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Closed-Loop Management System for Design of a Building Information Modeling Curriculum to Meet Industry Requirements*

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Building Information Modeling (BIM) has been one of the most significant and widely adopted advanced technologies in the architecture, engineering, and construction (AEC) industry in recent years. Unfortunately, the current BIM curriculum in colleges does not adequately prepare students for real-world AEC industry practices. Besides, numerous concerns regarding the competency requirements of the AEC industry for BIM practitioners and the targeted design of teaching content of BIM curricula, etc. remain unanswered. To enhance the preparation of BIM students for real-world AEC work, this study collected 280 questionnaires from 27 administrative regions in China and conducted data analysis to assess the disparity between the competency requirements in the AEC industry and the existing BIM curriculum in colleges. Additionally, this study presents innovative theories, namely directed closed-loop and undirected closed-loop theories, derived from the closed-loop management system. These theories are effectively integrated into college BIM education as project closed-loop and content closed-loop theories. It validates the effectiveness of the curriculum design through BIM students' academic performance. Results demonstrate that the closed-loop management design of the BIM curriculum can better match the AEC industry's competency requirements and that BIM students will better adapt to real-world AEC work.

Keywords: BIM education; college education; engineering education; closed-loop management

1. Introduction

Building Information Modeling (BIM) has received significant attention in the architecture, engineering, and construction (AEC) industry due to its potential in improving project efficiency [1] and changing the way projects are constructed [2]. However, the lack of experienced BIM professionals is a significant challenge for effective implementation of BIM in the current practice of the AEC industry [3, 4]. The AEC industry needs comprehensive education and training programs to facilitate the widespread use of BIM technology [5] and school education is key to that. The connections between higher education and industry are crucial for promoting productivity (For instance, colleges can train highly skilled professionals tailored to the needs of the AEC industry, thereby fostering its growth [6]). Unfortunately, the current BIM curriculum in colleges does not adequately prepare students for real-world AEC industry practices.

In China, BIM entered the university training system as an important curriculum of intelligent construction major since the Ministry of Education of the People's Republic of China approved Tongji University to take the lead in setting up intelligent construction major in 2018 [7]. While several universities worldwide have incorporated BIM curricula into their programs, others have not yet adopted it [8], or are still in the process of integrating BIM into their curricula [9]. Unfortunately, the current curricula could hardly meet the demands of the AEC industry [10]. There are still few BIM curriculum teaching methodologies and practice

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cases available for reference. Three hundred eighty-one relevant BIM-related articles were reviewed [11], while only three studies focused on BIM in the context of training and education curricula, indicating that BIM educational themes had not received sufficient attention in academic research.

The existing BIM education in colleges is primarily derived from the transformation and reference of engineer training. For example, the existing BIM education in colleges only focuses on the instruction of various BIM software applications (e.g., Revit, Navisworks, etc.). Such an instructional approach could help students get more familiar with all BIM-related software applications. Unfortunately, students often lack the requisite knowledge to address the following fundamental questions about BIM: (1) why we need to use BIM technology, (2) when should we use BIM technology, (3) how should we use BIM technology in the real practice, and (4) how BIM technology could help improve project efficiency [12]. Such a training mode only allows students to learn to build BIM models quickly, but they lack the cognition of the professional features and functions of components, the implementation and optimization methods of software, and the system application methods of engineering projects At present, recently introduced BIM curricula in colleges often prioritize direct instruction in the operation of BIM-related software applications. These BIM curricula are not linked up with the prerequisite curricula and lack the exercise of cases and project application practice.

This paper aims to bridge the gap between the competency requirements of the AEC industry and the existing BIM curricula in colleges by analyzing questionnaire data. The objective is to enhance the adaptability of BIM students trained in colleges for real-world AEC industry work. Subsequently, the study implements a closed-loop management design for the BIM curriculum teaching content in colleges, based on the directed and undirected closed-loop theories. The effectiveness of the BIM curriculum design is verified by the academic performance of BIM curriculum students at Beijing University of Technology (BJUT). This paper proposes the closed-loop management design of BIM curriculum teaching content for the AEC industry that can better align the BIM curriculum with the competency requirements of BIM practitioners in the AEC industry. In addition, college-trained BIM students will be more adaptable to BIM-related work in the AEC industry. In conclusion, this paper serves as a valuable guide for colleges that have implemented or plan to introduce BIM curricula, aiding in the development of high-quality, innovative, and industry-ready BIM personnel who are better adaptable to the AEC industry.

The remaining parts of this paper are structured as follows: The second section consists of a systematic literature review, including AEC industry competence requirements for BIM practitioners, the current status of BIM course teaching systems, and closed-loop management system in education (Section 2). The third section describes in detail the proposed methodology for the closed-loop management design of BIM curriculum teaching content for the AEC industry (Section 3). The fourth section provides the results of the BIM curriculum's teaching of content design instruction to validate the framework's viability (Section 4). The fifth section discusses the results and limitations of this study (Section 5). The final section of the paper (Section 6) concludes the paper with a summary and an outlook for future development.

