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A Comprehensive Model of Teaching Digital Design in Architecture that Incorporates Sustainability

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Abstract: Digital technology and its use in architecture support the construction industry in transitioning to more sustainable building development. Digital technology is widely taught in architecture programs in China, but there are few consistent strategies for combining digital architectural design with traditional architectural design in architectural education. Consequently, sustainable design concepts are not included in digital architectural design courses, and thus architectural education is not concerned with sustainable development. In this paper, we focus on the teaching of digital design in architecture and investigate how digital architectural design teaching can incorporate sustainability. Data from 15 universities were qualitatively analyzed, leading to the development of four models of teaching digital architectural design. Development of the models revealed that there are three increasing levels in digital architectural design teaching and that there is a close relationship between the teaching level and the transfer of architectural knowledge. This recognition led to the development of a single comprehensive model of digital architectural design teaching that is universally applicable. This research increases our understanding of digital architectural design teaching in architecture programs and strengthens the multi-level connections between digital architectural design teaching and designing and constructing sustainable built objects.

Keywords: digital architectural design teaching; sustainable architectural education; teaching model; architectural education; architectural knowledge

1. Introduction

A sustainable economy and sustainable production can be more readily achieved with the help of information technology [1,2]. This is true for the construction industry. Digital architectural design has been integrated into architecture through computerized design and modeling, which can represent both the appearance and performance of a building. Digital architectural design can improve the expression, creativity, efficiency, and quality of architecture, and it can be used to incorporate sustainability into construction projects [3–5]. As the use of digital architectural design increases in the construction industry, architectural education faces new challenges in the adoption of computer technology and changing to digital architectural design methods and digital architectural design thinking.

Architectural education and training are still greatly influenced by traditional architectural design techniques and have failed to respond to rapid changes in computer technology in a timely and systematic fashion [6,7]. The inclusion of digital technology in architectural education, the need to incorporate sustainability into designs for built objects, and the associated capacity to explore new possibilities in architecture have attracted great attention from educators and researchers [8,9].

The objectives of this study were to identify the essential characteristics of digital design teaching in architecture, to determine how digital technology and design methods could best be incorporated into the architecture curriculum, and to promote the concept of sustainable construction in digital design teaching. We prefer fitting digital architectural design into existing architectural design teaching to adapting architectural design teaching to exploit the potential of digital architectural design, because the former approach allows technologies to be integrated into teaching at a higher level. This is also supported by the SAMR model that defines four degrees of classroom technology integration [10]. In digital architectural design teaching, there are normally two approaches: The first is that based on their architectural design knowledge, students use computer technology to improve and refine the design model. The second is that with a good understanding of both computer technologies and the close relationship between technology and architectural design, students attempt to apply computer technologies creatively, including deriving new architectural design methods and improving architectural design processes. The first approach is similar to the Modification stage described by the SAMR model and the second one the Redefinition stage in this model. Based on the SAMR model, these two stages are, respectively, at the second and highest levels of the four degrees of classroom technology integration and are considered to be the “Transformation” steps of the SAMR model. A digital architectural design program needs to consider the design of sustainable structures since the goal of sustainability influences design concepts and design parameters and informs the choice of construction materials. We used grounded theory as the basis of our qualitative analysis to ensure the accuracy and reliability of our results in our in-depth investigation of the research problem.

We examined teaching materials, course offerings, numbers of courses, and course hours in programs that were representative of Chinese architectural education offered at 15 universities, some of which are renowned across the world, in our examination of how digital architectural design was incorporated into architectural education.

This paper is organized as follows. We begin by reviewing existing research into the status of digital architectural design teaching and the inclusion of sustainable design concepts in digital architectural design teaching. We describe our data collection and our qualitative data analysis and then present the results of our analysis. We present three major findings and discuss their significance. Finally, we summarize our research and present the conclusions we drew from it. Our study develops a framework for the incorporation of digital architectural design into architectural education. Digital architectural design can meet the demands for creating sustainable buildings that are being placed on architects. This is because digital design creates a visual digital model, which provides the basis and conditions for designers to analyze the sustainability of an architectural design. With the visual digital model, designers could not only take into consideration factors of sound, light, and heating, but also simulate building energy consumption, material performance, and transfer building information from the conceptual design stage to the construction stage in a non-destructive manner. Hence, sustainability of building design would be significantly improved, and digital design should be promoted in architectural design teaching. The digital architectural design needs to be able to meet the demands for creating sustainable buildings that are being placed on architects, and hence sustainability should be included in architectural education, and particularly in digital architectural design teaching. We also provide educators and researchers with well-organized information concerning digital architectural design that will support the teaching and research of digital architectural design and sustainability in architecture.

2. Literature Review

Research into digital architectural design teaching as a part of architectural education has increased over the past 30 years. The concept of paperless teaching was developed during the 1990s [11]. In the twenty-first century, building information modeling (BIM) and parametric design have become a part of architecture, introducing concepts such as collaborative design, life cycle management, programming, and algorithms to the profession [12–15] and leading to new developments in digital architectural

design and its teaching. During this period of time, sustainable development concepts have been increasingly becoming a part of digital architectural design teaching. This inclusion can be seen in the teaching of BIM and parametric design. Some educators have made BIM a part of digital architectural design teaching so that design project models include the dynamic control of design parameters and the use of sustainable materials and components in construction and life cycle management to ensure effective management of the design process [13,16,17].

The latest research shows that digital architectural design teaching is still developing in terms of course content and the use of computer technology. An obvious change is that robotic fabrication and performance-based design are frequently used in undergraduate teaching [18–20]. These technologies increase students' understanding of the relationships among structure, material, and form in design. At the same time, with robotic fabrication and data-driven design, they also promote the integration of sustainability into digital architectural design. Some educators have required students to include environmental considerations in architectural design. The use of algorithms and parametric design, as well as other digital technology such as computerized numerical control (CNC) fabrication and 3D printing, has made it possible to transform environmental concerns into architectural elements such as form, space, and structure, as well as built objects. Such technology provides the opportunity to integrate sustainable design into the entire architectural design process [19,21,22].

With the greater application of technologies to architectural design, there are studies that examined teaching models in the context of digital architectural design, such as the Kolb model [23,24], Bloom's taxonomy [7], and an information flow processing model using parametric design [25]. These models can provide some guidance in constructing a curriculum as well as a basic framework for digital architectural design teaching. However, the models have different purposes and are used in different contexts. It is therefore difficult to directly apply them to teaching digital design in architecture. Nowadays, how to better teach digital architectural design is a concern for educators and there is little consensus on course content or teaching models, although they have been widely researched. Many studies argue that digital architectural design should be taught in conjunction with architectural design [8,26–28], but there is no agreement on how to combine them, nor is there a common framework for the use of computers in architectural education [9]. This situation suggests that it will be difficult to fully integrate sustainable design into architectural education.

3. Research Methodology

We used qualitative analysis in investigating the components, characteristics, and other elements of digital architectural design teaching to ensure the reliability and accuracy of the conclusions we draw from the research. The value of qualitative analysis lies in its capacity to reveal the attributes and characteristics of the numbers of courses, course hours, and other elements of digital architectural design courses in ways that go beyond quantitative relationships, as well as the effects they have on digital architectural design teaching. Tsui [29] found that, in many cases, in the field of education, qualitative analysis permits the researcher to analyze problems in more depth and greater detail than quantitative analysis because qualitative analysis provides descriptive information related to the identification of quantitative relations [30].

Since there are few theories of digital architectural design teaching, we used grounded theory, which provides a framework for methodical analysis and theory formation, as the basis of our qualitative analysis. Grounded theory was developed by Glaser and Strauss in the 1960s and 1970s and is an approach well suited to informing research into architecture [31] and architectural education [32]. Its most distinctive feature is that an explanatory theory is formed in the course of analysis [31].

The first step in our research was to collect data. Glaser [33] treated everything as data, including interviews, texts, documents, and records. We used a conventional survey for data collection. It is important in creating a scientific survey to ensure that the objects selected for study are representative, or typical. We used three indicators to ensure fair representation. The first is the place of mainland Chinese universities in two widely used world university rankings: the Quacquarelli Symonds (QS)

World University Rankings by subject (2018) and the Times Higher Education World University Ranking (2018). The second is whether the architecture major program had passed the evaluation of the Chinese Authority for Architectural Education Institutions. The third is the ranking of university architecture programs published under the authority of the Chinese Ministry of Education. We identified the 15 most influential and significant university architecture programs from the information given by the three indicators, our literature search, and recommendations from architecture experts, and we limited our data gathering to these universities (Table 1). We undertook field research and conducted 2–4 h interviews with teachers and students at the universities. To assure the interrater reliability, we refer to Survey Research Methods [34]. According to factors such as teaching content, technology usage, and digital design approaches, we made Table 2 to select interviewees. We interviewed at least one teacher from each selected university. Each teacher interviewed met four of the six requirements in Table 2 and each student three of the six. By doing this, we assured all the teachers interviewed had experience in teaching digital design in architecture and were familiar with theories of teaching digital architectural design and approaches to the subject and possessed appropriate skills. The students interviewed included undergraduate, postgraduate, and doctoral students who had acquired and developed the relevant knowledge and skills. To further assure the reliability of the interviews, we asked the interviewees to rate the degree of their interest in the survey and recorded the degree from 1 to 5 points (for more detail, see Table A1 in Appendix A). As the last step of interviewee selecting, we invited fellow workers engaged in digital architectural design teaching to review the ones we selected. There were 29 interviewees in total, which meets the requirement that the sample size for qualitative research is 20–30 participants [35]. Among the interviewees, 23 were teachers and 6 were students (Table A1). All of them rated their interest in the interview between 4 and 5. Twenty-seven rated it 5 (very interested), accounting for 93% of 29 interviewees. We made notes during each interview, to form a memo. We also examined information published on the official university websites to gain data concerning the development of digital architectural design teaching in the universities.

