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A Pedagogical Approach to Incorporating the Concept of Sustainability into Design-to-Physical-Construction Teaching in Introductory Architectural Design Courses: A Case Study on a Bamboo Construction Project

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Abstract: Sustainable architectural education is offered in colleges and universities all over the world. Studies have emphasized the importance of sustainable architectural education in introductory courses of architecture major programs, but methods and strategies for teaching sustainable architecture at lower levels are scarce. This study focuses on the design-to-physical-construction process and creates a teaching framework that incorporates the concept of sustainable development from the perspectives of sustainable economy, environment and society. Based on the teaching method of learning through the design-to-physical-construction process and referring to the grounded theory, a case study on a bamboo construction project was conducted to explore approaches and strategies of sustainable architectural education in introductory courses. Results reveal that five systems, including the system of sustainable development, consist of a framework that illustrated the teaching effects. Based on the framework, we discovered five factors that should be considered in incorporating the concept of sustainable development into architectural design teaching, including the necessity of conducting sustainable architectural education in introductory courses. This study helps explore the potential role sustainability plays in incorporating interdisciplinary knowledge, connecting specialized knowledge across different program levels, and motivating student learning. It also provides a reference for the practice of sustainable architectural education.

Keywords: sustainable architectural education; sustainability; architectural design teaching; architectural education among lower levels; learning by doing

1. Introduction

Sustainability requires that a development does no harm to the resources on which it depends [1–4]. A goal of sustainability is to promote and maintain the wellbeing of social, economic and ecological systems [5]. The implementation of a sustainability strategy contributes to the transformation of economic growth from an extensive to an intensive pattern of resource use; it coordinates economic development with population growth, resource utilization and environmental protection to achieve a balanced development of the environment, the economy and society [3,6–8]. Sustainability has been adopted by many industries, including the construction sector [9]. The construction industry is considered to play a significant part in sustainable development [9–13]. It is closely related to resource consumption (eg. wood, steel), energy consumption, air pollution, waste and so on. In 2019, global building energy use was responsible for 35% of global energy consumption, whereas energy-related CO_2 emissions from building operations and construction reached the highest level, accounting for 38% of global CO_2 emission in the year [14–17]. We are entering a new industrial age, with a growth in social productivity, and more attention is given to environmental protection. Architectural design is required to propose buildings that are highly energy efficient and low polluting. The building industry must meet the challenges of raising production efficiency, improving project quality, decreasing production energy consumption, reducing emissions, and increasing recyclable resource utilization [18–22]. The building industry must meet these challenges as it transforms conceptual sustainability from the design drawing to a material built form. The realization of sustainable buildings, therefore, depends on architects changing their design methods and their ideas of building function. Sustainable architectural education is an important part of this transformation [23–26].

The main tasks of sustainable architectural education are to teach students the concepts of sustainable development and knowledge of sustainable architectural design, and to train them to incorporate sustainable technologies into architectural design [23,25–27]. This paper is concerned with the education of sustainable concepts. Sustainable architectural education enables students to acquire knowledge, methods and skills related to sustainable development, which can help resolve current and potential environmental issues in the building industry. One of the focuses of sustainable architectural education is to incorporate the education into architectural design teaching. Altomonte et al. [28] investigated the ways in which the two were combined and identified five paradigmatic program structure models. Sustainable architectural education has been prioritized by colleges and universities in recent years, and it has become more common to combine it with architectural design. In terms of academic levels, the combination of the two disciplines is more common in intermediate and senior years and in higher degree programs [23,27,29]. Research shows that architectural design teaching at these upper levels is likely to focus on sustainability [27,29,30]. This gives upper level students a wide perspective on sustainability that takes into account the physical environment, energy consumption, building technology, materials, and construction techniques. In introductory architectural design courses, sustainable architecture usually includes a consideration of the site environment and built form together with basic knowledge of architectural structures and building materials. Research shows that architectural design teaching at this level tends to slightly focus on or just pay minor attention to sustainability [27,29,30]. Therefore, students are able to gain only superficial knowledge of sustainability and lack any profound understanding of it.

Incorporating sustainable architecture into architectural design teaching is amenable to use of the teaching method learning by doing, which originated in the pragmatic educational philosophy developed by John Dewey early in the twentieth century [31,32]. The method has been a feature of the architectural program at Black Mountain College in North Carolina since the 1930s [33,34]. It is similar to the technique of learning design by modeling or creating physical representations of structures. Learning by doing is widely used in teaching architectural design [35]. In this study, we focused on one aspect of learning by doing, learning in practice; more specifically, on learning through the design-construction process. In terms of incorporating the concept of sustainable development into architectural design teaching, the method of learning through the design-construction process will play a more effective role in sustainable architectural education. Some researchers have analyzed the effect of Solar Decathlon Europe, an educational project-based competition, in the context of the learning in the design-to-physical-construction process approach in sustainable architectural education. Design-to-physical-construction in this study refers to building by hand in reality, rather than digital simulation. Fantozzi et al. [36] think that student participation in a design-to-physical-construction process activity has a positive effect on their architectural development. Students increase their architectural knowledge, skills, and sustainable awareness and also obtain experience in problem resolution and other practical experience, which are attributes that are difficult to acquire in traditional architectural education. Navarro et al. [37] found that Solar Decathlon Europe achieved educational goals and that learning through the design-to-physical-construction process deepened a student's understanding of a sustainable built environment and the solar energy cycle; improved their scientific, technical and social skills; and increased their ability to communicate and cooperate when working in interdisciplinary groups.

Our research also adopted a constructivist approach to teaching. This approach takes Dewey's educational philosophy as an important source of ideas [38] but differs from Dewey's philosophy of developing individual cognition and concept learning. Teachers were required to listen to and understand student perceptions to gain insights into the origin of their ideas. Thus, teachers could guide students in solving practical problems and reflecting on their own activity to increase their knowledge through new experience [39–42].

Although there are varieties of sustainable architectural education, and the topic has drawn extensive attention from design educators and researchers, it is not common that sustainable architecture education is fully integrated in architectural design curricula [24,27,43–45], let alone integrated in initial years of programs (the first year in a three-year program; the first and second years in a five-year program) [23,27,29,30]. The lack of attention given to sustainable architectural education in the junior years of architecture programs and the lack of relevant research result in unsuccessful incorporation of sustainable concepts into architectural design and construction and will even cause a series of problems. For example, when senior students are engaged in a complex architectural design, they will not know how to incorporate sustainability into the design [44], not having been previously introduced to sustainability, into the various stages of the design process or how to specify sustainable technology in building materials or construction activities during design implementation. When required to apply their knowledge of sustainability, students have been observed to unconsciously ignore principles of sustainability in their exploration of space, form and structure [45], showing an incomplete comprehension of sustainability [29,45]. Students are very likely to continue in such ignorance throughout their careers as architects. Therefore, for sustainable architectural education to be effective, it is extremely important to know how to introduce sustainable architecture in lower year classes of architecture major programs, especially in the field of architectural design. Researchers have pointed out that to better promote the integration of sustainability into architectural design education [27,29,46,47], gaps of sustainable architectural education and architectural design at different program levels and stages should be bridged [24,27,30,43].

This study examined the incorporation of sustainable architecture into an architectural design course at Zhejiang University of Science and Technology (ZUST). We focus on the teaching contents and aim to develop the thought of sustainable architecture via learning by doing activities in the design-to-physical-construction process. We hope students would realize the importance of sustainability in architectural design after finishing the course. It is necessary to point out that the concept of sustainability discussed in this study is limited to design-to-construction scope and refers to the sustainability of the design-construction process. The production and transportation of materials, alternative materials, life span and life cycle of an architect, reuse of an architect and architectural parts are not covered. As part of the study, an architectural design curriculum was developed that included concepts of sustainable development to provide a core component for teaching sustainable architectural design. The curriculum extended from architectural design to construction of the built form. It is in accordance with the most primitive and essential definitions and concepts of sustainability and narrows learning by doing—the hands-on nature of the artistic production education concept—to the design-to-construction process. At the same time, it also refers to the constructivism theory in pedagogy. Combining the three strands of economy, environment and society in the sustainability concept, and basing the pedagogical approach of learning in the design-to-construction process, this study examines the teaching methods and strategies that have been adopted while incorporating sustainable architectural education in architectural design teaching among lower levels. Teaching architectural design involves the application of computer technology, and knowledge of material performance, component processing, traditional construction techniques and public recognition. The study contributes to the implementation of sustainability at the initial design stage and into the whole design-to-construction process, making sustainable architectural education a reality at the introductory level. In addition, the study provides a reference point for educators and researchers who want to introduce sustainable architectural education at different levels.

