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Exploring the Cognitive Structure and Quality Elements: Building Information Modeling Education in Civil Engineering and Management*

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Undergraduate education in Building Information Modeling (BIM) area for Civil Engineering and Management (CEM) majors cultivates the students' abilities to handle the embedded context constraints, parametric modeling, and the corresponding education guidelines recommended by the assessment associations and agencies. This study focuses on the expected cognitive structure and the training contents of BIM education. The objective of this research is to design, implement, and adjust the subject areas of BIM courses to prepare students for the skills expected by job market. The authors studied the overlap of the scopes between undergraduate BIM education and the job market expectations on the skill structure of BIM abilities. The authors also reviewed the 2013 China Civil Engineering and Management Undergraduate Education Guideline (2013 CCEMUEG). Particularly, the authors developed the BIM cognitive structure concept and the unique, BIM-embedded, education knowledge tree in CEM major. To design the training contents, the authors adopted the Quality-Function-Development (QFD) house concept and its relationship principles, designed the knowledge units and knowledge points of 2013 CCEMUEG with the different corresponding encodings, constructed a path between BIM ability structure and CEM education, and performed the feasibility study of the implementation scheme. The research results include the blueprint of curriculum development and the knowledge framework showing the comparison of characteristics between BIM and 2013 CCEMUEG knowledge units and knowledge points. In conclusion, the research suggests that BIM education in CEM could be implemented in the whole undergraduate learning process, representing the life-span of construction/building projects. This research shines light on BIM education in CEM. Its analysis tool and knowledge tree will be a powerful revelation for the pedagogical design of BIM in undergraduate education.

Keywords: engineering education; QFD house; knowledge tree; quality elements; civil engineering and management; BIM

1. Introduction

Civil Engineering and Management (CEM) education has gradually expanded to a wide range of professional and technical fields, including the engineering and construction in roads, bridges, railways, undergrounds, tunnels, ports, mines, water conservancy, petroleum plants, electric power plants, etc. Due to the growth of CEM education in various colleges and schools, its contents and training practices will necessarily take on swift and diverse developments [1]. In engineering colleges and schools, one major advantage of Building Information Modeling (BIM) training is to help all motivated and talented students, who may not have access to visit real physical jobsites, to gain experiences regardless of their social backgrounds. With the access to abundant information of thousands of buildings, professors and students can explore the details of engineering and design of those projects without leaving their campuses. The integration of BIM contents in the traditional undergraduate education of CEM relates to the transformation of the education model in China in the information era. The trend of BIM-adaption in CEM majors reflects the demands of the civil and construction industries in the present and will affect their developments in the future.

BIM can facilitate the education reform of CEM majors. For example, the current CEM education in China still depends on the traditional graphical skills only, such as hand drafting and 2-dimensional computer aided design (CAD). It focuses on simple software skills, such as stand-alone building cost software and construction management software. With the implementation of BIM education in CEM, the following goal can be achieved: changing the conventional education contents of CEM into a new education model with the focus on BIM systems or large platforms of industrial data related to civil and construction engineering. Therefore, BIM education in CEM needs to show comprehensive considerations of cognitive structure and quality elements in the following 3 areas: (1) education

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guideline, e.g. 2013 China Civil Engineering Management Undergraduate Guideline [2]; (2) the industry demand for future development, and (3) the discipline positioning of CEM in a college or school. The American Council for Construction Education [3] has accreditation agreement with CCEMUEG, which makes the research findings to have broader impact. The industrial requirements on BIM affect the CEM education in terms of the teaching contents, requirements and pedagogical methods. The definition of BIM influences its integration with CEM education. The BIM capabilities expected by industries orient the core factors and contents of its education. Meanwhile, BIM practice adds value highly to the construction market [2]. Regardless of the differences in the extents and levels of BIM utilizations in the construction industries in various countries, CEM education encounters the same challenge of successful integration of BIM contents into CEM courses [3]. This research suggests to dynamically balance the academic perspective of demand and the industrial requirements on the undergraduate BIM education in CEM courses and training. Using several CEM courses as examples, this research demonstrates the BIM ability structure demanded by industries and the mapping of the knowledge units and points of CEM education. This detailed correlation and mapping structure and analysis will decompose BIM teaching requirements and integrate them with CEM education system.

The following paper is organized by 6 sections. Section 2 is the analysis of the BIM ability structure. Section 3 reviews the literature background and the BIM cognitive structure. Section 4 constructs Quality-Function-Development (QFD) house as the analysis model for BIM education in CEM. Section 5 is the application analysis of the QFD house model. Section 6 provides conclusions and suggestions for future research.

2. BIM ability structure

BIM becomes a powerful tool for engineering industries to reduce industrial wastes, increase product value, decrease environment pollution, and improve the usability of facilities. It is a shared knowledge resource of a facility and provides a reliable base for decision-making in the whole lifecycle of a building from concept to termination. As for engineering education, BIM technology helps students to understand the multi-dimensional engineering, technology, and process management practice. BIM has major applications in the modeling and simulation of 3D (geometrical components), 4D (3D + work sequence and arrangement), 5D (4D + cost) and 6D (5D + lifecycle information) objects [4].

