally, sustainable design teaching and learning are often treated as an add-on to the existing curriculum. For example, some courses only briefly mention the topic through theoretical content [47], and the delivery of sustainability knowledge tends to be fragmented, failing to systematically integrate ecodesign techniques throughout practical design activities. Furthermore, the social dimension of sustainability remains underemphasized. While many design education programs focus on environmental assessment using ecodesign tools and improving economic outcomes through circular economy models, they often neglect social considerations such as cultural diversity and user inclusivity [22]. As a result, students are not prepared to promote sustainable development in a holistic manner. One of the primary reasons for this gap lies in the complex and interdisciplinary nature of sustainable design itself [48]. Sustainable design encompasses a wide range of specialized domains, making it difficult for traditional teaching approaches to equip students with all the necessary knowledge within a limited timeframe. At the same time, many sustainability-related design problems are inherently complex, and students often struggle to interpret vast and diverse datasets to systematically develop design solutions catering to social, economic, and environmental dimensions [17]. In response to these challenges, there is a growing need for innovative teaching approaches that can better support the integration of sustainability into design education.

2.3 Generative AI in Design Education

In the design field, the emergence of generative AI is reshaping workflows and fostering new collaborative dynamics. A growing number of designers are using AI technology as a tool for better integrating data, sparking creativity and optimizing iterative processes [49]. The ability of generative AI to analyze vast datasets from various sources provides designers with actionable insights, facilitating more strategic decision-making [50]. Moreover, with AI's capacity to rapidly generate large volumes of highly original visual content, Artificial Intelligence Generated Content (AIGC) serves as a practical tool for idea exploration [51]. At the same time, the integration of AI is generating significant interest in higher education [16]. Introducing advanced AI technologies into teaching practices represents a major shift in educational methodologies, offering new opportunities for curriculum development, assessment innovation, and instructional enhancement [52]. Numerous studies highlight generative AI's effectiveness in stimulating creativity, integrating data rapidly, and facilitating iterative design processes in design education [53–56].

However, leveraging AI to cultivate students' sustainable design skills remains an emerging area of exploration [17]. This study addresses this gap by developing a sustainable design educational model that combines generative AI tools with ecodesign principles and implementing it in a project-based design curriculum. Based on the Double Diamond design process, this teaching model systematically integrates ecodesign tools throughout design phases, enabling students to make informed sustainability-oriented decisions at main stages. This approach ensures that social, environmental and economic considerations are embedded across the entire design process. Additionally, the use of AI tools is incorporated into design stages, leveraging AIGC's robust capabilities in complex data analysis and image generation to support eco-conscious design decisions. AI accelerates students' acquisition of interdisciplinary knowledge and enhances their capacity for systematic decision-making. Ultimately, this course framework helps students integrate sustainability in their design processes as a fundamental principle rather than merely a value proposition, equipping them with the skills to tackle real-world sustainable design challenges in their future careers

3 Materials and Methods

3.1 Sustainable Design Education Model Construction

This course introduces a pedagogical model that integrates the EcoDesign Strategy Wheel into the Double Diamond design process, systematically guiding students to apply sustainability principles at design stages while balancing environmental, social, and economic considerations.

3.1.1 Theoretical Framework

Introduced by the British Design Council in 2004, the Double Diamond model represents a design approach that combines divergent and convergent thinking, illustrating a standard problem-solving process (see Fig. 1) [57–58]. Starting with a design problem, the model emphasizes that the design process moves through the four stages of Discover, Define, Develop and Deliver to a to arrive at a viable solution.The Double Diamond model is a problem-solving process that closely aligns with the nature of sustainable design. It provides a structured framework that guides designers to address sustainability challenges in a logical and systematic way. Additionally, the Double Diamond model is a human-centered design approach, which enables designers to place greater emphasis on social aspects of sustainable design.

The EcoDesign Strategy Wheel, also known as Lifecycle Design Strategies (LiDS), is integrated into the Double Diamond process to systematically guide design students in making sustainable decisions (see Fig. 2) [59]. It serves primarily as a guideline tool [32], offering a structured framework of sustainability strategies such as material selection, energy efficiency, and circularity. It also functions as a matrix method, allowing designers to score each strategy area from good to bad. The completed matrix is used to focus attention on areas for improvement and enable sustainability comparisons between multiple designs [60]. The benefit of EcoDesign Strategy Wheel lies in its ease of use. It is a less technical approach with visual communication and minimal text presented in an understandable language, which makes it appreciated by designers in industry [61]. The EcoDesign Strategy Wheel is easy to implement, requires short setup or training [60], equally effective for classroom instruction [62]. In design education, the EcoDesign Strategy Wheel helps students grasp the core principles of sustainable design, supports them in managing trade-offs, and encourages a systems-thinking approach from the earliest stages of the design process.

3.1.2 Model Development

To develop the sustainable design education model, we first consulted four experts in Environmental Science, Industrial Design, Mechanical Design Engineering and Environmental Design, along with two senior product designers from the industry. Their insights regarding the integration of ecodesign strategies into design education and practice, along with the application of AI tools in design curricula and practice, were collected to inform the development of the pedagogical model. After consulting them and reviewing academic articles about the theory and case studies of both ecodesign tools and sustainable design education, we developed the initial draft of the pedagogical model. This draft was pre-tested by three third-year environmental design students in a 5-day workshop. During the workshop, we identified Midjourney and ChatGPT as the AI tools for student use, given their short learning curves, user-friendly interfaces, and exceptional text and visual generation capabilities. Based on student feedback and the experts' evaluation of the students' work, we refined the pedagogical model to its final version.

This pedagogical model integrates the EcoDesign Strategy Wheel into the Double Diamond design process, enhanced by generative AI tools (Midjourney and ChatGPT) to support sustainable design learning. The framework is divided into three project phases (see Fig. 3): The first project phase covers the Discover and Define stages, during which students conduct empirical studies. In the Discover stage, students conduct contextual investigations through fieldwork and user research. These empirical investigations enable students to develop a deeper understanding of people, cultures, and local scenarios [63], which helps students incorporate social considerations into their sustainable design decisions. Here, ChatGPT assists in generating comprehensive survey questions, helping students gain a well-rounded understanding of the design background from environmental, social, and economic perspectives. Students then synthesize their research findings in the Define stage to create a structured design brief. ChatGPT supports this process by helping them systematically organize and analyze qualitative and quantitative data. The second project phase is the Develop stage which consists of six modules. Each module incorporates specific strategies from the EcoDesign Strategy Wheel, guiding a structured process for sustainable design decision-making. In Concept Generation module, students generate various design concepts based on the design brief. ChatGPT expands students' design horizons by providing multidisciplinary insights, while Midjourney visualizes these concepts for initial screening. For Material, Energy and Distribution Consideration module, ChatGPT functions as both a reference book and an expert advisor, enabling students to efficiently access useful information and assisting in comparing and evaluating different solutions. For Appearance Design module, Midjourney enables rapid visualization of various forms with specific materials. In Structural Design module, both ChatGPT and Midjourney are applied to optimize modular structures for enhancing durability and repairability. Additionally, ChatGPT assists in analyzing production techniques to assess the feasibility of proposed solutions. Finally, in the third project phase, students use conventional software to create a 3D model of their final design solution and compile a detailed design report to communicate their outcomes.