2. Literature Review

2.1 AEC Industry Competence Requirements for BIM Practitioners

With the increase and acceptance of BIM technology applications, BIM education for undergraduate students in AEC-related disciplines has become essential [13–15]. The primary objective of contemporary technical higher education is to provide the labor market with specialized engineers with the knowledge and skills to undertake tasks of varying complexity [16]. The digitization of the AEC industry has necessitated a reevaluation of knowledge management, education and training, workflows and networks, roles, and relevance. Consequently, new approaches to teaching and learning are required to satisfy the requirements of new jobs and competencies, new communication channels, and new awareness in the AEC industry [17, 18]. The authors of Ref. [6] presented a teaching and learning proposal for project development in the subject of the final design project to meet the new demand for trained professionals for integrated project delivery (IPD) in the AEC industry. Additionally, the study by Ref. [19] discussed peer pressure, which challenges educators with the issue of developing students' BIM skills and preparing them for a career in the AEC industry. To enhance, improve and research state-of-the-art BIM technology in the AEC industry, academia must develop and implement an appropriate educational program [20].

2.2 Current Status of BIM Course Teaching System

The authors in Ref. [21] discussed the necessary prerequisites for designing a comprehensive curriculum that integrates Building Information Modeling (BIM) into primary engineering education. This curriculum aims to teach the fundamental principles of technical disciplines to first-year students specializing in construction. The authors of references [22–25] advocate for enhancing students' BIM knowledge and skills through methodical curriculum design and content development. The authors in references [26–29] employ a pedagogical approach using real-world projects in the BIM course to incorporate various disciplines. This approach enables students to comprehensively understand the practical application of BIM in the AEC industry, thus better aligning with industry requirements. The authors of Ref. [30] explored the extent of alignment between undergraduate BIM education and job market expectations regarding the skill structure of BIM competencies. They aimed to design, implement, and refine the subject areas of BIM curricula to better equip students with the skills sought after by the job market. The authors of Ref. [31] put forth a structured process that offers a consistent methodology for developing effective problem-based learning modules related to BIM. This process assists educators in creating impactful learning experiences.

2.3 Closed-loop Management System in Education

The closed-loop management system is applied extensively in higher education and holds a promising future. The authors of Ref. [32] constructed an applied engineering talent cultivation system with double closed-loop adaptability, which provides a new method for cultivating applied and inventive talents by enhancing the cultivation process' adaptability and stability. The author of Ref. [33–35] enhances the automation and intelligence of conventional classroom teaching by implementing a closed-loop feedback control system for course instruction, aiming to improve both student learning outcomes and organizational effectiveness. This approach also aims to reduce the workload of educators and related staff while ensuring the systematic organization and management of classroom instruction. The author of Ref. [36] provided a scientometrical review of BIM education research outcomes and predicts that BIM education will continue with multiple studies, such as educational innovations in BIM technology and management and interdisciplinary collaboration to reduce the fragmentation of AEC disciplines.

3. Methodology

As shown in Fig. 1, in this paper, we conducted a questionnaire survey for BIM and other practitioners in the AEC industry in mainland China to determine the demand for BIM talent in the AEC industry. Concurrently, we conducted a questionnaire survey for BIM course teachers and students in colleges to determine the current teaching content of BIM courses in colleges and universities. The disparity between the AEC industry's desire for BIM talent and the current curriculum of BIM courses at colleges is summarized through data collecting and analysis. In the meantime, this study presents innovative theories, namely directed closed-loop and undirected closed-loop theories, derived from the closed-loop management system. These theories are effectively integrated into college BIM education as project closed-loop and content closed-loop theories, addressing the competency requirements of BIM professionals in the AEC industry. To validate the effectiveness of these theories, we evaluated the academic performance of students enrolled in BIM courses at BJUT through data collecting and analysis.

3.1 The Questionnaire

3.1.1 The Questionnaire's Audience and Distribution

This questionnaire has four distinct audiences, including the AEC industry and the college. The

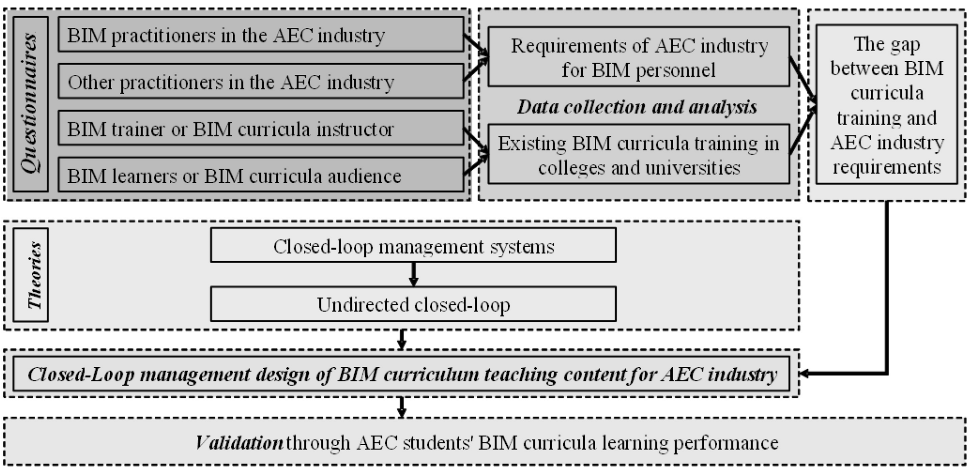

Fig. 1. Research framework.