2. Methodology

2.1. Establishment of the Teaching Framework Incorporating the Concept of Sustainable Development

The sustainable architectural design course module that we developed included the learning in the design-to-physical-construction process and introduced sustainable architecture concepts. We intended the teaching to adhere to the most original, essential, and globally recognized understandings of sustainable development to supplement what is considered to be sustainable engineering [48] and exploit the full potential of sustainable architectural design and construction. The introduction of definitions and concepts, and the framework of sustainability that they provide, was complemented by the concept of sustainable development presented in the 1987 report Our Common Future [1]. The sustainable framework established for additive manufacturing [49] is well suited for use as a paradigm of sustainability in this architectural design program. This paradigmatic framework was chosen for two reasons: it is, as stated, derived from the most original and essential concept of sustainable development; and additive manufacturing is similar to the design-to-physical-construction process for learning in that both include the need to understand component processing, pollution control, waste management and the like. We took the framework and improved some details to adapt it to our teaching program.

Our method of teaching architectural design using the sustainability framework we developed revolved around three aspects of sustainable development: the economy, the environment, and society. Concerns of the economy are efficiency and cost; the environment consists of the natural and artificial environment, use of resources and the effects of pollution; and society is affected by the quality of built forms and their public acceptance. In our teaching method, introductory classes in the architecture program explore, through perceiving the texture and characteristics of construction materials by touch and other senses, in order to develop a preliminary understanding of sustainable development. Sustainability changes design goals, so students must acquire a deeper understanding of sustainability. Examples are the development of an understanding of the interaction be-tween a building and its environment, the relationship between construction technology and construction economics, the selection of sites for building construction, the choice of building components and construction methods and techniques. Upon completion of an introductory course, students should have experienced how sustainability is influential throughout the architectural design process and how it informs architectural design decisions and construction decisions.

The pedagogical framework for the teaching method (Figure 1) shows how the teaching model is integrated with the concept of sustainability in combining architectural subjects for teaching in introductory courses. The learning framework includes computer technology, design skills and knowledge that help to further sustainable development. It also develops and expands the connection between traditional architectural design and sustainability in the digital age. This can encourage introductory level students to consider the influence of environment, technology, and economy on architectural design. It indicates an architectural design training into which sustainability is consciously integrated and which cultivates a student's ability to apply concepts of sustainability in architectural design. It helps to improve the quality of each step of a project from design to construction and increases the professional ability of future architectural practitioners.

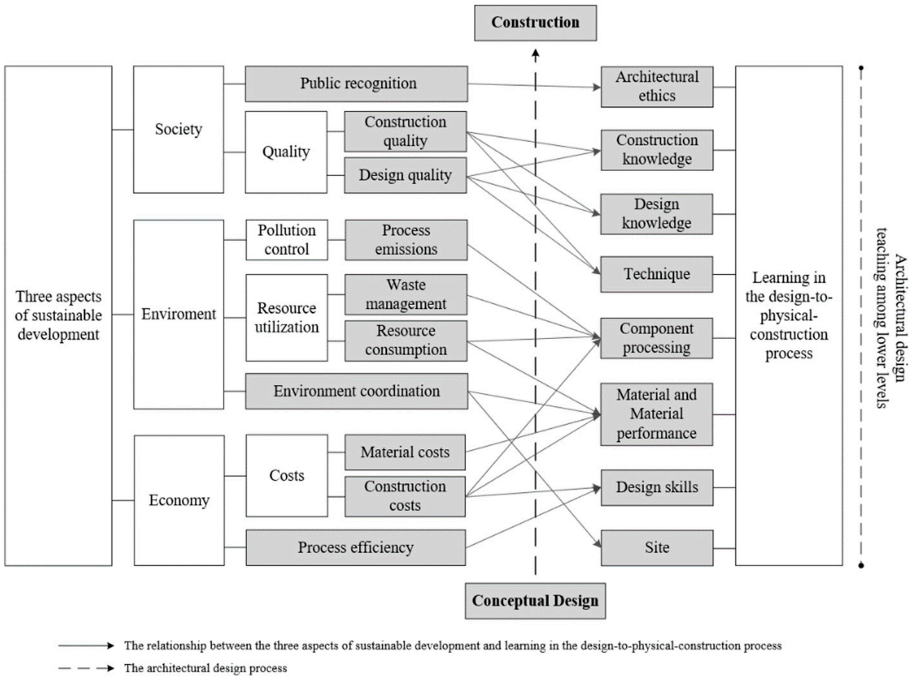

Figure 1. The pedagogical framework used in this architecture teaching.

2.1.1. Economy: Focusing on Efficiency and Cost

Efficiency and cost are the main indicators of economic sustainability. Efficiency refers mainly to efficiency of process, and cost includes construction costs and material costs. Their place within the entire program is shown in Figure 1. Our goal was to connect economic sustainability to design skills, materials and their performance as well as component processing, and to further connect economic sustainability to the subfield of the three. The intensive course was short (two weeks) and not excessively funded. Students needed to consider which design software was most appropriate (including whether to choose a design software package they were not familiar with) before conceptual design to ensure design quality and improve design efficiency with the use of design software. Students also needed to know how material behaved and how to process construction materials before conceptual design to reduce the time and costs (including labor costs) of material and component processing. The program is systematic; students are not necessarily required to decide efficiency and costs before conceptualization. However, they are expected to reflect on these issues before conceptualization and in modeling and processing materials so that they can spontaneously adjust the design or the conceptualization approaches, including the choice of design software.

2.1.2. Environment: Focusing on Environment, Resource and Pollution

Environmental sustainability requires maintaining ecosystem vitality and reducing resource utilization and environmental pollution. In this intensive teaching program, coordinating the building and the environment, making reasonable use of resources, and controlling pollution are three key issues for the realization of environmental sustainability. Resource utilization consists of resource consumption and waste management, which need to be adjusted in the design-to-physical-construction process. Pollution control mainly refers to the controlling of process emissions, which need to be considered throughout the design-to-physical-construction process. Resource consumption includes material use and energy consumption, and waste management includes recyclable and nonrecyclable waste. Our goal was to relate environmental sustainability to the site and materials being used as well as to material performance and component processing. Students are generally familiar with environmental coordination because the relationship between architectural form and its environment is emphasized in architectural teaching but they are largely unfamiliar with resource utilization, which is easily ignored by students in architectural design. We encouraged students to estimate resource utilization and pollution control before conceptual design, as we had encouraged them to prethink efficiency and cost issues. Students were allowed to adjust their estimates according to the specific situation in material processing that they encountered.

2.1.3. Society: Quality and Public Recognition

Social sustainability focuses on maintaining the integrity and diversity of the natural and cultural environments while improving livelihoods. Quality and public recognition are the primary manifestations of social sustainability in the teaching program. Quality consists of design and construction quality. The program goal is to relate quality to techniques, design knowledge and construction knowledge. Public recognition emerges from public participation in the critique of built forms. Design quality and public recognition are usually associated with landmark buildings that are the instantiations of high quality design concepts, and public recognition is the social discourse stimulated by such buildings. Learning in the design-to-physical-construction process is a positive force for recognizing the social sustainability of an architectural design. A built form presents the final effect of a designed entity and is a visual reminder of the relation between architecture and public participation. By integrating social sustainability into teaching, we hope that students will gain a more layered and extensive understanding of a sustainable building so that they will think more deeply about architectural problems such as site, space, form, construction and culture.

2.2. Teaching Sample

ZUST is a university in mainland China that is famous for cultivating applied talents. Its architecture major is a 5-year program, a typical program length in Asia. Since 2018, the ZUST program has offered an intensive 2-week construction activity course that we developed for first and second year students in the architectural design course. There were 32 students in the initial intensive course offering, and they created 11 structures with cardboard (Figure 2). The dimensions of each structure were 3–4.5 m long, 2–3.8 m wide and 1.8–4.2 m high. In 2019, ZUST signed a school–government coordinated educational cooperation agreement with the Anji government in Zhejiang. The agreement allows the university to design and construct artistic architectural forms using bamboo provided by the government. Judging from the teaching experience of the past year and the success of the cooperation, we plan to continue this construction activity in the architectural design course, with bamboo as the primary material. The ecological and environmental characteristics of bamboo and its renewability [50–52] convinced us to fully integrate the concept of sustainability into architectural design teaching. To this end, we designed and created an architectural design pedagogy and teaching method that emphasizes both physical construction using bamboo as a material and the inclusion of sustainable practices during construction.

There were 56 student participants in the second iteration of the 2-week intensive course; 30 were first year students and 26 were second year students. The students were divided into 8 groups, with 4–11 students in each group. Four groups contained only first year students, three groups contained only second year students, and the other group consisted of students from each level. There were four instructors. Two instructors were from ZUST and teach architectural design, thermal comfort, green building, and building physics. The other two instructors were from Zhejiang University and teach mainly architectural design; one interdisciplinary instructor has a background in mechanical engineering. Only three students had participated in the construction activity in the previous year (2018), but they had no experience of construction with bamboo. Thus, all the students were at the same level of knowledge and experience in using bamboo for construction; similar prior knowledge was the foundation that enabled us to use the same teaching method and pedagogical framework for all students; therefore, we could be generally consistent in teaching practice in the architectural design course.

Figure 2. Construction scenes and some completed design works in the construction activities in 2018.