By guiding students to apply sustainable design strategies, such as dematerialization, sustainable material selection, end-of-life planning, design for reuse, circular design, and design for sustainable behavior change, this pedagogical model offers a structured and practical framework for integrating ecological considerations into product and service design. With its vast database and robust data analysis capabilities, AI enhances students' understanding of sustainability knowledge and helps them evaluate trade-offs between different design concepts, ensuring that the final solutions meet both technical specifications and user needs.

3.2 Course Design

This study develops a sustainable design education model and applies it in a project-based university design course for evaluation.

3.2.1 Course Background

The research was conducted in a five-week Public Facility Design course at Chengyi College, Jimei University during the autumn semester of 2024. As the compulsory design course for undergraduate students majoring in environmental design, this course aims to equip students with the knowledge and skills needed to design functional, aesthetically pleasing, and sustainable public facilities. The course practice involved 24 third-year students, with a gender distribution of 37.5% male and 62.5% female. These students had completed fundamental to advanced courses and gained experience with design practice. They were divided into 8 teams, each consisting of 3 members, with all participants providing informed consent.

3.2.2 Course Content

The Public Facility Design course runs for 5 weeks, with 16 class hours per week. Based on project-oriented learning and team-based learning, this course uses signature pedagogy that mimics professional practice [64, 65], with the course project focusing on the redesign of campus-area bus stops. The teaching approach integrates theoretical lectures with a learning-by-doing methodology, enabling students to simultaneously acquire theoretical knowledge and apply it in practice.

Figure 4 illustrates the overall framework of the course integrated with the pedagogical model. This course is structured with theoretical and method instruction, followed by a three-phase design project. It is worth noting that videos and online materials covering sustainability theories, sustainable design case studies, and the use of AIGC tools have been uploaded to the university’s learning platform before the course begins, enabling students to engage in both pre-class preparation and post-class review [66]. The theoretical and method instruction lasts for one week and includes lectures covering the theoretical foundations of Public Facility Design and design for sustainability, the application of the EcoDesign Strategy Wheel and technical skills in using AI tools (ChatGPT and Midjourney). The design project lasts for four weeks, during which students apply the sustainable design education model to complete a public facility design. Three assignments are required to be completed throughout the project. By the end of Project Phase 1, each team is expected to submit a project research report that documents the empirical research process with the summary of key design insights. In Project Phase 2, each team presents three design proposals with an EcoDesign Strategy Wheel analysis to receive feedback and evaluation from instructors. During Project Phase 3, student groups need to complete a comprehensive design report that clearly explains their final design solution [67].

3.3 Sustainable Design Education Model Evaluation

Combining quantitative and qualitative research methods, this study adopted a mixed-research method to holistically assess the effectiveness of the AI-assisted sustainable design education model and students' learning process during the course. Figure 5 illustrates the major data collection approaches and their corresponding time points. Questionnaire surveys were carried out at eight points: after Project Phase 1, after each of the six modules in Project Phase 2, and at the end of the course. Three semi-structured interviews with student teams were conducted at the end of each project phase. In addition, the educators also maintained detailed observations throughout the project. Reflections and insights were generated by observing students' design performance in the classroom, evaluating their outputs on the online design whiteboard, and engaging with teams during group tutorials.

A total of eight questionnaire surveys were conducted throughout the course. Seven of them were carried out during the project phase to evaluate the effectiveness of AI in enhancing sustainable design-making across different design stages (see Table 1). These questionnaires shared an identical structure of 5 Likert scale questions. Each item was rated on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). The questions mainly evaluated students' perceptions of the usefulness (PU) and ease of use (PEOU) of AI-assisted sustainable design. These two aspects are key components of the Technology Acceptance Model (TAM), developed by Fred Davis in 1989 [68], which has been widely used to assess how users accept and adopt information technology [69]. An additional questionnaire was conducted at the end of the course, focusing on students' overall satisfaction with the course and their perceptions of AI integration in sustainable design education (see Table 2). The qualitative data was collected through the online platform and completed by a total of 24 participating students.

Table 1
In-course questionnaire design

Categories	Questions
Perceived Usefulness (PU)	PU1: Generative AI enables me to accomplish tasks more quickly. (work efficiency)
	PU2: Generative AI provided me with useful and inspiring content. (usefulness)
	PU3: Generative AI improves my design quality. (design quality)
Perceived Ease of Use (PEOU)	PEOU1: Generative AI tools are easy to use. (ease of use)
	PEOU2: Generative AI tools are controllable. (controllability)
	PEOU3: The AI-generated content is clear and understandable. (clear and understandable)

Table 2
End-of-course questionnaire design

No.	Questions
1	I am satisfied with the course.
2	This course enhanced my sustainable design capabilities.
3	I support the integration of AI into sustainable design education.
4	I am willing to use AI to support my sustainable design in the future.

Given the extended course duration, we conducted three rounds of interviews to enable students to accurately reflect on their design behaviors at different design stages. Interviews 1 and 2 aimed to explore how students worked with AI and how effectively AI supported sustainable design during the first two project phases (see Table 3). Interview 3 was carried out at the end of the course to gather students' perspectives on both the benefits and limitations of AI tools in sustainable design practice and education (see Table 4). Each interview was conducted with two randomly selected design teams and lasted between 15 to 25 minutes.

Table 3
In-course interview design

No.	Questions
1	How frequently do you use generative AI during each design step?
2	How effective is generative AI during each design step?
3	How generative AI influences your design decisions and process?
4	Views on the AI tools used on during each design step.
5	Additional insights.

Table 4
End-of-course interview design

No.	Questions
1	Benefits of generative AI in sustainable design learning, with practical examples.
2	Limitations of generative AI in sustainable design learning, with practical examples.
3	Benefits of generative AI during sustainable design practice, with practical examples.
4	Limitations of generative AI during sustainable design practice, with practical examples.
5	Additional insights.

