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Reconstructing Mechanical Engineering Education through Digital Twin Technology: Reform and Practice of the "Mechanical Engineering Knowledge" Course

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Abstract: In the context of intelligent manufacturing, engineering education is undergoing a paradigm shift toward digitalization and interdisciplinarity. Traditional mechanical engineering courses, however, often suffer from limited interactivity, insufficient practical engagement, and outdated content. To address these challenges, this study proposes a digital twin-driven teaching reform for the "Mechanical Engineering Knowledge" course. A novel teaching framework integrating virtual–real interaction, dynamic content updating, project-based learning, and blended teaching is developed. A digital twin platform is constructed to simulate mechanical systems and enable interactive experimentation. The reform is implemented over four academic years involving 110 undergraduate students. Comparative analysis shows that students' academic performance, practical skills, and innovation capabilities are significantly improved, with course evaluation scores consistently above 90/100. The results demonstrate that digital twin technology can effectively bridge the gap between theory and practice and provide a scalable model for engineering education reform.

1. Introduction

With the rapid advancement of intelligent manufacturing and digital technologies, engineering education is undergoing a profound transformation toward digitalization, interdisciplinarity, and practice-oriented learning [1-3]. Mechanical engineering education, as a fundamental component of industrial development, is required to cultivate talents with strong system-level thinking, innovation capability, and practical skills [4].

However, traditional teaching methods still rely heavily on lecture-based knowledge transmission, which limits student engagement and the development of engineering competence [5]. In particular, three major challenges persist. First, mechanical systems are inherently complex and dynamic, making it difficult for students to form intuitive understanding through static teaching materials [6]. Second, the lack of system-level experimental environments restricts students' ability to connect theoretical knowledge with real-world applications [7]. Third, the rapid evolution of industrial technologies leads to outdated course content and weak alignment with industry demands [8].

To address these issues, emerging educational approaches such as blended learning and project-based learning have been widely explored. Blended learning combines online and offline instruction to improve flexibility and learning effectiveness [9], while project-based learning emphasizes problem-solving and experiential learning [10]. Although these methods have shown positive effects, they still face limitations in providing realistic and dynamic representations of engineering systems.

Digital twin technology, defined as a virtual representation of physical systems with real-time interaction and data synchronization, has been increasingly applied in smart manufacturing and engineering systems [11-13]. By integrating physical and virtual environments, digital twin enables dynamic simulation, real-time monitoring, and system optimization. In recent years, researchers have begun to explore its application in education, demonstrating its potential to enhance visualization, interactivity, and experiential learning [14, 15].

Nevertheless, existing studies mainly focus on isolated virtual simulation tools and lack a systematic integration of digital twin technology into teaching frameworks. Moreover, there is still insufficient empirical evidence regarding its effectiveness in improving learning outcomes and engineering competencies.

Therefore, this study proposes a digital twin-driven teaching reform for the "Mechanical Engineering Knowledge" course. A comprehensive teaching framework integrating virtual–real interaction, dynamic content updating, project-based learning, and blended teaching is developed and implemented. The effectiveness of the proposed approach is validated through multi-year teaching practice.

2. Course Background and Problem Analysis

2.1. Course Characteristics

The "Mechanical Engineering Knowledge" course is a core course for undergraduate students majoring in Mechanical Design and Manufacturing. It integrates multiple disciplines, including mechanical manufacturing, artificial intelligence, intelligent measurement, and optimization technologies. The course focuses on intelligent manufacturing systems, covering system architecture, CNC equipment, process optimization, and knowledge acquisition techniques.

2.2. Existing Problems

Despite continuous improvements in curriculum design and teaching resources, several critical challenges remain in the delivery of the "Mechanical Engineering Knowledge" course.