AEC industry side consists of both BIM practitioners and non-BIM practitioners. It collects the skills requirement of BIM practitioners in the AEC industry based on the real BIM practice demand of BIM practitioners and non-BIM practitioners, respectively. The college side consists of instructors responsible for BIM personnel training in universities and BIM students in order to comprehend the instructional content of BIM courses from the perspectives of instructors and students, respectively. This paper's questionnaire audience is mainly distributed in mainland China, and the study objects span the four major BIM application regions of eastern, central, western, and northeastern China with varying BIM application levels to ensure a complete and scientific data source.

3.1.2 Questionnaire Design

The questionnaire first divided the audiences into four occupational categories: BIM practitioners in the AEC industry, non-BIM practitioners in the AEC industry, BIM teachers in universities, and BIM students, and then investigated the practice time of the first three categories separately to provide evaluation indices for the reference ability of the questionnaire data. In addition, the questionnaire was structured to include three groups of questions for distinct audiences. The first set of questions asks, "Which of the following issues have you faced while working in the BIM industry?" This question is intended primarily for BIM practitioners in the AEC industry, and the demand for BIM talent in the AEC industry is indirectly derived from the difficulties encountered by practitioners in their actual work. The second set of questions asks, "Which of the following topics were covered in the BIM course you taught or the BIM training in which you participated?" "Have you faced the following issues during BIM training or course instruction?" This series of questions is intended mainly for college and university BIM instructors. It examines the current setting of BIM course teaching content in colleges by analyzing the setting of BIM curriculum teaching material and the difficulties encountered by BIM teachers during the teaching process. The third set of questions is, "Have you studied engineering-related professional knowledge before learning the BIM course?" "What did you gain after learning the BIM course?". By examining the existing knowledge system of BIM students and their learning gains under the standard BIM course teaching content, this collection of questions aims to give a reference for the BIM course teaching content setup.

3.2 Closed-loop Management System

The concept of closed-loop management was proposed by Robert S. Kaplan and David P. Norton in their paper *Mastering the Management System* [37]. The term "closed-loop management system" refers to the set of processes and tools that a company uses to develop strategy, translate strategy into operational actions, and monitor and improve the effectiveness of strategy and actions. In order to ameliorate the current mode of college BIM courses and target the skills demand of the AEC industry for BIM practitioners, this paper innovatively introduces the concept of directed closed-loop and undirected closed-loop management theories into the teaching of BIM curricula in colleges and universities. Furthermore, it establishes a comprehensive closed-loop management system for BIM teaching programs in colleges and universities within the AEC industry.

3.2.1 Directed Closed-loop

As shown in Fig. 2, based on the closed-loop management system, this paper proposed the directed closed-loop which refers to periodic closed-loop activities with a certain logical sequence. The overall process exhibits a spiraling trend guided by the end goal. Each sub-loop of the closed-loop can be further divided into specific steps that can be iteratively performed.

3.2.2 Undirected Closed-loop

The undirected closed-loop is the set of all necessary conditions required to satisfy the purpose, as shown in Fig. 3. Guided by the goal, the undirected closed-loop considers all the necessary conditions. As shown in Fig. 4, each plank of the barrel is a necessary condition. If any plank is missing, the

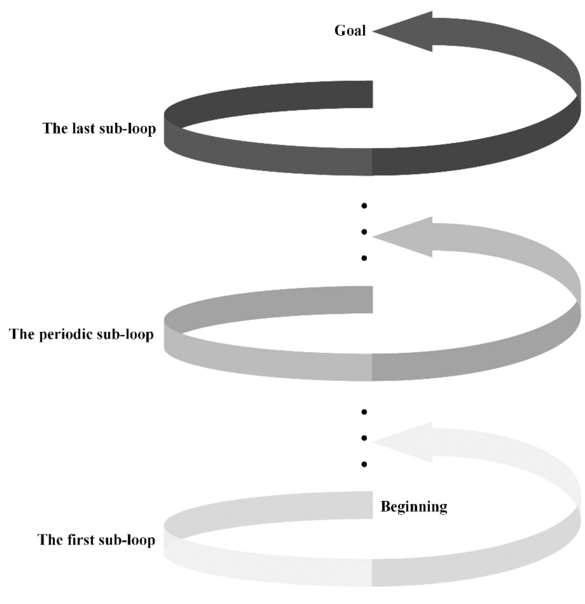

Fig. 2. Directed closed-loop.

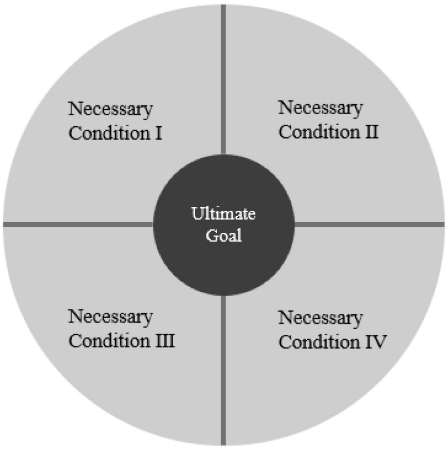

Fig. 3. Undirected closed-loop.