Table 1. List and initial of universities surveyed.

University	Initial
Beijing University of Civil Engineering and Architecture	BUCEA
Chongqing Jiaotong University	CQJTU
Chongqing University	CQU
Hubei University of Technology	HBUT
Hunan University	HNU
Huazhong University of Science and Technology	HUST
Nanjing Tech University	NJTech
Nanjing University	NJU
South China University of Technology	SCUT
Southeast University	SEU
Tsinghua University	THU
Tianjin University,	TJU
Tongji University	Tongji
Xi'an University of Architecture and Technology	XAUAT
Zhejiang University	ZJU

Table 2. List of criteria.

Criteria	Interpretation of Criteria
Academic achievement	Have publications about digital architectural design or digital architectural design teaching in the past 5 years
Architectural design works	Have architectural design works in the digital architectural design field in the past 5 years, including concept design and construction objects
Technology skills	Possess the ability to use technologies needed for digital architectural design, including design software and hard wares
Knowledge of digital architectural design	Possess a good understanding of digital architectural design methods, theories, and procedures
Course	Teacher: have taught a digital architectural design course in the past 5 years. Student: have taken a digital architectural design course in the past 5 years.
Peer recommendation	The interviewee was recommended by at least one expert in the field of digital architectural design

The second step in our research was coding, which consisted of data collection and analysis. There are three types of coding: open coding, axial coding, and selective coding. Open coding consists of coding the original data in a natural way to abstract and conceptualize the raw data. We used sentence-by-sentence coding to ensure semantic integrity and thorough analysis. We divided the data into three categories, according to the different sources, to better account for the diversity of data sources (Table A2): T represents data from an interview, L represents data from the literature, and W represents data from materials published on university websites. We divided open coding into three types, tagging, initial conceptualization, and core conceptualization, to identify the degree of data abstraction. In axial coding, the core concepts identified in open coding are classified, compared, and summarized into categories. The axial coding process is iterative. After reading and rereading the interviews, open coding, axial coding, and selective coding determine the core categories that underlie all the concepts and categories so far obtained. In order to improve the reliability of coding, the entire coding process was carried out independently by two researchers. When there were coding differences for the same original data, the two researchers discussed the differences and sought to reach an agreement. When the coding differences were difficult to resolve, a third researcher was invited to resolve the issue. Three colleagues in the field of digital architectural design teaching assessed the coding results and the validity of the results. The coding is shown in Table A3.

The third step of our research was to make a memo; that is, to construct a new theory. The construction of a new theory depends on the coding, which suggests theoretical concepts, theoretical categories, and the logical relations between entities. We identified attributes and relations through coding and show them as matrices (Figures A1 and A2). The matrix shows the correspondence between each university and the concepts derived from the survey data. Thus, it is clear what the specific content in each category was. We used concept maps to represent logical relationships (Figure 1). A concept map visually represents the various relationships that show how information is collected and shared [36]. It presents the knowledge structure [37] and can additionally be used as a graphical tool to organize and represent knowledge relationships [38] and, inferentially, to predict and recommend solutions [39]. The concept map can also explain complex relationships between concepts and categories and show how concepts and categories are developed in terms of attributes, conditions, and relations. The concept map is a set of nodes and connectors. In this research, the nodes show the initial concepts and the core concepts determined by open coding, and a directed line represents a logical connection between two nodes, while the linking phrases in the directed lines represent the logic of the connection (Figure 1). The concept map was created as follows. The initial and core concepts were shown by rectangles in the diagram, and any connections between concepts were shown by the directed lines. The reason for the connection was given by the linking phrases, such as involved, used by, or linked in. For core categories, the possibility of further development of category

attributes and significance was considered to provide the basis for the teaching model being developed. The approach was to examine each category and its related core concepts, and depending on the common characteristics of categories, the variables used to describe the core category were summarized in the table of common characteristics, and the teaching model was then drawn in combination with the matrices.

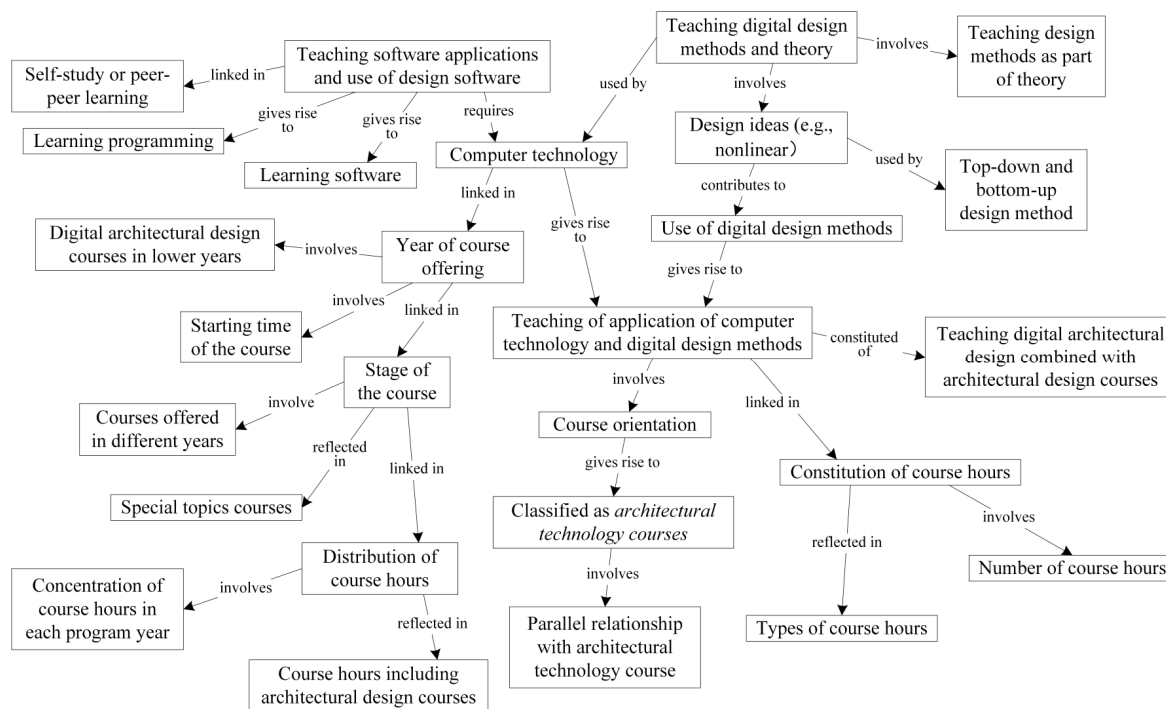


Figure 1. Concept map showing relationships between concepts and categories.

We used several techniques to ensure the reliability and validity of our results. We summarized the data recorded in the survey and communicated the summaries to the interviewees to ensure that the content accurately reflected their views. We alternately collected data and analyzed them during the research process. Additional concepts and categories identified by the analysis were compared with existing concepts and categories and were used to guide sample choice and data collection in the next iteration to ensure consistency of concepts and categories. Finally, several academics and experts in architectural education reviewed our preliminary results and conclusions to provide feedback and assessment of the study results.

4. Research Results

We present the results of our qualitative analysis graphically and derive four models of teaching digital architectural design in architecture programs. These are consistent with the requirements of grounded theory that research results should be presented by means of diagrams, tables, hypotheses, and descriptions [40]. When creating the teaching model diagram, it is necessary to consider any subsequent development of core category attributes and implications. The creation of a common characteristics table (Table 3) facilitates this development. The two variables type and time, which describe core categories, were derived by transforming teaching content, course offering, and other concept phrases in the analysis table into more abstract categories to make the teaching model diagram more general. These two variables provide the two-dimensional horizontal and vertical coordinate axes for the teaching model diagram. The matrices formed from analysis of the core concepts are introduced into the teaching model diagram. The matrices allow us to visually compare teaching material and the content of digital architectural design courses to identify similarities and differences between universities. The four models of teaching digital architectural design can be created according to these

similarities and differences. The teaching model diagram could be further developed by associating the conceptual map with these four models to create Figure 2. The figure represents the relationships between concepts and categories by the multi-level and multi-dimensional relationships between initial concepts and core concepts, forming the basis for a new theory. We summarized university teaching of digital design in architecture as four abstract teaching models (Progressive, Interspersed, Integrated, and Parallel), which can subsequently be used to develop new categories and new theories.

Table 3. Common characteristics.

