A Preliminary Study on Integrating Sustainable Product Design Elements into the Skill Development and Curriculum Planning of Industrial Design Students

Tien-Li Chen[1], Chun-Yueh Hou[2,*], and Rui Zhu[2]

[1]Department of Industrial Design, National Taipei University of Technology, Taipei, Taiwan
[2]College of Design, National Taipei University of Technology, Taipei, Taiwan
Email: chentl@ntut.edu.tw (T.-L.C.); houcy40203@gmail.com (C.-Y.H.); raynezhu@gmail.com (R.Z.)
*Corresponding author
Manuscript received November 23, 2024; accepted April 1, 2025; published June 10, 2025

***Abstract*—Designers play a crucial role in the sustainable development of products. Future designers must possess the ability to address sustainability trends; therefore, sustainable product design content should be integrated into design education curricula to equip design students with the necessary knowledge. To construct learning content for sustainable product design, this study first applied grounded theory to analyze 50 journal articles published in SCIE, SCI, and AHCI, summarizing key elements of sustainable product design. Six major dimensions were proposed: 'Functional Design', 'Material Utilization', 'Resource Utilization', 'Energy Utilization', 'Life Cycle Management', and 'Value Management'. Subsequently, the competencies and courses required for industrial design students were introduced and discussed. The analysis revealed that the cultivation of each dimension is linked to the development of 'Product Development Planning Skills', 'Human Factors Knowledge Skills', 'Aesthetic Design Skills', 'Engineering Application Skills', and 'Market Insight Skills'. These competencies can be taught through courses such as 'Marketing Planning', 'Materials Manufacturing', 'Deep Thinking', and 'Design Practice'. It is hoped that the findings of this study can serve as a reference for sustainable product design education curriculum planning and the formulation of educational goals, contributing to efforts toward sustainable development.**

***Keywords*—sustainable product design, industrial design education, design education competencies, design education curriculum**

I. Introduction

The World Commission on Environment and Development set the goal of ensuring that the needs of the present generation are met without compromising the ability of future generations to meet their own needs, defining the purpose of sustainable development [1]. In 2015, the United Nations proposed 17 Sustainable Development Goals, aiming to guide the global community in creating a better living environment [2]. However, current production and consumption patterns are causing irreversible harm to the environment and human well-being, countering the goals of sustainable development and demanding urgent solutions [3]. Design plays a critical role in achieving sustainable product development [4], as decisions made during the design phase have a significant impact on product sustainability [5]. Consequently, the role of the designer becomes crucial. Through sustainable product design education, future designers can be equipped with the knowledge, skills, and sense of responsibility to make informed strategic decisions, enhancing the social and environmental value of their work, particularly in higher education [3], while preparing students for future careers [6] to address global sustainability challenges [7]. However, current education primarily focuses on teaching the technical aspects of sustainable design, with little emphasis on its practical implementation [8]. Moreover, the methods students learn often do not clearly define the goals needed to achieve product sustainability [9]. As a result, when tasked with proposing innovative and sustainable solutions, students are often uncertain whether their proposals are effective enough [3]. This study compiles and reviews relevant literature, using sustainable product design as a foundation to gather and assess related research. It aims to refine the components and implementation goals of sustainable product design, and discusses the competencies and curriculum necessary for industrial design programs. The goal is to propose key elements of sustainable product design within various course plans, with the hope of contributing to the sustainable development of the planet and fostering greater well-being.

II. Literature Review

A. Sustainable Development's Impact on Product Design

While promoting sustainable development, product development and manufacturing remain significant contributors to ecological and social issues [10], countering the goals of sustainable development [3]. Therefore, integrating sustainability perspectives into product development is increasingly important [11], with the design stage being recognized as a critical phase for achieving sustainability [12]. This involves considering environmental, economic, and social factors through sustainable product design [13], optimizing resource utilization to secure long-term benefits for the environment, economy, and society [14]. However, sustainable development encompasses many diverse aspects of product design [11], making the role of designers essential [3]. Designers must prioritize sustainability during the design process [15], harnessing creativity and innovation to address sustainability challenges [16].