2.3. Interview and Grounded Theory

In order to obtain a better understanding of teaching results and ensure the quality of interviews, we used semi-structured interviews. A total of 26 students were involved in the interview, with 18 freshmen and 8 sophomores. The number of interviewees meets the requirement that the sample size is generally between 20 and 30 [53]. A higher proportion of freshmen were involved because their understanding of architecture and sustainable knowledge is in the initial stage, and they could absorb newly taught knowledge more quickly. The higher proportion of freshmen can help to better understand teaching effects and students' acquisition of knowledge. We made an interview outline as shown in Table 1. The interviews were conducted in a teacher's office. Each interview lasted 2–5 h and we recorded the interviews and sorted out data in a memorandum.

In view of the lack of relevant theories—and in many cases, qualitative analysis can analyze problems in education field in more depth and provide greater detail than quantitative analysis [54]—we used grounded theory to analyze interview data. We first selected two-thirds of the interview samples for open coding. In order to ensure complete semantic meaning and thorough analysis, coding was carried out in a sentence-by-sentence coding manner (Tables A1 and A2 in Appendix A). The letters "F" and "S" were used to indicate the interview data from freshmen and sophomores, and according to the degree of data refinement, coding was divided into three levels: concept labeling, initial concepts, and core concepts. Next, we performed axial coding on the data, which refers to the classification, comparison, and induction of the "core concepts" in the open coding, and then the "category" was obtained. Finally, we selectively encoded the data to get three "core categories". In addition, we used the method of writing memos to systematically analyze the data. The data cover concepts and categories and all were acquired from interviews. In this process, we can reflect on the relationship between concepts and the ten categories, explore teaching phenomena, and make the research conclusions closer to the truth, thereby laying a foundation for further research. For the relationship between the ten categories, we present it in the form of a concept map (Figure 3). A concept map is a diagram that expresses various relationships and shows how information is shared and collected [55]. It visually represents knowledge structure [56] and can be used as a graphical tool for organizing and describing knowledge and relationships [57], and as an induction tool for predicting and suggesting solutions [58]. It is particularly suitable for demonstrating complex connections between categories, and helps to realize further illustration of categories in terms of attributes, conditions, and relationships. The concept map contains nodes and marked lines. In this article, nodes are the 10 categories in Table A2 in Appendix A. The marked line refers to the connection between two nodes. The texts on the marked lines (such as involved and linked in) represent the internal logic of the connections. This concept map lays the foundation for further research.

Table 1. Interview outline.

NO.	Question Item
1	What sustainability concepts have you acquired from the course?
2	Do you think the teaching method of learning by doing deepened your understanding of sustainability? If yes, which specific points are deepened?
3	Constructivism teaching emphasizes that students learn knowledge through self-reflection. Did you do some self-reflection during the design-to-construct process? If yes, which self-reflections are related to sustainability?
4	Do you think your design ability was improved after learning the course? If yes, which abilities are related to sustainability?
5	What knowledge do you learn from the course? Which knowledge is related to sustainability?
6	What skills of you are improved by learning the course? If yes, which skills are related to sustainability?
7	Sustainability imposes some requirements on the design, construction efficiency, cost, etc. When you are designing a project, how will you select design software to meet these requirements?
8	In which perspectives do you think is design-to-construction related to sustainability?
9	What factors do you think demonstrate the important role sustainability plays in architectural design?
10	Which perspectives of sustainability will you take into consideration in future design activities?

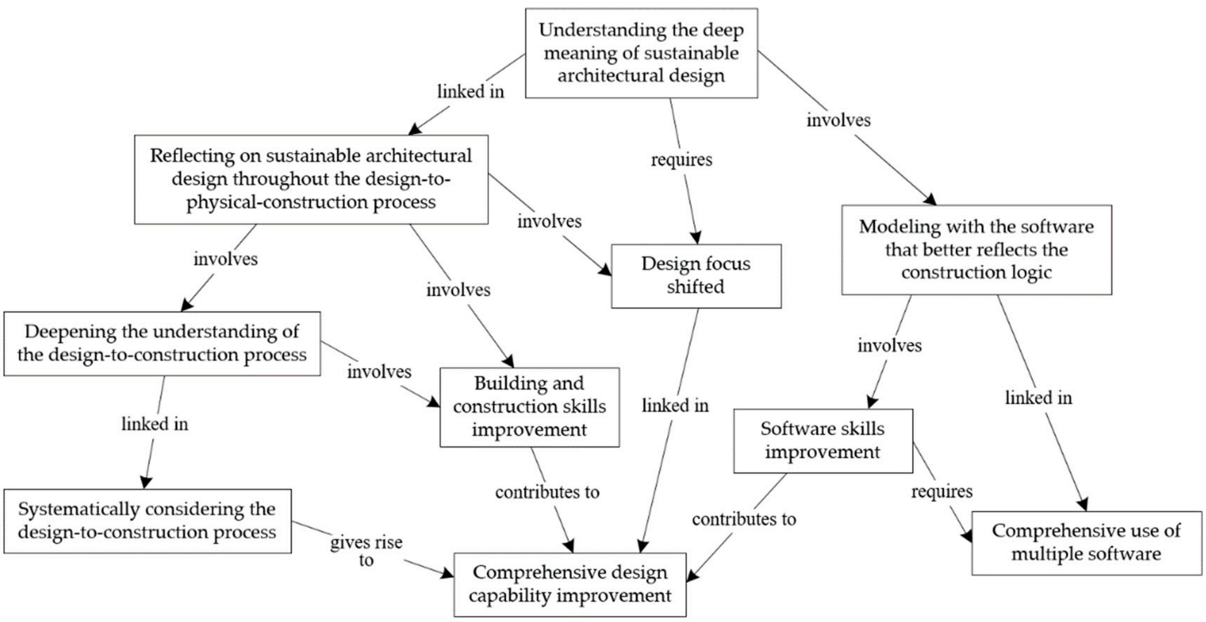

Figure 3. The relationship between the ten categories (refer to Table A2 in Appendix A for category list).

To ensure the quality of research, we took the following measures. Before the interview, we informed the interviewees about the interview purpose, contents and cautions. We created a relaxing atmosphere so as to build trust with the interviewees and encourage them to express their real thoughts. We aggregated the interview data and communicated the aggregated contents to the interviewees to ensure that the contents accurately reflected their views. The coding of the data was carried out independently by two researchers. When the analysis from the two researchers differed, we consulted a third researcher to resolve the differences. We used one-third of the interview sample that was not coded for theoretical saturation testing. The test results show that the categories summarized in this study are relatively complete. There are no new concepts and categories, nor new connections between different categories, indicating that the theoretical models constructed have reached theoretical saturation. Several scholars and experts in the field of architectural education reviewed the preliminary results and conclusions of the research, and put forward their opinions and suggestions on the research results.

3. From Design to Physical Construction

The teaching framework in Figure 1 shows that the teaching program is implemented through the approach of learning in the design-to-physical-construction process. The program is divided into four stages: conceptual design and modeling; schema expansion; component processing; and physical construction. Each stage requires the application of specific architectural design skills and knowledge and includes different sustainability concepts.

3.1. Conceptual Design and Modeling

This stage is the initial period of architectural design. The principal sustainability concepts explored in this stage are process efficiency and cost (economic sustainability), environmental coordination (environmental sustainability), and design quality (social sustainability). The concepts are translated into architectural design through design knowledge, design skills, knowledge of site and materials, and component processing. Sustainable development forces students to consider three items that were seldom thought of before it is introduced: choosing design software for modeling; knowing how materials perform and choosing component processing methods in advance; and estimating material quantities and material transportation and processing costs. Modeling software can represent the speed, efficiency, and details of a digital model as well as the final quality of the model. The method of component processing influences the visual effects of architectural forms and the cost restricts the flexibility of the forms. Students also need to be concerned with a traditional architectural theme, that is, if the architectural form is compatible with the site environment. Some students realized the design model is different from a drawn design which stays on paper, and that the items that must be considered are interrelated. Most students initially chose to use Sketch Up, with which they are familiar, to produce an outline design, and a few students chose to use Rhino in order to produce more flexible forms. But by the modeling stage, the students who used Sketch Up began to try BIM software (Revit; Figure 4). This is a joyous change, because the transition from Sketch Up, which emphasizes spatial effects, to Revit, which emphasizes the logic and effects of the construction, means that the students have changed the focus of their modeling and that sustainability can be more easily implemented in the design-to-physical-construction process.