(1) Lack of intuitive understanding

Mechanical engineering systems are inherently complex, involving multi-physics coupling, dynamic behaviors, and hierarchical structures. Traditional teaching methods, which rely primarily on static diagrams, mathematical descriptions, and verbal explanations, are insufficient to convey such complexity. As a result, students often struggle to form a clear mental model of system operation and dynamic processes, leading to superficial understanding rather than deep comprehension. This issue is particularly evident in topics such as intelligent manufacturing systems, process optimization, and system integration.

(2) Fragmented knowledge structure

The course integrates multiple disciplines, including mechanical manufacturing, artificial intelligence, and intelligent measurement. However, these knowledge components are often taught in isolation due to the limitations of traditional instructional approaches. Students tend to acquire fragmented knowledge without fully understanding the interconnections among system architecture, control logic, and process optimization. Consequently, they face difficulties in applying knowledge in a holistic manner when solving complex engineering problems.

(3) Insufficient practical training

Hands-on experience is essential for engineering education, yet access to physical experimental platforms is often limited due to cost, space, and safety constraints. Existing laboratory experiments are typically demonstration-based or limited in scope, preventing students from engaging in system-level design, parameter adjustment, and iterative optimization. This lack of experiential learning opportunities weakens students' ability to bridge theory and practice and hinders the development of engineering competence.

(4) Weak alignment with rapidly evolving industrial technologies

With the rapid advancement of intelligent manufacturing technologies, including digitalization, automation, and data-driven optimization, the gap between course content and industrial practice continues to widen. Traditional curricula are often updated slowly, making it difficult to incorporate emerging technologies and real-world engineering cases in a timely manner. As a result, students may lack exposure to current industry practices and technological trends.

2.3. Root Cause

The above challenges can be traced to a fundamental limitation in the current teaching paradigm: the absence of a system-level experiential learning environment that supports dynamic interaction, real-time feedback, and holistic understanding.

Specifically, traditional teaching approaches lack the capability to integrate knowledge representation, system behavior, and engineering practice into a unified learning environment. Without an interactive platform, students are unable to observe how different components of a mechanical system interact over time or how design decisions affect system performance. This disconnect leads to a separation between theoretical knowledge and practical application.

Furthermore, the lack of a dynamic and updatable teaching environment prevents effective integration of interdisciplinary knowledge and emerging technologies. As a result, students are confined to static learning contexts, which limits their ability to develop system-level thinking and adapt to complex engineering scenarios.

Therefore, there is a clear need for a new teaching paradigm that can provide:

- real-time interaction with engineering systems
- integration of multidisciplinary knowledge
- support for experimentation, iteration, and optimization
- continuous updating of teaching content

Such requirements highlight the necessity of introducing digital twin technology, which enables virtual–real integration and dynamic system representation, into mechanical engineering education.

3. Digital Twin-Based Teaching Framework

3.1. Framework Overview

To address the challenges identified in Section 2, a digital twin-driven teaching framework is proposed to reconstruct the relationship between knowledge acquisition and engineering practice. As illustrated in Figure 1, the framework follows a three-layer structure consisting of: Input layer: industrial needs, emerging technologies, and engineering cases. Core system layer: digital twin-based teaching system. Output layer: student competencies and learning outcomes.

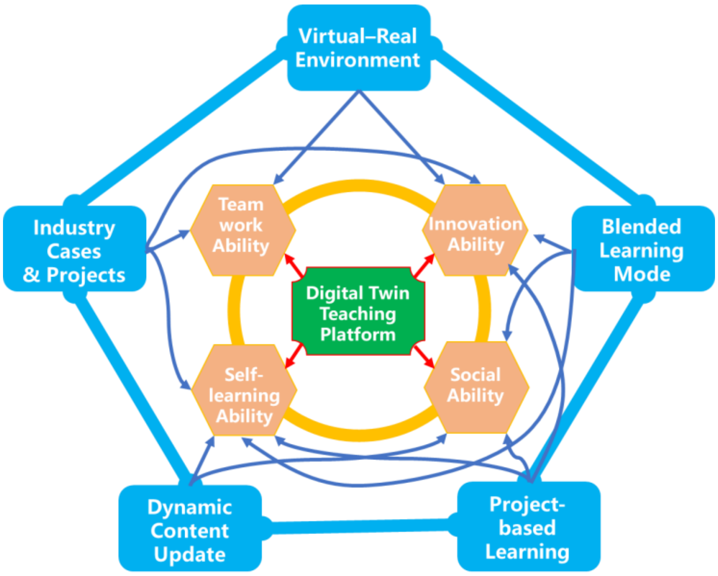

Figure 1 Digital twin-based teaching framework.