Core Concepts	Categories	Ideographic Conversion Words	Variables Used to Describe Core Categories	Diagram of Teaching Model
Teaching software applications and use of design software	Requirements for teaching content	Type (related to teaching content)	Variable 1: type	Establishing horizontal and vertical axes for the teaching model
Teaching digital design methods and theory				
Teaching of application of computer technology and digital design methods				
Year of course offering	Course setting	Type (related to course arrangement)	Variable 2: time	
Stage of the course				
Course orientation				
Constitution of course hours	Characteristics of course hours	Time (related to teaching time)	Variable 2: time	
Distribution of course hours				

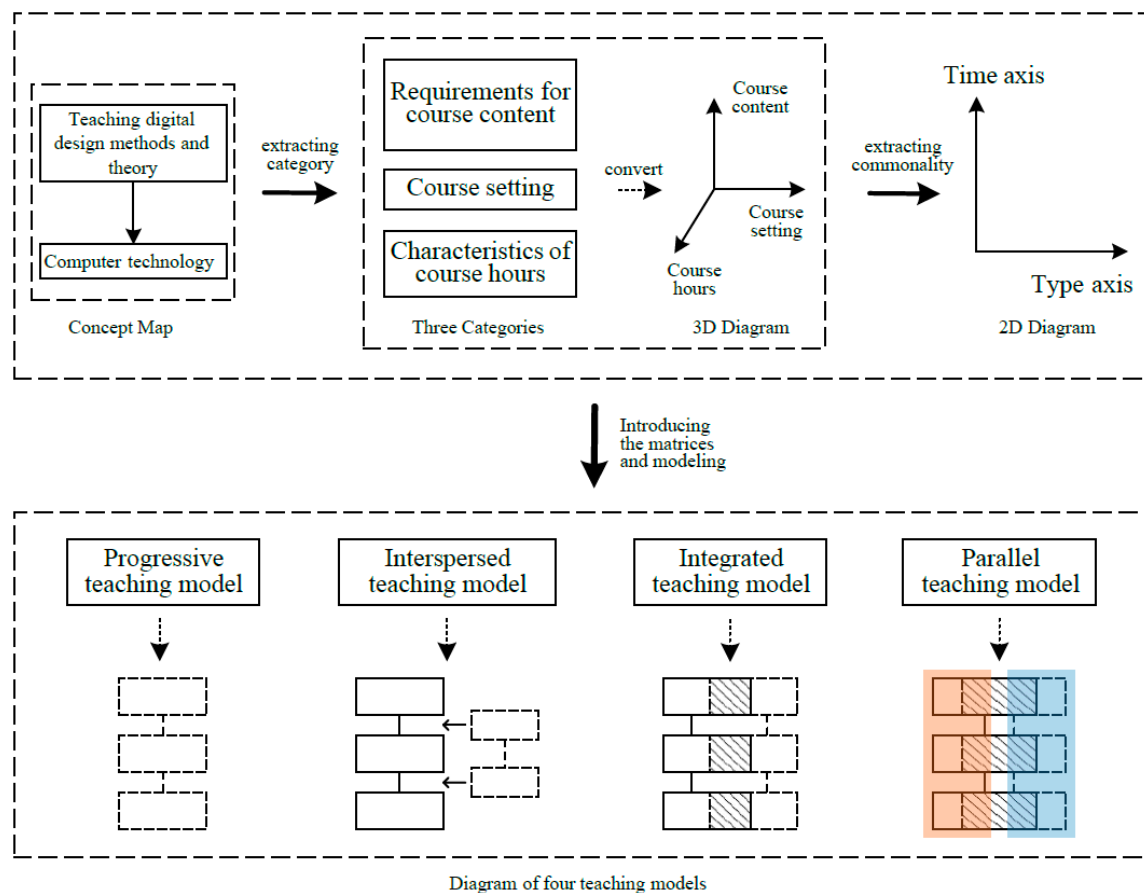


Figure 2. Transformation of concept map into teaching models.

4.1. Progressive Teaching Model

The Progressive teaching model (Figure 3) describes teaching at Tsinghua University (THU) and Tongji University (Tongji) in which digital architectural design is taught linearly. A preceding node and a successive node are clearly related in terms of course content and depth of knowledge: the later node depends on the earlier node for content, which the later node examines in greater depth. There is progression from the earlier to the later node, which is seen in the progressive development of digital design skills and methods and increasing knowledge. This progressive relationship is presented in course descriptions as a progressive transformation from Introduction to Digital Design in Architecture to Acquisition of Digital Design Skills to Using Algorithms in Architectural Design to Comprehensive Use of Digital Design Methods in Architecture in THU and Tongji. The model shows continuity in teaching and emphasizes the importance of the introductory course in digital architectural design by making it the keystone course.

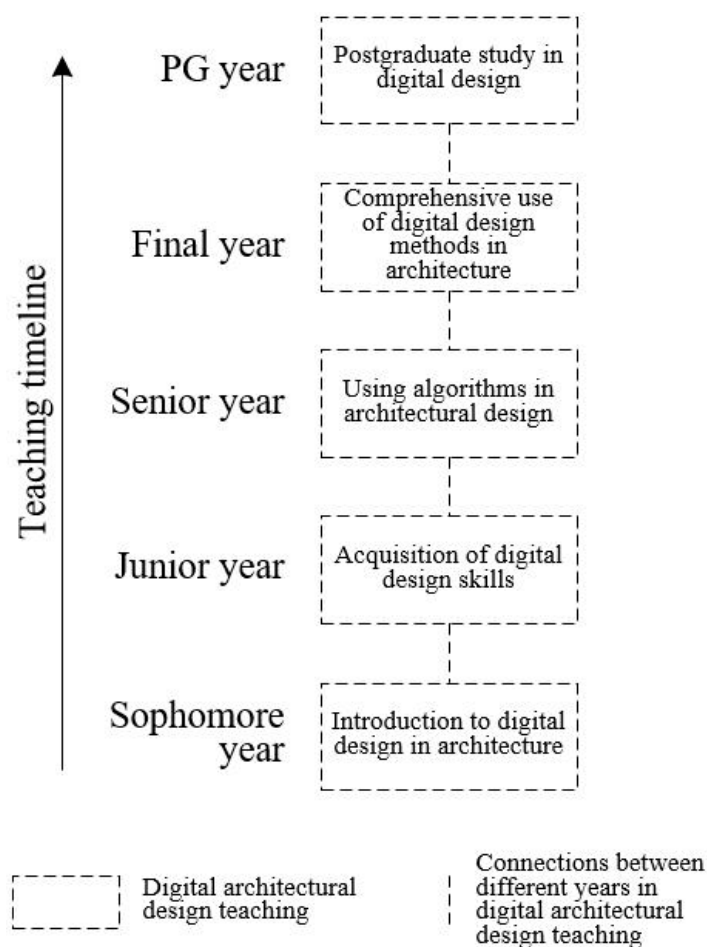


Figure 3. Progressive teaching model.

4.2. Interspersed Teaching Model

The Interspersed teaching model (Figure 4) describes teaching at eight universities: Southeast University (SEU), Chongqing University (CQU), Xi’an University of Architecture and Technology (XAUAT), Zhejiang University (ZJU), Nanjing University (NJU), Beijing University of Civil Engineering and Architecture (BUCEA), Nanjing Tech University (NJTech), and Chongqing Jiaotong University (CQJTU). These universities account for just over half of those in our sample. The Interspersed model has architectural design courses as a backbone, and digital architectural design courses provide support to other architectural design courses. The program functions in the following way. Computer

technology or digital design methods are associated with other architectural design courses and complement design training. At the same time, education in digital architectural design develops student design ability and gives students a greater breadth of knowledge. Although digital architectural design teaching in this model is instantiated as the design theme within a particular architectural course, it is essentially concerned with improving student skills in the use of computerized design and the use of computer technology within the entire program. In many standalone courses, these two aspects of digital architectural design are seen in the emphasis on teaching software usage skills. In ZJU, for example, in the senior year course *Special Topics in Parametric Design*, students are taught parametric design and robotic fabrication. However, software usage is a large part of the content taught in sophomore and junior years.

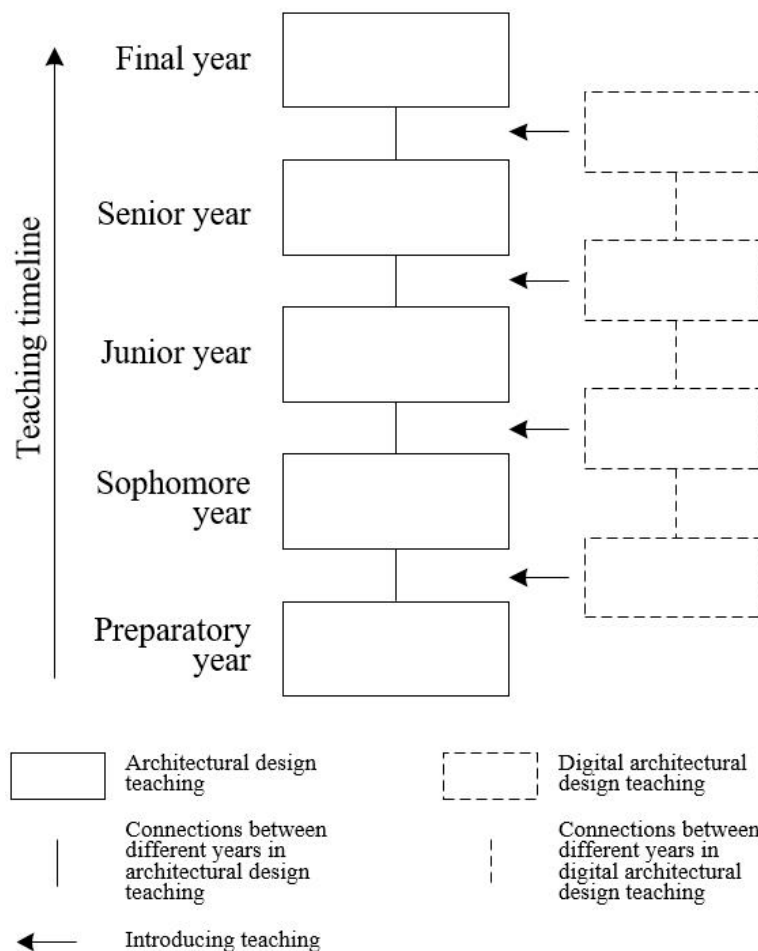


Figure 4. Interspersed teaching model.

4.3. Integrated Teaching Model

The Integrated teaching model describes teaching at Tianjin University (TJU), South China University of Technology (SCUT), Huazhong University of Science and Technology (HUST), and Hunan University (HNU) (Figure 5). The Integrated model emphasizes architectural design but recognizes the close relationship between digital architectural design and architectural design. From the freshman year on, digital architectural design is introduced into architectural design through applications such as BIM or virtual reality. In subsequent years, digital architectural design teaching depends on the teaching progress and goals of architectural design courses. Digital architectural design teaching is subordinate to architectural design teaching. In terms of course content and depth of knowledge, although digital architectural design teaching in the Integrated model becomes progressively more

prominent, it does so in that it services architectural design teaching. For example, in the freshman year at HUST, teachers asked students to complete the traditional architectural drawing assignments using Revit BIM software in the *Preliminary Architectural Design*. The purpose of the assignment was not to increase student proficiency in Revit but to enable them to gain a deeper understanding of plans, elevations, and sections. This relationship of digital architectural design supporting architectural design is shown by the hatched areas in Figure 5.