Observations were conducted throughout the project to gain insights into how students collaborated with AI tools, while reflections were drawn from students' assignment evaluations and tutorial discussions.

4 Results

This article aims to examine the effectiveness of the AI-assisted sustainable design education model implemented in the course and to explore how students utilize generative AI to enhance their ecodesign abilities, with a further focus on the impact of AI tools on sustainable design learning and practice. Subsequently, we will present the findings from our analysis of the collected quantitative and qualitative data.

4.1 Assessment of AI-assisted Sustainable Design Process

4.1.1 Overall Assessment

Figure 6 illustrates the average ratings of students' perceived usefulness (PU) and perceived ease of use (PEOU) in each design step. Except for slightly lower PEOU scores in appearance (3.25) and structure (3.46), all other aspects scored above 3.76 on the 5-point scale. These results suggest generative AI can support sustainable design implementation to a considerable extent. AI was most effective in material and energy consideration, with both PU and PEOU scores around 4. Additionally, scores for research, concept generation, and distribution consideration ranged from 3.83 to 4.01, indicating that AI showed a measurable effectiveness in supporting sustainable decision-making during these steps. However, its limitations became evident in appearance and structural design, suggesting significant room for improvement.

4.1.2 Assessment of AI-assisted Design Research

Table 5 illustrates the average results of PU and PEOU in design research. During the research step, students utilized generative AI to assist empirical research in order to explore context-specific design needs. Among the evaluated factors, work efficiency (PU1) received the highest score at 4.17, followed by ease of use (PEOU1) at 4.04 and usefulness (PU2) at 4, indicating that students highly valued AI's support in the research step. Previously, students spent a great deal of time gathering regional information through secondary research. AI tools have significantly accelerated this process, allowing students to focus more on sustainability factors. For survey design, generative AI provided standardized and well-structured templates, helping students overcome difficulties in organizing coherent and unbiased questions. One student stated, "ChatGPT provided me with ideas for questionnaire and interview design. Whenever I didn't know where to start, asking AI could give me a great entry point."

Table 5
Average results of PU and PEOU in design research

	PU 1	PU 2	PU 3	PEOU 1	PEOU 2	PEOU 3
Mean	4.17	4	3.83	4.04	3.79	3.83
Standard deviation	0.64	0.51	0.7	0.62	0.66	0.7

However, generative AI lacks an understanding of regional cultures. As the course project was set in Xiamen's Chengga cultural zone, some project teams aimed to make the design culturally appropriate. When students asked AI to provide design suggestions based on Chengga Architecture, AI tended to provide stereotypical representations of Chinese historical styles (particularly Ming/Qing dynasty aesthetics). This indicates that AI systems lack the capability to comprehend the underlying philosophy and visual representation of local culture.

4.1.3 Assessment of AI-assisted Concept Generation

At this step, students utilized ChatGPT to generate and evaluate multiple strategies related to Cradle to Cradle and Circular Economy strategies, followed by visualizing these strategies using Midjourney. Except for controllability (PEOU2), which scored moderately lower ($M = 3.46$), all other indicators ranged between 3.92 and 4.13 (see Table 6). These results indicate that the generative AI is generally effective in supporting the sustainable concept generation step. Due to the lack of circular economy training, AI technology effectively facilitates students' acquisition of core concepts such as product-service systems, multiple use cycles, and dematerialization. This process exemplifies a learning-by-doing approach, allowing students to internalize sustainability concepts through hands-on application. In the interviews, one student noted, "AI provided many examples that helped me better understand these strategies." Another student mentioned, "Through collaboration with AI in sustainable concept generation, I became more aware of the importance of designing for long life, sharing, repair, upgrade, reuse and service models in design." In addition, generative AI helps students generate many divergent and innovative concepts that effectively broaden their creative thinking. As evidenced by student feedback in the interview, "AI can produce unexpected ideas that help us think out of the box."

Table 6
Average results of PU and PEOU in concept generation

	PU 1	PU 2	PU 3	PEOU 1	PEOU 2	PEOU 3
Mean	4.08	3.92	3.92	4.13	3.46	3.92
Standard deviation	0.5	0.65	0.65	0.61	0.66	0.72

However, many students reported that their interactions with AI tools were not smooth, often requiring multiple rounds of prompt refinement and persistent questioning to get satisfactory answers. Moreover, the AI-generated design concepts are often difficult to use directly. This is primarily because AI tends to provide reasonable sustainability solutions for only one design requirement at a time. As more design constraints are added, the accuracy of AI suggestions tends to decrease. This forces students to use their own knowledge to assess whether and how to adopt AI's recommendations.

4.1.4 Assessment of AI-assisted Material Consideration

During the material consideration step, students leveraged ChatGPT to identify materials that enabled circularity and minimized environmental impacts. The evaluation results highlight the strong effectiveness of generative AI in assisting students with the selection of sustainable materials (see Table 7). Ease of use (PEOU1) received the highest score of 4.33, and all perceived usefulness (PU) factors were rated above 4. In contrast to searching for information through books and online sources, AI enables students to quickly identify applicable materials and assess their comparative lifecycle impacts (e.g., carbon footprint, recyclability). Several design teams directly adopted AI's recommendations. For example, Team 1 and Team 6 selected locally available bamboo-wood composite panels, while Team 5 chose low-carbon steel as the main construction material for their bus stop design. Semi-structured interviews revealed that students primarily believe that generative AI enhance their work efficiency and performance. Some students mentioned, "AI helped me discover new materials, which inspired more diverse design solutions." Others stated, "AI helped me source locally available materials, significantly reducing supply chain carbon emissions associated with long-distance transportation."

Table 7
Average results of PU and PEOU in material consideration

	PU 1	PU 2	PU 3	PEOU 1	PEOU 2	PEOU 3
Mean	4	4.17	4.08	4.33	3.83	3.92
Standard deviation	0.66	0.48	0.58	0.64	0.56	0.72

However, by tracking the interaction between students and AI, we found that AI often generated similar responses regarding material selection, and its comparative analyses of materials were sometimes ambiguous. This indicates the need for students to further verify the accuracy of AI-generated information.

4.1.5 Assessment of AI-assisted Energy Consideration

In this step, students aimed to identify suitable energy sources for their design concepts and conduct a comparative analysis of energy efficiency. Similar to the material consideration step, generative AI performed well in the energy consideration step, with ease of use (PEOU1) scoring notably high at 4.25, all other evaluation factors remained positive, from 3.88 to 4 (see Table 8). AI tools enable students to systematically evaluate energy feasibility based on specific design constraints. One student stated, "As our project is located in a coastal city, I used ChatGPT to evaluate the feasibility of wind and tidal energy by analyzing local climate and geographic features." Another student mentioned, "Through solar energy efficiency calculation by AI, I realized that using solar power would require reducing the size of electronic displays, as larger ones would consume more electricity than the system could generate."