At the core of the framework is a digital twin-based teaching system that integrates four key components: Virtual–real integrated experimental platform, Dynamic teaching resource system, Project-based learning mechanism, and Blended teaching model.

Unlike traditional teaching approaches that separate theory and practice, this framework establishes a closed-loop learning process in which students continuously interact with engineering systems, apply knowledge, and refine their understanding through feedback.

The framework emphasizes three essential transformations: 1) From static knowledge delivery to dynamic system interaction; 2) From fragmented learning to system-level cognition; 3) From passive learning to active problem-solving.

3.2. Virtual–Real Integrated Experimental Mechanism

The virtual–real integrated experimental mechanism forms the technological foundation of the proposed framework. A digital twin platform is developed to simulate mechanical systems and synchronize their operational states in real time. Unlike conventional simulation tools, the digital twin environment enables bidirectional interaction between users and system models. Students can: 1) observe system behavior dynamically under different operating conditions; 2) adjust key parameters (e.g., speed, load, control variables); 3) analyze system responses and performance variations; 4) conduct iterative virtual experiments.

This mechanism transforms abstract theoretical concepts into observable and manipulable system behaviors, significantly enhancing students' intuitive understanding. Moreover, the platform supports multi-level learning, including: component-level analysis (e.g., sensors, actuators), subsystem-level interaction (e.g., control loops), and system-level optimization (e.g., manufacturing processes). By enabling real-time feedback and iterative experimentation, this mechanism bridges the gap between theoretical knowledge and engineering practice.

3.3. Dynamic Content Updating Mechanism

To ensure alignment with rapidly evolving industrial technologies, a dynamic teaching resource system is established. This mechanism is designed to overcome the limitations of static curricula by enabling continuous updating of teaching content through. This work integrates up-to-date industrial cases and engineering applications, incorporates emerging technologies such as artificial intelligence and data-driven optimization, and organizes knowledge units into a modular structure for flexible updates.

In addition, the digital twin platform serves as a carrier for knowledge integration, allowing newly introduced technologies and cases to be directly embedded into virtual models and experimental scenarios.

This dynamic updating mechanism ensures that course content remains relevant to industrial development, students are exposed to real-world engineering challenges, and interdisciplinary knowledge can be effectively integrated.

3.4. Project-Based Learning Mechanism

Project-based learning (PBL) is incorporated into the framework to enhance students' problem-solving and innovation capabilities. In this mechanism, students are guided to complete engineering-oriented tasks that simulate real industrial scenarios. Typical project activities include: mechanical system design and modeling, manufacturing process optimization, and performance analysis and validation.

The digital twin environment plays a critical role by providing a low-cost and risk-free experimental platform, where students can test their ideas, perform parameter tuning, and evaluate system performance.

Furthermore, this mechanism supports iterative learning cycles, where students: propose design solutions, test them in the digital twin environment, analyze results and identify limitations, and refine their designs. Such iterative processes promote deeper understanding and foster innovation.

3.5. Blended Learning Implementation

To maximize the effectiveness of the proposed framework, a blended learning model is adopted, integrating online and offline teaching activities. The teaching process is structured into three stages:

(1) Pre-class (knowledge acquisition)

Students learn theoretical concepts through online materials, including videos, digital resources, and interactive content. This stage emphasizes self-paced learning and preparation.

(2) In-class (interactive learning)

Classroom activities focus on: digital twin-based experiments, problem-solving discussions, and collaborative learning. Students actively engage with the system, analyze results, and exchange ideas under instructor guidance.