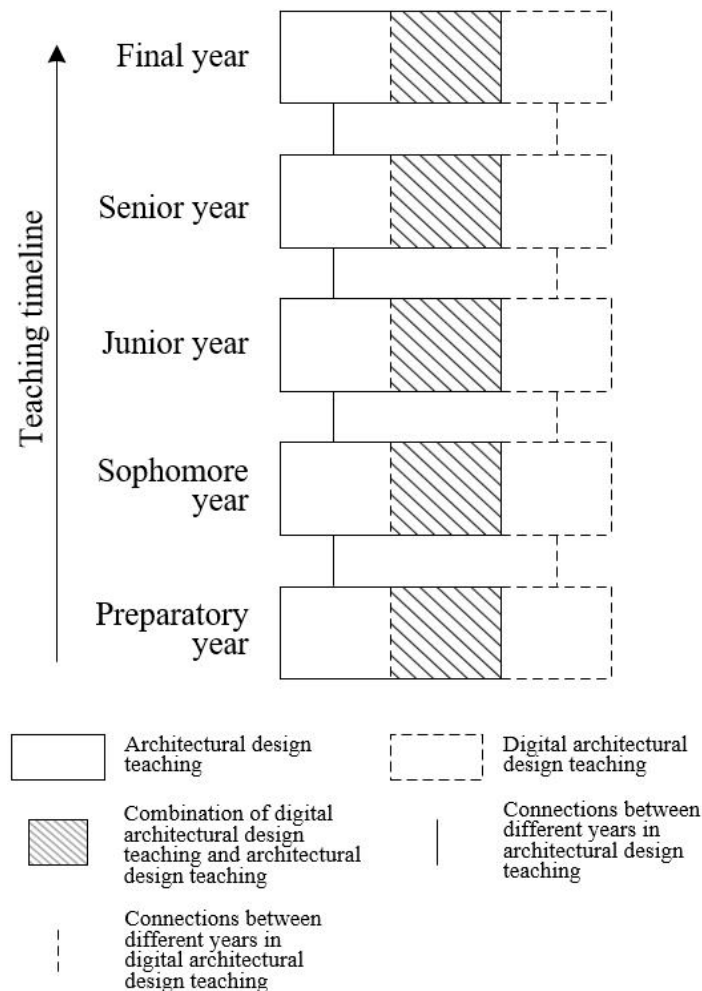


Figure 5. Integrated teaching model.

4.4. Parallel Teaching Model

The Parallel teaching model (Figure 6) describes teaching at Hubei University of Technology (HBUT). The Parallel model emphasizes proficiency in architectural design as well as proficiency in digital architectural design by simultaneously taking two approaches to architectural teaching. One approach is to follow the traditional teaching of architectural design, and the other is to teach digital architectural design in parallel. The former approach establishes all kinds of courses that are necessary in architecture major to teach space, shape, function, structure, material, and other elements traditionally taught. The parallel approach incorporates digital architectural design into the first approach and expands architectural teaching so that digital architectural design and computer technology become fully integrated into architecture courses. At HBUT, for example, architectural technology courses have been the principal courses in the architecture major since 2007. In the freshman year, students study digital and architectural design. In subsequent years, students learn about digital fabrication and, more importantly, use the techniques and design methods they learn to courses such as

Architectural Design, Architectural Construction, and Architectural Structures. This teaching arrangement has contributed to the close association and interaction between digital architectural design teaching and architectural teaching in general.

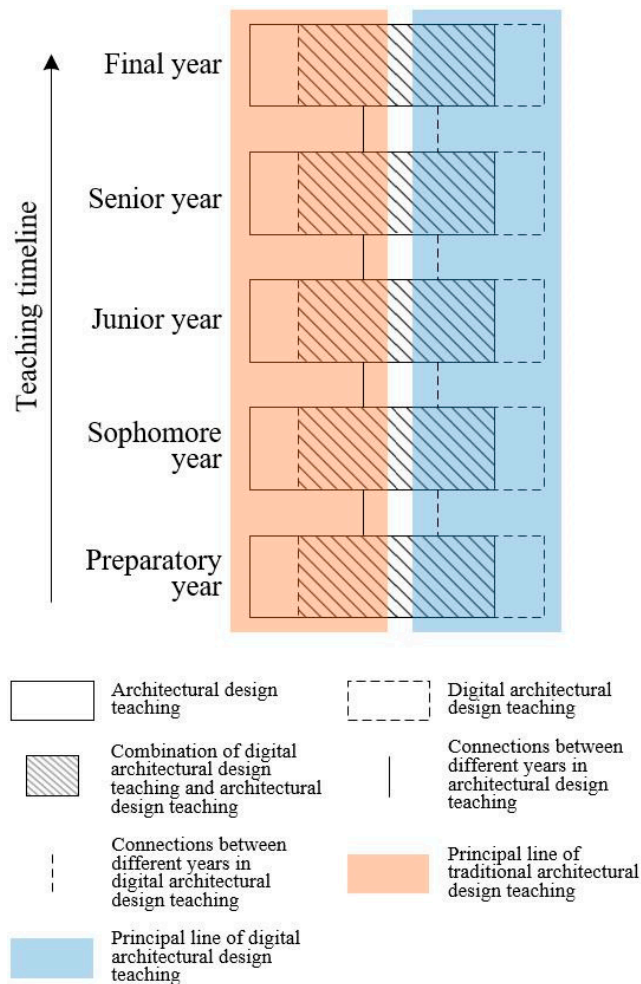


Figure 6. Parallel teaching model.

5. Discussion

Three main findings are discussed in this section: how digital architectural design teaching is divided across program years; the acquisition and development of student knowledge of digital architectural design; and an overall teaching model for teaching digital design in architecture.

5.1. Levels of a Digital Architectural Design Program Module

Our research shows that digital architectural design is taught at three levels across the years of a program. Figures A1 and A2 show that universities differ in their digital architectural design curricula. Similar courses are offered in different years, and courses offered at some universities are not available at others. For example, Nonlinear Design and Digital Fabrication, and other courses offered at THU and Tongji, are not offered by CQU or BUCEA. These observations are consistent with previous studies of the teaching of digital design in architecture, which examined the subject from different perspectives, such as architectural expression, the design software used, and the inclusion of BIM, digital fabrication, and material performance. Some studies found that different design software was more prominent in different areas of design; for example, the use of computer aided design (CAD) was largely restricted to the visual representation of student conceptual designs [41], BIM was used in courses that focused

on the systematic concept of architectural design [16], and digital fabrication was used in courses that focused on the expression and understanding of relationships between structure, material and form [22,25,42].

Teaching of digital architectural design progresses from lower to higher levels. Our research identified the following three levels. The lowest level, expression, includes software use and architectural representation of structures. Qualitative analysis (Figures A1 and A2) of the teaching of software use provided a basis for the four teaching models and identified the commonalities across universities in teaching digital architectural design. One of the commonalities is that students become proficient in using digital design software. Studies show that learning how to use software is an important step in digital architectural design education [9,26,43], and the representation of design concepts is fundamental to digital architectural design teaching [44,45].

The second level is implementation. This level is closely related to the construction of an object. Our research included qualitative analysis of topics addressed at the implementation level, including university commitment to the use of design software and computer technology. Not all universities teach digital architectural design at the implementation level: those that do, concentrate on structure, construction, and working drawings in architectural projects. This is in sharp contrast to the expression level, which is concerned with the expression of architectural design. The implementation level is concerned with the constructability of an architectural project. Various studies support these observations. Ibrahim and Rahimian [13] showed that Sketch Up was inadequate for use in conceptual architectural design and that BIM software was needed for designers to show the entire building life cycle, from initial design through to facility operation and maintenance. These findings are similar to those of Seletsky and other researchers, which emphasize the importance of digital technology in ensuring building constructability [3,46,47]. In this level, sustainable design concepts can be deliberately combined with digital technology (BIM) so that sustainable design techniques, such as optimizing construction projects, improving design efficiency, saving construction materials, and effectively managing the design process, are integrated into the digital architectural design teaching.

The third level is tectonics and performance. Our research included qualitative analysis of topics presented at this level, including the computer technology and digital design methods used by universities. Programming and digital fabrication are commonly introduced at this level. The use of data, such as material properties, physical factors, and human behavior, is examined at this level of design. The tectonics and performance level includes a greater exploration of the relationship between space and structure than the expression and implementation levels and it includes more of the core content of architectural design. Some studies have focused on the use of materials in terms of form and structure and the transformational relationship between form and space [48,49], and include digital fabrication technology such as CNC and robotic fabrication in digital architectural design teaching [27,50,51]. This level also combines sustainable development with digital technology, so that the incorporation of sustainable design into digital architectural design teaching is more complex than at the implementation level in that it informs the interaction of structure, material, and form.

5.2. Knowledge Evolution and Distribution across Levels

Our research shows that there is a close relationship between digital architectural design and architectural knowledge, which is indicated by the dissemination of architectural knowledge. In the four teaching models we devised, course content is represented by rectangles. Since digital architectural design is taught at three levels, and each of the four models is arranged in these levels, there is a correspondence between course content and these levels; that is, course content differs at these levels. This correspondence is embodied in the knowledge distribution within these levels.

