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Article

Research on the Application of Digital Twin Technology in Educational Design and Teaching Management

Man Wen [1,*]

[1] Faculty of Humanities and Arts, Macau University of Science and Technology, Macau, China
* Correspondence: Man Wen, Faculty of Humanities and Arts, Macau University of Science and Technology, Macau, China

Abstract: With the rapid development of digital technology, the field of education is undergoing profound and continuous transformation. As an emerging digital technology, digital twin technology has demonstrated significant potential for application in multiple domains, yet its systematic use in education remains at an exploratory stage. This paper focuses on the application of digital twin technology in educational design and teaching management. First, it clarifies the connotations, operating principles, and core elements of digital twins, drawing on application experience in engineering, manufacturing, and smart cities to construct a conceptual framework suitable for educational contexts. It then analyzes the current status and existing problems of educational design and teaching management, including limited personalization, fragmented resource allocation, and insufficient real-time monitoring of teaching quality. On this basis, the study explores innovative applications of digital twins in curriculum and instructional design, such as virtual replicas of learning environments, dynamic learner modeling, and scenario-based simulation to support personalized learning and adaptive teaching. Furthermore, it discusses how digital twins can optimize resource management, support data-driven decision-making, and enhance quality monitoring and evaluation in teaching management through continuous data collection and feedback. Finally, the paper outlines key implementation paths, including technical architecture, data governance, and organizational support, and summarizes the main conclusions, providing theoretical reference and practical guidance for the digital transformation of education.

Keywords: digital twin; educational design; teaching management; digital transformation; personalized learning; resource management; quality assurance

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1. Introduction

Digital technology is profoundly influencing the field of education, driving significant changes in educational models, teaching methods, and management approaches. In this context, digital twin technology has garnered increasing attention in education due to its unique advantages. This technology enables precise simulation, analysis, and optimization of entities, offering new perspectives and methods for addressing numerous challenges in educational design and teaching management. Research on the application of digital twin technology in these areas holds substantial practical value and theoretical significance for enriching educational theory and fostering innovation in educational practice.

Based on the current state of research both domestically and internationally, the exploration of digital twin technology in education remains in its early stages [1]. International studies primarily focus on its use in constructing virtual teaching environments, while domestic research emphasizes its application in integrating teaching resources. However, existing studies lack systematic exploration of its application in educational design and teaching management, with notable gaps in application models

and implementation strategies. This presents a broad scope for further investigation in this area.

This paper employs a literature review to examine the current research status of digital twin technology in educational design and teaching management, drawing on relevant domestic and international studies. The application of digital twin technology in these areas is analyzed and reasoned through logical analysis. Using a comparative research method, its applications across various fields are evaluated to extract valuable insights [2]. The innovation of this study lies in its systematic exploration of the innovative application of digital twin technology in educational design and teaching management, offering a comprehensive reference for the digital transformation of the education sector.

2. Overview of Digital Twin Technology

2.1. Connotation, Principles and Core Elements of Digital Twin Technology

Digital twin technology is a method that uses digital tools to create a virtual model accurately representing a physical entity in a virtual space, enabling real-time data interaction between the two. Its core concept is to simulate and dynamically reflect the state and behavior of physical entities through digital models, thereby supporting management, optimization, and decision-making processes related to physical entities [3].

The working principle of digital twin technology primarily involves collecting, transmitting, analyzing, and building models from data. Data collection serves as the foundation [4]. Using various sensors, monitoring equipment, and other methods, comprehensive data on physical entities, including state parameters and operational data, is collected. Data transmission relies on network technology to transfer the collected data to the data processing center in real time.

Digital twin technology includes multiple core elements. Physical entities serve as the foundation and mapping object for digital twins [5]. Virtual models are the core, acting as the digital representation of physical entities in virtual space, capable of simulating various properties and behaviors of physical entities. Data serves as the bridge connecting physical entities and virtual models, encompassing both real-time and historical data of physical entities. Connection ensures real-time data interaction between physical entities and virtual models through network communication technology. Service is the goal, providing various application services such as monitoring, prediction, and optimization to users based on virtual models and data analysis results. Figure 1 illustrates the relationship between digital twins and smart cities.

