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Digital Twins in Engineering and Design Education: A Systematized Review

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Introduction

Engineering education is changing to meet the needs of solving modern, real-world problems. Students now need to learn through practical and interdisciplinary experiences that prepare them for challenges in today's industries. Cornerstone and capstone design courses are key parts of this learning process. These courses give students the chance to connect what they learn in theory with hands-on projects. They help students build essential skills like problem-solving, teamwork, and thinking about entire systems. Engineering design education, as a discipline, focuses on combining creativity, technical knowledge, and analysis to develop solutions for real problems. This process often includes generating ideas, building prototypes, testing, and refining designs to create effective outcomes. In this context, digital twins have become a valuable tool in engineering education. A digital twin is a detailed virtual model of a physical system, constantly updated using real-time data, advanced computing, and visual modeling [1]. Unlike static models, digital twins allow two-way interaction between the physical and digital worlds. This makes it possible to run simulations, monitor systems in real time, and predict future performance. For instance, a mechanical engineering student could use a digital twin to test how stress affects a structure, while an electrical engineering student might explore how circuits behave under different loads. These examples show how digital twins can make complex engineering principles easier to understand and apply.

Using digital twins in classrooms has the potential to significantly improve how students learn engineering. Traditional teaching often relies on static models and theory, which can fall short of preparing students for the fast-changing, interconnected world of engineering. Digital twins fill this gap by offering interactive tools that connect theory with real-world applications. Students can use these tools to simulate processes, explore how systems work, and practice solving problems in a realistic, hands-on way [2]. Digital twins also support advanced teaching strategies. They make it possible to run real-time simulations and create virtual labs where students can test ideas without needing expensive physical prototypes. This saves time and resources while still giving students valuable experience. Collaborative activities using digital twins help students build teamwork and communication skills, which are essential competencies for engineering practice. Additionally, working with real-time data helps students develop the analytical skills needed to succeed in modern, data-driven industries [3]. One of the biggest advantages of digital twins is their ability to recreate complex, real-world scenarios that would be difficult to replicate in a traditional classroom. For example, digital twins can simulate smart manufacturing systems, allowing students to study advanced topics like automation, cyber-physical systems, and the Internet of Things [4]. Similarly, students can learn about renewable energy by using digital twins to model wind turbines or solar panels under different environmental conditions. These applications help students gain a complete understanding of how systems work and how to solve problems that involve many interconnected parts.

Despite their potential, confusion sometimes arises around what truly constitutes a digital twin. Many existing virtual or computational models simply approximate or simulate processes without maintaining a live data link to the physical object or system. A digital twin, by contrast, must incorporate real-time or frequently updated data from sensors, logs, or user inputs to replicate the physical system's behavior as accurately as possible. This synchronization makes it more than a typical simulation or computer-aided design (CAD) model [5] ,[6]. The unique advantage of digital twins– their ability to mirror reality under changing conditions– positions them as a powerful learning tool for remotely operating equipment and instruments, as well as observing real-time feedback on their actions. There is ample literature on the engineering design research related to the digital twin design [5], [7], [7], [8], [9]. To understand how digital twins can improve engineering education, this study uses a systematized literature review. This method involves systematically collecting, analyzing, and summarizing research to gain a clear picture of what is known about a topic [10]. A systematized literature review is not as rigid as a full systematic review, but it follows clear steps to ensure thorough and unbiased results. Using this approach, the study explores existing research on how digital twins are used in engineering education, focusing on their benefits, challenges, and applications. There are several reasons why this review focuses on digital twins in engineering education. First, digital twins are a relatively new technology in education, and little is known about their use in teaching engineering [1-4]. A thorough review can identify trends, highlight successful practices, and highlight areas where more research is needed. Second, because digital twins are so versatile, they align well with the evolving needs of engineering education, which increasingly requires students to think across disciplines and tackle real-world problems. Third, as industries continue to adopt digital twin technology, students must be prepared to work with these tools when they graduate. This review aims to provide insights that can help educators use digital twins to improve teaching and prepare students for future careers.

Research Scope and Questions

Despite their potential, the application of digital twins in engineering education remains underexplored, particularly in design-focused courses. This research seeks to highlight this gap by conducting a systematized literature review and providing insights on the use of digital twins in engineering design education. Specifically, it focuses on their implementation in cornerstone and capstone courses, aiming to answer the following research question: *how have educators incorporated digital twins in engineering education and specifically in engineering design education?*

This question aims to uncover the pedagogical strategies, technological infrastructures, and educational outcomes associated with digital twins. Understanding how digital twins enhance design competencies and critical thinking skills can provide actionable insights for educators and curriculum developers. This literature review aims to inform future efforts to integrate digital twins into engineering education by identifying best practices, challenges, and research gaps. The findings hold the potential to revolutionize engineering education by equipping students with innovative tools and methodologies, fostering their ability to solve complex, interdisciplinary problems, and preparing them for the demands of modern engineering practices.