Table 8
Average results of PU and PEOU in energy consideration

	PU 1	PU 2	PU 3	PEOU 1	PEOU 2	PEOU 3
Mean	4	3.96	3.88	4.25	3.96	3.88
Standard deviation	0.51	0.46	0.74	0.61	0.75	0.74

Like the material consideration step, the energy consideration step also exhibits issues with low response diversity and a lack of clarity in comparative data. As one student pointed out, “AI sometimes fails to adequately explain its suggestions, so it is important to verify the information it provides.”

4.1.6 Assessment of AI-assisted Distribution Consideration

During the distribution consideration step, ChatGPT was employed to identify an energy-efficient transport mode for the main materials and components of the bus station. Evaluation results demonstrate AI’s effectiveness at this stage, with all factors of PU and PEOU3 (clear and understandable) scoring around 4 (see Table 9). In contrast, controllability (PEOU2) received the lowest rating, with an average score of 3.67, indicating some limitations in users’ ability to control the AI system. Given the absence of prior coursework on this subject, generative AI assists students in considering distribution aspects as part of their design process. Many students mentioned during interviews, “Without AI, it would be difficult for me to make progress on distribution decisions.” It is worth noting that when the project reached the distribution consideration step, students conducted a systematic analysis of the design by synthesizing all prior design decisions. Through classroom observations, we found that many project teams considered transport solutions in conjunction with product component design, exploring how to efficiently utilize transportation space. This indicates that students have begun to adopt systems thinking, integrating various design elements and decisions made in earlier phases to optimize sustainability holistically throughout the project.

Table 9
Average results of PU and PEOU in distribution consideration

	PU 1	PU 2	PU 3	PEOU 1	PEOU 2	PEOU 3
Mean	3.96	4.04	4.04	3.88	3.67	4.04
Standard deviation	0.62	0.62	0.55	0.61	0.64	0.69

However, when multiple design constraints are posed to generative AI (e.g., product structure compatibility, transportation cost reduction), its suggestions tend to be vague and lack practical value, leading students to perceive a reduced sense of control over the AI tools. This requires students to develop effective questioning strategies by deconstructing design requirements and iteratively refining prompts in order to obtain more usable responses.

4.1.7 Assessment of AI-assisted Appearance Design

In this step, students applied both ChatGPT and Midjourney to support appearance design, considering aesthetic, minimalist and classic design principles. Among the evaluated factors, work efficiency (PU1) received the highest score (3.91), followed by usefulness (PU2), design quality (PU3), and clear and understandable (PEOU3), all ranging from 3.63 to 3.75. Ease of use (PEOU1) performed moderately with a score of 3.46, whereas controllability (PEOU2) showed an unsatisfactory score of 2.67 (see Table 10). Notably, all factors exhibited relatively high standard deviations (0.82–0.96), indicating considerable variation in student perceptions. The results indicate that although AI tools offer certain supportive value during the appearance design step, their effectiveness remains limited.

Table 10
Average results of PU and PEOU in appearance design

	PU 1	**PU 2**	**PU 3**	**PEOU 1**	**PEOU 2**	**PEOU 3**
Mean	3.91	3.75	3.63	3.46	2.67	3.63
Standard deviation	0.83	0.9	0.97	0.88	0.96	0.82

Midjourney can quickly generate diverse visual concepts and effectively visualize product usage scenarios, often producing images with strong aesthetic appeal. However, among the large volume of generated images, only a small number were favored by students. All students mentioned in the interview that many of the images generated by Midjourney deviated from their intended design concepts, contributing to the lowest controllability score. Furthermore, the need for repeated adjusting prompts reduced students' perceived ease of use. As one student noted, "We have to consider the prompts carefully, otherwise the generated images may deviate significantly from our intentions." Variations in students' prompt engineering abilities resulted in differing perceptions of AI's effectiveness during this design step. Some students who were proficient in prompt engineering efficiently generated visually valuable images that significantly influenced their final design outcomes. Conversely, others perceived AI as offering limited support during this stage.

4.1.8 Assessment of AI-assisted Structural Design

During this step, students employed generative AI tools to explore modular design strategies, particularly focusing on module configurations and assembly methods. As with the appearance step, AI demonstrated limited effectiveness in supporting sustainable design strategies during this step. Work efficiency (PU1) and usefulness (PU2) were rated the highest, each scoring 3.88, whereas controllability (PEOU2) scored the lowest at 2.92. The remaining factors ranged between 3.67 and 3.75 (see Table 11). Generative AI supports design students in bridging deficiencies in structural design knowledge. As one student remarked, "Rather than spending much time learning the theory, I prefer using ChatGPT to quickly identify usable structures. Through interactive dialogue, AI can answer my questions about a particular structure, making the learning process fast and efficient."

Table 11
Average results of PU and PEOU in structural design

	PU 1	PU 2	PU 3	PEOU 1	PEOU 2	PEOU 3
Mean	3.88	3.88	3.67	3.75	2.92	3.71
Standard deviation	0.74	0.68	0.7	0.79	0.88	0.81

However, Midjourney shows limited understanding of structural elements. By tracking students' design processes, we found that Midjourney consistently failed to integrate modular structures into product form, regardless of whether structural information was conveyed through image references or detailed textual prompts. As a result, students had to rely on their design skills and experience to balance both aesthetic and structural requirements.

4.2 Course Evaluation

A quantitative survey was conducted at the end of the course to evaluate student satisfaction with the course and students' views on AI's integration into sustainable design education (see Table 12). The results indicated a high level of satisfaction (mean score = 4.29). Notably, participants agreed that the course significantly enhanced their sustainable design capabilities (mean score = 4.54). Additionally, students strongly supported integrating AI into sustainable design education (mean score = 4.29). They also expressed positive attitudes toward using generative AI tools to assist sustainable design practice in the future (mean score = 4.42). Overall, these findings suggest that AI can serve as an effective tool in supporting sustainable design education.

Table 12
End-of-course questionnaire results

	Question 1	Question 2	Question 3	Question 4
Mean	4.29	4.54	4.29	4.42
Standard deviation	0.75	0.59	0.62	0.65

4.3 Impact of AI Technology on Sustainable Design Learning and Practice

A semi-structured interview was also conducted at the end of the course to identify the challenges and opportunities of using generative AI tools in sustainable design practice and education. The interview transcripts were analyzed using thematic analysis to identify recurring patterns and to synthesize underlying conceptual relationships. Key insights were derived from this process, with the main findings summarized in Table 13.