At present, BIM capability has become one of the key skills of practitioners (e.g. architects, engineers, contractors, manufacturers, and other professionals) [5]. The synergistic, modeling characteristic of BIM makes it the effective tool for all practitioners to communicate. BIM can integrate model design with automated calculation, cost analysis, and shop-drawing production. Manufacturers can obtain from a BIM model the prefabrication costs, safety requirements, quality expectations, and timelines of structural components and MEP components. The business-integration capacity of BIM software is essential.

One deficiency of BIM education and training is the insufficiency to adapt the BIM contents and requirements to the engineering education in an organized and integrated way in a short time. Fig. 1 shows the structure to align the BIM education with the industrial demands. The industrial demands include the fundamental capacity structure, which includes the abilities to operate, model, and apply; and the advanced capacity structure, which includes the abilities to implement, manage, and integrate. Each item of Fig. 1 is explained as follows:

1. Operate: BIM professionals must have abilities to operate one or several BIM software applications.
2. Model: This is the ability to build models for different specialties and purposes of engineering projects with BIM software. The different types of models include construction models, structural models, site models, electromechanical models, performance analysis models, safety precaution models, etc.
3. Apply: This is the ability to analyze, simulate, and optimize various tasks in the different phases of engineering projects, such as project demonstration, performance analysis, design inspection, operation/process simulation, etc.
4. Implement: This is the ability to build a technical environment for the BIM applications of an engineering project, consisting of the organization and delivery of design and engineering standards, workflows, inventories of component assemblies, software and hardware configuration, network establishment, etc.
5. Manage: This is the ability to manage and coordinate individual BIM project teams to achieve the goal of BIM applications, including the establishment and training of project teams. It is the required ability of a BIM project manager.
6. Integrate: The ability to integrate BIM applica-

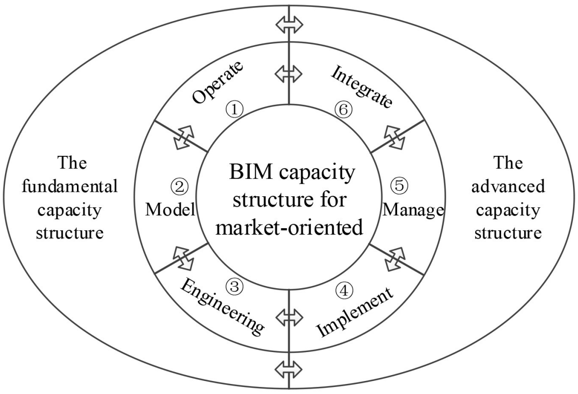


Fig. 1. BIM capacity structure for 6 market-oriented, industrial demands

tions and the business targets of enterprises includes the alignment of the value of BIM to the strategies of enterprise businesses, the calculation and estimation of the Return of Investment (ROI) of BIM technology, and the establishment of new business models. It is the required ability of a BIM strategy director.

In order to enhance the engineering competence [6] of BIM education, BIM education in CEM has the following 5 stages: concept guidance, basic skill training, advanced skill training, core ability formation, and professional practice. The 5 stages embody the process from simple modeling to complicated application of skills. Through engineering practices, students can adapt to the BIM requirements of the CEM industries and gradually gain the business integration capacity. Therefore, BIM tools and techniques aiming to orient to the requirements of industrial applications should gradually advance from fundamental level to advanced level [7, 8]. Educators should pay attention to the specific cognitive structure that reflects the 5 stages of skill-construction process to help students to get familiar with the implementations of BIM technologies in engineering projects. With the development of the CEM industries, the capability structure of BIM should be adjusted dynamically to meet the training demands.

3. Background

3.1 Context Analysis

To properly design BIM courses, it is necessary to take the context analysis, such as the analysis on the major education guidelines, into consideration. For BIM education in engineering majors, there are various guides and methods that could be used for course development. For example, Civil Engineering Body of Knowledge (CEBOK) is the long-term plan of the American Civil Engineering Teaching Guideline for 2025. In the 2025 CEBOK, BIM is not directly mentioned; but it is indirectly defined as the technology for future engineers. For example, future engineers must become experts at the technology for the engineering information to be delivered explicitly, continuously, and timely [9–11]. CEBOK states that the knowledge and skills of BIM-supported communication, cooperation, problem identification, and solution become very critical to civil engineers [12]. CEM reinforces that enhancing BIM education by building systematic and comprehensive BIM education methods has become the focus of the reform of college courses. During the first and second years of college education, BIM courses mainly concentrate on the communication of fundamental engineering information, computer modeling of engineering design, and other technical tools [13, 14]. The intermediate and advanced BIM courses in the third and fourth years of college education should concentrate on the implementation of BIM technology as an engineering and management system. The focus is on the implementation-oriented BIM teaching, such as design coordination, planning, and construction project control. In the graduate programs of CEM, BIM courses should focus on the cooperation and management at the cross-organization and cross-project levels [15–17]. For example, Ahn [18] proposed that the introduction of BIM contents in one week in the "Civil Engineering and Computer Basis" course could be arranged in the first year of its CEM program. The course was integrated into other courses and delivered dispersedly through the following 3 years. The learning objectives of the 3-stage curriculum included understanding basic BIM principles and applications; applying BIM capabilities and engineering standards to problem-solving; and building comprehensive BIM systems of civil engineering projects.