3.2. Schema Expansion

This stage is the stage of expanding the initial conceptual design. Aspects of sustainability incorporated into this stage are primarily the costs of economic sustainability, resource consumption (mainly material utilization) in terms of environmental sustainability, and the design and construction quality as they influence social sustainability. These factors influence architectural design through design knowledge, construction knowledge, knowledge of materials and their properties, material performance, and component processing. At this stage, the student needs to direct their attention to construction-related issues, such as material performance and structural details. At the same time, students need to gain an understanding of methods of processing materials to adapt them to the overall architectural form and the designed structure. We encourage students to use structural analysis software, for example, to determine a suitable architectural structure and from there to investigate and model the mechanical performance of construction materials. However, the students are in an introductory course and lack adequate knowledge of structures and construction, and few of them have prior experience of the software. Revit provides some capability to examine alternative schemes in the structural analysis of architectural forms. Students who use Revit improve the construction logic of buildings and add construction information for components as part of the gradual transformation of an architectural design into a built structure. Revit also tracks the costs of processing construction materials and so the construction costs of a built structure are monitored by Revit (Figure 5). The objective of this stage is to improve the constructability of the design, and the elements of the conceptual design are transformed from space and form to structural details and construction methods. Sustainability is incorporated into architectural design teaching during this transformative process by developing detailed construction-related technical designs.

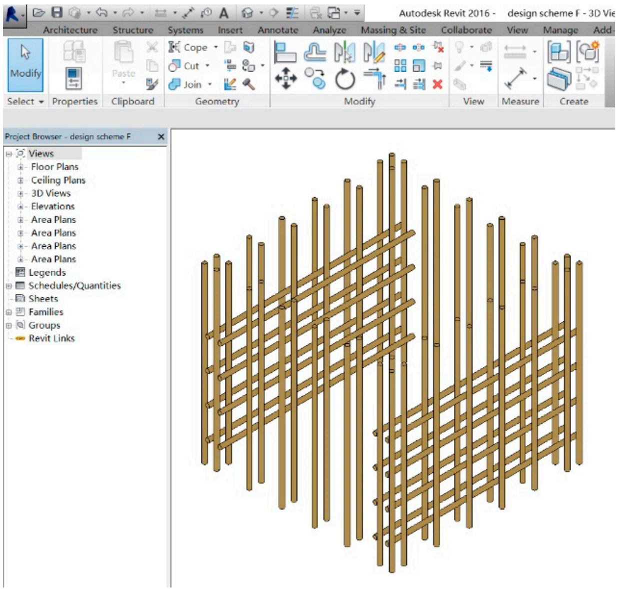

Figure 4. A screenshot of modeling using Revit.

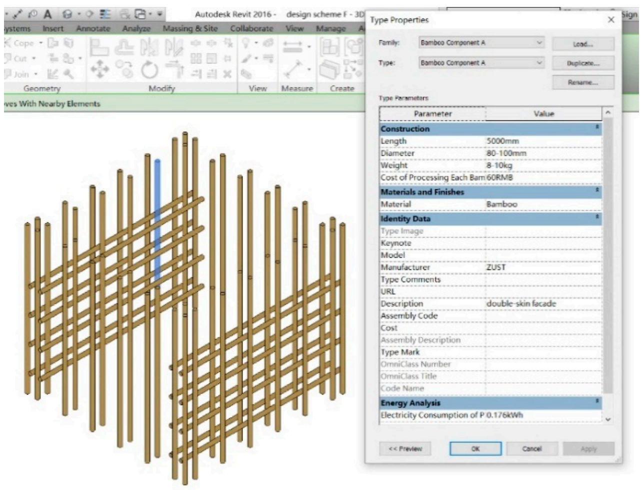

Figure 5. A screenshot of construction information in a Revit model.

3.3. Component Processing

The component processing stage is a stage in which students gain hands-on experience of materials. Sustainability concepts incorporated into this stage are primarily cost issues in economic sustainability and resource utilization (include resource consumption and waste management) and pollution control in environmental sustainability. These factors influence construction principally through the use of construction materials. The learning in the design-to-physical-construction process is important in this stage. Students can experience the texture and characteristics of the materials, as well as learning methods and techniques of working with materials (Figure 6). Students generally lack experience of hands-on working with construction materials and, as a result, encounter difficulties during their initial encounters with the materials in thinking about resource consumption, pollution control, and waste management problems that are related to sustainability. We created a specific lecture-seminar to introduce issues of resource consumption and waste management to guide students in their thinking about these problems and methods. The lecture-seminar had some successful outcomes. Some students tried to control dust pollution from bamboo processing by watering. Some students found ways to utilize the waste produced by bamboo processing through online searching and in conversations with service workers at the host university; two solutions the students found were to use the waste bamboo as a fence for landscape protection, and to turn the bamboo into flowerpots for indoor and outdoor greening and decoration (Figure 7). There is not a single standardized method of material processing, applying traditional techniques, or pollution control. Thus, there is a certain degree of randomness and uncertainty in the teaching and learning of students at this level, and this requires both instructors and students to increase their communication and cooperation to create flexible and efficient solutions to the architectural design and construction problems that the students encounter.

Figure 6. Students experience the texture and characteristics of bamboo materials by manual labor.

Figure 7. Turning useless bamboo into flower pots.

3.4. Physical Construction

Conceptual design schemas are transformed into material entities in this stage. Sustainability concepts incorporated into this stage are primarily cost issues in economic sustainability, resource consumption issues (mainly material utilization) in environmental sustainability and the construction quality and public recognition issues in social sustainability. The concepts are embodied in the architectural design via construction knowledge, materials and techniques, and architectural ethics. Learning in the design-to-physical-construction process is important in this stage. Students need to understand and become proficient in the ways of bamboo jointing and construction. Given that material processing should minimize environmental damage and resource consumption, and the building is a temporary one, students chose to use traditional techniques to join bamboo and other components, and construct the body of the design object. Because the students lacked experience in bamboo construction, we invited craftsmen who possessed expertise in traditional bamboo construction techniques as guides to instruct the students in order to ensure a high-quality final product (Figure 8). Thanks to the patient instruction of the craftsmen, students actively and enthusiastically participated in each step of construction (Figure 9). Many students focused on construction details, such as the angle of connection and the method of bundling. They used computers in constantly observing, comparing, and inspecting differences between the model and the real building as they strove to make the built object consistent with the design model. Such pursuit of design quality is what we desire to see.

Figure 8. Students learn how to work bamboo.

The architectural designs were constructed along the river, in the main landscape area of the campus, which is also one of the most populated areas of the campus. This enabled us to determine the popularity of each structure. We used a platform that is functionally equivalent to Amazon Mechanical Turk to post the completed architectural designs (Figure 10) online for voting to identify the most popular (Figure 11). A total of 807 people, including the general public, voted over three days (one vote per person); students and teachers in the architecture major program and architectural professionals participated in the voting. We hoped the objects would win people's affirmation, and we encouraged their suggestions for improvement through the poll. We hope more people become aware of sustainable architectural design education and the role of buildings in promoting sustainability. In addition, we also observed the impact of the constructions on enhancing the vitality of the campus. Every day from 4:00 p.m. to 5:00 p.m., the campus is most crowded as students are on their way to their dorms after class, engage in outdoor activities, or take a walk after meals. Therefore, on the 18 no-rain days during the display time (30 days in total), we recorded visitor volume at each site where a construction is located (Figure 12), the behaviors and activities of people at the sites (Figures 13 and 14), and the duration of the behaviors and activities (Figure 14). The data collected revealed that:

the visitor volume where the constructions are located has increased, especially at the sites that were rarely visited before; people's behaviors and activities at the sites became diverse, including having fun and taking photos; the behaviors also lasted longer. Some people were even reading for a long time at the site. This may indicate that the constructions have been accepted by people to some extent. People are willing to come to the site for recreation, and the vitality of campus has thus been enhanced.

Figure 9. Students actively participate in each step of construction.

Figure 10. Nine completed architectural design works. Notes: Subfigure a is Scheme a called *Bamboo Cottage*; Subfigure b is Scheme b called *Bamboo Porch*; Subfigure c is Scheme c called *Bamboo Mountain*; Subfigure d is Scheme d called *Dancing Dragon*; Subfigure e is Scheme e called *Mobius Bridge*; Subfigure f is Scheme f called *Bamboo Rubik Cube*; Subfigure g is Scheme g called *Bamboo Sailboat*; Subfigure h is Scheme h called *Bamboo Flower Basket*; Subfigure i is Scheme i called *Bamboo in Wind*.