Table 13
Summary of the key findings from the end-of-course interview

Category	Aspect	Insights
Advantages	Enhance efficiency	AI enables diverse visual inspirations, rapid design suggestions, instant feedback, thereby accelerating learning and significantly improving design efficiency.
	Broaden thinking	AI provides a wide range of sustainable solutions and case studies, which broaden the scope of design possibilities.
	Foster interdisciplinary learning	AI helps students rapidly acquire the core interdisciplinary knowledge for sustainable design, including material selection, energy utilization, logistics distribution, business models and structural design.
	Promote personalized learning	AI facilitates a personalized learning journey, allowing students to engage in targeted learning to address individual knowledge gaps through deep dialogues.
	Provide data comparison and analysis	AI enables data comparison and multi-solution analysis, fostering multifaceted thinking and providing opportunities to develop logical evaluation skills.
	Aesthetic value	Midjourney produces a wide range of visually appealing design proposals and usage scenarios, providing rich aesthetic materials and inspiration.
Disadvantages	Complex prompt tuning	Prompt tuning typically requires multiple iterations of trial; otherwise, it may generate irrelevant or repetitive outputs. Mastering this skill requires considerable time and practice.
	Excessive reliance	During the sustainable design process, students often encounter unfamiliar knowledge and complex analyses. Overreliance on AI may lead students to adopt its solutions directly without sufficient independent thinking.
	Lack of solution reliability	AI-generated responses may be ambiguous, overly general, or even incorrect, particularly in sustainability-related data analysis. This requires students to verify the accuracy of proposed solutions.
	Lack of regional specificity	AI-generated information is typically based on general data resource, potentially causing misconceptions and biases when generating locally specific content.
	Lack of systematic analysis	AI often struggles to simultaneously satisfy multiple constraints, demonstrating limitations in dealing with comprehensive and systematic problems.

Findings from the interview suggest that generative AI can serve as an effective tool for supporting sustainable design learning. Just-in-time knowledge scaffolding and multiple case demonstrations improved students' comprehension of interdisciplinary sustainability-related knowledge. Students perceived AIGC as an effective personalized learning tool that supports collaborative data analysis and dialogic design iteration. The AI system offers knowledge, visual stimuli and strategic recommendations, expanding students' design thinking while accelerating and optimizing sustainable design decisions. However, mastering prompt tuning requires overcoming a certain learning curve. The limitations of AI in processing sustainability-related content, including unreliable solutions, lack of regional adaptation and systematic analysis, highlight the need for students to critically evaluate and adopt AI-generated suggestions. Moreover, educators should be cautious of students' overreliance on AI, as it may impede their deeper engagement with sustainability issues. Overall, AIGC demonstrates significant potential but also poses certain challenges. Therefore, how to fully leverage AI's strengths to better support education in sustainable design remains to be explored.

5 Discussion

5.1 Need for a Teaching Model for Embedding AI into Sustainable Design Learning

This research employs the EcoDesign Strategy Wheel in conjunction with the Double Diamond design framework to develop an AI-implemented teaching model targeting sustainable design education. Through a combination of quantitative and qualitative methods, this study confirms the effectiveness of this pedagogical model, indicating that AI can serve as a valuable tool to support sustainable design learning.

To begin with, generative AI helps address a significant challenge in sustainability education—students' limited expertise in sustainability. As Faludi states, sustainability must be integrated into all design practices, but there are many different fields of expertise and not everyone can be an expert [70]. Traditionally, learning multidisciplinary knowledge, such as materials, energy systems, use-phase considerations, structural design, and business models, requires substantial time and effort [71]. AI tools speed up this process. When tracking students' design practice, it was observed that they utilized AI tools as core learning resources. These tools provided instant answers to specific questions and enabling personalized learning through in-depth dialogue. Overall, generative AI lowers the entry barrier to sustainable design knowledge, allowing students to balance knowledge accumulation and design practice.

Furthermore, generative AI builds a solid foundation for developing systems thinking. First, it enables students to rapidly acquire multidisciplinary sustainability-related knowledge, which enhances their ability to approach problems from multiple angles. Second, by liberating students from repetitive and technical tasks, AI allows them to channel more energy into systemic analysis [72]. Third, AI excels at comparing and analyzing data within single dimensions (e.g., material selection, energy efficiency), thereby supporting more structured and systematic decision-making in that specific area.

Finally, the pedagogical model provides a structured framework to guide AI involvement in the sustainable design process, ensuring precision across task modules and simultaneously fostering systems thinking through the integration of the EcoDesign Strategy Wheel. First, this model sets clear decision boundaries to mitigate potential errors caused by AI as design constraints grow and design dimensions expand. By decomposing a sustainable design task into interrelated subtask modules, clarifying their implementation steps and logical relationships, and employing AI tools to support design strategies within each subtask module, this model achieves seamless integration of generative AI into sustainable design processes. Second, by using the EcoDesign Strategy Wheel to evaluate the pros and cons of various strategies, students learn to manage trade-offs in complex systems [73]. This model helps students systematically map lifecycle interactions, reinforcing the understanding that decisions made at each design step are interrelated. This fosters a holistic perspective on how every design choice may impact broader systems.

5.2 Pedagogical Strategies for AI-Integrated Sustainable Design Education

In the tide of digital transformation, integrating AI into education has become an inevitable trend. Within this context, there is a growing need to rethink and optimize teaching strategies in sustainable design education to address the pedagogical challenges and opportunities introduced by AI integration.

Fundamentally, a comprehensive grasp of sustainability theory and knowledge through traditional pedagogical approaches remains essential. This aligns with the findings of Fareed et al. [74], which indicate that students should acquire basic professional knowledge before integrating AI as an additional layer to enhance engagement and support deeper understanding. First, only with adequate sustainability knowledge can students formulate high-quality questions, thereby facilitating more effective communication with AI systems. Students need to build prompts to communicate their specific requirements to the AI, including precise word choice and well-defined instructional contexts [75]. Terminologies, technical approaches, and methodologies from sustainability theory enable students to articulate their design thinking more clearly and to establish a shared language for AI collaboration, which supports the generation of high-quality answers and design solutions. Second, as AI sometimes generates far-fetched, irrelevant, or even incorrect responses, designers remain ultimately responsible for reviewing and validating AI-generated content. The need for accuracy verification of the design strategies relies on knowledge that students have cultivated through foundational learning of sustainability theory in traditional teaching methods, such as lectures and assigned readings.