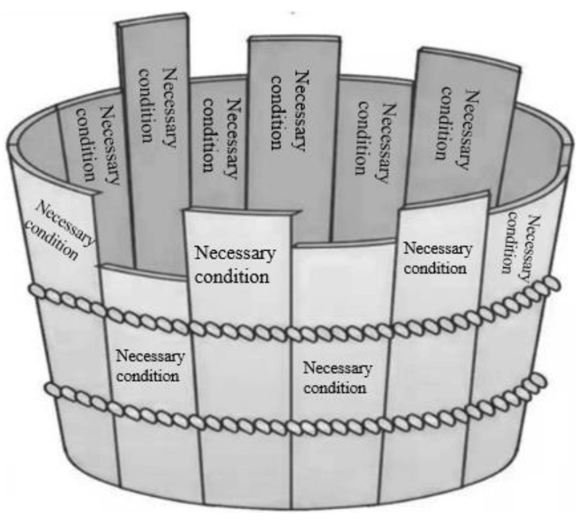

Fig. 4. Barrel undirected closed-loop.

barrel does not have the ability to hold water. This means that the barrel cannot accomplish the set goal. At the same time, the length of the plank affects the capacity of the barrel to hold water. Similarly, the completion of the necessary conditions in the undirected closed-loop also affects the degree of goal achievement.

4. Result

4.1 Data Collection and Analysis

In this study, 280 questionnaires were collected from 27 provincial-level administrative regions in China (Fig. 5). The respondents of 47 surveys are BIM practitioners in the engineering industry who have averaged 6.91 years of experience in the BIM industry. In the engineering industry, 42 surveys are from non-BIM practitioners with an average of 12.95 years of experience. Ninety-five respondents are college instructors of BIM courses, with an average of 4.67 years of BIM teaching experience. Ninety-six questionnaires are students in BIM courses at colleges.

Table 1 analyzes the findings of the three groups of questions in the questionnaire described in section 3.1.2, summarized by requirements of the AEC industry for BIM personnel, existing BIM curriculum training in colleges and universities, and matching degrees with the source of the data appended to each item. While Table 2 presents the effectiveness of the closed-loop management system by evaluating students' academic performance throughout a 1-year teaching implementation at BJUT.

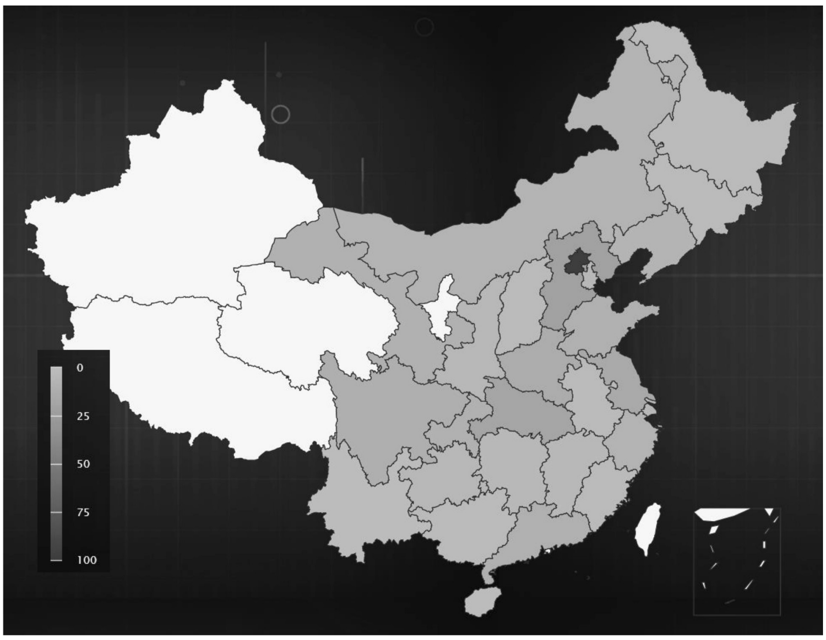

Fig. 5. The questionnaire's audience and distribution.

Table 1. Elements of the BIM curriculum training system that cannot meet the requirements of AEC industry for BIM personnel

Requirements of AEC industry for BIM personnel	Existing BIM curriculum training in colleges and universities	Matching degree	Data sources (questionnaires)
Comprehensive understanding of engineering structures, engineering construction and other professional knowledge	Insufficient (50%) convergence between BIM curriculum and AEC professional curriculum	× Most (72%) students lack a reserve of engineering expertise	I.4 III.2 III.4
Familiar with the fundamentals of BIM-related software & Skilled in using BIM-related software (Revit) to create complex components	Most (67.37) of the BIM curriculum teach the fundamentals of related software	× Many (44.6%) engineering BIMers are not clear about the fundamentals of the related software and the theoretical methods of building complex components	I.4 III.2
Flexible application of BIM technology to solve practical engineering problems	Most (70.53%) BIM curriculum lack the application-oriented teaching of the BIM model combined with engineering reality	× Nearly half (48.94%) of BIMers do not know how to use BIM technology in specific engineering projects. & Few (33.33%) students master the specific application of BIM technology in engineering projects.	I.4 III.4 IV.7
Component-level modeling and applications & master the simple operation of BIM-related software (Revit)	Most (62.11%) BIM curriculum stop at teaching component-level modeling and applications	√ Most (72.92%) students are able to master	III.2 IV.7
Situation-level modeling and applications	Few (27.37%) BIM curriculum teach modeling and applications by specialty. & Most (57.14%) BIM curricula do not teach the deepening application of BIM models by specialty	×A small number of (39.58%) students master Matching situation-level modeling and applications	III.2 IV.7
Project-level modeling and applications	Few (29.47%) BIM curriculum teach project-level modeling and applications	× Few (29.17%) students master project-level modeling and applications	III.2 IV.7