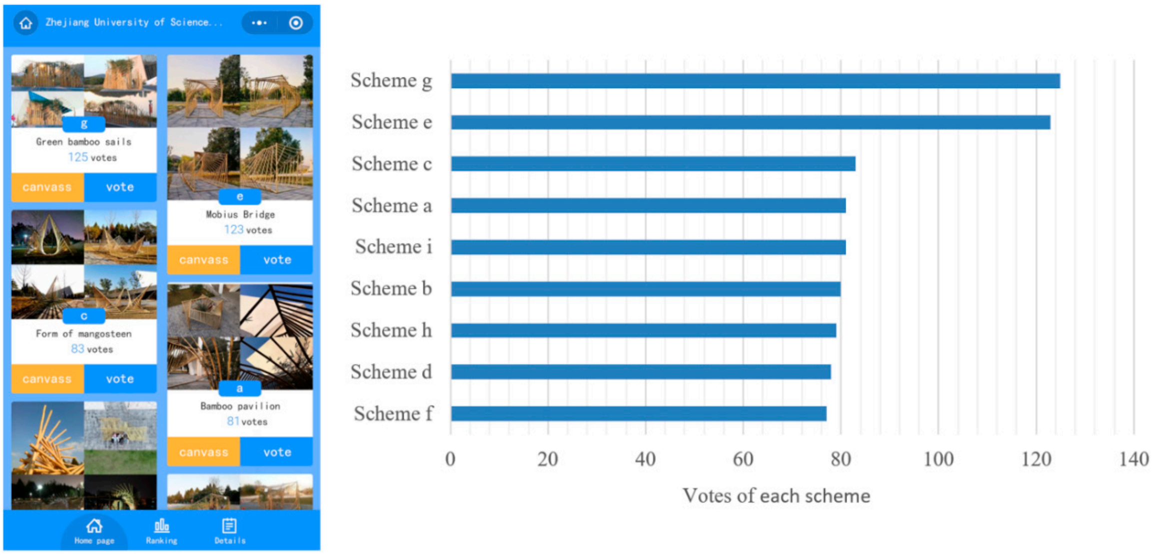

Figure 11. Mobile phone screenshots of the voting screen and the final result of the voting.

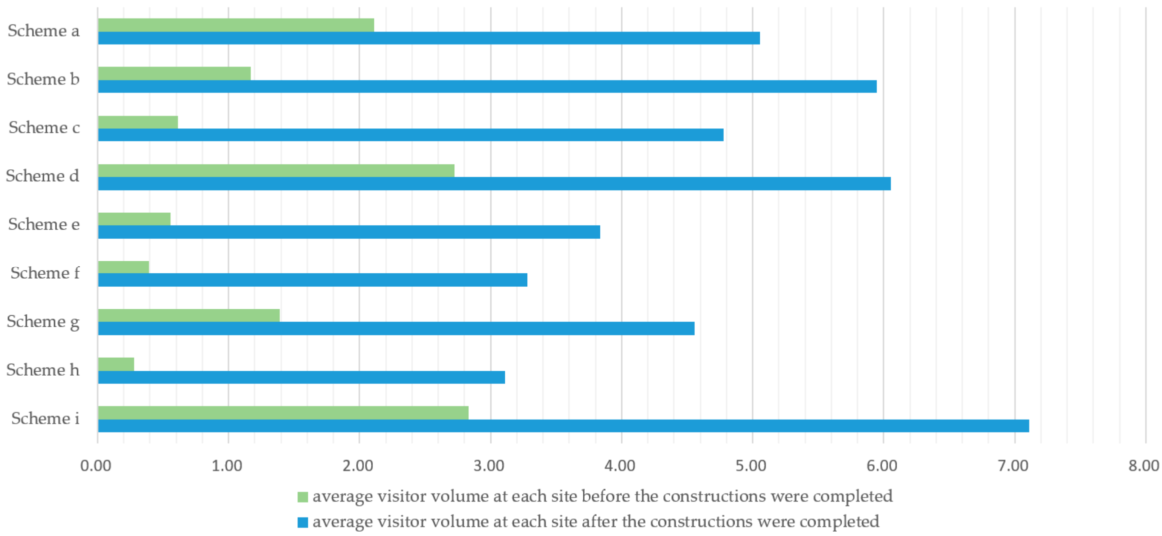

Figure 12. Visitor volume at each site before and after the constructions was completed.

Figure 13. People's behaviors and activities at the site before and after Scheme b and i were constructed.

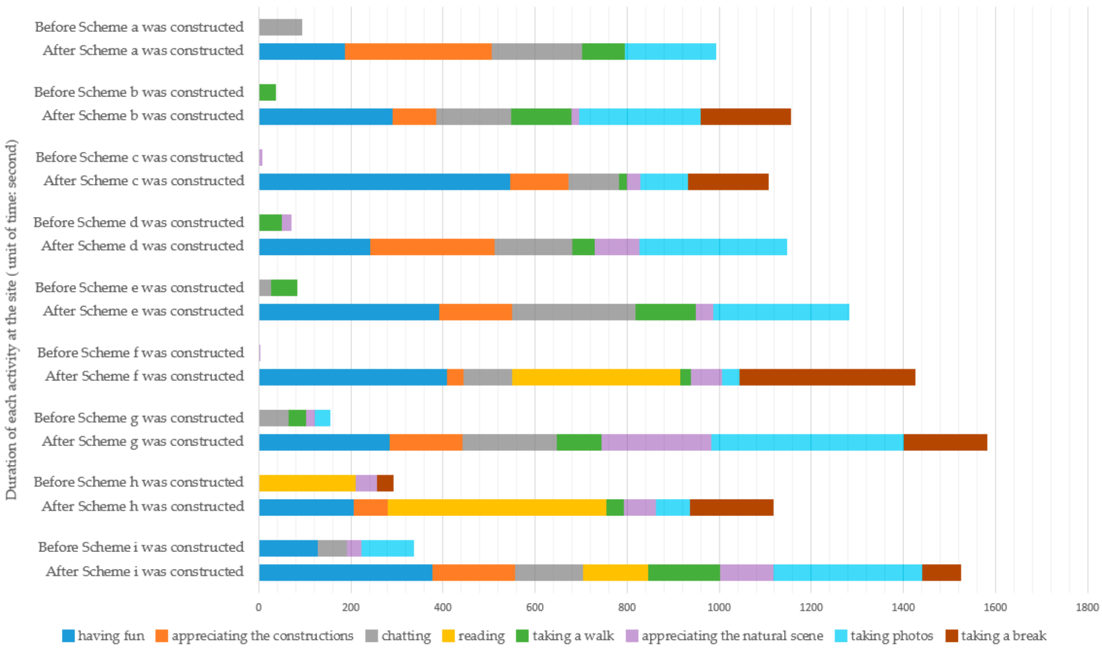

Figure 14. People's behaviors and activities at the nine sites before and after the nine schemes were constructed and the duration of the behaviors and activities. Notes: Scheme a is located at the inner courtyard of ZUST's Student Center; Scheme b is at the open space next to the Student Center; Scheme c is on the grassland next to the Student Center; Scheme d is at the open space next to the Student Center; Scheme e is at the open space between the university gymnasium and the Student Center; Scheme f is on the grassland next to the gymnasium; Scheme g is at the open space by the campus lake; Scheme h is located on the grassland by the campus lake; Scheme i is located in the open space next to the Student Center.

4. Results and Discussion

We display the research results via diagrams. This is in line with the grounded theory's requirement to use diagrams, tables, hypotheses, and descriptions to present research conclusions [59]. By focusing on the categories established in the coding stage, and adjusting and simplifying the diagram established in the memorandum stage, we developed the structural framework that reflects the characteristics of teaching results (Figure 15). The experience system, which is also the inherent characteristic of "learning from design to physical construction", is the basic element of this structural framework. The system of sustainability is at the core of this structural framework. It relates to students' improvement in understanding sustainable concepts and acquiring sustainable knowledge. The system is also connected with the other four systems, which means sustainable ideas can be incorporated with the other four systems and be carried out throughout the entire process of design to construction. The comprehensive design system and skill system are the other two key elements of this structural framework. They are related to our teaching quality and affect students' improvement of academic knowledge and professional skills. Together with these two systems, the system of sustainability constitutes the backbone of the structural framework. The software system is the supporting element of this structural framework, providing external conditions and technical support for smooth teaching activities. The above five systems integrate concepts and categories into the entire process from design to construction from different perspectives, and promote the integration of knowledge and skills. Through the relationships shown by this structural framework, we find that this structural framework is consistent with our teaching framework in terms of the contents contained. This actually indicates that we have to a certain extent achieved the predetermined goal of integrating the concept of sustainable development into the teaching of architectural design in introductory courses.

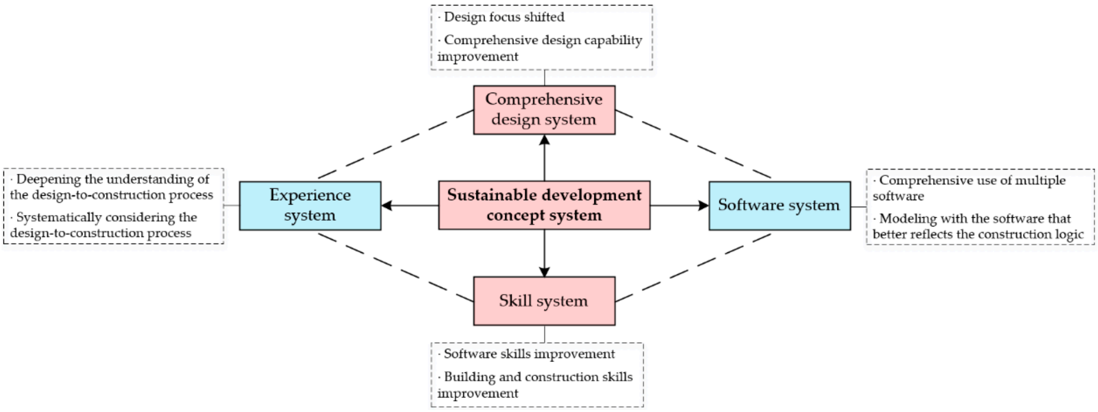

Figure 15. The structural framework that reflects the characteristics of teaching results.