For CEM education in the US, though colleges have added BIM contents to the existing courses and delivered them in various approaches and methods, it does not mean that BIM teaching is generally implemented with high quality [19]. Many colleges provide BIM education only in 1–3 separated courses. This setting reduces the knowledge coverage of BIM to an introduction level with the retaining duration of only 1–2 weeks [14, 20]. This is equivalent to treating BIM technology as the substitute of CAD. This practice undermines the full potential of BIM technology. The cause of this problem is that most CEM courses (for example, engineering measurement, engineering evaluation, planning and scheduling, quality management, and construction safety) are still delivered together with traditional 2D drawings for project information. In CEM industries, 3D modeling and BIM serve as the main media for engineering design, analysis, implementation, and management. If BIM is considered to be a basic skill of CEM graduates, it means that students should receive the basic instructions of it from the first year of college [21]. To improve the application level of BIM in CEM, educators should incorporate BIM instructions in an independent course in the primary stage of CEM education. Moreover, BIM contents can gradually penetrate through other courses. The design and development of the BIM-integrated courses should depend on the analysis of course development theory, current demands, trends of construction engineering education, and the production process of construction management [22]. To identify the multilateral relationships among BIM contents and the possible CEM courses to integrate and to organize the contents in a consistent and coordinate manner, this research designed the Quality-Function-Development (QFD) house method for the implementation.

For the integrated relationship analysis, Quality-Function-Development (QFD) house method shines a light of a solution to the problem. QFD house is applied in a wide variety of services, consumer products, and emerging technology products [23]. QFD house helps to transform customer needs into engineering characteristics for a product or service [24]. House of Quality appeared in 1972 in the design of an oil tanker by Mitsubishi Heavy Industries. It was a useful tool to help planners to focus on characteristics of a new or existing product or service from the viewpoints of market segments, companies, or technology-development needs [25]. This paper assimilated the concept of QFD house and integrated it with the knowledge system of the CEM majors in China. Particularly, the structure of BIM capability was built based on the QFD house model and the 2013 China Civil Engineering and Management Undergraduate Education Guideline (2013 CCEMUEG). Through the relation analysis of the required knowledge units and points for BIM capability and the requirements of the 2013 CCEMUEG, the authors provided suggestion for the application of QFD in the BIM education of CEM majors. The structure of BIM capability and the QFD application process would help the development of BIM courses in CEM programs.

3.2 Cognitive structure of BIM

2013 CCEMUEG sets up the knowledge system of CEM majors in 3 levels: knowledge domain, knowledge unit, and knowledge point. CCEMUEG has 5 professional knowledge domains, which are (1) technical foundation of civil engineering and other engineering domains; (2) theory and methodology of management; (3) theory and methodology of economics; (4) theory and methodology of law; and (5) computer and information technology. CCEMUEG further defines 197 core knowledge units and 846 core knowledge points, which all together build the essential knowledge for students in CEM majors. BIM is classified into the computer and information knowledge domain of 2013 CCEMUEG. In this case, it only has one knowledge unit "computer and information technology application". There are 2 knowledge points which should be completed within 24 recommended credit hours. The 2 knowledge points are "completing the related specialties of CEM by related professional software" and "construction information model" [1, 2]. The knowledge points of fundamental computer and information knowledge are arranged in the tool knowledge of 2013 CCEMUEG, with more emphasis on implementation and problem solving.

The above analysis indicates that the explicit reference of BIM in the education guideline categories it as a professional application of computer and information technology; but it is never equivalent to exclusively a software course. The implementation of BIM in CEM education involves a wide range of knowledge, such as technology, management, and contract. Fig. 2 shows the cognitive structure of BIM in CEM. The left side of Fig. 2 shows the levels of how knowledge is built-up through BIM education levels. The right side of Fig. 2 demonstrates the CEM education objectives using Bloom's Taxonomy.

As shown in Fig. 2, BIM training in CEM should include the theories and methods of technology,

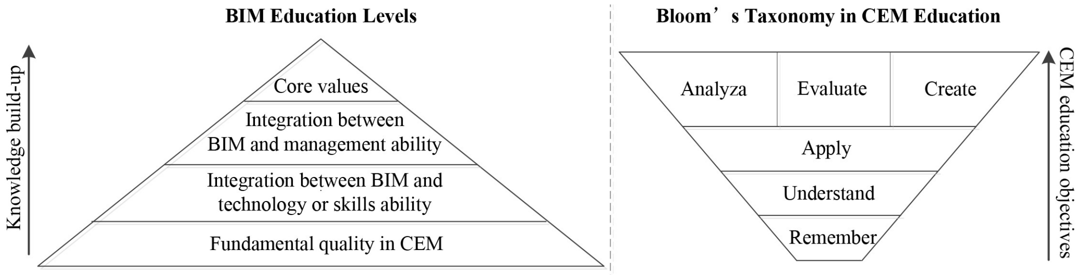


Fig. 2. Building Information Modeling (BIM) education levels in Civil Engineering and Management (CEM) education.