B. Integrating Sustainability into Industrial Design Education

Design education serves as a preparatory stage for students before entering the industry, and instilling sustainable design thinking, along with equipping designers with the necessary knowledge and confidence, is considered the responsibility and value of teaching design [6]. Therefore, integrating sustainability into design practice is crucial for education, as it forms the foundation and future of sustainable development [17], playing a pivotal role, particularly in the education of industrial design students [18]. Sustainable design education should be driven by social and industrial demands while addressing forward-looking issues, such as developing innovative products with low energy consumption and reducing energy intensity in the manufacturing process [19]. It is also essential to fully integrate the essence of sustainable design into the curriculum without compromising or undermining the completeness of the courses in any way [3]. However, current sustainable design education primarily focuses on conveying operational techniques for sustainable design, with less emphasis on how to implement them effectively [8]. Moreover, the methods currently taught to students do not clearly define the goals required for product sustainability [9]. Therefore, course materials need to support students in developing the skills necessary for sustainable design [20].

C. Development of Industrial Design Skills and Curriculum Planning

Industrial design is a discipline that integrates multiple specialized fields [21]. To cultivate an industrial designer, it is essential to develop competencies in nine areas: Product Planning and Development, Market-Related Knowledge, Design Humanities, Aesthetics and Form, Engineering, Hand-drawing Expression, Computer-Aided Design, Human Factors Engineering, and the Personality Traits of Industrial Designers [22]. Liu *et al.* [21] compiled the professional competencies that industrial design students should possess, including Aesthetic Literacy, Design Expression, Creativity, Planning and Integration, Engineering Capability, Computer Application, Ergonomics Knowledge, and Foreign Language Proficiency. In terms of courses, Lu & Ji categorize industrial design courses into five main types: the 'Marketing Planning Course', which focuses on product planning, brand marketing, design case studies, patents, and intellectual property; the 'Materials Manufacturing Course', which emphasizes materials and manufacturing processes, mechanical engineering, and ergonomics; the 'Expression Skills Course', which covers computer-aided design, expression techniques, and color theory; the 'Deep Thinking Course', which delves into design psychology, aesthetics, and artistic creation; and the 'Design Practice Course', which involves product development, product design, and project design [23].

III. METHODS AND MATERIAL

A. Methods

This study is primarily conducted using grounded theory. It is a qualitative research method that involves systematically collecting and analyzing relevant data [24]. It starts with data analysis to develop theories and is a well-known research method widely used in various studies [25]. This study uses grounded theory to consolidate literature and develop a framework to explore factors related to product sustainability design and its component dimensions.

B. Material

This study's grounded theory literature was collected through Web of Science, using SCI-Expanded, SSCI, and AHCI as sources. Keywords 'sustainable' & 'product design' and 'sustainability' & 'product design' were used to search for relevant literature. The focus was on open-access articles published between 2020 and 2024, resulting in a total of 50 articles consolidated for review.

IV. RESULT AND DISCUSSION

A. Compilation of Product Sustainability Design Factors

This study consolidated 50 articles, resulting in 290 codes, which were progressively refined into 54 open codes. These were further distilled into 15 axial codes, ultimately resulting in 6 selective codes, representing the six major dimensions of product sustainability design elements: Functional Design, Material Utilization, Resource Utilization, Energy Utilization, as shown in Table 1, the following sections will elaborate on each dimension:

Table 1. Product sustainability design coding results

Selective Coding	Axial Coding	Open Coding
Functional Design	User Needs Characteristics	Emotional Aesthetic Design (5) Health and Safety Design (5) User Needs Satisfaction Design (5) Comfort Design (3) Human-Centered Design (3)
	Product Characteristics	Recyclable Design (17) Product Longevity Design (16) Reuse Design (14) Remanufacturing Design (13) Modular Design (12) Disassembly Design (11) Repairable Design (8) Durability Design (6) Upgradable Design (5) Reliability Design (4) Parts Reduction Design (4) Maintainable Design (4) Life Cycle Theory Application (3) Manufacturability Design (3) Simplified Design (3) Lightweight Design (2) Standardized Design (2)
Material Utilization	Material Selection Characteristics	Eco-Friendly Materials (11) Biodegradable Materials (6) Recyclable Materials (6) Durable Materials (3) Reusable Materials (3) Non-Toxic Materials (3) Compostable Materials (2) Lightweight Materials (2)
	Material Usage Characteristics	Material Reduction (5) Avoiding Harmful Materials (4) Avoiding Non-Recyclable Materials (2)
Resource Utilization	Resource Selection Characteristics	Resource Recycling and Reuse (2)