Methods

We employed a systematized literature review methodology to provide a structured and rigorous analysis of existing research on digital twin applications in engineering education. We chose a systematized literature review to address the relative novelty of digital twins in engineering education and to ensure a transparent, replicable process. A systematized literature review integrates elements of systematic reviews, such as predefined inclusion criteria and transparent methodologies, while allowing for flexibility to address emerging topics in rapidly evolving fields. According to Grant and Booth [10], systematized reviews differ from systematic reviews in terms of comprehensiveness. Systematized reviews typically omit the quality appraisal step, use a smaller set of eligible articles, and still incorporate a systematic search, review, and synthesis process. In line with this, the study followed the steps outlined by Kim [11] for conducting a systematized review, including defining a scope and research questions, establishing inclusion criteria, identifying and cataloging sources, and synthesizing the findings.

Search Strategy and Sources

To ensure adequate coverage, the study searched multiple academic databases, including Google Scholar, IEEE Xplore, Web of Science, and Scopus. These databases were selected due to their relevance to engineering and educational research, extensive coverage of peer-reviewed articles, and inclusion of interdisciplinary studies. The search strategy was designed to capture various perspectives on digital twin applications in engineering education. The keywords and combinations used for the searches included "Digital twin" AND "engineering education," "Virtual labs" AND "digital twins," "Simulations" AND "engineering education," "Cyber-physical systems" AND "engineering education," "Model-based systems engineering" AND "engineering education," "Digital twins in mechanical/electrical/civil engineering," AND "Digital twins" or "symbiotic autonomous cognitive systems" combined with "education," "engineering," or "design."

These search terms were chosen to encompass a wide range of potential applications and terminologies related to digital twins, reflecting their interdisciplinary nature and varying implementations across engineering fields. For example, terms like "cyber-physical systems" and "model-based systems engineering" were included to capture research that might not explicitly use the term "digital twin" but aligns conceptually. Lastly, to ensure temporal relevance, we reviewed scholarly works published between 2014 – 2024.

When searching the databases, various methods were applied to identify the most relevant articles based on the search strings and the coverage of initial results. For Google Scholar queries, the database searched the entire article for the presence of the search string components to maximize the number of articles that reference our key terms and can be used in the review. For the search, we found that the keyword combinations mentioned earlier had the best output of initial results. Our database search yielded articles in Google Scholar, IEEE Xplore, Web of Science, and Scopus as shown in Table 1.

Table 1 Database Search Results (before removing duplicates)

Database	**Search Result (Number of articles)**
Google Scholar	57
IEEE Xplore	41
Web of Science	44
Scopus	39

Inclusion and Exclusion Criteria

The inclusion criteria were carefully chosen to ensure that the reviewed studies were directly relevant, of high quality, and focused on higher education contexts. Only studies specifically focused on engineering disciplines were included, as the research aimed to explore the role of digital twins within this academic domain. The inclusion of English-language publications ensured accessibility and consistency in the analysis. Studies conducted in higher education settings were prioritized to align with the pedagogical focus of the review. Additionally, only peer-reviewed journal articles or conference papers were considered, as these sources are recognized for their academic rigor and credibility. Both international and US-based studies were included to capture a global perspective on using digital twins in engineering education.

The exclusion criteria were applied to narrow the scope and eliminate studies not aligned with the research objectives. We excluded papers published prior to 2014. Research sponsored by private industry or government agencies was excluded to focus specifically on educational applications rather than proprietary or policy-driven studies. Similarly, studies that did not explicitly relate to engineering education were excluded to maintain the relevance of the findings. Papers that did not address the use of digital twins in educational contexts were also excluded, as they fell outside the primary scope of this review.

Screening and Selection

The screening process involved several stages. Initially, the titles and abstracts of retrieved articles were reviewed for relevance to the research questions. Subsequently, full-text articles were examined to ensure they met the inclusion criteria. Articles that discussed the implementation, outcomes, or pedagogical strategies of digital twins in engineering education were retained. Studies that lacked sufficient methodological rigor, detailed descriptions, or direct relevance to the research questions were excluded. Duplicates across databases were also removed.

