Design of a Blended Learning System for a Digital Twin-Based Modular Construction Course

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Abstract. In the context of the accelerated digital transformation of the construction industry, digital twin technology offers a novel approach to integrating virtual and physical education in the domain of prefabricated buildings. This study draws upon the construction of prefabricated building courses as a practical foundation and puts forward a design framework for a virtual-physical integrated teaching system based on digital twins. The objective of this framework is to address issues such as the disconnection between traditional teaching and engineering practice, as well as students' limited spatial imagination. The construction of a trinity model of "virtual-physical mapping teaching scenarios—dynamic knowledge maps—multi-dimensional evaluation systems" integrating technologies such as BIM, VR, and big data enables the full life cycle simulation and dynamic optimisation of teaching scenarios. The research demonstrates that this system significantly improves students' design capabilities, increases the award rate of students participating in competitions by 20%, and enhances their engineering literacy. The study also establishes an integrated, closed-loop mechanism of "teaching-learning-doing-evaluation". Furthermore, the research highlights the potential of digital twin technology in the field of education, offering both theoretical underpinnings and practical methodologies for nurturing intelligent construction talent.

Keywords: Digital twin, Prefabricated Building, Curriculum Development

1   Introduction

The construction industry is undergoing profound transformation fueled by digital twin technology, which enables real-time synchronization between physical entities and virtual models throughout facility lifecycles (Müller et al., 2021)[1]. Within Construction Industrialization 4.0, the prefabricated construction sector faces urgent demands for professionals skilled in digital design and intelligent project delivery (Smith & Lee, 2022)[2]. However, traditional modular construction education confronts three critical limitations: outdated curricula misaligned with technological advancements (Lu et al., 2023), overreliance on 2D representations hindering spatial cognition development, and static evaluation systems lacking process-oriented feed

back[3]. These systemic deficiencies highlight the imperative for pedagogical innovation integrating emerging digital tools (Zhang, 2024)[4]. Digital twin technology has already demonstrated significant advantages in the field of engineering training through high-fidelity simulation and real-time data feedback. The fundamental strength of this technology lies in its ability to construct an immersive learning environment that seamlessly integrates the virtual and the real, thereby enhancing learners' comprehension of complex engineering systems (Wang & Zhang, 2023)[5]. This technology facilitates dynamic simulation of the entire life cycle of buildings, while simultaneously optimising the allocation of teaching resources through data-driven approaches, thereby infusing new dynamism into the digital transformation of education. Consequently, the development of a novel teaching system that integrates digital twin technology with the characteristics of prefabricated buildings has emerged as a pivotal undertaking in the ongoing educational reform agenda.

The present study is centred on the innovative application of digital twin technology in empowering curriculum reform in the domain of prefabricated buildings. The central objective of this study is to construct a teaching system that integrates the virtual and the real, with the aim of addressing the structural contradictions inherent in the conventional teaching model, such as the division between theory and practice, and the delay in technology application. The specific objectives of the research are as follows: firstly, to explore the potential of digital twin technology in reconfiguring the teaching scenario to achieve a virtual-real mapping of the entire process of 'design-production-construction'; secondly, to investigate the quantitative mechanism of action of a teaching system that integrates the virtual and the real in improving students' engineering literacy and innovation ability; and thirdly, to ascertain the means by which the elements of ideological and political education and the concept of sustainable development can be effectively incorporated into the system. To achieve these goals, the research takes the 'Introduction to Prefabricated Construction' course at the Yunnan Economics Trade and Foreign Affairs College as a practical vehicle, integrates technologies such as BIM, VR, and big data, and proposes a three-in-one system framework of 'virtual-real mapping of teaching scenarios—dynamic knowledge maps—intelligent evaluation systems'.

2 Digital Twin-based Curriculum Design for Prefabricated Buildings

2.1 Analysis of Student Learning and Clear Teaching Objectives

The course is designed for civil engineering students in their second year, with a focus on enhancing their practical skills in prefabricated building structures. Students demonstrate a certain level of production ability, but their understanding of new technologies, processes and knowledge is limited. Their awareness of the workplace is present, but their professional abilities are inadequate. While they have participated in professional internships and are familiar with the working environment and roles in prefabricated buildings, most students lack the ability to articulately define the com-

petency requirements of these positions. Their adaptability in their chosen careers is underdeveloped, and their career development is not optimised. Additionally, their professional conduct is inadequate. It is imperative that they develop a more profound comprehension of the application of prefabricated construction in the construction industry, its significance in terms of energy conservation, environmental protection and sustainable development, and to further enhance their commitment to the pursuit of craftsmanship. An analysis of the students' situation reveals that the teaching team has adhered to the talent training plan and curriculum standards, closely monitored job requirements, and incorporated skills competitions to determine teaching objectives.