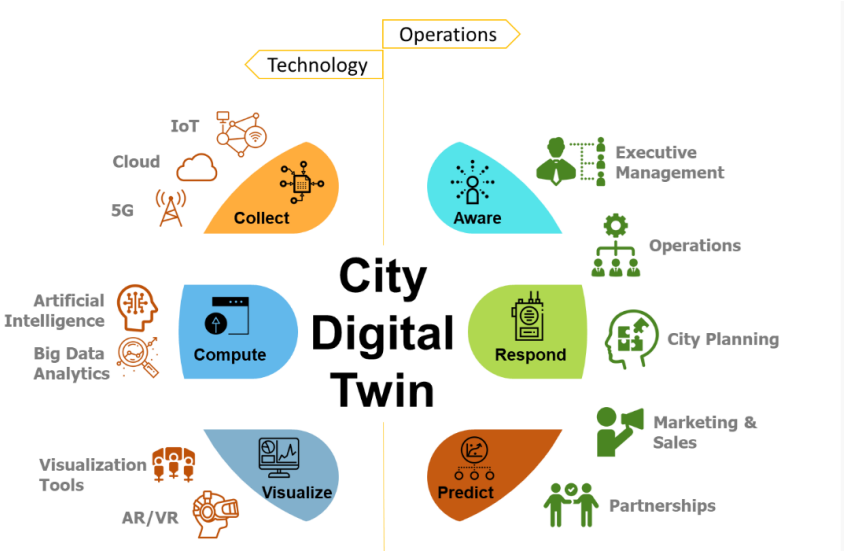

Figure 1. The relationship between digital twins and smart cities.

2.2. Cross-Domain Applications of Digital Twin Technology

Digital twin technology has extensive and mature applications in the manufacturing industry. During the product development stage, companies utilize digital twin technology to create virtual models of their products. Through simulation testing of virtual models, defects and problems in product design can be identified in advance, significantly reducing the product development cycle and lowering research and development costs. For example, automobile manufacturers can utilize digital twin technology to virtually assemble and conduct performance tests on automobile engines and chassis, thereby optimizing product design and development [6].

In the medical field, digital twin technology also plays an important role. By building a digital twin model of the patient, doctors can accurately diagnose the patient's condition and simulate treatment plans. For example, before performing a complex operation, doctors can utilize the patient's digital twin model to simulate the operation, plan the surgical path, mitigate risks, and enhance the success rate [7].

The field of urban planning also benefits from digital twin technology [8]. The city's digital twin model can integrate the city's geographic information, traffic data, and energy consumption to provide city planners with a comprehensive and intuitive view of the city's operating status. Through simulation and analysis of virtual models, urban traffic congestion and environmental pollution can be predicted and optimized, thereby improving the efficiency of urban management.

Cross-domain application experience demonstrates that digital twin technology possesses powerful capabilities for simulation, analysis, and optimization. In the field of education, the concept of achieving precise management and optimization through virtual models can be applied. By building corresponding digital twin models, new methods and means can be provided for educational design and teaching management [9].

3. Current Status of Educational Design and Teaching Management

3.1. Dilemma and Breakthrough of Educational Design

Educational design has experienced significant development, transitioning from traditional to modern approaches. Traditional educational design is teacher-centered, with relatively fixed course content and teaching methods, primarily focusing on imparting knowledge [10]. With the continuous evolution of educational concepts, modern educational design has shifted to being student-centered, emphasizing students' learning experiences and the development of their abilities.

Despite these advancements, many practical challenges persist in current educational design. An unreasonable curriculum system remains a major issue, with some course content disconnected from the actual needs of society [11]. Furthermore, there is a lack of personalized design, which neglects individual student differences and limits the ability to address the diverse learning needs of students.