Our research shows that the teaching method similar to "learning by doing" in the experience system can promote the development of sustainable architectural education in the teaching of architectural design in introductory courses. Introductory architecture classes are the loci of induction for learning architecture. At this level, students acquire architectural knowledge of proportion, scale, space and function. Some universities include construction teaching activities in introductory classes to allow students to sense, experience, and understand the concepts of proportion, scale, and space through learning by doing in order to increase their architectural knowledge. Use of methods similar to learning by doing, and incorporating concepts of sustainability into the learning in introductory classes, can also help students to sense and experience sustainability, form a systematic understanding of sustainability, and comprehend its connotations. Research supports this view. Chiles and Holder [60] taught an architectural education program Live Project on Live Projects. The program, which includes themes of ecological sustainability, allows students to instantiate architectural designs in a real world context. The researchers developed the program to provide students with opportunities to participate in the design-to-construction process, and it allows the students to accumulate architectural knowledge, experience application and teamwork, and acquire customer communication skills. Students gain needed skills in architectural design and increase their understanding of construction technology. They also develop their own perspectives on environmental, economic, and social issues related to sustainable development, and take a critical position on these issues. Herrera-Limones et al. [61] use Solar Decathlon, a practical sustainable architectural design competition, as a transformative tool in higher education. It has created an educational ecosystem that favors learning. The practical experience can be used to introduce conceptual and procedural content related to sustainable development, thus giving students the opportunity to increase their understanding of the relationships between architectural design elements, such as architectural form, architectural functions, construction materials and design tools, and sustainability elements, such as material ecology and construction economics, to help them achieve balance between design and sustainability.

We need to stay aware that the incorporation of sustainability into architectural design teaching must be a continuous process. The sustainable development concept system also indicates that students need to think about sustainable design throughout the design-to-physical-construction process, and understand the deep meaning of sustainable design from the perspectives of people, architecture, environment, and society. As a result, with regard to the continuous process and the sustainability concept, be it considered from the perspective of the integrity of the process, or from the perspective of the time and knowledge required for students to fully and profoundly understand the sustainable architectural design, integrating sustainability at the introductory level is not only important but also necessary. Some researchers make a similar argument. Iulo et al. [62] hold that although the concept of sustainability is introduced early in a program, it may not become the predominant theme. However, sustainability can become a necessary part of the curriculum during that time because teachers and students who have learned sustainability may be able to acquire an understanding of sustainability from a philosophical and creative point of view. In this case, sustainability is more likely to become a familiar part of architectural design in intermediate and upper levels of a program rather than an additional, excessive, learning and teaching load. Altomont et al. [45] advocate teaching the major values and principles of sustainability at the undergraduate level in introductory classes (for example, in the first and second year of a five-year program) to increase student understanding of sustainability issues, make students enthusiastic about sustainability, motivate them to tackle contemporary challenges in architecture, and strengthen their creativity in solving sustainability problems such as decreasing environmental pollution or reducing resource consumption. Boarin et al. [29] observed that the scientific dimension of sustainability should be integrated into architectural education as early as possible to make sustainability a driver for creativity in architectural design, thus fostering the morphogenesis of the architectural project. As a starting point, choosing appropriate software and computer technology when creating a digital model can be a significant point in the design process at which to introduce sustainability into architectural design teaching. A suitable software and computer technology can increase design efficiency and quality, reduce design cost, and increase the continuity of information flow between design and construction; it can also ensure the inclusion of sustainability in architectural design, either at the beginning or the end of the design phase. Many researchers have noted the effectiveness of software and computer technology in increasing student learning and understanding and in developing sustainability-related concepts [9,26,61,63]. Mavromatidis [9] shows how elements of technology, architecture, art, building physics, and the environment are complementary. The use of technology allows the parameters of building physics to be visibly displayed and constantly optimized; they can thus influence the building volume and the creation of architectural forms. This improves architectural quality in terms of energy consumption, and creates an adaptive design environment for exploring and verifying design schema.

We observed two noteworthy phenomena in the course of the research. The first, which was discovered in the comprehensive design system, was that when designing an object, students would consider as much in advance as possible the design and construction problems they might meet in the next stage. For example, in the conceptual design and modeling stage, they thought about issues such as building cost or pollution control. The second, which happened both in the comprehensive design and skill systems, was that to incorporate sustainable development, students consciously chose an appropriate design software that permitted them to make timely adjustments in the design-to-construction process and allowed them flexibility in creating reasonable strategies for waste recycling and pollution control. That the students were able to make these choices was due to the learning in the design-to-physical-construction process teaching method. The method compensates for the lack of practical content in sustainable architectural education and provides a hospitable teaching environment in which the two phenomena can emerge.

We think the first phenomenon is a way of anticipating architectural design problems and trying to solve the problems; however, it is also a requirement for integrating sustainability into architectural design. It indicates a way of thinking about architectural design problems within the framework of sustainability. It also indicates knowledge preposition, which is the inclusion of knowledge (e.g., construction knowledge) of a later stage in an earlier (design) stage, and positioning knowledge (e.g., of material performance) used in a later stage for use in an earlier stage. Knowledge preposition is explained as part of Bloom's taxonomy, which represents the process of learning as the transition from using simpler to using more complex thinking skills [64]. The revised Bloom taxonomy, in the 2001 edition [65], includes a cognitive process dimension and a knowledge dimension. Each dimension contains hierarchical levels (Table 2) that are correlated between dimensions. Correlation does not mean that a higher level of cognitive processes necessarily results in more complex knowledge but that an increase in levels in the cognitive process dimension increases opportunities to use or acquire more complex knowledge. In our course, students are expected not only to know, recognize and describe concepts of sustainability but also to comprehend them, apply them in conceptual design, and analyze their characteristics and differences, in order to select and incorporate the appropriate concept into the architectural design. Our pedagogy, therefore, according to Bloom's taxonomy, involves at least remembering, comprehending, applying and analyzing, which means that this course is more likely to involve more professional knowledge in contrast to a course with only a single level or a few levels of cognitive processes. For example, the introduction of knowledge used in a later stage of design into an earlier stage, and the introduction of higher program level knowledge to a lower program level, are forms of knowledge preposition. With an intention to predict the potential for sustainability to act as a bridge to facilitate the transfer of academic knowledge between higher and lower program levels, we tried to identify relationships between sustainability and more detailed design skills and between sustainability and more detailed architectural knowledge (Figures 16–18). The potential was revealed by feedback from a student:

"I thought about how to incorporate the concept of sustainable development in the conceptual design stage and the physical construction stage and in thinking about the concept of sustainable development, I naturally paid attention to knowledge about structural forces, material properties, and component connections. I didn't realize that knowledge of these was supposed to be learned in senior years in university. I just accepted it as new knowledge. Perhaps it is not necessary to schedule knowledge acquisition strictly for each university year."

Table 2. Two dimensions of Bloom's Taxonomy.

Cognitive Process Dimension (from Lower Level to Higher Level)	Explanation	Knowledge Dimension (from Lower Level to Higher Level)	Explanation
Remembering	Emphasis on retrieving knowledge from long term memory.	Factual knowledge	The basic elements that students must know to be familiar with a discipline or solve problems in it.
Understanding	Comprehending the meaning of facts and information such as oral, written and graphic communication.	Conceptual knowledge	Emphasis on the interrelationships among the basic elements that enable them to work together in a larger structure, such as knowledge of categories, knowledge of theories.
Applying	Carrying out or using facts, rules, or ideas in an already arranged or a particular situation.	Procedural knowledge	Methods of doing and inquiry, and criteria for using skills, algorithms, techniques and methods, such as knowledge of subject-specific skills, knowledge of subject-specific methods.
Analyzing	Separating material into component parts and detecting the relationships between the parts and the connection between the parts and the entire structure or purpose.	Metacognitive knowledge	Knowledge of common cognition, and awareness and knowledge of self-cognition, such as strategic knowledge and self-knowledge.
Evaluating	Judging or forming an opinion according to criteria and standards.		
Creating	Putting elements together to make a new whole.		