	Resource Usage Characteristics	Resource Waste Reduction (16) Resource Efficiency Improvement (4)
Energy Utilization	Energy Selection Characteristics	Energy Recycling and Reuse (2) Renewable Energy Use (2)
	Energy Usage Characteristics	Energy Loss Reduction (10) Energy Efficiency Improvement (3)
Life Cycle Management	Processing and Production Characteristics	Production Efficiency Improvement (4) Processing Time Reduction (2)
	Transportation Management Characteristics	Transportation Emission and Cost Reduction (3)
	Waste Management Characteristics	Waste Management (6) Waste Reduction (3)
Value Management	Environmental Management Characteristics	Emission Reduction (8) Environmental Impact Reduction (5) Environmental Pollution Prevention (5)
	Economic Management Characteristics	Profit and Investment Increase (6) Cost Reduction (5)
	Personnel Management Characteristics	Stakeholder Attention (3) Employee Well-being Improvement (2) Labor Efficiency Optimization (2)
	Social Management Characteristics	Social Moral Responsibility (2)

1) Functional design

The Functional Design dimension is composed of 22 open codes, including ‘Emotional Aesthetic Design’, which evokes emotional resonance through product aesthetics; ‘Health and Safety Design’, which ensures health and safety during use; ‘User Needs Satisfaction Design’, which meets users’ needs; ‘Comfort Design’, which ensures the product is comfortable to use; and ‘Human-Centered Design’, which satisfies ergonomic and human factors requirements in usage. Since these five open codes all stem from user needs and sensory considerations, they are consolidated into the axial code ‘User Needs Characteristics’.

In the design process, several considerations were made, including ‘Recyclable Design’, which enables the product to be recycled after disposal; ‘Product Longevity Design’, which extends the product’s lifespan; ‘Reuse Design’, which considers the reapplication of the product after disposal; ‘Remanufacturing Design’, which focuses on reprocessing the product after disposal; ‘Modular Design’, which structures product components in a modular manner; ‘Disassembly Design’, which facilitates the disassembly of product components; ‘Repairable Design’, which allows for the repair and restoration of damaged products; ‘Durability Design’, which ensures the product is sturdy and long-lasting in use; ‘Upgradable Design’, which allows the product to be upgraded over time; ‘Reliability Design’, which ensures stable product performance; ‘Parts Reduction Design’, which reduces the number of product components; ‘Maintainable Design’, which allows for product maintenance; ‘Life Cycle Theory Application’, which considers the product’s life cycle; ‘Manufacturability Design’, which enhances the product’s ease of manufacturing; ‘Simplified Design’, which reduces product complexity; ‘Lightweight Design’, which minimizes the product’s weight and volume; and ‘Standardized Design’, which unifies product specifications in manufacturing. These 17 open codes describe product characteristics and are therefore grouped under the axial code ‘Product Characteristics’..

2) Material utilization

The Material Utilization dimension is composed of 11 open codes, including ‘Eco-Friendly Materials’, which refers to the use of environmentally friendly materials; ‘Biodegradable Materials’, which can be decomposed through biological processes; ‘Recyclable Materials’, which can be recycled after use; ‘Durable Materials’, which are strong and long-lasting; ‘Reusable Materials’, which can be reused after recycling; ‘Non-Toxic Materials’, which are free from harmful substances; ‘Compostable Materials’, which can be used in composting; and ‘Lightweight Materials’, which are lighter in weight. These eight open codes describe the characteristics of the materials used and are consolidated into the axial code ‘Material Selection Characteristics’.

‘Material Reduction’, which focuses on minimizing material usage; ‘Avoiding Harmful Materials’, which avoids the use of toxic or environmentally harmful substances; and ‘Avoiding Non-Recyclable Materials’, which avoids using materials that cannot be recycled—these three open codes describe the characteristics of material usage and are consolidated into the axial code ‘Material Usage Characteristics’.

3) Resource utilization

The Resource Utilization dimension is composed of 3 open codes. ‘Resource Recycling and Reuse’, which refers to the recycling and reuse of resources, describes how resource selection is made and is therefore consolidated into the axial code ‘Resource Selection Characteristics’.