In the expression level, learning how to use design software is fundamental to learning digital architectural design. Thus, course content needs to include knowledge of software use. Even if students can become proficient in software use from self-study outside the classroom, they do need to be guided and instructed. After becoming proficient in the basics of software use, students need to

depend on their proficiency with the software to conceive, model and draw design objects. Because these operations are usually associated with space, which is a basic concept in modern architectural education, knowledge taught and learned at the expression level overlaps with knowledge in the traditional architectural canon, such as proportion, scale, shape, function, structure, and site. At the implementation level, digital architectural design cannot be taught independently of the use of computer technology, so teaching at this level still depends on knowledge of basic software operation. However, knowledge of software operation is not the focus of the implementation level, which is more concerned with architectural design and knowledge of construction (knowledge of structure, construction techniques, and materials) in contrast with the expression level. At the tectonics and performance level, knowledge of software operation is also indispensable. At this higher level, students are required to become proficient in programming and mathematics and expected to use their knowledge of these disciplines to create algorithms, using logical thinking, that provide support for generative design and practical design. At this highest level, learning is concerned with the connections between material, structure, construction techniques, architectural design, building performance (in terms of data), and the architecture of form, space, and function. Thus, knowledge of construction—material behavior and performance, design and construction modeling, and architectural projects—becomes important at this level. The distribution of knowledge at the three levels of digital architectural design teaching is shown in Figure 7.

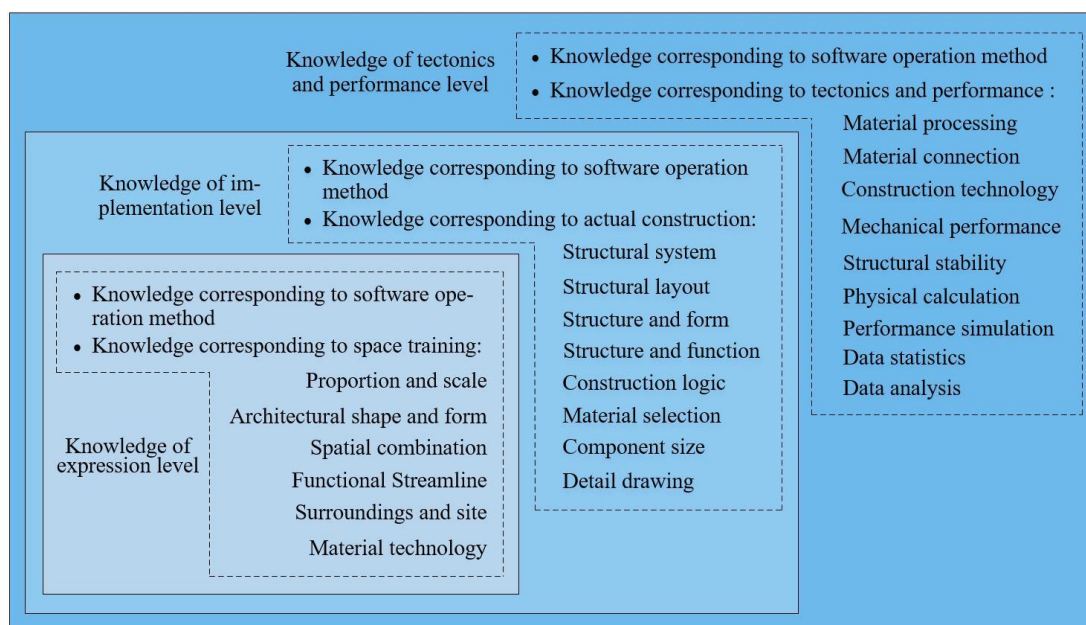


Figure 7. Knowledge distribution of digital architectural design teaching at the three levels.

Those findings are consistent with the results of various studies. The knowledge acquired at different levels overlaps with the knowledge learned in a traditional architecture program [49,52]. Thus, a course in a digital architectural design module can be extended to become part of a traditional architectural curriculum. Looking at particular digital architectural design course content, courses in design software (including design modeling) and design methods are highly relevant to traditional architectural knowledge. Sass and Oxman [12] found that CAD provided a means of incorporating professional knowledge into the design process. They argued that designing an assembly enabled students to engage in aspects of manufacturing early in the design process, introducing them to construction, and that using computer design enabled students to learn how knowledge can be represented in the form of parameters and how modeling supports design, change, and remodeling. Cheng [53] argued that software users, including students, need to understand the tool and possess knowledge of materials and construction methods when using BIM software for object design.

Denzer and Hedges [16] found that students using BIM software needed an adequate grounding in the fundamentals of architecture because BIM introduced them to sophisticated questions about construction early in the design process. Kara [54] investigated the efficacy of using design software in terms of student knowledge acquisition when comparing digital architectural design education between two universities. Kara's view was that digital tools could only be utilized at their full potential when students had already cultivated knowledge and acquired thinking skills relevant to the relation between space and building tectonics. In both universities in the study, digital architectural design was supported by other courses, and the content of the supporting courses was focused on the basics of using software to draw or model. Ibrahim and Rahimian [12] argued that, during architectural design, design software such as AutoCAD and Sketch Up were used to express design ideas, thereby translating implicit knowledge into explicit knowledge. Sun et al. [55] found that the learning of skills in architecture courses was related to the direction of knowledge transfer: top-down skill learning moved from explicit to implicit knowledge, whereas bottom-up learning moved in the opposite direction. Oxman [36] thought that a digital architectural model was itself a form of architectural knowledge and that, through modeling, students would acquire conceptual knowledge and learn cognitive skills in the design process. She [25] combined knowledge, concept, and design to determine the key cognitive concepts of design thinking. She included computational design concepts, such as algorithmic design and scripting languages, because of the relationship they had with the core concepts. Ghonim and Eweda [56] concluded that architecture programs should include various theoretical, practical and studio courses in which knowledge can be transmitted and design and skills are developed. It is expected that, as an integral part of an architecture program, digital architectural design courses will have a similar relationship with traditional courses and the knowledge and skills they impart.

Another link between digital architectural design teaching and architectural knowledge is seen in the growth of architectural knowledge. The qualitative analysis shows that the design software, digital technologies, and digital design methods used by different universities are diverse and complex and that the inclusion of digital architectural design in architectural design courses is more common for some universities than others in the middle and senior years. This observation indicates that there are differences between different universities in the depth of content or the learning gradient in the teaching of digital architectural design. Consideration of this in conjunction with differences in the distribution of knowledge at the three levels leads to the conclusion that knowledge disseminated across the three levels of digital architectural design teaching develops in an evolutionary fashion.

At the expression level, the core knowledge is of software use and the use of space in design. This knowledge may not constitute a sufficient condition for the acquisition of knowledge at the implementation level, but it provides great support for learning at a higher level. At the implementation level, students acquire greater knowledge of practical construction, including knowledge of structure, construction, and materials. This type of knowledge is often drawn on to solve engineering construction problems and therefore includes a distinction between aesthetics and practicality that is developed from knowledge gained at the expression level, but it is important not to lose sight of the relationship between them. Students need to acquire traditional architectural knowledge, and some knowledge acquired at the implementation level is an extension of the knowledge of space that is acquired at the expression level. For example, knowledge of functional streamlining that is acquired while learning about space will evolve to become knowledge of structure and function as the student learns more refined architectural functions. Knowledge of spatial combination will be adapted to become engineering knowledge of structural systems or construction methodology as a student learns to understand space as an object rather than an abstract entity. Knowledge at the tectonics and performance level depends on knowledge at both the expression and implementation levels as a student becomes aware of relationships between architectural form and space and the structure, construction, materials, and performance of a built object. If a student does not acquire knowledge at the expression and implementation levels, then they may not make the best choices in the selection of construction materials and technology or make the best use of building performance data. Knowledge

at this high level requires the assimilation of knowledge at the expression and implementation levels as preparation. The evolution of knowledge across the different levels is shown in Figure 8.

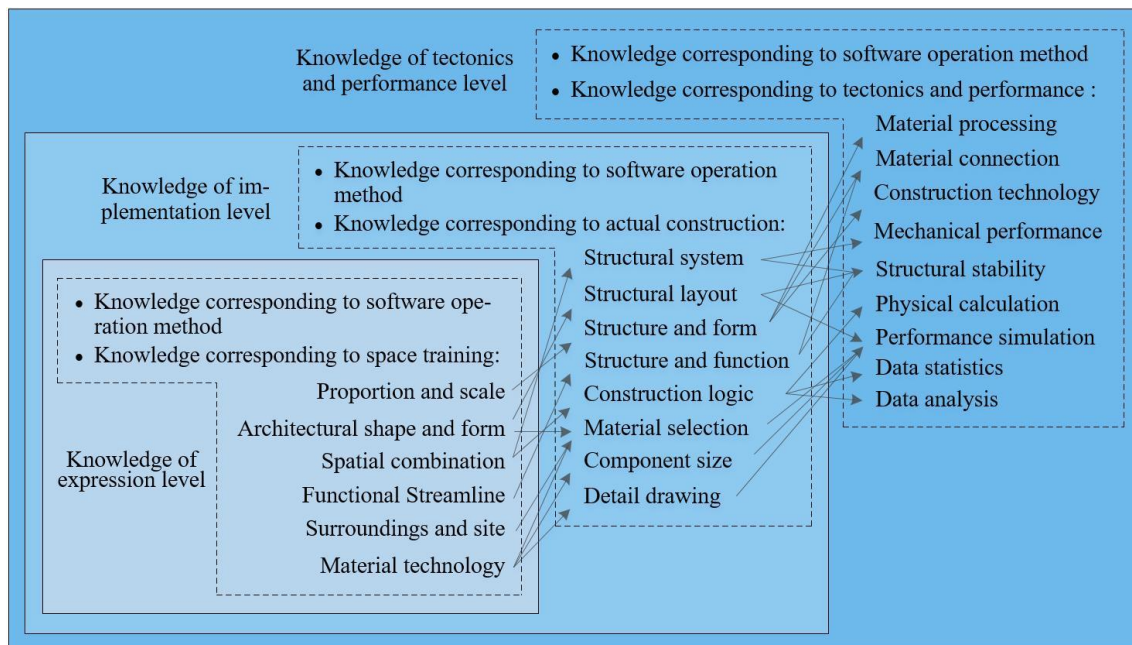


Figure 8. Evolution of knowledge across the three levels.