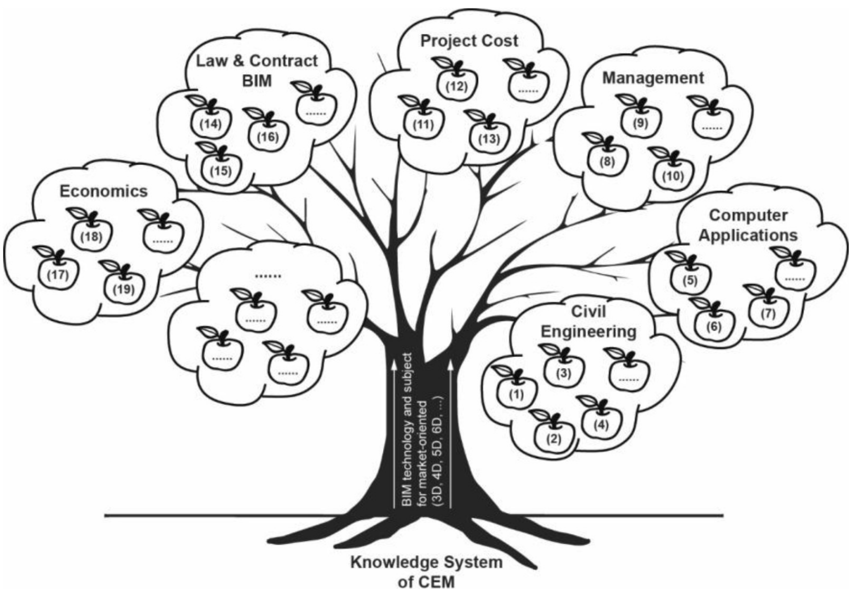


Fig. 3. Knowledge tree of building information modeling (BIM) education in civil engineering and management (CEM).

management, economics, and legal aspects, which are associated with CEM. Students should be equipped with the fundamental abilities to carry out design management, investment control, process control, quality control, contract management, information management, and organization ordination in civil engineering or other engineering domains. The comprehensive professional abilities include discovering, analyzing, studying, and solving practical problems of engineering management. Therefore, the authors argued that the required skills and management abilities of BIM education are impossible to be included in just one course. Further, the authors noticed that the contents of BIM courses intersected the 5 required knowledge-domains of 2013 CCEMUEG to form a crossing knowledge unit, with unit points spread in all the 5 knowledge domains of CEM education, as described in Section 3.2 of this paper. The crossing knowledge points of BIM could be organized and delivered in the corresponding courses in the domains. Fig. 3 shows the knowledge tree of BIM education in CEM. Table 1 has the supplementary explanation on the terms shown in Fig. 3. The knowledge tree describes the cultivation of BIM capabilities through an undergraduate program. As shown in Fig. 3, demand-oriented BIM technology and theme are blended into the CEM knowledge system as the nutrition for the knowledge tree. The tree carries great outputs or delivers BIM technology to other courses, such as construction cost, scheduling, and construction management. In the tree, the CEM knowledge system is composed of the technical foundations of civil engineering, theories and methods of management, economics, law, and computer information technology. BIM is combined with the courses of these knowledge systems to build the crossing knowledge units and points. With the variation of industrial demands for BIM skills and themes, course directions and contents should be updated dynamically. Generally speaking, the BIM technology and themes shown in Fig. 3, which are integrated into CEM knowledge system, can meet the current industrial demand for BIM. It contains not only the technology of BIM core tools and engineering practices, but also includes the experience gained from engineering projects.

4. QFD house analysis for BIM education in CEM

BIM teaching needs the recombination of subjects at various technical levels to adapt to different learning periods. The objectives of BIM education should be aligned with the outlines and curriculum plans of CEM education. This alignment can meet the demands from the construction industry for graduates of CEM in terms of BIM skills while avoiding the fracture and conflict in teaching contents. For example, BIM can be inserted into the course of construction equipment for demonstrations and simulations. With BIM technology, students in the construction equipment class can save the costs of expensive field trips and equipment manual purchase. Schools can also avoid possible liability issues when sending students to jobsites. To do this, instructors are required to have the related application experiences of BIM tools. Fig. 3 has the

Table 1. Possible Courses in Civil Engineering and Management under 2013 China Civil Engineering and Management Undergraduate Education Guideline (CCEMUEG)

Number	Subject	Number	Subject
(1)	Engineering drawing	(11)	Project pricing
(2)	Engineering design	(12)	Cost accounting
(3)	Building construction	(13)	Theory of project cost
(4)	Building architecture	(14)	Project contract management
(5)	Auto CAD	(15)	Project consultation
(6)	Software of engineering design	(16)	Project bidding
(7)	Software of project cost	(17)	Financial management
(8)	Material management	(18)	Engineering economics
(9)	Construction project management	(19)	Feasibility research
(10)	Facility management		

typical BIM applications and interface as the background.

The integration of BIM knowledge into multiple CEM courses should take a systematic and organized approach. Many knowledge units of CEM are associated with BIM, such as construction materials, construction contracts and management, building structure and engineering mechanics, guidance of engineering practice, engineering construction and management, project cost and management, and construction safety, etc. The authors designed a QFD house framework to integrate BIM technology and the CEM courses (or parts of the courses). Fig. 4 shows the template of the QFD house analysis of BIM education. The QFD house analysis seeks for the capability structure and quality factors of BIM education and gradually develops and improves the BIM education in CEM knowledge units. The following contents discuss the details of implementing the QFD house analysis.