‘Resource Waste Reduction’, which focuses on minimizing resource usage and reducing waste, and ‘Resource Efficiency Improvement’, which enhances resource efficiency to maximize effectiveness, describe the characteristics of resource usage and are consolidated into the axial code ‘Resource Usage Characteristics’.

4) Energy utilization

The Energy Utilization dimension is composed of 4 open codes. ‘Energy Recycling and Reuse’, which refers to the recycling of energy, and ‘Renewable Energy Use’, which involves the use of renewable energy, describe the characteristics of energy selection and are therefore consolidated into the axial code ‘Energy Selection Characteristics’.

‘Energy Loss Reduction’, which focuses on minimizing energy loss, and ‘Energy Efficiency Improvement’, which enhances energy efficiency for greater effectiveness, describe the characteristics of energy usage and are consolidated into the axial code ‘Energy Usage Characteristics’.

5) Life cycle management

The Life Cycle Management dimension is composed of 5 open codes. ‘Production Efficiency Improvement’, which focuses on enhancing processing efficiency for greater effectiveness, and ‘Processing Time Reduction’, which aims to reduce the time taken during the processing phase, describe the characteristics of processing management and are therefore consolidated into the axial code ‘Processing and Production Characteristics’.

‘Transportation Emission and Cost Reduction’, which aims to lower transportation demand during the life cycle to reduce emissions and costs, describes the characteristics of transportation management and is therefore consolidated into the axial code ‘Transportation Management Characteristics’.

‘Waste Management’, which refers to the proper management of waste disposal and recycling applications, and ‘Waste Reduction’, which focuses on minimizing waste generation, describe the characteristics of waste management and are therefore consolidated into the axial code ‘Waste Management Characteristics’.

6) Value management

The Value Management dimension is composed of 9 open codes. ‘Emission Reduction’, which aims to decrease greenhouse gas emissions; ‘Environmental Impact Reduction’, which focuses on minimizing adverse environmental effects; and ‘Environmental Pollution Prevention’, which seeks to avoid pollution to the environment—these three open codes describe the characteristics of environmental issue management and are therefore consolidated into the axial code ‘Environmental Management Characteristics’.

‘Profit and Investment Increase’, which aims to enhance the owner’s return on investment in the product, and ‘Cost Reduction’, which focuses on minimizing the owner’s expenses related to the product—these two open codes describe the characteristics of economic management for the owner and are therefore consolidated into the axial code ‘Economic Management Characteristics’.

‘Stakeholder Attention’, which focuses on the rights and concerns of individuals related to the product; ‘Employee Well-being Improvement’, which aims to enhance employee safety and overall satisfaction; and ‘Labor Efficiency Optimization’, which seeks to ensure effective utilization of the workforce—these three open codes describe the characteristics of personnel management and are therefore consolidated into the axial code ‘Personnel Management Characteristics’.

‘Social Moral Responsibility’, which emphasizes ethical responsibilities and social welfare, describes the characteristics of managing social issues and is therefore consolidated into the axial code ‘Social Management Characteristics’.

B. Development of Industrial Design Learning Abilities and Course Compilation

In the abilities required for industrial design courses, the competencies identified in the literature show a high degree of similarity. Chang & Yu highlight the ‘Product Planning and Development Field [22]’, while Liu *et al*. [21] refer to ‘Planning and Integration’, both of which explore abilities related to product design development and project planning problem-solving. Therefore, this study consolidates them into ‘Product Development Planning Skills’.

Chang & Yu propose the ‘Aesthetics and Form Field [22]’, and Liu *et al*. [21] mention ‘Aesthetic Literacy’, both of which explore abilities related to evaluating and applying aesthetic design and form. Therefore, they are consolidated into ‘Aesthetic Design Skills’.

Chang & Yu propose the ‘Engineering-Related Field [22]’, and Liu *et al*. [21] mention ‘Engineering Capability’, both of which explore abilities related to mechanical structures, manufacturing processes, and material use. Therefore, they are consolidated into ‘Engineering Application Skills’.

Chang & Yu propose the ‘Computer-Aided Design Field [22]’, and Liu *et al*. [21] mention ‘Computer Application’, both of which explore abilities related to computer-assisted design. Therefore, they are consolidated into ‘Computer Application Skills’.