These findings are consistent with the results of other studies. The knowledge overlap previously mentioned is part of the evolution of knowledge and can be leveraged in architectural teaching. Ghonim and Eweda [56] thought that courses could be classified according to their degree of specialization in a range that extended from general courses, which taught general knowledge or skills, to extremely specialized courses, which taught advanced architectural topics. Menges [49] held the view that digital architectural design does not exclude traditional modes of conceiving form, structure, and space, but often absorbs these modes. This view implies that the knowledge of digital architectural design teaching is likely to evolve in the same way as knowledge evolves in traditional architectural teaching. Kara [54] examined common practices in digital architectural design at a university by analyzing teaching hours and teaching approaches in digital architectural design courses. Kara found that students acquired basic design skills in the first semester and began to address questions of buildings and sites at a small scale in the second year, and in subsequent years were introduced to more complex building programs and larger scale site operations. Chiu [57] showed that, at the same architectural design stage, students in different years need different degrees of design knowledge. Juniors needed knowledge that could inspire design ideas and enable them to evaluate design solutions during the programming stage in order to develop individual designs. In contrast, seniors needed more generalized knowledge, such as knowledge of methods of analyzing and planning, to define spatial requirements or select a building site. Klahr and Nigram [58] drew conclusions similar to Chiu. They found that novice students benefitted from direct guidance in basic skills and acquired basic knowledge, while advanced students benefitted from independence and synthesized knowledge. Doyle and Senske [7] used Bloom's taxonomy to analyze the teaching objectives in digital architectural design courses and found that the learning process moved from the acquisition of simpler thinking skills to the acquisition of more sophisticated thinking skills. This process shows that lower levels of cognition support higher levels. Knowledge and cognition are closely related [42], so the work of Doyle and Senske implies that architectural knowledge at the three levels is transformed from a low level to a high level.

5.3. Comprehensive Teaching Model

The four teaching models that we developed can be developed into a comprehensive model of digital architectural design teaching. The comprehensive model has greater generality and is therefore more universally applicable. It has three major components: a coordinate system, a knowledge arrangement, and the relation between digital architectural design teaching and other architecture courses.

The coordinate system is derived from the coordinate system of the four teaching models and uses the same coordinates of *type* and *time*. The horizontal (X) axis shows the type of teaching, which is a representation of course content in digital architectural design teaching. The vertical (Y) axis shows time, which is the years over which an architecture program is offered. The factors *the relation between digital architectural design teaching and architectural design teaching* and *class teaching time* can be added into the coordinate system to give it the following meanings. The X-axis represents course content and knowledge to be imparted in digital architectural design teaching; the negative X-axis represents course content and knowledge to be imparted in digital architectural design teaching outside the field of architecture. The positive Y-axis shows the program year in which in-class digital architectural design classes are offered; the negative Y-axis shows digital architectural design learning that occurs outside the classroom. Each of the four quadrants defined by the coordinate system thus has a particular significance in positioning the components of digital architectural design teaching at the three levels.

Knowledge arrangement refers to the positioning of knowledge in digital architectural design teaching and the relationships between various types of knowledge. Knowledge distribution across the different levels of teaching and knowledge evolution provide the basis for knowledge arrangement. The distribution of knowledge shows how knowledge is categorized within the model and shows how particular knowledge corresponds to course content. The evolution of knowledge shows that knowledge acquisition follows a gradient of increasing complexity over time and this offers an indicator to decide teaching contents at the different levels of an architecture program accordingly.

The relationships between digital architectural design teaching and other architecture courses form the final component of the comprehensive model. Digital architectural design teaching does not exist in isolation and is not limited by association only with architectural design teaching. It is also related to the teaching of architectural history and architectural technology. Such interrelation, or perhaps potential relations, provides a framework within which digital architectural design teaching can be placed within a wider architectural education context.

The comprehensive model of digital architectural design teaching was formed as follows (Figure 9 and Table 4). Different colors were used to represent years within a program. Letters represent teaching levels. Letters within rectangles show course content and associated knowledge at different levels. Lines that connect rectangles showing courses or software indicate a relationship between teaching level and program year for the various courses. The upper right quadrant of the model has two parts. The left-hand part shows course content and knowledge that are not software-related at different levels. The right-hand part shows three elements of an architecture program: architectural design, architectural history, and architectural technology. The architectural design needs to be taught in-class by teachers in a classroom. Architectural technology is relatively independent of design and history. The two-way arrows show that there are some connections between the various elements. The upper left quadrant of the model shows two items: course content and related software knowledge at different levels, and non-software related course content and knowledge at different levels. The lower left quadrant contains course content and software knowledge for different levels. This course content and knowledge (mostly skill-based knowledge) are external to the field of architecture; students are self-taught, and learning is not planned by year.

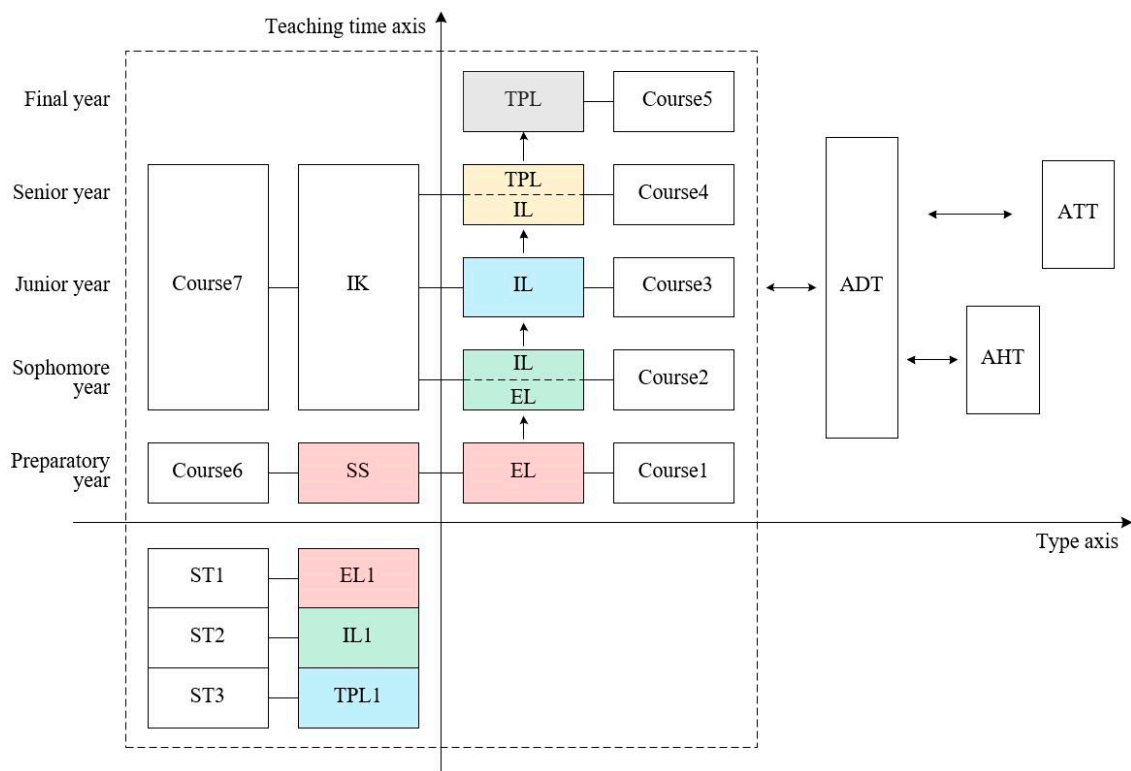


Figure 9. The comprehensive model of digital architectural design teaching (for more detail, see Table 4).

Table 4. Explanation of abbreviations and codes.

Color	Color represents digital architectural design teaching in different years: red, preparatory year; green, sophomore year; blue, junior year; yellow, senior year; gray, final year	Axis	X-axis represents the type of architectural teaching, including architectural design teaching; Y-axis represents the program year of teaching (i.e., undergraduate, all years)
EL	Course content and knowledge related to space training at expression level	IL	Course content and knowledge related to actual construction at implementation level
TPL	Course content and knowledge related to tectonics and performance at tectonics and performance level	SS	Knowledge of skills and subjects (some basic subjects), such as programming or mathematics
EL1	Course content and knowledge related to software operation at expression level	IL1	Course content and knowledge related to software operation at implementation level
TPL1	Course content and knowledge related to software operation method at tectonics and performance level	IK	Interdisciplinary knowledge such as data statistics or data analysis, and knowledge of sustainable development
Course1	Design course: emphasizing development of basic digital design skills and methods through exercises in architectural design I or architectural design II Individual standalone course: courses including freehand architectural drawing, or representation media, such as representation, digital representation	Course2	Design course: continuing development of digital design skills and methods through projects in architectural design III or architectural design IV Individual standalone course: courses including software use and digital tool use, such as computer applications in architecture, digital tools for architecture

Table 4. Cont.