2.2   Analysis of Student Learning and Clear Teaching Objectives

2.2.1 Content Development

Restructure the course content system from the three levels of 'concept + foundation + expansion'. It is imperative to maintain currency with novel concepts and technologies in the realm of construction industry development, underpinned by the principles of standardised design, factory production, assembly construction, and information management of prefabricated buildings. This encompasses the requisite knowledge and technical proficiencies demanded by various prefabricated building job roles. The integration of these competencies into vocational skills competitions, the establishment of talent training standards, and the provision of services are of paramount importance. regional economic development, and meet the talent needs of enterprises such as design institutes, prefabricated component factories, construction, project management, and cost consulting for prefabricated buildings, to cultivate high-quality technical and skilled talents with a craftsman's spirit and digital literacy who can design, produce, assemble, and manage well. The curriculum has been meticulously structured into modular teaching content, encompassing the four fundamental work tasks of design, production, installation and management.

A political and ideological education system has been constructed from the perspectives of 'society + enterprise + individual'. In the contemporary context, the construction industry is undergoing a period of significant transformation, characterised by the concepts of 'greening', industrialisation, and the integration of industrialised practices. This industrial evolution necessitates a recalibration of the industry's talent structure to align with the imminent construction era. A pivotal aspect of this transformation is the cultivation of a consciousness among students concerning the responsibility and mission of the construction industry. This is achieved through a focused examination of the energy crisis, the interpretation of green development and the dual carbon strategy. Moreover, the introduction of novel trends, business models and paradigms within the industry is instrumental in fostering confidence and a sense of responsibility and mission.

2.2.2 Resource Construction

In the process of teaching implementation, the establishment of three-dimensional resources is imperative. Such resources encompass course materials, training bases, virtual simulation software, and experimental training room equipment, among others. The integration of theory, practice and reality is pivotal in facilitating the combination of theoretical knowledge and practical operation. This integration serves to enhance students' comprehension and retention of course content, with a particular emphasis on problem-solving skills and the mastery of key technologies and methodologies. Furthermore, it contributes to the enhancement of students' practical abilities.

Online resources. The following online resources are available for students to access: 51 online learning videos, 31 non-video resources, 402 quizzes and homework exercises, 504 exercises from the test bank, and 39 after-school learning materials.

Virtual experiment platform. In collaboration with company, the prefabricated construction IDT practical exercise system was constructed. Utilising innovative technologies such as VR and AR, comprehensive teaching resources encompassing the entire industry chain were developed, and a virtual simulation training room was established. Students are now capable of designing and constructing prefabricated buildings in a virtual environment, intuitively comprehending the construction process and critical technical aspects, thereby providing an immersive learning experience.

Other resources. The AIoT Internet of Things training platform, intelligent construction robot training platform, and engineering construction intelligent management platform are pioneering immersive teaching through real-world scenario simulation.

2.3   Teaching Design

Transform 'passive indoctrination' into 'task-driven' problem-based and heuristic teaching. The pedagogy is centred on the student, with an emphasis on cultivating professional and technical skills and consolidating foundational knowledge through the initial classroom phase. Vocational and professional capabilities are fostered in the subsequent classroom phase, with the instruction of practical skills, task-driven teaching methodologies, and the facilitation of project-based learning. The task projects are designed to be self-directed, with students undertaking independent study or research, and the complexity of the questions is strategically increased to guide students in discussions and exchanges. Peer assessment, joint assessment by students and teachers, and teacher summaries are employed to inspire students to draw inferences.

Transform 'traditional classroom teaching' into 'close to engineering practice' case and virtual experiment teaching methods. The analysis of typical prefabricated construction cases has been shown to cultivate students' critical thinking and problem-solving abilities. Furthermore, it has been demonstrated that students can gain an in-depth understanding of the applications and challenges in actual projects. The use of virtual laboratories, VR, AR and other technologies, combined with engineering cases, has resulted in the creation of a virtual environment for prefabricated construction. This virtual experimental teaching environment has been shown to facilitate the learning process. The integration of theory with practical engineering allows students

to operate in a simulated construction site, facilitating the understanding of the construction process and key technical points. This approach addresses the limitations of traditional teaching methods by providing a more intuitive and comprehensive learning experience.

Competency output orientation, collaborative participation from multiple parties, and a sound evaluation system. The student growth path is customised based on the teaching objectives and vocational skills requirements, combined with competition standards and with the aim of cultivating students' core vocational competencies. Comprehensive evaluation is carried out in multiple dimensions and in a diversified manner around the 3D teaching objectives. Process evaluation, outcome evaluation, and value-added evaluation are digitalised and visualised to generate students' personal third-order growth and value-added curves, enabling individual value-added evaluation.

