Digital Twin Technology as a Tool for Developing Professional Competencies of Future Engineers

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Abstract

This article examines the pedagogical potential of Digital Twin technology in developing the professional competencies of engineering students. The study analyzes the theoretical foundations of Digital Twin-based learning, identifies its main educational advantages, and proposes a conceptual framework for integrating Digital Twin technology into engineering education. The proposed approach focuses on the interaction between theoretical learning, virtual modelling, simulation, experimentation, and professional problem-solving. The findings indicate that Digital Twin-based educational environments can improve students' practical skills, analytical thinking, digital competence, and ability to make engineering decisions. The study concludes that the systematic integration of Digital Twin technology into higher engineering education can contribute significantly to the preparation of competitive and professionally competent engineers for the digital economy.

Keywords

Digital Twin, engineering education, professional competence, future engineers, digital technologies, simulation, Industry 4.0, virtual modelling.

Introduction

The contemporary development of science, technology, and industry has significantly changed the requirements for engineering professionals. The transition toward Industry 4.0 has resulted in the widespread implementation of intelligent production systems, automation, artificial intelligence, cloud computing, the Internet of

Things, and cyber-physical systems. These technological transformations require higher education institutions to reconsider traditional approaches to engineering education and focus more strongly on developing the practical and professional competencies of future specialists. Engineering education has traditionally been based on the combination of theoretical instruction, laboratory experiments, practical training, and industrial internships. Although these approaches remain important, they are not always sufficient for preparing students to work in highly digitalized industrial environments. Modern engineering systems are becoming increasingly complex, interconnected, and automated. Consequently, future engineers must be able to analyze complex technical processes, predict system behavior, identify potential failures, optimize operational parameters, and make data-driven decisions.

One of the promising technologies capable of addressing these educational challenges is Digital Twin technology. A Digital Twin is generally understood as a virtual representation of a physical object, system, or process that reflects its characteristics, behavior, and operational conditions. Through the integration of simulation models, sensors, data analysis, and computational technologies, Digital Twins enable users to observe and analyze physical systems in a virtual environment.

The application of Digital Twin technology in engineering education provides students with opportunities to interact with realistic technical systems without being limited by the availability of expensive laboratory equipment or industrial facilities. Students can model engineering systems, simulate different operating conditions, identify technical problems, test alternative solutions, and evaluate the consequences of their decisions.Therefore, the purpose of this study is to analyze Digital Twin technology as an educational tool for developing the professional competencies of future engineers and to propose a conceptual approach to its integration into engineering education.

Literature Review and Theoretical Background

The Concept of Digital Twin Technology

The concept of the Digital Twin has become increasingly important in industrial and technological research. Initially associated with product lifecycle management and advanced manufacturing, Digital Twin technology has gradually expanded into various fields, including energy systems, transportation, construction, healthcare, and education. A Digital Twin can be defined as a dynamic digital representation of a physical object or process. Unlike conventional computer models, a Digital Twin can interact with real-world data and continuously reflect changes occurring in the physical system. This interaction allows users to simulate, monitor, analyze, and optimize system performance.

The main components of a Digital Twin include:

1. **Physical object or system** – the real engineering object being represented.
2. **Virtual model** – the digital representation of the physical system.
3. **Data connection** – the exchange of information between the physical and digital environments.
4. **Simulation and analytical tools** – technologies used to analyze system behavior.
5. **Decision-making mechanisms** – processes that support optimization and problem-solving.

The educational potential of Digital Twin technology lies primarily in its ability to connect theoretical concepts with practical engineering processes.

Methodology

This study is based on theoretical analysis and conceptual modelling. The research methodology includes:

- analysis of scientific literature related to Digital Twin technology and engineering education;

- comparative analysis of traditional and Digital Twin-based learning approaches;
- identification of professional competencies required by modern engineers;
- development of a conceptual framework for Digital Twin-based competence development.

The proposed methodology is based on the principle that engineering education should combine theoretical knowledge with practical modelling and professional problem-solving.

The Digital Twin-based learning process can be organized into five stages.

Stage 1. Theoretical preparation

Students study the theoretical principles associated with the engineering system.

For example, students studying electrical power engineering may investigate:

- electrical circuits;
- power generation;
- transformer operation;
- electrical networks;
- renewable energy systems.

Stage 2. Digital modelling

Students create or interact with a digital model of the engineering system.

The model may represent:

- an electrical network;
- a transformer;
- a solar power plant;
- an industrial energy system;
- an automated production process.

Stage 3. Simulation

Students simulate different operating conditions and observe changes in the behavior of the engineering system.

For example, they may investigate:

- overload conditions;
- equipment failures;
- voltage fluctuations;
- changes in energy consumption;
- renewable energy generation.

Stage 4. Problem-solving

Students identify engineering problems and develop possible solutions.

At this stage, students apply their theoretical knowledge to practical situations.

Stage 5. Evaluation and reflection

Students analyze the results of their decisions and evaluate the effectiveness of different engineering solutions.

This process supports the development of analytical thinking and professional decision-making skills.

Digital Twin-Based Model for Professional Competence Development

The proposed model for developing the professional competencies of future engineers through Digital Twin technology consists of four interconnected components.

Cognitive Component

The cognitive component is associated with the acquisition of theoretical knowledge.

Students develop an understanding of:

- engineering principles;
- technical processes;
- system structures;

- operational parameters;
- mathematical models.

Digital Twins help students visualize theoretical concepts and understand complex relationships between engineering variables.

Discussion

The results of the theoretical analysis demonstrate that Digital Twin technology has considerable potential for improving engineering education. Traditional educational approaches often separate theoretical instruction from practical engineering activity. Digital Twins can provide a technological environment where these two components are integrated. The main pedagogical value of Digital Twin technology lies in its ability to create realistic learning situations. Instead of simply studying engineering principles, students can apply their knowledge to virtual engineering systems.This approach corresponds to competency-based education because students are evaluated not only according to the amount of theoretical knowledge they possess but also according to their ability to apply knowledge in practical situations.

However, the successful implementation of Digital Twin technology requires several important conditions:

1. adequate digital infrastructure;
2. appropriate engineering software;
3. teacher training;
4. integration into the curriculum;
5. development of Digital Twin-based learning materials;
6. appropriate assessment criteria.

Therefore, the implementation of Digital Twin technology should be considered as a systematic transformation of engineering education rather than simply the introduction of new software.

Conclusion

Digital transformation is changing the professional requirements imposed on future engineers. Modern engineering specialists must possess not only theoretical knowledge but also advanced digital, analytical, practical, and problem-solving competencies. Digital Twin technology provides significant opportunities for developing these competencies. By creating virtual representations of real engineering systems, Digital Twins enable students to model, simulate, analyze, and optimize technical processes. The proposed Digital Twin-based learning model integrates theoretical preparation, digital modelling, simulation, problem-solving, and reflection. This approach can contribute to the development of technical, digital, analytical, and practical competencies. The findings suggest that Digital Twin technology can serve as an effective educational tool for improving the quality of engineering education and preparing future engineers for professional activity in the context of Industry 4.0 and the digital economy.

Future research should focus on the experimental implementation of Digital Twin-based learning environments and the statistical evaluation of their impact on students' professional competence.

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