Chang & Yu propose the ‘Human Factors Engineering Field [22]’, and Liu *et al*. [21] mention ‘Ergonomics Knowledge’, both of which explore knowledge related to human factors. Therefore, they are consolidated into ‘Human Factors Knowledge Skills’.

Chang & Yu propose the ‘Personality Traits of Industrial Designers [22]’, and Liu *et al*. [21] mention ‘Creativity’, both of which address creativity and collaborative skills. Therefore, they are consolidated into ‘Creative Collaboration Skills’.

Chang & Yu propose the ‘Design Humanities Field [22]’, which involves understanding different design styles, the historical development of design, and design professional culture. To ensure consistency in naming across various capabilities, this study labels it as ‘Design Humanities Skills’.

The second capability, ‘Market-Related Field [22]’, involves understanding the product market and business operations, as well as conducting further investigation and developing relevant marketing strategies. This study refers to it as ‘Market Insight Skills’.

Furthermore, Liu *et al*. [21] independently propose ‘Foreign Language’, which this study also includes, as shown in Table 2.

Table 2. Competencies of industrial design students

Skills Items	Chang & YU [22]	Liu, *et al.* [21]
Product Development Planning Skills	Product Planning and Development Field	Planning and integration
Aesthetic Design Skills	Aesthetics and Form Field	Aesthetic literacy
Engineering Application Skills	Engineering-Related Field	Engineering capability
Hand-drawing and Expression Skills	Hand-drawing Expression Field	Design expression
Computer Application Skills	Computer-Aided Design Field	Computer Application
Human Factors Knowledge Skills	Human Factors Engineering Field	Ergonomics knowledge
Creative Collaboration Skills	Personality Traits of Industrial Designers	Creativity
Design Humanities Skills	Design Humanities Field	X
Market Insight Skills	Market-Related Field	X
Foreign Language Skills	X	Foreign Language

C. Integrating Product Sustainability Design Requirements into Industrial Design Education

The study integrates the elements of ‘sustainable product design', 'industrial design learning abilities', and 'curriculum planning', resulting in the following conclusions.

In the 'Functional Design' dimension, 'User Needs Characteristics' emphasizes a focus on users' requirements for product humanization, usage needs, health and safety, and emotional aesthetics. Therefore, it is related to the development of 'Human Factors Knowledge Skills', which explores ergonomics, and 'Aesthetic Design Skills', which focuses on aesthetic application. It is also closely related to 'Product Development Planning Skills', which involves planning and problem-solving. In the curriculum, this is reflected in the 'Marketing Planning Course' for learning product planning, the 'Materials Manufacturing Course' for studying ergonomics, the 'Deep Thinking Course' for design aesthetics and psychology, and the 'Design Practice Course' for product development.

In the 'Product Characteristics' dimension, which focuses on the necessary features of the product itself, aspects such as Modular Design, Remanufacturing Design, and Manufacturability Design are explored. This dimension is therefore more closely related to the development of 'Product Development Planning Skills' and 'Engineering Application Skills', which involve planning and problem-solving as well as knowledge of engineering structures and manufacturing processes. In the curriculum, this is reflected in the 'Marketing Planning Course' for product planning, the 'Materials Manufacturing Course' for understanding manufacturing procedures and mechanics, and the 'Design Practice Course' for product development.

In the 'Material Utilization' dimension, both 'Material Selection Characteristics' and 'Material Usage Characteristics' explore the selection and use of materials. This dimension is therefore related to the development of 'Product Development Planning Skills' and 'Engineering Application Skills', which involve planning and problem-solving as well as knowledge of manufacturing processes and materials. In the curriculum, this is reflected in the 'Marketing Planning Course', which focuses on product planning, and the 'Materials Manufacturing Course', which covers material knowledge and manufacturing procedures.

In the 'Resource Utilization' dimension, both 'Resource Selection Characteristics' and 'Resource Usage Characteristics' explore the selection and use of resources. Therefore, this dimension is related to the development of 'Engineering Application Skills', which involve knowledge of manufacturing processes and engineering. In the curriculum, this is associated with the 'Materials Manufacturing Course', which covers understanding manufacturing procedures.