5. Application analysis

5.1 QFD house analysis and CCEMUEG knowledge domains, units, and points

In this research, the authors designed QFD houses for the cognitive structure and quality elements of BIM education in CEM. Particularly, 2013 CCE-

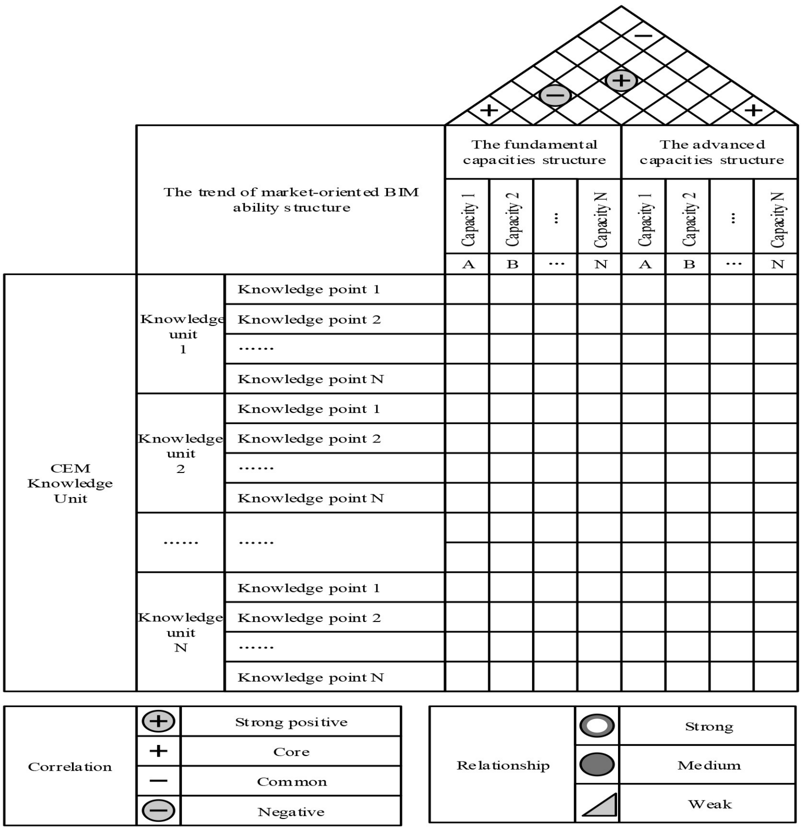


Fig. 4. Template of Quality-Function-Development (QFD) house analysis between Building Information Modeling (BIM) ability structure and Civil and Engineering Management (CEM) education.

MUEG was adopted as a reference for the education objectives of CEM. From the reference, core knowledge units and points were retrieved from the 4 knowledge domains of CCEMUEG for the analysis in the following areas:

Domain 1: "foundation of civil engineering and other engineering technologies",
Domain 2: "management theory and method",
Domain 3: "legal theory and method", and
Domain 4: "economic theory and method".

The purpose is to build the capability structure and quality elements of BIM education. To facilitate the description, the knowledge units and points of corresponding knowledge domains were coded according to the Appendix 1 of the 2013 CCEMUEG [26]. For example, "C1-1" in Table 2 indicates the first knowledge point "basic regulations of drawing", in the first core knowledge unit "basic drawing knowledge" of the knowledge domain 1, which is "foundation of civil engineering and other engineering technologies" and denoted with letter "C". "M16-1" in Table 3 indicates the first knowledge point of "the target and basis of project schedule control" in the 16th knowledge unit of "schedule control" of Domain 2, which is "management theory and method" and denoted with letter "M". It should be noted that computer technology and application knowledge domains only have 2 summarized knowledge units and points which are highly consistent with the capability structure of BIM of the CEM students.

For the BIM capability units in CEM, as shown in Fig. 4 and Fig. 2, 4 components were identified and selected respectively from the fundamental and advanced capabilities of BIM, namely Fundamental BIM Concept (FBC), Fundamental Plan Reading (FPR), Fundamental MEP Modeling (FMM), Fundamental Basic 3D Simulation (FB3D), Advanced Classification System (ACS), Advanced Schedule Monitoring (ASM), Advanced Cost Management (ACM), Advanced 4D Simulation (A4D). The example shown in Table 2 takes part of knowledge units and points in Domain 1 to build the QFD analysis between the capability structure of BIM and CEM. The related technosphere is shown in Fig. 5. Table 3 shows the knowledge units and points in Domain 2. Fig. 6 shows the QFD analysis between the capability structure of BIM and Domain 2. In other words, Table 2 and Fig. 5 are related. Table 3 and Fig. 6 are related.

Fundamental BIM Concept (FBC), Fundamental Plan Reading (FPR), Fundamental MEP Modeling (FMM), Fundamental Basic 3D Simulation (FB3D), Advanced Classification System (ACS), Advanced Schedule Monitoring (ASM), Advanced Cost Management (ACM), Advanced 4D Simulation (A4D).