Data Extraction and Synthesis

Once the relevant works were identified, detailed data were extracted from each article. The data extraction process focused on multiple critical aspects to comprehensively understand digital twin applications in engineering education. The context and scope of digital twin applications were analyzed to identify the specific engineering disciplines and the educational settings in which the technology was employed. Pedagogical strategies, including the use of virtual labs, project-based learning, real-time simulations, and collaborative activities, were documented to understand how digital twins were integrated into teaching methodologies. The technological frameworks and tools used in these applications, such as Internet of Things (IoT) integration, machine learning algorithms, computer-aided design (CAD) platforms, and simulation software, were also detailed to highlight the technical infrastructure supporting these initiatives. Furthermore, the reported educational outcomes were examined, particularly concerning improvements in student engagement, problem-solving skills, and design competencies. Challenges faced during the implementation of digital twins, including infrastructure requirements, high costs, and faculty training needs, were also identified to provide a balanced perspective on the feasibility and effectiveness of these technologies in educational contexts. The extracted data was synthesized into thematic categories to address the research questions. Themes revolved around the role of digital twins in developing design competencies, fostering critical thinking, and enhancing collaborative problem-solving, the methods of implementation of digital twins, enabling hybrid education, and industry-academia collaboration.

Figure 1 is the PRISMA flowchart illustrating the process of refining the search results in this study. At the step of identification, we found 119 articles from the 4 databases (Table 1) with the search string described earlier. We removed the articles that were not peer-reviewed. Then we performed a preliminary screening based on the title and abstract and shortlisted 52 articles as detailed in the Appendix. Considering the research scope and questions, we developed the inclusion and priority criteria (as detailed earlier) and applied them to the next steps. Through the screening and eligibility evaluation, we arrived at a total of 16 articles. The 16 articles are highlighted in the Appendix table. The details of the inclusion and exclusion process can be found in the PRISMA flowchart.

The synthesis highlighted best practices, technological requirements, and research gaps, offering a comprehensive overview of the current landscape of digital twin applications in engineering education. By elaborating on these findings, this study provides actionable insights into the potential of digital twins to revolutionize engineering education, bridging the gap between theoretical knowledge and practical applications. Additionally, it identifies future directions for leveraging digital twins to address emerging challenges and opportunities in engineering pedagogy.

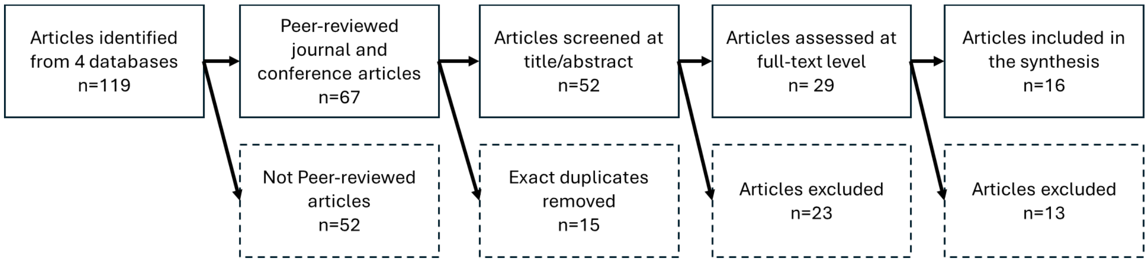

Figure 1 PRISMA flowchart illustrating the process of refining the search results in this study

Analysis

We carried out a thematic analysis of the 16 shortlisted articles. We conducted a thematic analysis by reviewing each article and taking notes on key aspects of digital twin research. We examined how digital twins were defined, the participants involved, the contexts in which they were used, their implementation, and the specific findings reported. Additionally, we documented the type of research conducted, the disciplines represented, the authors' definitions and explanations of digital twins, and the data sources used. We also analyzed the research questions posed, the methodologies applied, and the discoveries made. After an initial review across works, the research team noted which frameworks were used in each study and their relevance to our research question. The focus of each article was assessed based on its research question, applied methods, and intended contributions. Our review of the scholarly works revealed four themes that emerged across the context of digital twins in engineering and design education. These themes highlighted the potential of digital twins in engineering and design education and can guide the readers to develop their curriculum involving digital twins based on their pedagogical goals.

Findings

Theme 1: Digital Twins as a Bridge Between Theory and Practice

The first theme that emerged from our analysis was the use of digital twins as a bridge between theoretical learning and practical application. This theme refers to how real-time, data-driven models help students move beyond abstract concepts by letting them apply and test engineering theories in lifelike simulations, thereby linking classroom knowledge to actual systems. Traditional engineering education often relies on abstract theory, which can be challenging for students to relate to real-world problems. Digital twins offer an innovative way to bridge this gap by allowing students to interact with and manipulate virtual representations of real systems.