To overcome these challenges, educational design must identify breakthrough directions. Leveraging technological advancements, it is essential to adopt advanced technologies, such as digital twin technology, to improve curriculum design and teaching methods. Simultaneously, greater attention should be given to the personalized needs of students, fostering a more flexible and diversified educational design model to meet the evolving demands of talent development in the modern era.

3.2. Existing Problems and Development Bottlenecks in Teaching Management

The development of teaching management has evolved through distinct stages, transitioning from experience-based management to scientific management, and subsequently to information management [12]. Experience-based management relies heavily on the personal judgment and subjective insights of managers. Scientific management introduces standardized methods and theories to enhance the structure and efficiency of teaching management. Information management leverages technology to digitize and automate processes, significantly improving overall management efficiency.

Despite advancements, several challenges persist in current teaching management practices [7]. One prominent issue is the low efficiency of management processes. In some schools, these processes remain overly complex, leading to unnecessary consumption of time and manpower. Additionally, the teaching quality evaluation systems are often inadequate, characterized by limited evaluation criteria that fail to address the holistic development of students' abilities and comprehensive qualities. Decision-making frequently lacks robust data support, relying instead on managerial experience without thorough analysis or data-driven insights.

Teaching management also encounters significant bottlenecks during its development. The continuous growth in student populations has exacerbated the imbalance between the supply and demand of educational resources, placing considerable strain on management systems. Furthermore, disparities in resource allocation between regions and schools remain a critical issue [13]. The dynamic nature of education policies imposes additional challenges, requiring managers to adapt their strategies promptly to align with evolving policy requirements.

4. Innovative Application of Digital Twin Technology in Educational Design

4.1. Digital Twin Technology Assists Course Design and Development

4.1.1. Course Content Optimization Based on Digital Twins

Digital twin technology provides substantial support for optimizing course content [14]. By creating a virtual teaching environment and student models, various data on students' learning progress and time allocation can be collected in real-time. These data effectively reflect students' learning status and needs.

Using this data, teachers can accurately adjust and refine course content. For knowledge areas that students generally master well, teaching time and difficulty can be appropriately reduced. Additionally, by considering changes in societal development and industry demands, the digital twin model can simulate and predict course content, enabling timely updates and ensuring the relevance of the curriculum.

4.1.2. Innovation of Virtual Experiments and Practical Teaching

Traditional experimental and practical teaching often face constraints such as limited venues, equipment, and funding. Students have fewer opportunities for hands-on practice, and certain safety risks are associated with these activities [8]. Digital twin technology enables the creation of highly realistic virtual environments for experiments, offering students a richer and safer practical learning experience.

Within virtual experimental environments, students can freely operate simulated experimental equipment and engage in various experimental projects. These environments effectively replicate phenomena and data encountered during experiments, allowing students to observe results and analyze data as though they were in a physical setting. This approach not only increases opportunities for practical engagement but also encourages students to explore and experiment boldly without concerns about safety, fostering their practical skills and innovative thinking.

Moreover, virtual experiments and practical teaching eliminate the constraints of time and space. Students can learn and practice anytime and anywhere, enhancing the flexibility and efficiency of their education. Teachers can also provide real-time guidance and evaluate students' practical processes within the virtual environment, promptly correcting errors and improving the overall effectiveness of practical teaching.

4.2. Digital Twin Technology Promotes Personalized Learning and Teaching

4.2.1. Accurate Analysis of Students' Learning Behavior

Digital twin technology enables a comprehensive and precise analysis of students' learning behaviors. By establishing monitoring points within the virtual learning environment, diverse data related to learning behaviors—such as students' learning paths, response patterns, and interactive communication—can be collected. These data cover all facets of the learning process, providing an accurate reflection of students' habits, abilities, and needs.

Advanced big data analysis techniques can process and deeply analyze these datasets to uncover patterns and characteristics underlying students' learning behaviors. For instance, analyzing the types of errors students make when answering questions can reveal weak areas in their understanding of specific knowledge points. Examining the duration and frequency of their study sessions can provide insights into their learning enthusiasm and self-discipline. These analyses allow educators to gain a holistic understanding of each student's learning status, offering a solid foundation for personalized teaching approaches.