Course3	Design course: continuing development of digital design skills and methods through complex architectural projects in architectural design V or architectural design VI, and developing special topics in design, such as parametric design, architectural design based on BIM technology Individual standalone course: courses including exploration of digital design tools, methods, and techniques; can also be combined with the content of courses such as <i>building materials, building structures, building construction, building technology</i>	Course4	Design course: emphasizing development of advanced digital design skills and methods through advanced programs in architectural design VII or architectural design VIII, and developing special topics in design, such as computational design, architectural generative design, digital fabrication Individual standalone course: courses including exploration of advanced digital design tools, methods, and techniques, such as <i>advanced computer applications, computer programming in architecture, advanced fabrication</i> ; can also be combined with other course content such as building materials, building structures, building construction, building technology
Course5	Design course: emphasizing development of digital design skills and methods through programs in graduate architectural design, and developing special topics in design, such as computational design, architectural generative design, digital fabrication	Course6	Courses emphasizing programming, algorithms, mathematics, computational thinking, such as <i>geometry and architecture, geometry and mathematics of design, computer technology, spatial computational thinking</i>
Course7	Courses emphasizing physical calculation, data statistics, data analysis or sustainable design concept, such as <i>materials science (embodied performance), advanced social statistics, sustainable design, site and sustainability, performance and sustainability</i>	ST1	2D and 3D representation software such as AutoCAD, Sketch Up, Photoshop, Vray, InDesign, and virtual reality software
ST2	BIM software such as Revit, ArchiCAD	ST3	Algorithm platform based on Java language, Rhino, Grasshopper; CNC machine tools, laser cutting machines; 3D printers, industrial robots.
ADT	Architectural design teaching	AHT	Architectural history teaching
ATT	Architectural technology teaching		

The diagram of the model shows knowledge and skills in some basic subjects, such as programming and mathematics, that students may find difficult to acquire. However, the knowledge and skills are basic for software use and should be formally taught to undergraduates in the early years. Non-software related course content and knowledge, in the upper left quadrant, requires the possession of complex interdisciplinary knowledge, such as statistics or data analysis, and knowledge of sustainable development, such as the sustainable use of resources and environmental protection. This knowledge supports learning at different levels, and formal teaching in middle and upper undergraduate years can increase the depth of knowledge at these levels. The comprehensive model incorporates diversity and flexibility in teaching. For example, software use can be taught in different years or in the same year: course content in a given year is not limited to a certain teaching level but can include or exclude course content from other levels. The comprehensive model allows different universities to independently teach digital design in architecture according to their own priorities.

Our comprehensive model is supported by various studies. Some studies advocate that digital architectural design teaching should be incorporated into conventional architectural design teaching and design studios, as shown in the upper right quadrant of the model. Kvan et al. [59] argued that students should acquire a comprehensive understanding of architecture earlier in their programs rather

than just before they graduate. The studio is the forum in which architectural paradigms and theories can be explored, so the curriculum of a design studio is central to the integration of digital ideas in architectural education. Celani [60] argued that digital architectural design should be incorporated into existing courses or design studios because architectural education focuses on issues of building, space, and place rather than technology. Savic and Kashef [61] showed that architectural education depended heavily on the studio format because it brought students together and created dynamic interactions that energized students into competing and performing to reach specific goals for their design projects. Kara [54] observed that the use of digital tools still required conceptualization in seeing, thinking, and making space that could not be cultivated solely in a digital environment.

Some studies suggest that digital architectural design teaching should include programming, mathematics, architectural theory, design skills and sustainable development concepts. These ideas can be seen in the two left-hand quadrants. Kvan et al. [59] thought that students should know how to use software tools and have some knowledge of programming and mathematics to be able to control CNC processes and create controls appropriate to the material being machined. Özkar [62] observed that computerized tools and computational thinking could be introduced into architectural design education at a fundamental level in the first undergraduate year, for example, by initially teaching elementary design skills to first-year architecture students and then basic notions of computation. Woodbury [63] argued that designers needed to extend their knowledge in order to understand the diversity and structure of the mathematical toolbox in a parametric design environment. In a similar vein, Oxman and Gu [64] noted that, for parametric design, designers needed to possess more than merely basic architectural knowledge. Oxman [65] observed that in order to understand how a parametric schema supported the logic of a digital process model, the designer needed diverse knowledge and skills, including parametric design, mathematics, and associative geometry. She [25] also thought that sketching by creating code was not only a possibility but probably a new norm of skill and knowledge. Shi [22] argued that architecture students need to have interdisciplinary knowledge that included programming, use of algorithms and the concept of sustainable development when using advanced digital tools such as robots in automated construction. A teacher may use class time to teach programming knowledge, mathematical knowledge and interdisciplinary knowledge because they can be difficult to acquire otherwise, which is why they appear in the upper left quadrant as a demand for teaching time. However, not all knowledge and skills need to be taught in class. Relatively basic knowledge and simple skills can be learned by self-study or through peer interaction. Chastain and Elliot [66] observed that knowledge sharing between students is a significant learning mechanism in collaborative design. Craig and Zimring [67] recognized that a creative design solution developed by a student could be inspired by knowledge and information sharing between peers. Chiu [57] showed that collaborative behavior, in the form of knowledge sharing, occurred in design studios and argued that knowledge sharing is an important way for students to acquire design knowledge. Knowledge sharing among students was apparent, and relatively ill-defined complicated design projects led to more frequent knowledge sharing and interaction between students.

Studies show that our comprehensive model is consistent with other teaching models. Newland et al. [68] summarized Powell's research on the learning styles of architectural students, which was based on Kolb's learning style model, and divided the styles into four learning tendencies, which can be placed in the four quadrants of the comprehensive teaching model. For example, the learning tendency *concrete experience* fits in the upper right and lower left quadrants; the tendency *abstract conceptualization* fits in the two upper quadrants. Demirbas and Demirkan [23] also used the Kolb model to divide the learning styles of architectural students of design into *doing and experiencing* and *reflecting and thinking*. In the comprehensive model, the lower left quadrant is concerned with *doing and experiencing*, the upper left quadrant is more concerned with *reflecting and thinking*, and the upper right quadrant matches a combination of the two. Doyle and Senske [7] examined the learning process in developing a digital architectural design module for architecture students based on Bloom's taxonomy. Their outcome was consistent with the *differences in difficulty* category of our comprehensive

model in terms of course content: course content gradually increased in difficulty and complexity with year level. Thus, the comprehensive model conforms, to some degree, to Bloom's taxonomy. Oxman [25] developed a process model of information flow that placed designers at the center for their use of parametric design. The comprehensive model includes knowledge transfer, which allows it to represent, through the three quadrants, Oxman's processes of visual re-representation, performance, and generation.

5.4. Implications

The comprehensive teaching model was based on data derived from a survey of digital design teaching in architecture programs in Chinese universities, but it is also applicable to architectural education in other countries. In part, this is because architecture major programs offered by the Chinese universities surveyed have been successfully evaluated and assessed by the Chinese educational authorities, and the evaluation document *National Architectural Education Evaluation Document for Higher Education Institutions* gains authority from long-term international cooperation between Chinese architecture programs and NAAB (National Architectural Accrediting Board), as well as RIBA (Royal Institute of British Architects). There are close parallels between this evaluation document and those of NAAB and RIBA, which are considered to be international yardsticks for architectural accreditation in Asia [69]. Another reason is that the Chinese universities surveyed communicate and cooperate with many universities around the world, which means that Chinese architectural education is becoming increasingly globalized. This globalization exposes Chinese faculty and students to internationally accepted standards of architectural education, new educational concepts, new methods of digital design teaching, and mainstream architectural design software and hardware. Data obtained in the survey and the teaching cases support this view.

The comprehensive teaching model is not intended to explain or prescribe the teaching of digital architectural design in architecture programs but to provide a manner to promote the sustainability of teaching digital architectural design. It provides a framework within which educators can work. The path for teaching digital architectural design combines architectural design and studio design, thereby providing an environment for using design tools, disseminating design knowledge and teaching design skills. The model also adds rigor to conversations about the future of digital architectural design in architectural education and can inform strategies for the cultivation of sustainable design concepts that can be incorporated into digital architectural design teaching at various levels, thus promoting sustainable design as a topic in its own right within architectural education.

The comprehensive model exists as a technique rather than a method. The model enables the user to position and compare different courses in digital architectural design using the quadrants. The positioning and comparison are flexible and adaptable. For example, program components are generally variable and optional. They can be updated and adapted according to circumstances without disrupting the overall structure of the model. Thus, the model can respond easily and rapidly to new developments and emerging phenomena in digital architectural design teaching. In terms of sustainable design, the positioning and comparison can indicate how sustainable development can be continuously incorporated into the teaching of digital architectural design to better meet the need for educating architects in sustainable architecture.

6. Conclusions

This study was intended to provide an understanding of the patterns and characteristics of digital architectural design teaching so that we could view the digital architectural design education in a more general context. A survey of 15 universities in mainland China provided data on digital architectural design teaching in architecture programs. Qualitative analysis of the data resulted in four models of teaching digital architectural design, and, based on the four models, a comprehensive model with great generality was generated. The comprehensive model meets the requirements of modern teaching of digital architectural design and can be used to evaluate and compare different digital architectural

design courses so that the courses would be appropriately placed within existing architecture programs. This model also provides a framework for digital architectural design teaching and can be used to establish course modules, improve course design, and adjust course contents. Meanwhile, the model incorporates sustainable development concepts into digital architectural design teaching and allows sustainable development to be comprehensively integrated into architectural designs through teaching.

However, this study had a major limitation. It focused exclusively on Chinese universities and all the research was conducted in the Chinese education system. It is necessary to extend future research to an international context and provide an in-depth analysis of similarities and differences of digital architectural education in different nations. The next step of our research, based on the result of this study, is to conduct surveys at universities in different countries and compare their teaching contents, methods, and technologies of digital architecture design teaching with those at Chinese universities. A comparative analysis would provide readers with a complete vision of the topic, and, more importantly, such a comparative analysis would enable us to refine the comprehensive model proposed in this study in terms of course content, knowledge transfer, and program levels and better incorporate sustainable design concepts into digital architectural design teaching.

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

Appendix A

Table A1. List of interviewee and rating.