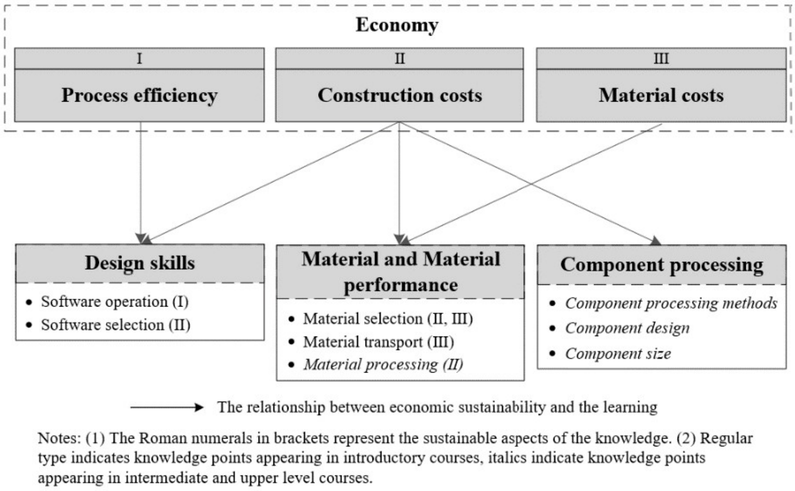

Figure 16. The relationship between economic sustainability and design skills and architectural knowledge.

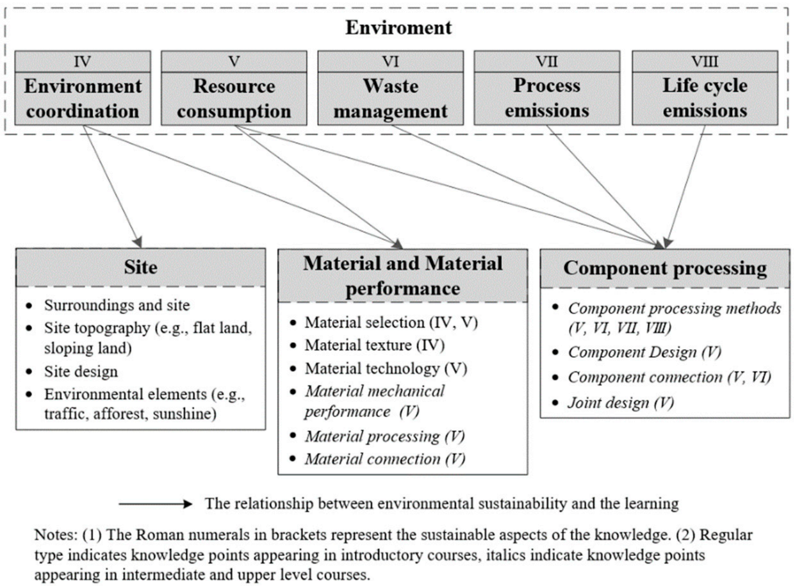

Figure 17. The relationship between environmental sustainability and design skills and architectural knowledge.

In terms of design skills, since sustainability requirements such as improved efficiency and reasonable costs need to be considered at both the design and construction stages, some students used BIM software (Revit) to improve the constructability of the design plan and the accuracy of the design and construction data. These students acquired the skills not only for 2D drawing and 3D visualization modeling, but also for parametric modeling, data management, design and construction parameter optimization, and software combination. Considering the simplicity and efficiency of Sketch Up, students used the software mainly in the conceptual design stage. With Sketch Up, students could quickly conceive design plans, flexibly adjust the volume and form of the design plans, and adapt them to the environment and construction sites. Revit is mainly used in the deepening stage of the design plans, involving the input and management of design and construction data, the modeling of components and nodes (achieved through the Revit Family Function of Revit), and the overall structure optimization of the plans. By using Revit, students coordinated the amount of construction materials used, refined the material processing methods, adjusted and optimized the component parameters, and the connection and logic between nodes. Students were enabled to better consider subsequent construction issues during the plan deepening stage. This helped not only to improve the construction accuracy of the plan, but also to avoid waste caused by blind processing of materials, and rework caused by improper component parameter design and joint connection.

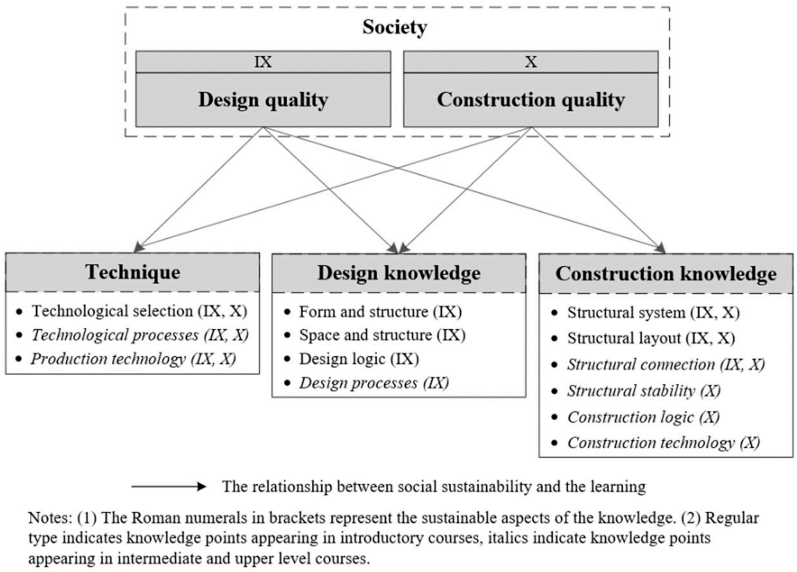

Figure 18. The relationship between social sustainability and design skills and architectural knowledge.

The second phenomenon indicates that students have developed an understanding of the relationships between architectural skill, knowledge acquisition and sustainability. A student's understanding is derived from their perception, experience, exploration, and reflection on their actions which, coupled with the possibility of discovering new ideas, pave the way for a deeper understanding of sustainable architectural design. This phenomenon displays the characteristics of constructivism. Martinez et al. [40] pointed out that learning is concerned with an individual's construction of knowledge. On the one hand, in most respects knowledge is flexible and moldable rather than fixed and stable. On the other hand, a student is a (re-)constructor of knowledge, not a passive recipient. In Splitter's view [42], engaging in knowledge construction is more important than just acquiring knowledge. Teachers are responsible for ensuring that students acquire skills and tools for thinking, reasoning and exploring to prevent them from being trapped in a predetermined and prepackaged knowledge framework, so that students can participate in the process of knowledge integration and synthesis and so gain genuine understanding and knowledge. The use of constructivism as a teaching method is supported by many sustainability educators. Iulo et al. [62] believe that the integration of the aesthetic, ethical and technical aspects of sustainability is a complex activity that demands compatible approaches and that a comprehensive and collaborative design process should be encouraged. An integrated and collaborative design process, therefore, should be encouraged not only to meet the requirements of specifications and certifications but also to develop actual sustainable design thinking. Altomonte et al. [45] observe that to resolve the current challenges posed by architectural sustainability requires efforts in many areas. In education, for example, effort should be invested in encouraging students to become critically aware of the factors associated with sustainability and to reflect on them. There is also a need to improve student creativity in sustainability problem solving and to engage in architectural activities that increase students' knowledge of sustainability. One effective approach is to expose students to experiential learning activities at the disposal of educators, such as field trips, laboratories, and computerized learning tools. Grover et al. [60] emphasize both the importance of the design process and the role of teaching methods in sustainability education. For the former, they suggest prioritizing enrichment through various learning experiences by emphasizing the design process. For the latter, they suggest that sustainability is introduced through critical and reflective interactions between students and educators, because teaching through specific standalone tutorials can undermine critical approaches to sustainability.

In the course of the research, we also found that the continuous design process based on the software system was important for the incorporation of sustainability. Such a process will help to connect each component of sustainability, allowing all components to be brought to bear at any stage of the process as well as in the overall design-to-physical-construction process. Although construction of the design object in this case principally required the use of traditional techniques, students were still encouraged to reduce manual work, and realize small scale automation using tools and technologies in the design process to increase the holism and continuity of the design process. This is another reason why we are concerned that students choose appropriate software and computer technology. Kromoser et al. [63] found that by reducing human–computer interactions and promoting human and mechanical collaboration, a more cost-effective process can be created that combines traditional production techniques with the use of modern technology.

It is reasonable to conclude that the process developed in our teaching program is not unique and that it suggests the value of teaching BIM, teaching with emerging technologies such as VR, and robotic teaching when including sustainability in architectural design. The continuous design process also demonstrates that traditional design methods and computer design methods are not mutually exclusive in architectural design teaching in the digital age, particularly in teaching introductory courses in architectural design. It is more likely that sustainability will become part of architectural design when traditional and computer design techniques become compatible and are blended. Shi et al. [26] provide a good example of how this can be done. Their robotic wood processing and assembly method gave students and teachers remarkable insights for the potential inclusion of sustainability in many aspects of robotic tectonics and automated construction, such as processing precision, efficiency, material economy, and human–robot collaboration.