In the 'Energy Utilization' dimension, both 'Energy Selection Characteristics' and 'Energy Usage Characteristics' focus on the selection and use of energy. Therefore, this dimension is related to the development of 'Engineering Application Skills', which involve knowledge of manufacturing processes and engineering. In the curriculum, this is associated with the 'Materials Manufacturing Course', which covers understanding manufacturing procedures.

In the 'Life Cycle Management' dimension, 'Processing and Production Characteristics', 'Transportation Management Characteristics', and 'Waste Management Characteristics' focus on the goals related to manufacturing, transportation, and subsequent disposal stages. Therefore, this dimension is related to the development of 'Product Development Planning Skills' and 'Engineering Application Skills', which involve knowledge of manufacturing processes and engineering. In the curriculum, this is associated with the 'Marketing Planning Course', which covers product planning, and the 'Materials Manufacturing Course', which includes understanding manufacturing procedures.

In the 'Value Management' dimension, 'Environmental Management Characteristics', 'Personnel Management Characteristics', and 'Social Management Characteristics' all focus on achieving various value creation goals. Therefore, this dimension is related to the development of 'Product Development Planning Skills' and 'Market Insight Skills', which involve understanding product markets and business operations. In the curriculum, this is associated with the 'Marketing Planning Course', which deals with product planning, and the 'Materials Manufacturing Course', which includes understanding manufacturing procedures. The results are shown in Table 3.

Table 3. Alignment of sustainable product design principles with skill development and course structure

Selective Coding	Axial Coding	Skills	Course
Functional Design	User Needs Characteristics	Product Development Planning Skills, Human Factors Knowledge Skills, Aesthetic Design Skills	Marketing Planning Course, Materials Manufacturing Course, Deep Thinking Course, Design Practice Course
	Product Characteristics	Product Development Planning Skills, Engineering Application Skills	Marketing Planning Course, Materials Manufacturing Course, Design Practice Course
Material Utilization	Material Selection Characteristics	Product Development Planning Skills, Engineering Application Skills	Marketing Planning Course, Materials Manufacturing Course
	Material Usage Characteristics		
Resource Utilization	Resource Selection Characteristics	Engineering Application Skills	Materials Manufacturing Course
	Resource Usage Characteristics		
Energy Utilization	Energy Selection Characteristics	Engineering Application Skills	Materials Manufacturing Course
	Energy Usage Characteristics		
Life Cycle Management	Processing and Production Characteristics	Product Development Planning Skills, Engineering Application Skills	Marketing Planning Course, Materials Manufacturing Course
	Transportation Management Characteristics		

	Waste Management Characteristics		
Value Management	Environmental Management Characteristics	Product Development Planning Skills, Market Insight Skills	Marketing Planning Course, Materials Manufacturing Course
	Economic Management Characteristics		
	Personnel Management Characteristics		
	Social Management Characteristics		

D. Discussion

This study has compiled the elements of sustainable product design, gathering design elements related not only to environmental aspects but also to social, economic, and human factors. This reflects the importance of addressing multiple environmental, economic, and social dimensions in sustainable product design [13]. In the discussion and analysis of capability development and curriculum for industrial design students, it was also confirmed that various aspects of sustainable product design encompass different skill developments and courses, making it a multidisciplinary and interdisciplinary curriculum [19, 26]. Additionally, the complex nature of sustainable design presents challenges for implementation and acceptance in education [27]. This study compiles and analyzes the elements of sustainable design, learning capabilities, and curriculum to clarify their interrelationships, aiming to provide a reference for industrial design educators to contribute to sustainable development.

V. Conclusions and Recommendations

This study aims to integrate the elements of sustainable product design into the cultivation of industrial design skills and curriculum planning. Therefore, it first employed a grounded theory approach to consolidate the elements of sustainable product design, resulting in six major dimensions: Functional Design, Material Utilization, Resource Utilization, Energy Utilization, Life Cycle Management, and Value Management. Subsequently, the study consolidated the competencies needed for industrial design students and curriculum planning and further analyzed these in relation to the elements of sustainable product design.