Furthermore, fostering critical thinking equips students to evaluate AI-generated content and helps prevent overreliance on algorithmic outputs. A good approach for this challenge is to ensure that students gain a deep understanding of AIGC’s capabilities and constraints [53], along with its societal and ethical implications, before applying AI tools in sustainable design contexts. Another viable strategy is to implement critical pedagogy into major courses to cultivate students' critical thinking skills. Through theoretical study and workshop-based practice, students gradually learned to question assumptions, engage in reflective thinking, and critically evaluate the design outputs. In this way, students actively question and analyze AI’s responses, while the process of interacting with AI further strengthens their critical thinking abilities.

Lastly, the social dimension of sustainable design should be emphasized in teaching, as it equips students with competencies in culturally responsive and contextually relevant design [20]. This requires students to consider design in a holistic manner, ensuring that their solutions not only optimize environmental performance but are also well-integrated into rural, indigenous, and local scenarios. First, students should deeply explore the needs of users and communities, thoroughly evaluate the design's cultural adaptability and bring inclusive design into consideration. In particular, the role of empirical research should be strongly emphasized in this process. The people-centered approach is highly relevant to this design practice, as it encourages designers to engage in embodied observation and contextual analysis to uncover users’ deeper needs. In doing so, design can possibly influence users and their behaviors regarding energy efficiency, product longevity, and end-of-life management [62]. Second, students must recognize AI’s limitations in interpreting local cultures. This is consistent with the findings of Bartlett and Camba [51], who suggest that students should be made aware of cultural variations and trained to recognize the limitations of AI in presenting a well-rounded representation of global design narratives and styles.

6 Conclusions

The study introduces an AI-assisted pedagogical model and evaluates its effectiveness based on student usage data and survey responses. It offers an in-depth and holistic exploration of AI’s role in sustainable design education, addressing gaps in prior studies concerning AI-assisted learning in this domain. The research findings suggest that the AI-integrated teaching approach facilitates not only the acquisition of sustainability knowledge, but also its systematic application across design process.

This study makes a novel contribution by developing an AI-supported teaching model that integrates the EcoDesign Strategy Wheel with the Double Diamond design framework to support the sustainable design curriculum. AI’s advanced data-processing capabilities enable students to efficiently acquire interdisciplinary sustainability knowledge, enhancing their learning efficiency and accelerating design iteration. Embedding ecodesign strategies into the Double Diamond process allows students to systematically evaluate and holistically integrate sustainable solutions across environmental, social, and economic dimensions. By demonstrating the effectiveness of the pedagogical model, this study provides a new method for design education and serves as a useful reference for future curriculum innovation in AI-assisted sustainable design.

Moreover, this study puts forward strategic recommendations for advancing AI-integrated sustainable design education. First, it is necessary for students to build a solid foundation in sustainability theory through traditional learning approaches, which supports the development of precise AI prompting and ensures high-quality design outcomes. Second, cultivating students' critical thinking skills is essential, as it enables them to assess AI-generated content effectively and avoid overreliance on algorithmic outputs. This can be achieved by integrating both AI ethics knowledge and critical pedagogy into major courses. Third, the social dimension of sustainable design must be emphasized to equip students with the ability to develop culturally appropriate and inclusive solutions. Teachers should ensure that students are aware of AI's limitations in interpreting cultural diversities and encourage them to conduct empirical studies to build user empathy and gain deep insights into the local context.

However, we must acknowledge the limitations of this study. Firstly, the sample size is limited to 24 students, which may restrict the generalizability and representativeness of the results. Secondly, this study employs a cross-sectional empirical approach, focusing on a five-week design course as the main context for data collection and analysis. This short-term approach may lack the depth that a longitudinal study could provide. In future research, we aim to increase the sample size and involve students from diverse design backgrounds, such as product design and communication design. In addition, we plan to track students' performance across multiple courses to assess the long-term impact of the AI-embedded teaching model on their ability to make sustainable design decisions.

Declarations

Conflict of interest

The author declares no competing interests.

Ethics approval and consent to participate

This study was approved by the ethics committee of Chengyi Collage, Jimei University. All participants provided informed consent before completing the survey. The informed consent to publish was also obtained from all the participants.

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Author Contribution

Y.W. performed original draft writing, formal analysis, investigation and funding acquisition; X.Z. conducted methodology, investigation, visualization and data curation; W.S. performed validation, project administration, supervision. All authors reviewed the manuscript.

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Data Availability

Data is contained within the article or Supplementary Material.