Table 2. Targeted design of college teaching programs and students' academic performance

Requirements of AEC industry for BIM personnel	Targeted design of college teaching content	Students' academic performance (evaluated by correctness rate of corresponding after-class assignments)
Comprehensive understanding of engineering structures, engineering construction and other professional knowledge	Teachers led students to review key professional knowledge from former major courses such as *housing architecture*, *principles of concrete structure design*, and other important specialized knowledge that might facilitate forthcoming BIM lessons.	They had a very strong (97.5%) grasp of the expertise that might be used in later BIM course.
Familiar with the fundamentals of BIM related software & Skilled in using BIM related software (Revit) to create complex components	For the knowledge of software, teachers started teaching gradually from download and installation, overall introduction to the working interface and basic operation. After that, students were encouraged to explore the software on their own and create more complex components.	They quickly mastered (87.78%) the functional architecture of the software and were able to use it flexibly for a number of essential operations.
Flexible application of BIM technology to solve practical engineering problems	Teachers conducted application-oriented teaching of the BIM model combined with engineering reality.	Most (83.65%) students could perform appropriate operations on Revit based on actual engineering data.
Component-level modeling and applications & master the simple operation of BIM-related software (Revit)	For the component-level, teachers involved many authentic cases including sloped roofs, catchment floor slabs, curtain walls modeling, etc.	Most (90.62%) students could build the required model accurately.
Situation-level modeling and applications	For situation-level, students were required to simulate real building modeling, for instance, their tasks included drawing the complete axis grid of a six-story building, creating walls and placing windows and doors, constructing roof models and assigning materials to it, etc.	Many(76.5%) students could perform well and solve practical problems in specific contexts.
Project-level modeling and applications	At the end of the curriculum of *BIM operational technology*, students cooperated in groups to finish complete projects which reflected multiple majors including architecture, structure, electromechanics, etc.	Every student could participate and contribute in a project-level modeling process.

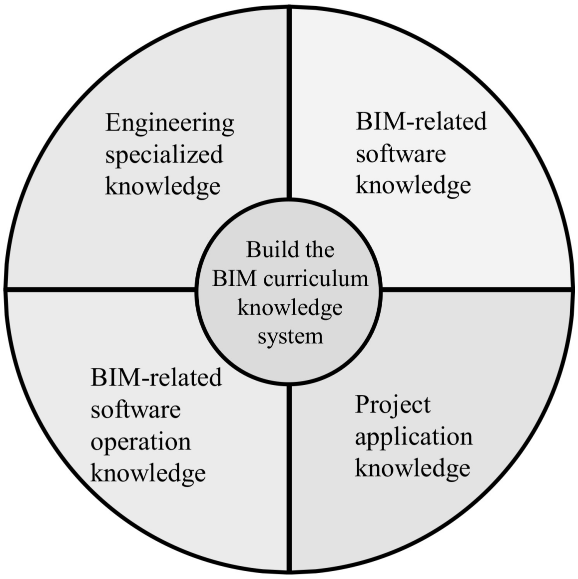

Fig. 6. The content closed-loop.

4.2 The Content Closed-loop

The audience of BIM education in colleges and universities are college students, who have obvious differences from the audience of social BIM training in enterprises, namely engineers. College students have active thinking and strong ability to accept new things, but they have shallow knowledge of the profession and lack practical engineering experience. However, the existing BIM education in colleges and universities is generally borrowed from the training of engineers, which often focuses only on software operation in terms of knowledge dimension, and does not deeply involve engineering expertise, software implementation logic, and engineering application methods. Under such training mode, students can quickly create BIM models, but they lack knowledge about the professional characteristics and roles of components, software implementation, and optimization methods, and the system application methods of engineering projects.

The content closed-loop mainly solves the problem of what teaching contents need to be set for BIM curriculums. Colleges gradually become the main channel for advanced BIM personnel training. However, according to Table 1, most of the BIM curricula are not systematic and have certain defects. Trained under the current BIM curriculum teaching mode in colleges and universities, most of the students do not have a deep apprehension of the specialized knowledge of engineering and the basic principles of BIM-related software. These students also do not have a comprehensive mastery of BIM-related software operation and are unable to apply BIM-related software to build complex components. In addition, they do not have a clear train of thought on how to apply BIM technology flexibly to solve practical engineering problems. In order to train BIM personnel with systematic knowledge. This study surveyed the AEC industry on the working knowledge requirements for BIM engineering personnel by the questionnaire I.7 in Appendix.1. This paper constructs a content closed-loop of BIM curriculum teaching consisting of engineering specialized knowledge, BIM-related software knowledge, BIM-related software operation knowledge, and project application knowledge. The content closed-loop is an undirected closed-loop, as shown in Fig. 6. Fig. 7 shows the framework of the content closed-loop and its specific details.