It was found that within Functional Design, ‘User Needs Characteristics’ is related to the development of Product Development Planning Skills, Human Factors Knowledge Skills, and Aesthetic Design Skills. This can be taught through courses such as the Marketing Planning Course, Materials Manufacturing Course, Deep Thinking Course, and Design Practice Course. ‘Product Characteristics’ is related to the development of Product Development Planning Skills and Engineering Application Skills, which can be taught through the Marketing Planning Course, Materials Manufacturing Course, and Design Practice Course.

In the Material Utilization aspect, ‘Material Selection Characteristics’ and ‘Material Usage Characteristics’ are related to the development of Product Development Planning Skills and Engineering Application Skills and can be taught through the Marketing Planning Course and Materials Manufacturing Course. In the Resource Utilization aspect, ‘Resource Selection Characteristics’ and ‘Resource Usage Characteristics’ are associated with the development of Engineering Application Skills and can be taught through the Materials Manufacturing Course.

In the Energy Utilization aspect, ‘Energy Selection Characteristics’ and ‘Energy Usage Characteristics’ are related to the development of Engineering Application Skills and can also be taught through the Materials Manufacturing Course.

In the Life Cycle Management aspect, ‘Processing and Production Characteristics’, ‘Transportation Management Characteristics’, and ‘Waste Management Characteristics’ are linked to the development of Product Development Planning Skills and Engineering Application Skills, which can be taught through the Marketing Planning Course and the Materials Manufacturing Course.

In the Value Management aspect, ‘Environmental Management Characteristics’, ‘Economic Management Characteristics’, ‘Personnel Management Characteristics’, and ‘Social Management Characteristics’ are connected to the development of Product Development Planning Skills and Market Insight Skills, and can be cultivated through the Marketing Planning Course and the Materials Manufacturing Course.

This study aims to provide concrete educational objectives for sustainable product design education through the presentation of relevant results. By systematically consolidating literature to derive these results, it is suggested that future researchers use this framework as a foundation for conducting practical field studies. This approach will offer validation for the framework proposed in this study and contribute to the advancement and refinement of sustainable design education.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Tien-Li Chen proposed the research idea and organized resources; Chun-Yueh Hou conducted and analyzed the research and wrote the manuscript; Rui Zhu reviewed the manuscript; all authors had approved the final version.

Funding

This work was supported in part by the National Science and Technology Council, Taiwan (Project no. NSTC 113-2410-H-027-009).

References

[1] Report of the World Commission on Environment and Development: Our Common Future, World Commission on Environment and Development, 1987.

[2] The SDGs in Action, United Nations. (2015). [Online]. Available: https://www.un.org/sustainabledevelopment/cities/

[3] M. Watkins *et al*., "Sustainable product design education: Current practice," *She Ji: J. Des. Econ. Innov*., vol. 7, no. 4, pp. 611–637, 2021. doi: 10.1016/j.sheji.2021.11.003

[4] E. Delaney and W. Liu, "Insights into environmental sustainability implementation during the design stage of new product development: An industry perspective," *J. Eng. Technol. Manage*., vol. 71, 101803, 2024. doi: 10.1016/j.jengtecman.2024.101803

[5] A. W. L. Lee *et al*., "Enhancing the environmental sustainability of product through ecodesign: A systematic review," *J. Eng. Des.*, vol. 34, no. 10, pp. 814–843, 2023. doi: 10.1080/09544828.2023.2261094

[6] M. Leerberg, V. Riisberg, and J. Boutrup, "Design responsibility and sustainable design as reflective practice: An educational challenge," *Sustain. Dev.*, vol. 18, no. 5, pp. 306–317, 2010. doi: 10.1002/sd.481

[7] K. Kuzmina and V. Lofthouse, "Sustainable design education in higher education and implementation," *Sustainability*, vol. 15, no. 6, p. 5002, 2023. doi: 10.3390/su15065002

[8] S. Giloi and L. Quinn, "Assessment of sustainable design: The significance of absence," *Des. J.*, vol. 22, no. 6, pp. 833–851, 2019. doi: 10.1080/14606925.2019.1651601

[9] K. Raoufi *et al*., "A cyberlearning platform for enhancing undergraduate engineering education in sustainable product design," *J. Clean. Prod*., vol. 211, pp. 730–741, 2019. doi: 10.1016/j.jclepro.2018.11.085