5. Conclusions

The aim of this study was to increase the inclusion of concepts of sustainability in introductory architectural design courses so as to gain insights into suitable methods and approaches for the full incorporation of sustainability into introductory architectural design courses. We developed a pedagogy that explores how to provide a sustainable architectural education from the perspectives of economic, environmental and social sustainability. The major issue we addressed was how to integrate concepts of sustainability into architectural design using a design-to-physical-construction process. Results show that there is a framework that illustrates teaching effects and the framework consists of experience system, sustainability system, comprehensive design system, skill system and software system. We found that it is necessary to conduct sustainable architectural education in introductory courses and a feasible approach to realize this is via the design-to-physical-construction process, which is an approach of learning by doing. By introducing sustainable education via the design-to-physical-construction process in introductory courses, we could turn the incorporation of sustainability into a continuous activity that happens from lower to higher architectural program levels. This strategy allows students to become systematically aware of sustainability at an early stage of their program and so enables them to consider architectural design issues more comprehensively, and thus become more motivated to think of sustainability in architecture. Besides, this study also identifies the importance of incorporating sustainability in architectural education as a continuous process.

The study illustrates the transformation needed in sustainable architectural education. The teaching framework, approach, and pedagogy involved are applicable to sustainable architectural education based on the design studio. The study shows how to bridge the knowledge gap between environment, economy, society and introductory architectural design education. Techniques include changing the teaching method and curriculum in introductory courses; exploring potential means of combining sustainability knowledge, architectural design knowledge, and design skills; motivating students to create sustainable architectural designs; increasing the continuity of sustainable architectural education at the undergraduate level; and providing a reference point for the introduction of educational techniques such as an integrated curriculum, interdisciplinary learning, and problem-based learning into sustainable architectural education at the undergraduate level.

One major limitation of the study is that it did not discuss the influence of "learning from design to physical construction" on the teaching of architectural design in advanced courses. In fact, some students have mentioned that they will pay more attention to the entire process of design and at the same time, will consider structures, materials and architectural designs in the future designs. They will no longer just focus on the concept of design and the representation of the concept as they did in the past. Our next research is to conduct interviews to understand the performance of these students in their senior architectural design courses. We will use grounded theory to analyze interview data and study the continuous influence of "learning from design to physical construction" on teaching architecture design. We also intend to promote the incorporation of sustainability into architectural design teaching by referring to the methods and practices of sustainability-oriented labs in real-world contexts.

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Institutional Review Board Statement: Ethical Review and Approval were waived for this study, because this study does not involve the biomedical research of human beings. It does not involve human physiological and psychological behaviors, pathological phenomena, causes and mechanisms of diseases, as well as prevention, diagnosis, treatment and rehabilitation of diseases. It also does not involve the collection, recording or use of research materials related to samples of humans, medical records and behavior of the interviewees. In addition, the interviewees in this study do not involve vulnerable subjects, including children, adolescents, pregnant women, and the elderly.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data sharing not applicable.

Acknowledgments: The authors would like to acknowledge the students who have helped us to collect photos.

Conflicts of Interest: The authors declare that they have no conflict of interest.

Appendix A

Table A1. Example of initial data coding.

Data Source	Data	Open Code
Freshman (No. A01; interview data marked with letter F)	The students interviewed think that they have learned a lot in the construction activities, including the physical properties of different materials and the knowledge of structural mechanics. Students realized that there is a big difference between conceptual design and physical construction, and many practical factors need to be considered, including site, material cutting method, and construction difficulty. In terms of sustainability, students believe that starting from the mining and handling of materials, they should consider how to save energy. They also believe that they should consider how to reduce the use of materials at designing stage and how to avoid waste in material processing . . .	F1: Material properties F2: Knowledge of structural mechanics F3: Difference between conceptual design and physical construction F4: Consideration of site factors . . .

Table A2. Content identified by coding.

Open Coding (Concept Labeling)	Open Coding (Initial Concepts)	Open Coding (Core Concepts)	Axial Coding (Categories)	Selective Coding (Core Category)
F3; F9; . . . S5; S7; . . .	Factors that do not meet construction requirements exist in the conceptual design	Experiencing the difference between conceptual design and physical construction	Deepening the understanding of the design-to-construction process	Experience system
F15; F16; . . . S12; S14; . . .	Uncertainties exist in the construction process			
F1; F5; . . . S6; S8; . . .	The impact of form, structure, material processing method, and node connection method on the design-to-construction process	Experiencing the multiple influencing factors in the design-to-construction process		
F23; F26; . . . S16; S17; . . .	The impact of cost, price, and energy consumption on the design-to-construction process			
F10; F19; . . . S4; S11; . . .	Impact of form on construction method	Reflecting on the relationship between form and construction	Systematically considering the design-to-construction process	
F32; F35; . . . S29; S33; . . .	Considering how to transform design parameters into construction parameters			
F6; F7; . . . S1; S2; . . .	Refining the issues related to form and structure in the conceptual design	Comprehensively considering design, structure, and construction issues at the early design stage		
F14; F18; . . . S3; S9; . . .	Considering the issues related to construction and nodes in the conceptual design			
F21; F24; . . . S25; S26; . . .	Considering sustainability issues from the perspectives of site and environmental factors at design stage	Considering sustainability issues at design stage	Reflecting on sustainable architectural design throughout the design-to-physical-construction process	Sustainable development concept system
F37; F38; . . . S30; S34; . . .	Considering sustainability issues from the perspectives of building form, structure, and design quality at design stage			
F49; F51; . . . S43; S44; . . .	Considering the energy consumption, cost and carbon emissions during material mining, transportation, and processing	Considering sustainability issues at construction stage		
F55; F59; . . . S48; S49; . . .	Considering the maintenance cost and environmental load upon completion of the design scheme			

Table A2. *Cont.*

Open Coding (Concept Labeling)	Open Coding (Initial Concepts)	Open Coding (Core Concepts)	Axial Coding (Categories)	Selective Coding (Core Category)
F72; F75; . . . S79; S81; . . .	The impact of the design scheme on enhancing the vitality of the campus	Considering the relationship between the design scheme and people, building, and the environment	Understanding the deep meaning of sustainable architectural design	
F76; F83; . . . S85; S86; . . .	The impact of the design scheme on the campus building and campus landscape			
F73; F77; . . . S82; S83; . . .	The input of various resources in the construction process of the design scheme	Reflecting on sustainable architectural design from a social perspective		
F87; F91; . . . S89; S91; . . .	The public's recognition of the design scheme			
F2; F4; . . . S10; S13; . . .	Focusing on site, environment, structure, material and construction	Focusing on multiple factors related to design and construction during design	Design focus shifted	Comprehensive design system
F20; F22; . . . S23; S24; . . .	Focusing on cost, energy consumption, efficiency, and the sustainability of the design-to-construction process			
F8; F13; . . . S15; S20; . . .	Focusing on the feasibility and ecology of the design scheme	Changing in design ideas and concepts		
F12; F28; . . . S22; S27; . . .	Focusing on structural form, material processing method, construction method, construction process and construction procedure			
F29; F30; . . . S36; S40; . . .	The understanding of architectural aesthetics is enhanced	Raising the awareness of space	Comprehensive design capability improvement	
F31; F39; . . . S35; S37; . . .	The understanding of design principles is enhanced			
F33; F42; . . . S31; S38; . . .	Increasing design and structure knowledge	Acquiring the knowledge taught in senior years		
F45; F48; . . . S32; S41; . . .	Increasing material and construction knowledge			
F50; F53; . . . S47; S56; . . .	Learning the knowledge of the life cycle of building			

Table A2. *Cont.*

Open Coding (Concept Labeling)	Open Coding (Initial Concepts)	Open Coding (Core Concepts)	Axial Coding (Categories)	Selective Coding (Core Category)
F40; F43; ... S50; S51; ...	Familiarizing with Sketch Up operation	Learning a variety of modeling software	Software skills improvement	Skill system
F44; F52; ... S58; S60; ...	Learning about Revit and Rhino operation			
F41; F46; ... S52; S53; ...	Modeling with Sketch Up	Modeling with multiple software		
F57; F60; ... S63; S65; ...	Trying modeling with Revit and Rhino			
F89; F95; ... S88; S93; ...	Learning material processing skills	Master building and construction skills	Building and construction skills improvement	
F96; F97; ... S78; S80; ...	Obtaining building and construction experience			
F106; F108; ... S74; S75; ...	Using of material processing tools	Hands-on ability improvement		
F109; F111; ... S76; S77; ...	Using of building and construction tools			
F62; F63; ... S97; S98; ...	Using Sketch Up, AutoCAD and Rhino in the conceptual design	Using different software at different stages of design-to-construction	Comprehensive use of multiple software	Software system
F79; F81; ... S103; S104; ...	Using Revit in the plan deepening and in the construction			
F106; F113; ... S109; S119; ...	Sketch Up, AutoCAD, and Rhino are suitable for expressing design concepts	Applicable scope of different software		
F121; F125; ... S111; S112; ...	Revit is suitable for showing structure details and construction details			
F107; F112; ... S117; S120; ...	Displaying materials, structures, and nodes through 2D and 3D visualization software	Using software to display materials, structures, and nodes	Modeling with the software that better reflects the construction logic	
F131; F138; ... S125; S129; ...	Displaying materials, structures, and nodes through parametric design software			
F123; F128; ... S127; S136; ...	Facilitating design and building with Revit	Using Revit to improve the construction ability of design		
F126; F133; ... S128; S133; ...	Revit modeling is more accurate			

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