4.2.1 Engineering Specialized Knowledge

Engineering specialized knowledge is the founda-

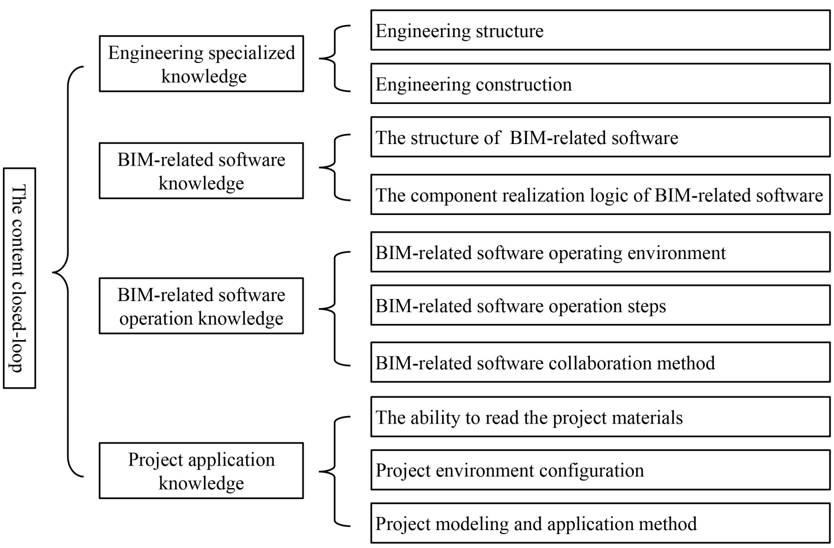

Fig. 7. The framework of the content closed-loop.

tion of BIM application. The impact of having or lacking engineering specialized knowledge on the learning of BIM technology has been examined through questionnaire IV.2 in Appendix 2–4.

The BIM curriculum should consider the existing professional curricula and coordinate the prerequisite curricula in order to ensure the continuity of the engineering specialized knowledge [38]. Therefore, the BIM curriculum should include the review and the expansion of related engineering specialized knowledge, to realize the effective connection between the prerequisite curricula and the introduction of this curriculum. This paper mainly describes the BIM curriculum by giving examples from the teaching of engineering structure and engineering construction of the casement window.

Engineering structure mainly refers to the combination of each component part of the building and the basic principles and methods of building structure [39]. As shown in Fig. 8 is an explanation of the structure of the casement window in house architecture. There is not only the composition of each part of the window but also the names, shapes, materials, and colors of the components. And this explanation provides the basis for the composition, naming, shape, material, and color matching of the detailed BIM model of the window. The model built in this way conforms to the actual engineering and can be accepted and used by engineering practitioners.

Besides static structural knowledge, BIM application encompasses architectural technology simulation or construction progress visualization, requiring students to acquire expertise in engineering construction. When applying BIM technology for construction simulation, it is necessary not only to build the three-dimensional modeling, but also to set up a virtual construction environment and define the movement sequence and movement relationship of the building components, to realize the virtual simulation of the construction process, and then carry out the detection of the simulation results and the analysis of the plans. It is difficult for students to understand the operation of BIM software when they are not clear about the construction process and related complex processes, let alone analyze the results of construction simulation effectively and optimize the construction process.

4.2.2 *BIM-related Software Knowledge*

Software knowledge mainly includes the system structure of software and the component realization logic of the BIM software (2017). Fig. 9 is an example of the system architecture of Autodesk Revit software, which is divided into four hierarchies: category, family, type, and instance.

The software structure characteristics determine the component realization method, possible boundaries, and limitations for establishing a BIM model. In the 2018 version of the Revit software, there are only 45 model family categories at the top level of the classification of the components, (which are:

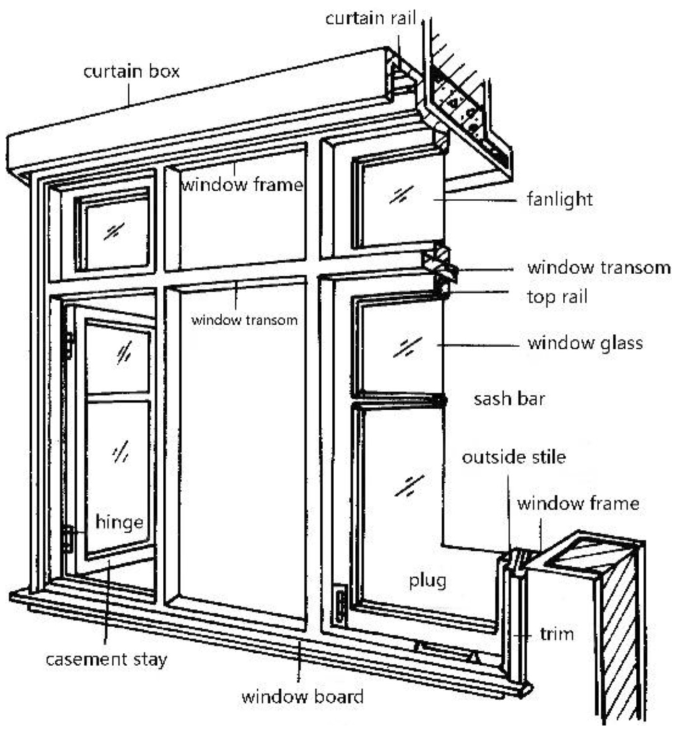

Fig. 8. Engineering structure of the casement window.