University	Interviewee	Title/Position	Number of Criteria Met	Rating of Interest in the Interview ¹
BUCEA	Teacher 1	associate professor; dean	5	4
	Teacher 2	lecturer	4	5
	Teacher 3	lecturer	4	5
CQJTU	Teacher 1	Professor; assistant dean	5	5
	Teacher 2	lecturer	4	5
	student	undergraduate	3	5
CQU	teacher	professor	5	5
HBUT	teacher	associate professor; dean	6	5
	student	postgraduate	3	5
HNU	teacher	associate professor	6	5
HUST	teacher	associate professor	4	5
NJTech	teacher	associate professor	4	5
NJU	teacher	Professor; dean	6	5
	student	doctoral student	4	5
SCUT	Teacher 1	associate professor	5	5
	Teacher 2	associate professor	4	5

Table A1. Cont.

University	Interviewee	Title/Position	Number of Criteria Met	Rating of Interest in the Interview ¹
SEU	Teacher 1	professor	6	5
	Teacher 2	associate professor	5	5
	Teacher 3	lecturer	4	5
THU	Teacher 1	Professor; dean	6	5
	Teacher 2	professor	6	5
	student	postgraduate	4	5
TJU	teacher	Professor; assistant dean	6	5
	student	postgraduate	4	5
Tongji	teacher	professor	6	5
XAUAT	teacher	associate professor; dean	5	5
ZJU	Teacher 1	Professor; assistant dean	6	5
	Teacher 2	lecturer	4	5
	student	undergraduate	3	4

¹ We recorded the interviewees' interest in the survey on a scale of 1–5. By referring to the Likert scale, we divided the scores from 1 to 5 into five intervals: 5, very interested in the survey; 4, interested in the survey; 3, unsure whether or not interested in the survey; 2, uninterested in the survey; 1, completely uninterested in the survey.

Table A2. Example of initial data coding.

Data Source	Data	Open Code
Interview (marked T)	The teachers interviewed emphasized the necessity and importance of programming for architectural design. He thinks the role of an architect could change to that of a software engineer or an engineer operating an intelligent machine, but current architectural education is weak in developing student programming skills, and computer courses still teach outdated knowledge. In his opinion, there are three types of programming languages, among which “dumb” programming languages are suitable for architecture majors and help students quickly understand the relationship between computer language and architectural design.	T1: Necessity and importance of learning programming T2: Changes in the role of architects T3: Teaching software skills T4: Types of programming languages
literature (marked L)	1. Xu, W. G., Huang, W. X., and Yu, L. (2015). Digital architectural education in Tsinghua University. <i>Urbanism and Architecture</i> , 28(10), 34–38 2. Xu, W. G., and Leach, N. (2013). <i>Advanced Computer Research</i> . Beijing: China Architecture and Building Press 3. Xu, W. G., and Leach, N. (2015). <i>Design Intelligence Advanced Computational Research</i> . Beijing: China Architecture and Building Press 4. Xu, W. G. (2015). <i>Parametric Nonlinear Architectural Design</i> . Beijing: Tsinghua University Press	L1: Changes of computer technology that pertain to architectural design teaching L2: Development of digital architectural design teaching in Tsinghua University L3: Composition of digital architectural design teaching in Tsinghua University
Official website information (marked W)	The architecture major program in Tsinghua University has two academic streams, five years and four years, for bachelor of architecture and bachelor of engineering degrees. The curriculum of the two streams is basically the same, as is the digital architectural design teaching	W1: The undergraduate program and architecture degree in Tsinghua University W2: Digital architectural design teaching in Tsinghua University is not affected by the program curriculum

Table A3. Content identified by coding.

Open Coding (Concept Labeling)	Open Coding (Initial Concepts)	Open Coding (Core Concepts)	Axial Coding (Categories)	Selective Coding (Core Category)
T1; T2; L7; L13; W6; W12;	Learning programming	Teaching software applications and use of design software	Requirements for teaching content	Teaching model of digital architectural design teaching
T3; T7; L9; L10; W10; W15;	Learning software such as Revit or Rhino			
T15; T66; L71; L97;	Self-study or peer-peer learning			
T11; T23; L8; L14; W3; W7;	Design ideas (e.g., nonlinear or parametric design)	Teaching digital design methods and theory		
T13; T31; L47; L50; W18; W25;	Teaching design methods as part of theory	Teaching of application of computer technology and digital design methods		
T9; T28; L25; L33; W14; W33;	Teaching digital architectural design combined with architectural design courses			
T5; T10; L1; L5; W9; W13;	Computer technology			
T17; T21; L27; L35;	Use of digital design methods	Year of course offering		
T19; T76; L11; L15; W20; W22;	Program year of course			
T41; T88; L6; L12; W29; W30;	Digital architectural design courses in lower years			
T52; T106; L16; L26; W2; W21;	Courses offered in different years	Stage of the course	Course setting	
T83; T132; L29; L63; W55; W67;	Special topics courses	Course orientation		
L85; L116; W37; W40;	Classified as <i>architectural technology courses</i>			
T723; T739; L424; L496; W187; W196;	Parallel relationship with architectural technology course	Constitution of course hours		
T73; T121; L2; L3; W34; W46;	Types of course hours			
L22; L43; W11; W38;	Number of course hours			
T46; T75; L17; L36; W43; W52;	Course hours including architectural design courses	Distribution of course hours	Characteristics of course hours	
L31; L37; W1; W4;	Concentration of course hours in each program year			

	Software Teaching Tendency			Software Usage Tendency				Design Method and Design Theory Teaching			Use of Computer Technology				Use of Digital Design Methods						Course Hours of Standalone Courses			
	A1	A2	A3	B1	B2	B3	B4	C1	C2	C3	D1	D2	D3	D4	E1	E2	E3	E4	E5	E6	F1	F2	F3	F4
BUCEA	•						•			•		•							•		•			
CQJTU	•					•				•	•		•	•				•	•		•			
CQU	•					•				•			•	•				•	•				•	
HBUT		•				•		•	•		•	•	•	•	•			•	•		•			•
HNU		•		•	•					•	•	•			•		•				•			•
HUST		•				•		•			•		•	•	•			•	•				•	
NJTech	•						•			•		•							•		•			
NJU		•					•			•	•	•			•		•				•			
SCUT			•			•		•			•	•	•	•	•			•	•		•			
SEU			•	•	•					•	•	•				•	•					•		
THU			•	•	•			•	•		•	•			•	•	•						•	•
TJU		•		•	•					•	•	•	•	•	•	•	•				•			•
Tongji			•	•	•			•	•		•	•	•		•	•	•				•			•
XAUAT	•						•	•			•				•						•			
ZJU	•						•			•	•	•			•		•						•	

Figure A1. Matrix showing the attributes and significance of core concepts (codes and topics are shown in Table A4).

	Course Attribute		Starting Time of the Course						Setting of Different Courses in Each Year										Centralized Distribution of Courses (Year with Digital Architectural Design Course)					
									J1					J2										J3
	G1	G2	H1	H2	H3	H4	H5	H6	1st Yr.	2nd Yr.	3rd Yr.	4th Yr.	5th Yr.	1st Yr.	2nd Yr.	3rd Yr.	4th Yr.	4th Yr.	5th Yr.	1st Yr.	2nd Yr.	3rd Yr.	4th Yr.	5th Yr.
BUCEA	•			•					•	•	•					•				•	•	•	•	
CQJTU	•					•				•	•					•	•		•		•	•	•	•
CQU	•			•					•						•	•	•			•	•	•	•	
HBUT	•		•						•	•	•			•	•	•	•		•	•	•	•	•	•
HNU	•			•					•	•	•			•		•	•		•	•	•	•	•	•
HUST		•			•					•	•				•	•	•		•		•	•	•	•
NJTech	•			•					•	•		•					•		•	•		•	•	•
NJU	•				•					•		•			•			•			•	•	•	
SCUT	•			•					•	•	•	•				•	•		•	•	•	•	•	•
SEU		•		•					•															
THU		•				•				•					•	•	•		•		•	•	•	•
TJU	•			•					•	•				•		•	•		•	•	•	•	•	•
Tongji		•			•					•	•				•	•	•		•		•	•	•	•
XAUAT		•					•				•					•		•			•	•	•	•
ZJU	•				•					•	•										•	•	•	

Figure A2. Matrix showing the attributes and significance of core concepts (codes and topics are shown in Table A4).

Table A4. List of codes and topics.

Code	Topic	Code	Topics
A1	Software operation method	F1	At least 76 course hours
A2	Application of design software in architectural design	F2	At most 32 course hours
A3	No related individual standalone courses	F3	Between 32 and 76 course hours
B1	Parameterized design software or plug-ins such as Rhino or Grasshopper	F4	Architectural design workshop (1–2 weeks)
B2	Algorithm platform based on Java language such as Processing or Eclipse	G1	Courses clearly classified as Architecture Technology courses
B3	BIM software such as Revit or ArchiCAD	G2	Courses not clearly classified as the Architecture Technology courses
B4	Traditional design software such as AutoCAD, Sketch Up	H1	First semester of preparatory year
C1	Courses teaching topics such as nonlinear design methods	H2	Second semester of preparatory year
C2	Courses teaching topics such as digital tectonics	H3	First semester of sophomore year
C3	No related individual standalone courses	H4	Second semester of sophomore year
D1	Parametric modeling	H5	First semester of Junior year
D2	Digital fabrication	H6	Second semester of Junior year
D3	Virtual reality	J1	Individual standalone digital architectural design courses
D4	Building information modeling	J2	Integrated computer technology and architectural design courses
E1	Parametric design method (based on Rhino or Grasshopper)	J3	Integrated computer technology and architecture graduating design courses
E2	Architectural generative design methods	1st Yr.	Preparatory year(s)
E3	Digital fabrication methods	2nd Yr.	Sophomore year(s)
E4	Parametric design methods (based on building information modeling)	3rd Yr.	Junior year(s)
E5	Architectural design methods based on BIM-based virtual reality	4th Yr.	Senior year(s)
E6	Virtual reality technology (fully immersive)	5th Yr.	Final year(s)

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