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Figures

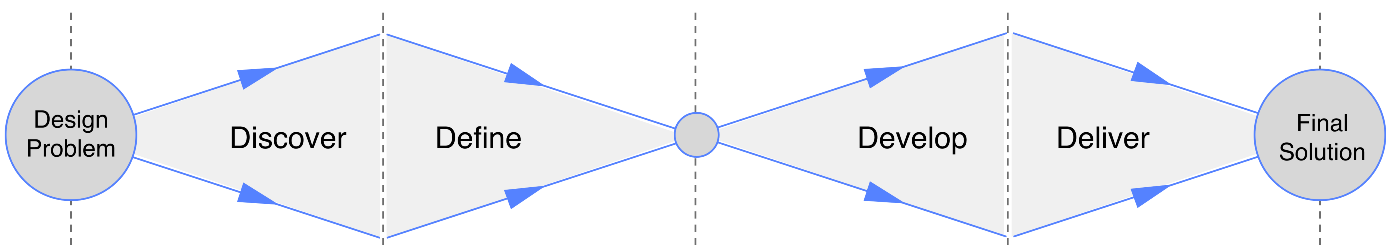

Figure 1

Double Diamond model

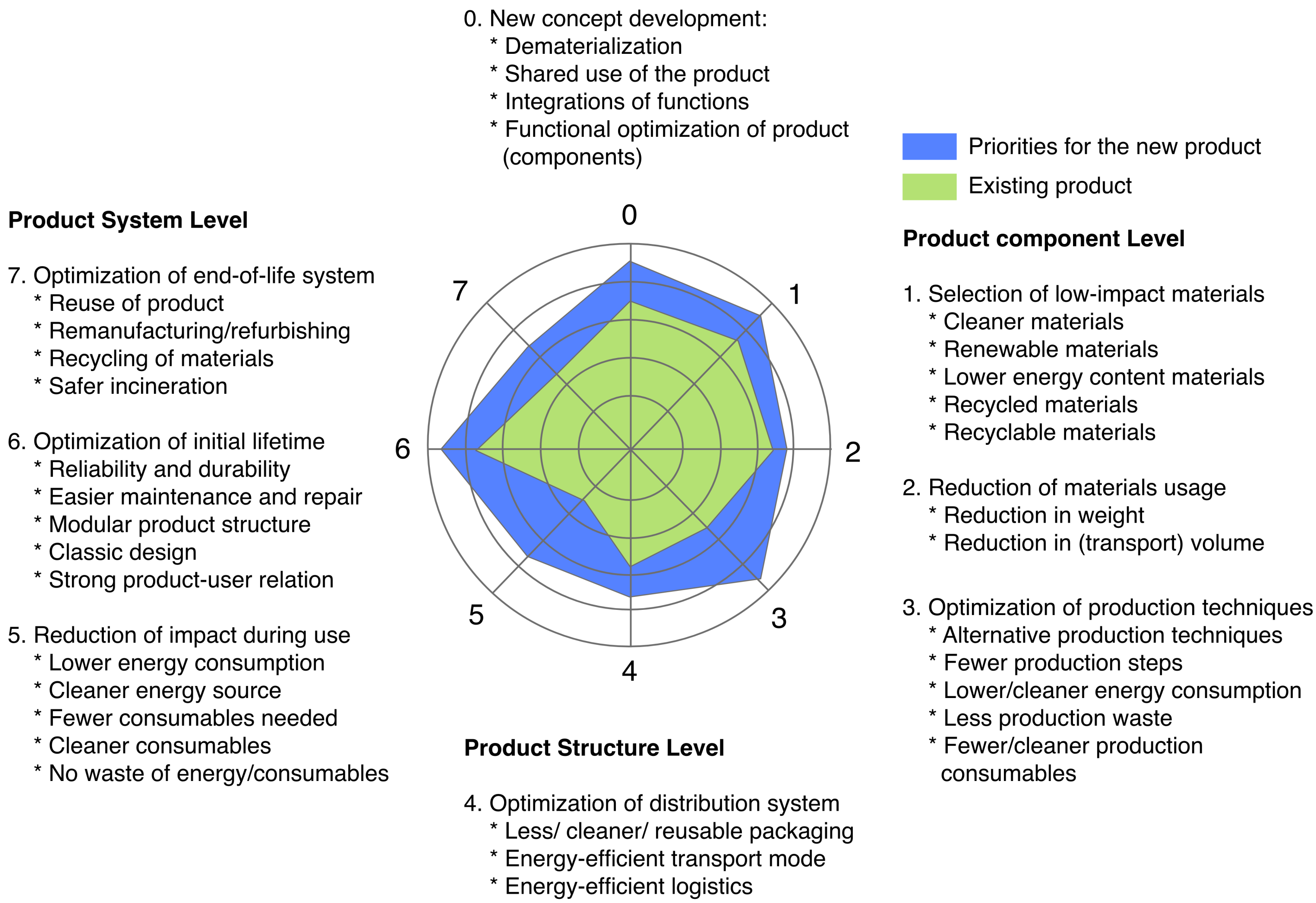

Figure 2

EcoDesign Strategy Wheel

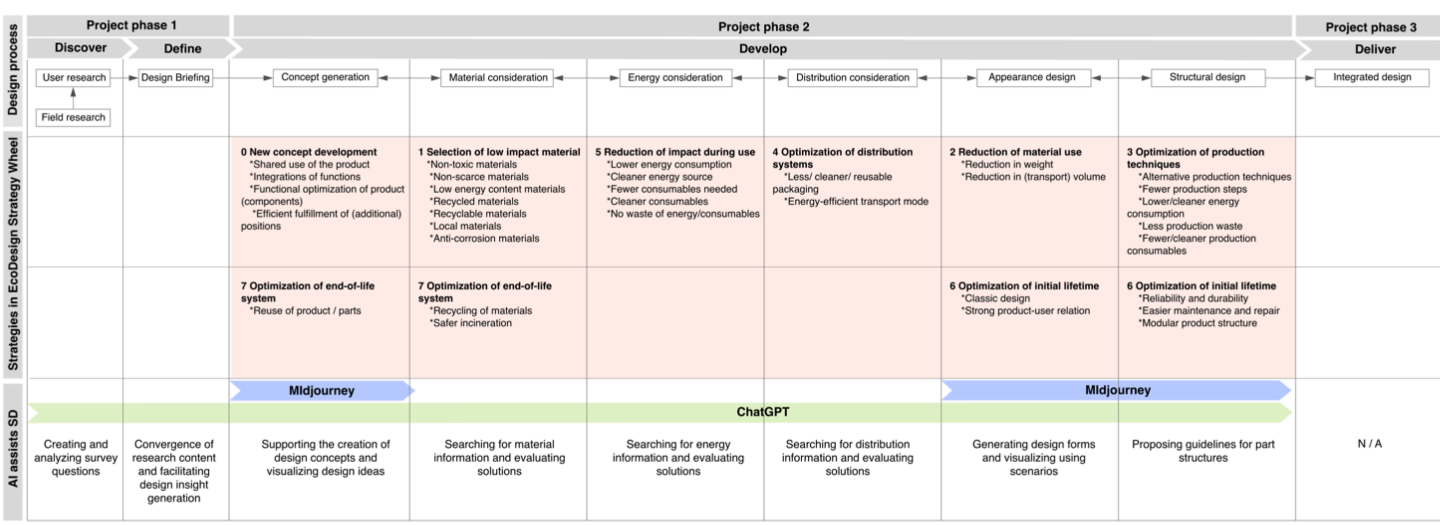

Figure 3

Sustainable design education model

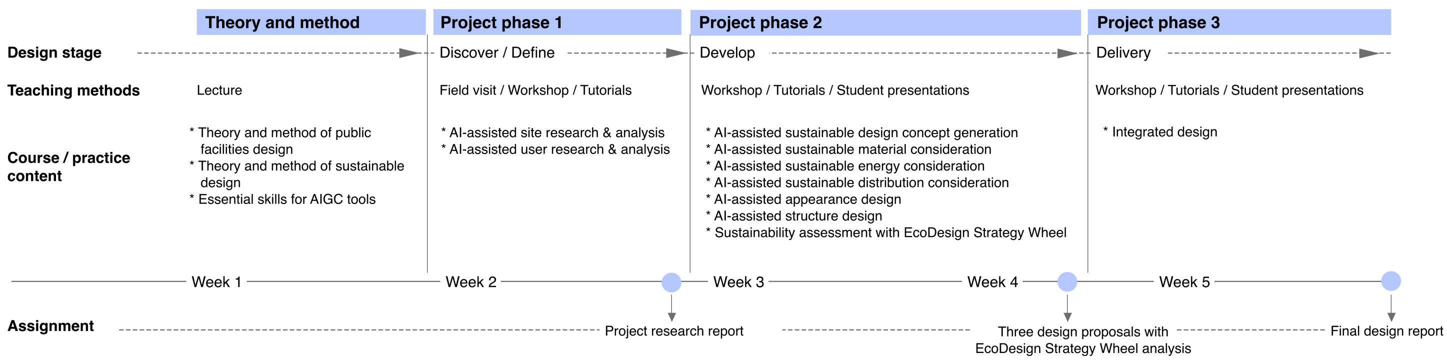