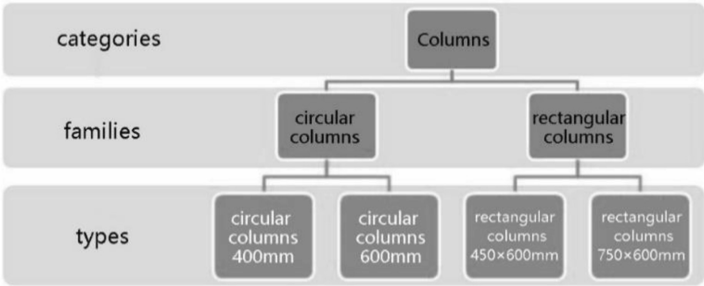

Fig. 9. The system structure of the Revit software.

Specialty Equipment, mass, parking, Plumbing Fixtures, Sprinklers, Topography, Site, walls, Ceilings, Security Devices, Furniture, Furniture System, Roofs, Generic Models, Nurse Call Devices, Data Devices, Mechanical Equipment, Columns, Railings, Planting, Floors, Casework, Fire Alarm Devices, Lighting Devices, Lighting Fixtures, Entourage, Electrical Fixtures, Electrical Equipment, Cable Tray Fittings, Telephone Devices, Windows, Pipe Fittings, Pipe Accessories, Conduit Fittings, Structural Stiffeners, Structural Foundations, Structural Columns, Structural Framing, Structural Connections, Communications Devices, Doors, Duct Fittings, Duct Accessories, Air Terminals, Stairs), while families that are not in these family categories can only be implemented by utilizing and altering these 45 families. For example, the category of pile foundation does not exist in these family categories. In practical projects, the pile foundation component is often implemented with the help of the category of structural column. Software knowledge is also indispensable in the teaching system of BIM curriculums in colleges and universities, and it is the prerequisite for teachers to teach practical software operation techniques.

4.2.3 BIM-related Software Operation Knowledge

Software operation is the main teaching content and form at colleges and universities that offer BIM curricula and it is the emphasis of teaching and learning in BIM class teaching. The relevant operation commands of the software are mainly taught in combination with the engineering structure and software implementation, to create components and construction simulation.

4.2.4 Project Application Knowledge

Project application knowledge mainly includes three aspects: the ability to read project drawings and picture files, the ability to configure the project environment, and the building and application methods of the project model. Project application knowledge is a comprehensive application of professional knowledge, software knowledge, and software operation. And at the same time, project application knowledge can expand students' knowledge of BIM project-level environment configuration and model application. Project application knowledge is mainly reflected in two forms in the BIM curriculum. The first involves small-scale case practice during and after class, focusing on specific project components. The second form entails constructing a BIM model and utilizing authentic project data to apply and analyze it in the curriculum design of BIM class teaching.

4.3 The Project Closed-loop

The AEC industry employers and students demand more practical knowledge and hands-on experiences than ones in other domains do [40]. As shown by questionnaire III.2 and IV.3 in Appendix 5–6, most of the teachers/students are only interested in learning BIM technology related to components and modeling, and application. There are few BIM curricula involving professional-level, especially project-level modeling, and application. Consequently, students lack practical experience in applying BIM technology, hindering their comprehensive understanding and mastery of BIM.

The project closed-loop for BIM curricula proposed by this paper is the solution to this problem. The project closed-loop in the teaching process is specifically reflected in the following three links, as shown in Fig. 10. Firstly, during the curriculum lectures, students gradually learn about component modeling. Secondly, students independently complete the combination and connection of components within their specific majors, such as architecture, structure, electromechanics, etc., along with other comprehensive creations. Finally, when doing a complete project, the knowledge related to multiple majors needs to be reflected in all aspects, and all majors cooperate with each other. It will involve a mature and complete project modeling practice.

4.4 Validation

The curriculum of *BIM operational technology* is newly opened in the intelligent construction major

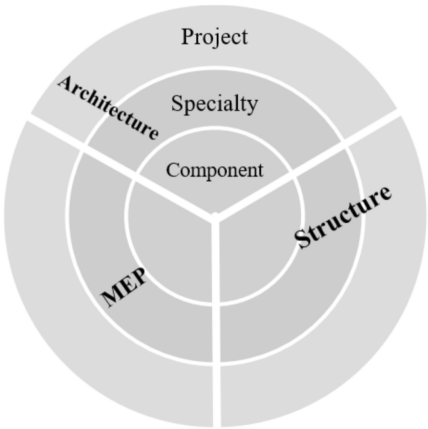

Fig. 10. The project closed-loop.

at BJUT. The *BIM operational technology* effectively implements the closed-loop management system of the college BIM curriculum and achieves remarkable results. We tracked the students' learning outcomes in real-time through their performance on assignments during the courses, as shown in Table 2. From which we can see, a considerable percentage of students attained better understanding and mastery through the learning of closed-loop management design of BIM curriculum teaching programs for the AEC industry. They performed well not only in the grasp of engineering specialized knowledge, BIM-related software knowledge, and BIM-related software operation knowledge, but also in mastering component-level modeling, situation-level modeling, and project-level modeling in architecture, structure, and MEP areas. Based on the targeted design of BIM teaching programs, BIM students have successfully mastered the AEC industry's basic skill requirements for BIM practitioners and can better adapt to the actual practice of the AEC industry upon graduation. In this way, the closed-loop management design of BIM curriculum teaching programs contributes to filling the gaps between AEC industry requirements for BIM personnel and current BIM education in universities and colleges.