(3) Post-class (knowledge application and extension)

Students complete project tasks and conduct extended exploration, applying what they have learned to solve practical problems.

This blended structure enables a shift from teacher-centered instruction to student-centered learning, improving both engagement and learning efficiency.

4. Teaching Implementation and Evaluation

To validate the effectiveness of the proposed digital twin-based teaching framework, a systematic teaching implementation and evaluation process was carried out in the "Mechanical Engineering Knowledge" course over four academic years, involving a total of 110 undergraduate students.

4.1. Platform Development and Resource Construction

A digital twin-based virtual simulation platform was developed to support teaching activities. The platform integrates system modeling, real-time simulation, and interactive operation, enabling students to observe and manipulate mechanical systems in a virtual–real environment.

The platform includes the following functional modules:

- System modeling module, supporting the construction of mechanical system models
- Real-time simulation module, enabling dynamic visualization of system behavior
- Interactive control module, allowing parameter adjustment and response analysis

Based on this platform, a comprehensive teaching resource system was constructed, including:

- digital twin models representing key mechanical systems
- virtual experimental modules for system analysis and optimization
- industrial case libraries derived from real engineering applications

These resources provide a solid foundation for implementing interactive and practice-oriented teaching.

4.2. Teaching Organization and Experimental Design

The teaching process was redesigned according to the proposed framework and implemented in a structured manner, as illustrated in Figure 2.

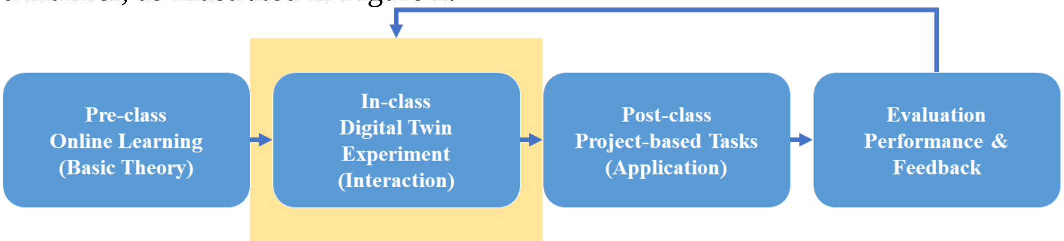

Figure 2 Digital twin-based blended teaching process with a closed-loop structure of learning, interaction, application, and evaluation.

The overall teaching process consists of four stages:

(1) Theoretical introduction: Fundamental concepts and principles are introduced through lectures and online materials, preparing students for subsequent activities.

(2) Virtual experiment: Students interact with the digital twin platform to observe system behavior, adjust parameters, and conduct exploratory experiments.

(3) Project-based task: Students are assigned engineering-oriented tasks, such as system design, process optimization, and performance improvement. These tasks require applying theoretical knowledge in practical scenarios.

(4) Analysis and discussion: Students analyze experimental results, discuss findings in groups, and reflect on design strategies under instructor guidance.

To evaluate the effectiveness of the teaching reform, a comparative study was conducted between a control group using traditional teaching methods and an experimental group using the digital twin-based framework.

Multiple evaluation indicators were adopted, including academic performance, ability development, and student feedback.

4.3. Learning Performance Analysis

The comparison results show a significant improvement in students' academic performance after implementing the proposed teaching framework. Specifically: 1) the average course score increased from 78 to 87, representing an improvement of approximately 12%, 2) the failure rate decreased significantly, indicating better overall comprehension.

These results suggest that the integration of digital twin technology enhances students' understanding of complex concepts and improves learning outcomes.

4.4. Ability Development Evaluation

Beyond academic performance, students' engineering abilities were evaluated through project outcomes and instructor assessments.

The results indicate notable improvements in the following aspects:

▪ Practical skills: students demonstrated stronger capability in system operation and parameter tuning

▪ System-level thinking: students showed improved understanding of interactions among system components

▪ Innovation capability: students proposed more creative and feasible solutions in project tasks

These improvements confirm that the proposed framework effectively supports competency-based education.