Figure 4

Course framework

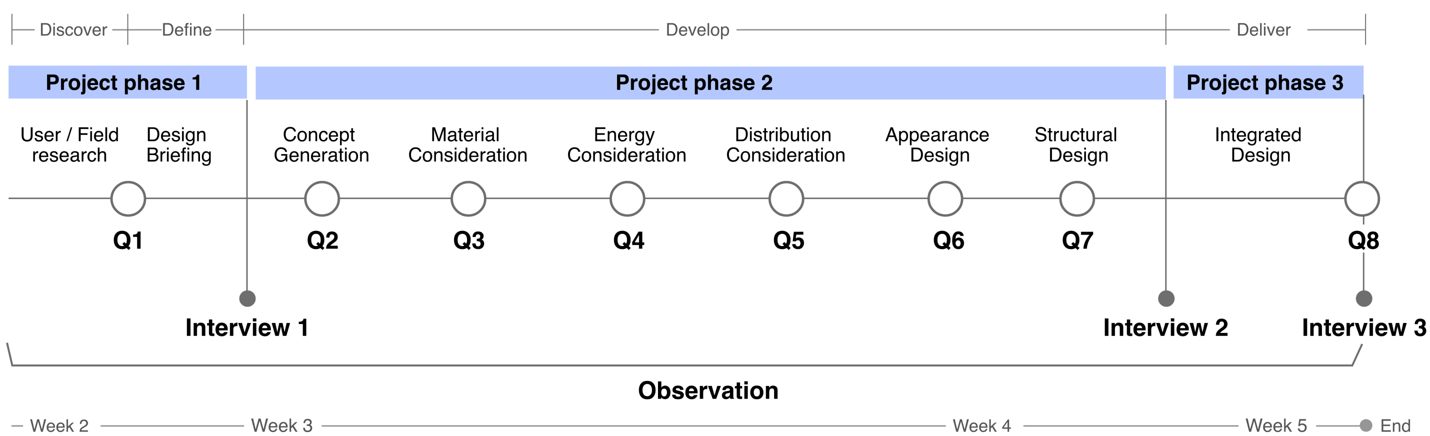

Figure 5

Timeline of data collection activities throughout the course

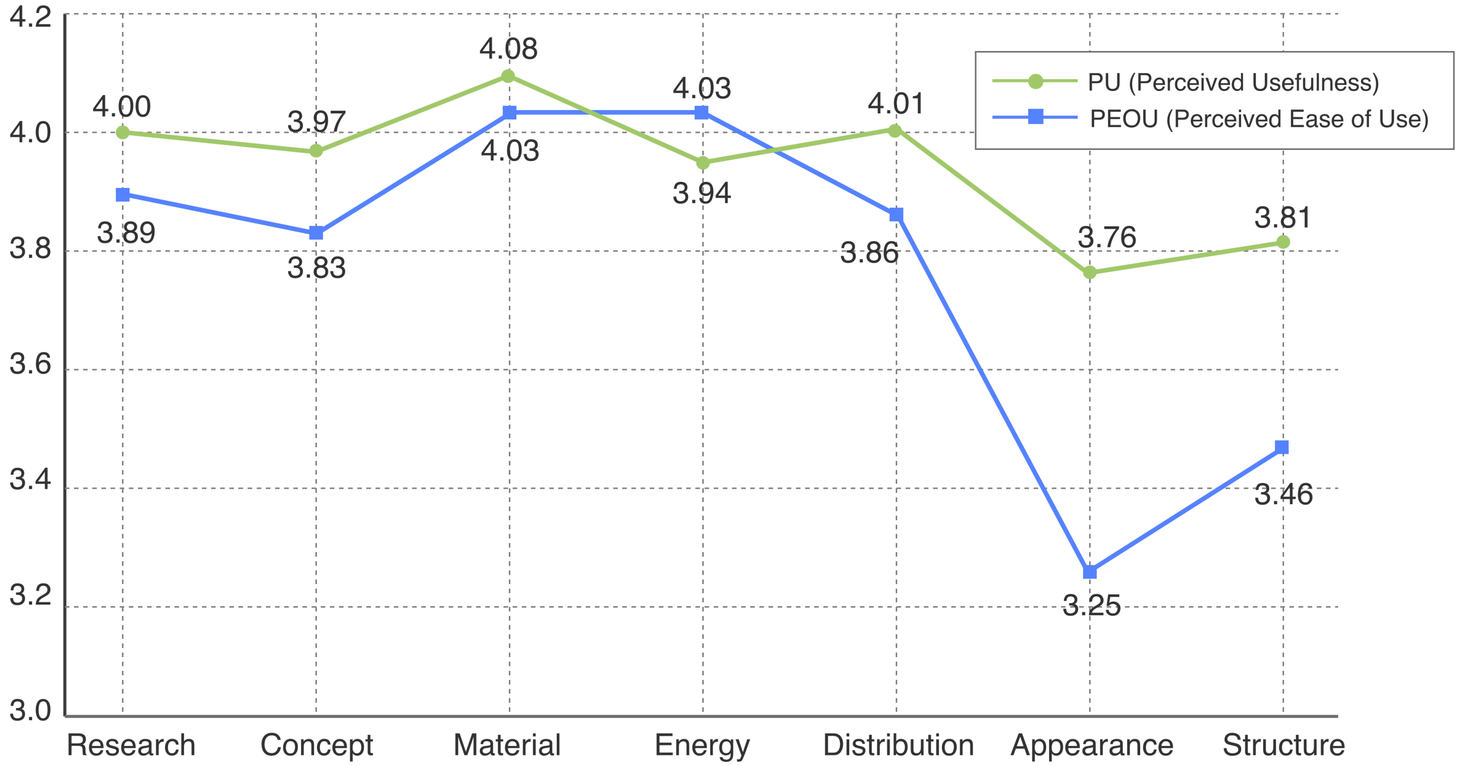

Figure 6

Average result of PU and PEOU across design steps

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterials.zip
- AppendixA.docx