4.2.2. Customization of Personalized Learning

Based on a precise analysis of students' learning behaviors, digital twin technology can create a personalized learning path tailored to each student [15]. By evaluating students' mastery of knowledge points, learning abilities, and goals, the virtual model can automatically recommend appropriate learning content, resources, and methods for individual students.

For students with strong learning abilities and a solid foundation, learning content with higher difficulty and greater expansibility can be recommended to accelerate their progress. Conversely, for students facing learning challenges and possessing a weaker foundation, intensive content focused on basic knowledge points and simpler tasks can be suggested to gradually enhance their abilities. Additionally, the learning path can be adjusted in real-time based on students' progress and feedback, ensuring they remain on the most suitable track for their development.

In summary, tailoring personalized learning paths effectively acknowledges and respects the unique differences among students. This approach enables each student to learn at their own pace and in their preferred manner, ultimately improving the efficiency and quality of learning. Moreover, it fosters greater interest and initiative in the learning process.

5. Innovative Application of Digital Twin Technology in Teaching Management

5.1. Digital Twin Technology Optimizes Teaching Resource Management

5.1.1. Digitalization and Integration of Teaching Resources

Digital twin technology enables the comprehensive digitization and effective integration of teaching resources. Traditional teaching resources exist in various forms, such as textbooks, handouts, courseware, and videos. These resources are often dispersed across different locations, making them difficult to access and inconvenient to manage. By utilizing digital twin technology, these teaching materials can be digitized, transformed into virtual digital resources, and stored on a unified digital platform.

During the digitization process, teaching resources are standardized, with unified data formats and classification standards established to ensure compatibility and sharing across different types and sources [16]. Additionally, the virtual modeling capabilities of digital twin technology are employed to create virtual models of teaching resources, enabling an intuitive display of their content, structure, and interrelationships.

Integrating digital teaching resources through digital platforms eliminates barriers between resources, allowing for centralized management and efficient retrieval [7]. Teachers and students can quickly locate the necessary teaching materials based on their requirements, thereby enhancing resource utilization efficiency. Furthermore, the

digitization of teaching resources simplifies their updating and maintenance, ensuring the content remains timely and accurate.

5.1.2. Intelligent and Dynamic Resource Allocation

Digital twin technology enables the intelligent and dynamic configuration of teaching resources. By constructing a digital twin model of school teaching resources, the utilization of various resources can be monitored in real-time, including classroom occupancy rates, equipment operation statuses, and teacher assignments. These real-time data provide a precise foundation for resource allocation.

Through the application of artificial intelligence algorithms to analyze and predict this data, an optimal resource allocation plan can be automatically formulated based on teaching requirements and resource availability [17].

When teaching requirements change, such as adjustments to courses, the digital twin model can promptly and dynamically revise the resource allocation plan to ensure alignment with evolving needs [6]. This intelligent and dynamic resource allocation approach enhances the efficiency of resource utilization.

5.2. Digital Twin Technology Improves Teaching Quality Monitoring and Evaluation

5.2.1. Real-Time Monitoring and Early Warning of the Teaching Process

Digital twin technology enables the monitoring and provision of real-time warnings during the teaching process. By constructing a model that mirrors the actual teaching process within a virtual teaching environment, real-time data, such as teachers' instructional behaviors and students' learning statuses, are mapped onto the virtual model. This allows teachers and teaching managers to gain an intuitive understanding of the teaching process's progress through the virtual representation.

Real-time monitoring facilitates the rapid identification of issues in the teaching process, such as teachers progressing at an inappropriate pace or students losing focus. When abnormalities occur, the digital twin system automatically generates early warning signals, prompting teachers and managers to take timely corrective actions. By addressing problems promptly through real-time monitoring and early warnings, the accumulation and escalation of issues can be prevented, ensuring the smooth progression of the teaching process and improving teaching quality.