5.2 *Analysis of curriculum construction*

The CEM education programs have various emphases, such as civil engineering, engineering finance, or project cost. CEM undergraduate education is mostly skill-type or application-type. CEM education puts first priority on the shaping of value concepts and the second is on the professional skills. Classroom teaching is usually the solitary approach to train professional skills. The skills trained in the core courses are listed as follows: engineering drawing and identification, construction cost, bidding,

Table 2. The Extracted Knowledge Units and Points of Civil and Engineering Management and the Related Technosphere of Domain 1

Knowledge Unit		**Knowledge Point**			
No.	Description	#	Description	Learn Level	Coded
1	Basic knowledge of drafting	1	The basic rules of drafting	Synthesize	C1-1
		2	The tools of drafting	Understand	C1-2
		3	Geometric drawing and drafting	Understand	C1-3
		4	Introduction to computer graphics	Understand	C1-4
2	Basic knowledge of projection	1	Basic knowledge of projection	Synthesize	C2-1
		2	The basic properties of projection	Synthesize	C2-2
		3	The method of drafting commonly used in engineering	Apply	C2-3
		4	The formation and characteristics of Orthographic views	Apply	C2-4
91	Waterproof and thermal insulation of building	1	Waterproof roof construction	Synthesize	C91-1
		2	Waterproof of exterior wall	Synthesize	C91-2
		3	Thermal insulation	Apply	C91-3
		4	Heat insulation structure of peripheral building components	Apply	C91-4
92	Deformation joints of building	1	Classification and setting requirements of building joints	Synthesize	C92-1
		2	The structure arrangement of deformation joints	Synthesize	C92-2
		3	Crack covering of deformation joints	Synthesize	C92-3

Source：2013 CCEMUEG Appendix Table 1-3

Table 3. The Extracted Knowledge Units and Points and Related Technosphere of Domain 2

Knowledge Unit		**Knowledge Points**			
No.	Description	#	Description	Learn Level	Coded
13	Project Manageme nt organizatio n	1	Organization structure of engineering project and decomposition coding	Synthesize	M13-1
		2	The contracting organization mode of engineering project	Synthesize	M13-2
		3	Organization structure of engineering project management	Synthesize	M13-3
		4	Organization mode of engineering project management	Understand	M13-4
		5	Scheme, planning and manual of engineering project management	Understand	M13-5
16	Schedule control	1	Target and basis of project schedule control	Synthesize	M16-1
		2	Establishment and operation of project schedule control system	Understand	M16-2
		3	Preparation method of project schedule plan	Synthesize	M16-3
		4	Schedule control in the project construction stage	Synthesize	M16-4
17	Quality control	1	Target and basis of project control	Synthesize	M17-1
		2	Establishment and operation of project quality system	Synthesize	M17-2
		3	Quality control in the design of project	Synthesize	M17-3
		4	Quality control in the project construction stage	Synthesize	M17-4
		5	Completion and acceptance of engineering project	Synthesize	M17-5
33	Integer program.	1	Problems and mathematical model of integer programming	Synthesize	M33-1
		2	Branch and bound method	Synthesize	M33-2
		3	Cutting plane method	Synthesize	M33-3
		4	Integer programming and the implicit enumeration method	Apply	M33-4
34	Basic knowledge of graph theory	1	Concept and characteristics of graph	Synthesize	M34-1
		2	Shortest question	Synthesize	M34-2
		3	Maximum flow question	Synthesize	M34-3
		4	Minimal tree question	Synthesize	M34-4
		5	Network planning method	Synthesize	M34-5

Source：2013 CCEMUEG Appendix Table 1-4

project management, and engineering technology. With the analysis on the QFD between the capability structure of BIM and CEM education, the core knowledge units, crossing knowledge points, core skill units, and skill unit experiments of BIM education are listed in Table 4 for curriculum construction and development ideas. BIM education in CEM calls for distributed teaching. The teaching contents can be in a singular course or across several courses. BIM education also needs to have a comprehensive course of application to integrate the knowledge of engineering drawing and design, construction cost, bidding, engineering project management, and BIM design/simulation/analysis, to enable students to master BIM technology and the comprehensive skills of engineering.

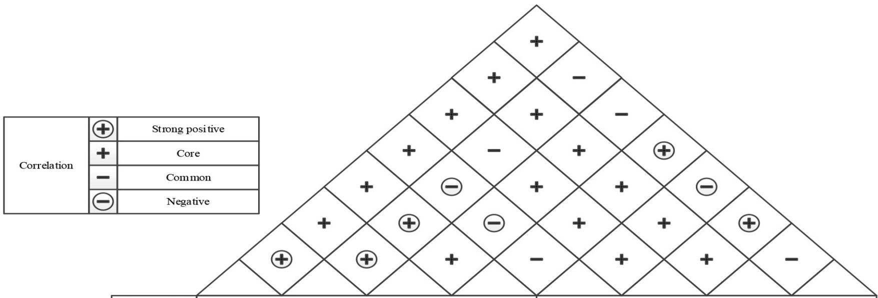
5.3 Feasibility study and limitations of the knowledge framework

In this research, The QFD house method was used to develop the knowledge frameworks of major CEM courses. The QFD house method can be used in both semester-long courses and quarter-long courses. Using the method, instructors could identify the homework or project exercises that help students to build or strengthen BIM ability structure. For example, in a course related to civil engineering theory and method, the following question is a C1-2 type of question. It is about the basic knowledge of drafting and helps student to understand the tools of drafting.