3   Teaching Implementation and Effectiveness

3.1   Teaching Implementation

Lay a solid foundation, improve skills, and collaborate to educate and organise teaching. The institution of learning and the business entity collaborate to provide an educational experience for students, with dual tutors overseeing instruction and dual classrooms facilitating skill development. The primary classroom focuses on knowledge acquisition, skill cultivation, ideological and political immersion, and hands-on exercises to solidify fundamental competencies. The secondary classroom encompasses skill-based competitions, engagement in on-campus prefabricated construction projects, and enterprise-related construction initiatives, along with practical activities to enhance skills. The students' skills are developed through a combination of learning, production, and practical experience, and they are trained to become quasi-employees.

Task-driven, practical-oriented, step-by-step implementation of teaching. The learning process is divided into three stages: 'independent exploration (before class) - classroom practice (during class) - expansion and improvement (after class)'. Task-driven runs through the whole process. The four progressive steps of 'online pre-training before class, software simulation training, practical training during class, and real project training after class' have been shown to improve professional skills and enable students to effectively achieve the goals of quality, knowledge and ability through the closed-loop learning process of 'theory - practice - trial and error - error correction - proficiency – improvement'.

Course assessment methods. A combination of formative and summative assessments, in both online and offline formats, is utilised. The assessment methods employed are diverse, the assessment items are varied, and the assessment criteria are measurable.

3.2   Teaching Effectiveness

It is evident that students possess the capacity to distribute labour within a team in a reasonable manner, in accordance with task requirements, thereby ensuring the efficient completion of tasks. A significant proportion, constituting 30% of the student body, demonstrate an aptitude for articulating and elucidating the fundamental principles and methodologies associated with the task at hand. This aptitude is further evidenced by their ability to demonstrate a profound comprehension and practical application of the knowledge they have acquired. Moreover, the mean score attained on the post-class test was 86.5, signifying that the students have attained a commendable level of success in terms of the knowledge objectives set forth.

The course has been meticulously designed to align with the current job requirements and competition standards. Consequently, students have demonstrated a substantial enhancement in their proficiency in assembling and installing products. Moreover, students participating in this class have achieved notable success in various related skill competitions, securing 3 third prizes at the national level, 1 first prizes at the provincial level, 3 second prizes, and 5 third prizes.

The outcomes of the teaching reform initiative have been recognised with the second prize at the provincial level and the first prize at the school level.

4   Features and Innovations

The course team is committed to exploring and innovating while upholding the responsibility of green development. Important elements such as the craftsmanship spirit, green energy and environmental protection strategies are studied in depth and organically integrated into the entire teaching process. Through policy learning and the practice of specific tasks, students are guided to cultivate and practise the craftsmanship spirit in practice.

The integration of school-enterprise resources is pivotal in achieving a precise alignment between teaching content and the forefront of industry developments. Knowledge maps can facilitate dynamic real-time integration of knowledge in emerging fields such as intelligent construction and carbon-neutral buildings. The construction of a new teaching model of 'main classroom + virtual scenario classroom' can be achieved by utilising classrooms, school-enterprise training bases and experimental training rooms, thereby effectively addressing the previous situation of insufficient student training channels and limited training equipment. Furthermore, it is imperative to overcome the constraints imposed by objective factors, including physical limitations, temporal constraints, environmental factors, and financial constraints. This is essential to address the incongruity between the limited capacity of classrooms and the stringent requirements of enterprises, as well as the disparity between pedagogical practices and technological advancements.

The integration of virtual and real teaching methods in collaboration has led to the development of a closed-loop training process involving 'physical operation-virtual verification-real-time feedback'. This process is facilitated by a digital twin platform, enabling students to undertake a portion of the training in a virtual reality environ-

ment. This approach has the potential to significantly reduce the consumption of physical materials and facilitate the transformation of abstract knowledge into concrete concepts. The utilisation of actual construction processes and methods in the training environment allows students to immerse themselves in the construction site, providing them with a comprehensive and immersive learning experience.

The enhancement of online teaching resources to address the demands of independent online learning, in addition to compensating for the constraints of time and space inherent in offline classrooms, is imperative.

5   Conclusion

The construction industry is experiencing a growing demand for highly qualified prefabricated construction personnel, which has led to a recognition of the limitations of traditional teaching methods in meeting the demands of modern education. The design of a virtual-real integration teaching system for prefabricated construction courses, underpinned by digital twin technology, aims to address these limitations by integrating advanced digital technology to create a comprehensive teaching platform that seamlessly combines theory with practice, incorporating both virtual and real-world elements. The proposed teaching model utilises digital twin technology as its core, encompassing theoretical instruction, virtual experimentation, case studies and practical operations. This comprehensive approach addresses the limitations of traditional teaching methods, particularly in terms of hands-on learning and problem-solving skills, and offers a scalable solution to address the rapid technological advancements in the construction industry.

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