[10] M. Watz and S. I. Hallstedt, "Towards sustainable product development - Insights from testing and evaluating a profile model for management of sustainability integration into design requirements," *J. Clean. Prod*., vol. 346, 131000, 2022. doi: 10.1016/j.jclepro.2022.131000

[11] P. Jiang *et al*., "A bibliometric review of sustainable product design," *Energies*, vol. 14, no. 21, p. 6867, 2021. doi: 10.3390/en14216867

[12] M. C. Chiu and C. H. Chu, "Review of sustainable product design from life cycle perspectives," *Int. J. Precis. Eng. Manuf*., vol. 13, pp. 1259–1272, 2012. doi: 10.1007/s12541-012-0169-1

[13] J. Zhou, T. Xiahou, and Y. Liu, "Multi-objective optimization-based TOPSIS method for sustainable product design under epistemic uncertainty," *Appl. Soft Comput*., vol. 98, 106850, 2021. doi: 10.1016/j.asoc.2020.106850

[14] C. W. Chen, "A framework of hybrid method for developing optimal sustainable product strategies and sustainable product roadmap," *Sustainability*, vol. 16, no. 4, p. 1374, 2024. doi: 10.3390/su16041374

[15] R. Prabhu, M. A. Alzayed, and E. M. Starkey, "Feeling the heat: Investigating the influence of novice designers' trait empathy, and their beliefs, attitudes, and intentions towards sustainability on their identification of problem requirements," *Res. Eng. Des*., vol. 34, no. 1, pp. 61–76, 2023. doi: 10.1007/s00163-022-00398-9

[16] V. Lofthouse, "Engaging designers in sustainability," *Routledge Handbook of Sustainable Product Design*, Routledge, 2017, pp. 112–126. doi: 10.4324/9781315693309

[17] Y. Bakırlıoğlu and M. McMahon, "Co-learning for sustainable design: The case of a circular design collaborative project in Ireland," *J. Clean. Prod.*, vol. 279, 123474, 2021. doi: 10.1016/j.jclepro.2020.123474

[18] Y. Mao *et al*., "Performance and eye movement patterns of industrial design students reading sustainable design articles," *Sci. Rep*., vol. 14, no. 1, 16267, 2024. doi: 10.1038/s41598-024-67223-2

[19] D. Tate *et al*., "Transdisciplinary approaches for teaching and assessing sustainable design," *Int. J. Eng. Educ*., vol. 26, no. 2, p. 418, 2010.

[20] M. K. Watson *et al.*, "Comparing measures of student sustainable design skills using a project-level rubric and surveys," *Sustainability*, vol. 12, no. 18, p. 7308, 2020. doi: 10.3390/su12187308

[21] S. F. Liu *et al*., "Applying quality function deployment in industrial design curriculum planning," *Int. J. Technol. Des. Educ*., vol. 23, pp. 1147–1160, 2013. doi: 10.1007/s10798-012-9228-2

[22] C. M. Chang and W. L. Yu, "Required competencies for industrial designers: A review of domestic and international literature," *Ind. Des*., no. 126, pp. 20–25, 2012. doi: 10.29918/ID.201206.0004

[23] C. C. Lu and T. F. Ji, "The relationship between education and employment in college industrial design department," *J. Des*., vol. 28, no. 3, pp. 47–70, 2023.

[24] C. Urquhart, H. Lehmann, and M. D. Myers, "Putting the 'theory' back into grounded theory: Guidelines for grounded theory studies in information systems," *Inf. Syst. J*., vol. 20, no. 4, pp. 357–381, 2010. doi: 10.1111/j.1365-2575.2009.00328.x

[25] Y. Chun Tie, M. Birks, and K. Francis, "Grounded theory research: A design framework for novice researchers," *SAGE Open Med*., vol. 7, 2050312118822927, 2019. doi: 10.1177/2050312118822927

[26] J. R. Seay, "Education for sustainability: Developing a taxonomy of the key principles for sustainable process and product design," *Comput. Chem. Eng*., vol. 81, pp. 147–152, 2015. doi: 10.1016/j.compchemeng.2015.03.010

[27] J. Nickel, P. R. Duimering, and A. D. A. Hurst, "Distilling sustainable design concepts for engineering design educators," *Int. J. Eng. Educ*., vol. 38, no. 1, pp. 44–55, 2022.