4.5. Student Feedback and Perception

Student feedback was collected through questionnaire surveys and course evaluations.

The results show that:

▪ the overall course satisfaction score exceeded 90/100

▪ more than 85% of students reported improved understanding of course content

▪ over 80% of students indicated increased learning interest and engagement

Students also highlighted that the digital twin platform provided a more intuitive and interactive learning experience compared with traditional teaching methods.

5. Conclusion

This study proposes a digital twin-based teaching framework for mechanical engineering education and validates its effectiveness through multi-year teaching practice. By integrating virtual–real interaction, dynamic content updating, project-based learning, and blended teaching, the proposed approach reconstructs the relationship between knowledge acquisition and engineering practice.

The results demonstrate that the framework significantly improves students' academic performance, practical skills, and innovation capabilities, while also enhancing learning engagement and satisfaction. The findings indicate that digital twin technology provides a powerful tool for bridging the gap between theory and practice in engineering education.

This study offers a scalable and practical model for curriculum reform in the context of digital transformation. Future work will explore the integration of artificial intelligence and the extension of the framework to broader engineering disciplines.

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References

[1] NEGRI E, FUMAGALLI L, MACCHI M. A Review of the Roles of Digital Twin in CPS-based Production Systems [J]. Procedia Manufacturing, 2017, 11: 939-948.
[2] TAO F, QI Q, LIU A, et al. Data-driven smart manufacturing [J]. Journal of Manufacturing Systems, 2018, 48: 157-169.
[3] TAO F, ZHANG H, LIU A, et al. Digital Twin in Industry: State-of-the-Art [J]. IEEE Transactions on Industrial Informatics, 2019, 15(4): 2405-2415.
[4] KRITZINGER W, KARNER M, TRAAR G, et al. Digital Twin in manufacturing: A categorical literature review and classification [J]. IFAC-PapersOnLine, 2018, 51(11): 1016-1022.
[5] PRINCE M J, FELDER R M. Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases [J]. Journal of Engineering Education, 2006, 95(2): 123-138.
[6] FELDER R M, BRENT R. Understanding Student Differences [J]. Journal of Engineering Education, 2005, 94(1): 57-72.
[7] KOLB D. Experiential Learning: Experience as the Source of Learning and Development [J]. Pearson Schweiz Ag, 1983, 1(3): 16-17.
[8] CRAWLEY E F, MALMQVIST J, STLUND S, et al. Rethinking Engineering Education: The CDIO Approach [M]. Rethinking Engineering Education: The CDIO Approach, 2007.
[9] GRAHAM C R. Emerging practice and research in blended learning [M]. Handbook of distance education. Routledge, 2013: 333-350.
[10] BLUMENFELD P C, SOLOWAY E, MARX R W, et al. Motivating Project-Based Learning: Sustaining the Doing, Supporting the Learning: Educational Psychologist: Vol 26, No 3-4 [J]. Educational Psychologist, 1991.
[11] FULLER A, FAN Z, DAY C, et al. Digital Twin: Enabling Technologies, Challenges and Open Research [J]. IEEE Access, 2020, 8: 108952-108971.
[12] JONES D, SNIDER C, NASSEHI A, et al. Characterising the Digital Twin: A systematic literature review [J]. CIRP Journal of Manufacturing Science and Technology, 2020, 29: 36-52.
[13] BOSCHERT S, ROSEN R. Digital Twin—The Simulation Aspect [M]. Digital Twin—The Simulation Aspect, 2016.
[14] UHLEMANN T H J, LEHMANN C, STEINHILPER R. The Digital Twin: Realizing the Cyber-Physical Production System for Industry 4.0 [J]. Procedia CIRP, 2017, 61: 335-340.
[15] MOURTZIS D, DOUKAS M, BERNIDAKI D. Simulation in Manufacturing: Review and Challenges [J]. Procedia CIRP, 2014, 25: 213-229.