5.2.2. Improvement of Teaching Quality Evaluation System

Traditional teaching quality evaluation systems often face challenges such as reliance on single indicators and significant subjectivity. Digital twin technology offers multidimensional and objective data support, enhancing the teaching quality evaluation system [5, 12].

The digital twin system can gather diverse data during the teaching process, including teachers' instructional content, teaching methods, students' academic performance, and practical skills [12]. These data provide a comprehensive and objective foundation for assessing teaching quality from multiple perspectives.

Utilizing these data to establish a multidimensional evaluation index system enables a more scientific and precise assessment of teaching quality. For instance, evaluations should not only focus on students' test scores but also consider their classroom engagement, practical achievements, and innovative abilities. Furthermore, analyzing and comparing historical data allows for predicting and assessing trends in teaching quality, offering guidance and recommendations for improvement [13].

A robust teaching quality evaluation system can encourage teachers to continuously refine their teaching methods, enhance their instructional proficiency, and promote sustained improvements in teaching quality [1].

6. Implementation Strategy for Digital Twin Technology Application

6.1. Construction and Adaptation of Technical Platform

Building a digital twin technology platform forms the foundation for its application in the field of education. During the construction process, several key factors must be considered [4]. First, it is important to clarify the application requirements and goals of the platform, determining its functions and performance indicators based on the actual needs of educational design and teaching management. Second, appropriate technical architecture and development tools should be selected to ensure the platform exhibits strong stability, scalability, and compatibility. Third, standardizing data interfaces is essential to facilitate seamless data interaction with various teaching systems and equipment.

Selecting a suitable technology platform requires a comprehensive evaluation of multiple factors. It is crucial to assess the technical maturity and reliability of the platform, choosing one that has been proven effective in practice and has a strong reputation. Additionally, the cost and maintenance complexity of the platform must be considered to ensure it can be developed and sustained over the long term within the school's budget.

The adaptation of the technical platform is equally important. The platform should be adjusted and optimized to align with the school's existing hardware facilities, network environment, and other relevant conditions. This ensures stable operation under the current infrastructure while maximizing the platform's functionality and capabilities [11].

6.2. Data Governance and Security System Construction

Data governance is a critical component in the application of digital twin technology. Establishing a comprehensive data governance mechanism is essential to regulate and manage the entire process of data collection, storage, processing, and utilization. It is important to clearly define the responsible parties for data to ensure its authenticity, accuracy, and integrity. Developing data quality management standards is also crucial; regular cleaning, verification, and updating of data contribute to improving its overall quality.

Furthermore, a robust data security system must be implemented to safeguard teaching data. Strengthening the application of data encryption technology is necessary to protect sensitive information and prevent data breaches. A data access control mechanism should be established to strictly regulate access rights, ensuring that only authorized personnel can access specific data. Regular data security audits and risk assessments are essential to promptly identify and address potential security risks.

It is also important to enhance data security awareness among teachers and students, fostering their ability to recognize and prevent security risks. Creating an environment where all staff actively participate in data security efforts is vital for maintaining a secure and collaborative atmosphere [4].

7. Conclusion

This paper explores the application of digital twin technology in educational design and teaching management. By leveraging virtual mapping and real-time interactive features, digital twin technology introduces innovative possibilities to the education sector. Its core elements, including physical entities and virtual models, along with cross-domain application experiences, offer valuable insights for educational advancements.

Current educational design faces challenges such as an unbalanced curriculum system, while teaching management encounters issues like inefficiency and an incomplete evaluation framework. Digital twin technology presents solutions by enabling curriculum optimization, personalized teaching approaches, improved management of teaching resources, and enhanced effectiveness in quality monitoring and evaluation processes.

The successful implementation of digital twin technology necessitates the development of an adaptation platform and a robust data governance and security system. Additionally, overcoming technical barriers, transforming educational ecosystems and

management models, and strengthening policy support frameworks are essential steps to facilitate its application within the education sector.

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