Sample Question: Which of the following is (or are) the commonly used drafting tools:

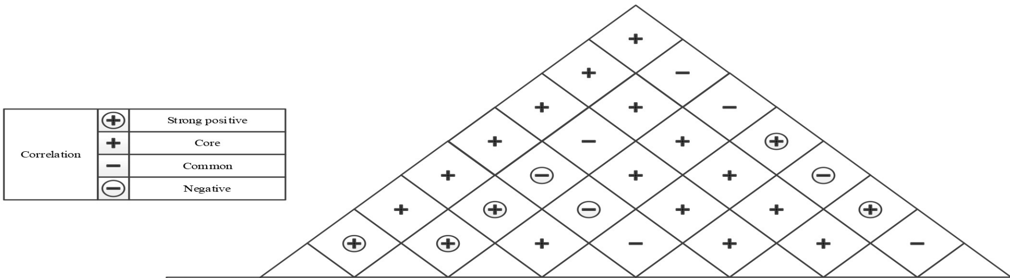
Pencil; B. Drawing board; C. Scales; D. T-square; E. All of the above.

But the above question does not contribute to the BIM ability structure. It is currently part of the core knowledge of Fundamental Plan Reading (FPR). This is shown in the line item of C1-2 of Fig. 5. So this type of questions should be reduced. The following question is a C2-4 type of question. It is about the basic knowledge of projection and helps student to apply the formation and characteristics of the three views.



	The trend of market-oriented BIM ability structure	The extracted BIM fundamental ability and learn level				The extracted BIM advanced ability and learn level			
		FBC	FPR	FMM	FB3D	ACS	ASM	ACM	A4D
		know	understand	analyze	synthesize	apply	synthesize	evaluate	synthesize / evaluate
Codes of foundation knowledeg units and points taken from civil engineering	C1-1	−	⊕	⊕	⊕	⊖	−	−	⊕
	C1-2	−	+	−	−	⊖	⊖	⊖	⊖
	C1-3	−	+	−	−	⊖	⊖	⊖	−
	C1-4	−	+	⊕	⊕	⊖	⊖	⊖	⊕
	C2-1	+	⊕	⊕	⊕	⊖	⊖	⊖	⊕
	C2-2	−	⊕	⊕	⊕	⊖	⊖	⊖	⊕
	C2-3	+	⊕	⊕	⊕	⊖	+	+	⊕
	C2-4	+	⊕	⊕	⊕	⊖	−	−	⊕
	C91-1	⊖	⊕	+	+	−	+	+	+
	C91-2	⊖	⊕	+	+	−	+	+	+
	C91-3	⊖	⊕	+	+	−	+	+	+
	C91-4	⊖	⊕	+	+	−	+	+	+
	C92-1	−	−	+	⊕	+	−	−	⊕
	C92-2	⊖	+	+	+	−	+	+	+
	C92-3	⊖	+	+	+	−	+	+	+

Fig. 5. QFD house analysis between BIM ability structure and Domain 1 (civil engineering theory and method).



	The trend of market-oriented BIM ability structure	The extracted BIM fundamental ability and learn level				The extracted BIM advanced ability and learn level			
		FBC	FPR	FMM	FB3D	ACS	ASM	ACM	A4D
		know	understand	analyze	synthesize	apply	synthesize	evaluate	synthesize / evaluate
The extracted knowledge unit and point of Management theory and method	M13-1	+	+	−	−	+	−	−	−
	M13-2	−	⊖	⊖	⊖	⊖	+	+	⊖
	M13-3	+	⊖	⊖	⊖	+	+	−	⊖
	M13-4	+	⊖	⊖	⊖	−	+	−	⊖
	M13-5	+	⊖	⊖	⊖	−	+	+	⊖
	M16-1	+	+	−	−	⊖	⊕	⊕	−
	M16-2	+	+	−	−	⊖	⊕	⊕	−
	M16-3	+	+	−	−	⊖	⊕	⊕	−
	M16-4	−	+	−	−	⊖	⊕	⊕	−
	M17-1	+	+	⊖	⊖	⊖	⊕	⊕	−
	M17-2	−	+	⊖	⊖	⊖	⊕	⊕	−
	M17-3	+	⊕	⊕	⊕	⊖	⊕	⊕	⊕
	M17-4	+	⊕	⊕	⊕	⊖	⊕	⊕	⊕
	M17-5	⊖	+	+	+	⊖	⊖	⊖	+
	M33-1	−	⊖	⊖	⊖	⊖	+	+	⊖
	M33-2	−	⊖	⊖	⊖	⊖	+	+	⊖
	M33-3	−	⊖	⊖	⊖	⊖	+	+	⊖
	M33-4	−	⊖	⊖	⊖	⊖	+	+	⊖
	M34-1	⊖	+	+	+	⊖	⊖	⊖	+
	M34-2	⊖	+	+	+	⊖	−	−	+
	M34-3	⊖	+	+	+	⊖	−	−	+
	M34-4	⊖	+	+	+	⊖	−	−	+
	M34-5	⊖	+	+	+	⊖	+	−	+

Fig. 6. QFD house analysis between BIM ability structure and Domain 2 (management theory and method). Fundamental BIM Concept (FBC), Fundamental Plan Reading (FPR), Fundamental MEP Modeling (FMM), Basic 3D Simulation (FB3D), Advanced Classification System (ACS), Advanced Schedule Monitoring (ASM), Advanced Cost Management (ACM), Advanced 4D Simulation (A4D).