5. Discussion

5.1 Achievements

With the rapid development of the building informatization, the AEC industry urgently needs colleges to cultivate BIM personnel who possess comprehensive mastery of BIM technology. Nonetheless, we have identified certain aspects of the BIM training system that fail to meet the AEC industry's demands for competent BIM professionals. Consequently, there is an urgent necessity to develop suitable BIM curricula that equip students with essential industry-specific skills. Therefore, in this paper, we have proposed a closed-loop management system including content closed-loop and project closed-loop, which can effectively improve the teaching quality of BIM curricula and promote the practical innovation of the whole professional teaching system. More importantly, this system ensures that students have a well-rounded understanding and mastery of BIM and thus enhances their competitiveness in the industry.

5.2 Limitations

Despite the strengths mentioned above, it is essential to consider the limitations inherent in this study design.

5.2.1 Limited Geographical Scope

The data collection for this study was conducted within 27 provincial-level administrative regions in China, which may restrict the generalizability of the findings to a broader international context. Further studies across different countries and regions would facilitate a more robust examination of the effectiveness of the closed-loop management system in BIM education.

5.2.2 Lack of Long-Term Assessment

The efficacy of the proposed closed-loop management system was evaluated based on a 1-year teaching implementation at BJUT. Although short-term outcomes were assessed through students' performance on assignments, the long-term impact on their career development and industry readiness remains uncertain. Further research employing prolonged studies would be beneficial to verify the sustained effects of the closed-loop management system on students' professional growth and employability.

5.2.3 Lack of Comparison Group

The study did not include a direct comparison group to allow for a thorough assessment of the relative effectiveness of the closed-loop management system. The complex nature of BIM education, including the expertise and presentation of instructors, the competencies and characteristics of students, and the variability of institutional contexts, complicates the establishment of a reliable comparison group. Given these inherent complexities, it is important to approach the results of the study with caution and recognize that while the results show positive outcomes, it is difficult to determine whether these improvements were solely attributed to the proposed system or whether other factors, such as general advances in BIM education or increased student motivation, played a role.

5.3 Future Directions

It is necessary to conduct continuous evaluation and improvement in future studies. Implementing an ongoing evaluation process to gather feedback from stakeholders, including students, faculty, and industry experts, will facilitate continuous improvement of the closed-loop management system. Regular assessments and adjustments will ensure that the system remains effective and relevant in meeting the evolving needs of the AEC industry.

In addition, exploring opportunities for increased collaboration between academia and industry stakeholders will enhance the practical relevance and industry integration of the BIM curricula. Partnerships with industry experts and organizations can provide students with real-world project experience, internships, or collaborative projects, further bridging the gap between academia and industry.

6. Conclusion

In conclusion, the study provides valuable insights into the gaps between the competency requirements of the AEC industry and the current BIM curricula in colleges. In order to bridge these gaps, our study introduces innovative theories, namely directed closed-loop and undirected closed-loop theories, derived from the closed-loop management system. These theories can be integrated into college BIM education as project closed-loop and content closed-loop theories. The effectiveness of the curricula design was validated through the academic performance of BIM students. The results demonstrate that the closed-loop management design of the BIM curricula can better align with the competency requirements of the AEC industry, enabling BIM students to adapt more effectively to real-world AEC work. Overall, the proposed closed-loop management system of the BIM teaching programs serves as a bridge to prepare BIM students for industry practices. The study's findings and methodologies can be used to inform the design of BIM curricula in colleges and improve the quality of BIM education.

Data availability statement – All data, models, and code generated or used during the study appear in the submitted article.

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Appendix

1. Questionnaire I.7:

What factors do you think make you feel that your current knowledge base does not fully meet the demands of your job? [Multiple choice]

A. Imperfect understanding of engineering structure, engineering construction and other professional knowledge. (57.69% answered)

B. Not familiar with the principle of BIM-related software (such as Revit software) and not clear about the way of implementing complex components in BIM-related software. (26.92% answered)
C. Not familiar with the operation of BIM-related software (such as Revit software). (26.92% answered)
D. Unclear ideas on how to apply BIM technology in specific practical engineering projects. (46.15% answered)
E. Insufficient understanding of other sub-disciplines in the BIM model, such as architecture, structure, mechanical or electrical. (46.15% answered)
F. Others. (19.23% answered)

2. Questionnaire IV.1:

Did you study engineering-related expertise before taking the BIM curriculum?
Results: 55.21% answered Yes and 44.79% answered No.

3. Questionnaire IV.2-1:

Does the BIM curriculum you have taken consolidate and deepen your understanding of the previous engineering specialized knowledge?
Results: 96.23% answered Yes and 3.77% answered No.

4. Questionnaire IV.2-2:

Have you encountered any problems when studying BIM curriculum due to the lack of relevant engineering specialized knowledge?
Results: 81.40% answered Yes and 18.60% answered No.

5. Questionnaire III.2:

Which of the following learning components are included in the BIM course you are studying? [Multiple choice]

A. Component-level modeling and applications (60.42% answered)
B. Professional-level modeling and applications (40.62% answered)
C. Project-level modeling and applications (27.08% answered)

6. Questionnaire IV.3:

Which of the following are included in the BIM curricula or BIM training you have been involved in?

A. Component-level modeling and applications (33.68% answered)
B. Professional-level modeling and applications (27.37% answered)
C. Project-level modeling and applications (29.47% answered)

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