Table 4. Curriculum Structure of BIM Education

Course	Knowledge Units and Points: Core Knowledge	Knowledge Units and Points: Cross Point in BIM	BIM Skills: Core Skills Module	BIM Skills: Experiments or Exercises	Possible Improvements
Engineering graphics	1. Identify structural images and details. 2. Detailing.	1. Identify engineering images. 2. BIM simulation. 3. 4D models. 4. Application skills.	1. Identify engineering images. 2. BIM simulation. 3. 4D models. 4. Application skills.	1. Simulation of structure and construction drawing in BIM. 2. BIM modeling. 3. BIM browser.	Using actual cases to help students to: 1. Identify graphics theory and improve theoretical knowledge. 2. Architectural and structural drawings, municipal construction drawings, and professional installation requirements. 3. Understand design intents using 3D simulation technology.
Project cost and bidding	1. Budget of project installation, engineering, and decoration. 2. Cost control. 3. Project bidding, contract MGMT. 4. Engineering settlement.	1. Computation, steel flat method, engineering tendering and bidding transaction management, collaborative pricing management. 2. BIM in construction. 3. 4D models. 4. Skills application.	1. Engineering quantity list. 2. Budget calculation. 3. Engineering quantity list valuation. 4. Preparation of tendering documents. 5. Engineering settlement.	1. Construction valuation. 2. Installation amount. 3. Municipal amount. 4. Hardcover amount. 5. Amount of steel structure. 6. Project bidding sandbox.	1. Experimental courses and tools + core professional knowledge + actual case; 2. Construction engineering measurement and valuation; 3. Installation, decoration, municipal budget, cost control; 4. Project bidding, project settlement and other professional knowledge. Use BIM functions to prepare project quantity takeoff, bidding and tender documents.
Project Construction and Management	1. Management of project construction. 2. Analysis of project profitability. 3. Building construction technology. 4. Building material.	1. The experiment of project sand-table. 2. Construction simulation and experiment. 3. Building material simulation experiment. 4. 4D micro course. 5. Teaching platform for skills application.	1. Building material. 2. Construction and organization management.	1. Experiment of project management system. 2. Network planning experiment. 3. 3D layout construction. 4. Construction planning and preparation. 5. Materials management. 6. BIM-5D project management system.	1. Through actual cases to learn the core knowledge and the concept of project management, construction materials, and engineering project management; 2. Learn about the actual project management knowledge and skills through the project management system, construction management software, material management, BIM5D system and so on.
Integrated curriculum of BIM project management	Integrate the knowledge from different categories about identifying project images and mapping, engineering cost, bidding, and project management.	Through BIM technology, master the skills of the understanding images and graphics of engineering, calculating engineering cost and bidding, project management etc.	Learn BIM technology and be able to identify the engineering images and graphs, calculate engineering costs, and manage project etc.	Combined professional features with the use of BIM technology to study the knowledge, skills, and tools used in real BIM projects.	

Sample Question: Using the provided BIM model to create the floor plan, front elevation, and east side elevation of the building.

According to Fig. 5 of this research, this question has strong positive relationships with Fundamental Plan Reading (FPR), Fundamental MEP Modeling (FMM), Basic 3D Simulation (FB3D), and Advanced 4D Simulation (A4D). It is the core knowledge of Fundamental BIM Concept (FBC) and common to Advanced Schedule Monitoring (ASM) and Advanced Cost Management (ACM). It only has negative correlation with Advanced Classification System (ACS). So this type of questions should be increased. Using this method, instructors can effectively create and update their course contents and assessments.

One limitation of this research is that the framework has not been implemented yet. The authors plan to first implement the framework in the course of Civil Engineering Theory and Method at the Department of Civil Engineering and Management in a university in Xi'an, China. The course contents and assessment methods will all be revised. The pedagogical methods will be changed as well. More emphasis will be placed on hands-on exercises.

6. Conclusion

In summary, the implementation of BIM technology in CEM education is a complicated process. Educators need to consider the expected cognitive structure of BIM and the training contents of BIM education. Particularly, educators should design, implement, and adjust the subject areas of the BIM courses to prepare students for the skills and subject areas expected by job market. The combination of BIM related topics with CEM courses will help to strengthen the CEM education with information integration in engineering, technology, management, and construction systems. The QFD house framework discussed in this paper demonstrated the method to achieve the BIM education objectives. Without redeveloping the entire existing curriculums, CEM education would be able to maintain the cognitive structures as defined by the accreditation criteria and evolve itself by synthesizing the cutting-edge topics of BIM.

This research suggested an attempt in incorporating the industries' needs into the curriculum development of engineering education. Engineering education needs to involve the hot topics of the engineering industries in the recent 5–10 years and train students with industry-leader awareness. Engineering education must keep consistent with the development of the industries, make sure students can perceive or learn the new experiences, skills or policies of the industry, and prepare students for their future careers. For future research, the authors plan to implement the findings from this study in 2 CEM courses and revise their teaching contents and assessments.

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