Of the 16 papers we analyzed for our research, seven articles had applications of the digital twins in a classroom environment connecting theory with experiments [6], [12], [13], [14], [15], [16], [17]. For example in Chacón and Estela [13], digital twins enable students to visualize complex systems and experiment with them in real-time. This interactive learning approach facilitates a deeper understanding of engineering principles by showing students the consequences of design decisions and system interactions in a simulated environment. The ability to experiment with systems virtually allows students to explore design alternatives, test different scenarios, and gain insight into the real-world implications of their work. Similarly, Schluse et al. [14] highlight how digital twins enhance simulation-based learning, offering students the opportunity to interact with complex industrial systems without the need for physical prototypes. This is particularly relevant in areas such as mechanical and civil engineering, where physical prototyping can be expensive, time-consuming, and resource intensive. By offering virtual alternatives, digital twins lower the barriers to experimentation and provide students with immediate feedback, helping them refine their design skills in a controlled yet dynamic environment.

Theme 2: Support for Remote and Hybrid Learning Models

The second theme revolves around the support for remote and hybrid learning environments. Six out of 16 articles revealed this theme [15], [18], [19], [20]. The COVID-19 pandemic has forced educational institutions to adopt remote learning technologies, but many disciplines, particularly engineering, require hands-on, interactive experiences. Digital twins offer a solution by enabling remote access to virtual laboratories and experimental setups. For example, as Deniz et al. [18] noted, using digital twins allows students to interact with lab-based experiments remotely, providing an experience that closely mirrors in-person learning. Johra et al. [19] explored how digital twins of building physics experimental setups are used for effective e-learning, allowing students to simulate complex experiments involving heat transfer, energy consumption, and airflow in buildings. This remote learning approach enhances students' engagement and understanding of complex systems, as they can actively interact with the digital twin models and make design changes in real-time. Guc et al. [15] emphasize how digital twins in mechatronics education offer a similar experience, allowing students to virtually interact with robotic systems and mechanical components. This is particularly valuable in situations where students are geographically dispersed or unable to access physical labs. The shift towards remote and hybrid learning models is likely to continue in the post-pandemic era. As a result, digital twins represent a long-term solution for providing high-quality, hands-on learning experiences that can be accessed anywhere, anytime. This flexibility offers significant advantages in engineering education, particularly in reaching students in remote or underserved areas.

Theme 3: Student Learning Experiences

The integration of digital twins with immersive technologies such as augmented reality (AR), virtual reality (VR), and mixed reality (MR) represents another important theme. Four out of 16 articles contained various learning experiences within the digital twins [21], [22], [23], [24].

For example, Zacher [21] discusses how immersive digital twins are used in robotics education, allowing students to interact with virtual models of robots in 3D environments. This technology enhances the learning experience by allowing students to visualize and manipulate robots in a virtual space, offering an interactive and engaging way to learn about robotic systems. In the context of engineering design education, digital twins combined with immersive technologies allow students to experience complex systems more intuitively. Balla et al. [23] emphasize the role of digital twins in project-based learning (PBL), where students work on real-world design challenges and interact with virtual models of engineering systems. This immersive approach encourages experimentation and iteration, helping students to refine their design thinking and problem-solving skills. The use of digital twins in combination with AR/VR technologies also promotes active engagement and enhances spatial reasoning, which is crucial in engineering design.

Theme 4: Cross-Disciplinary Collaboration and Industry-Academia Integration

Finally, the last theme that emerged from our study is related to cross-disciplinary collaborations between industry and academia. Digital twins are particularly valuable in cross-disciplinary education, where students from various engineering fields collaborate on a shared project. Students can greatly benefit from interacting with virtually built industrial equipment and environments. Four out of 16 articles had the central theme of offering industrial exposure and cross-disciplinary collaboration opportunities via digital twins [14], [20], [25], [26].

For example, as Kartashova et al. [20] noted, digital twins provide a shared platform where students can simulate, design, and optimize systems involving multiple engineering disciplines. This is especially important in modern engineering practice, where systems often require input from several areas of expertise, such as mechanical, electrical, and civil engineering. Digital twins foster teamwork and communication among students from different disciplines by providing a common platform for collaboration. This collaborative approach mirrors real-world engineering practices, where professionals from various fields must work together to solve complex design challenges. Furthermore, as highlighted by Acker et al. [26], the use of digital twins allows students to engage with real-world industry problems, gaining exposure to the tools and methodologies used in the professional world. This industry-academia integration enhances the relevance of students' learning and better prepares them for future careers in engineering.

Discussion

In this section, we discuss the major observations from the literature review and their implications on future directions for engineering education researchers and engineering design educators. We also posit the use of digital twins in the capstone and cornerstone projects in engineering design. For engineering education researchers, future work should focus on evaluating the effectiveness of digital twins in improving learning outcomes, particularly in enhancing students' problem-solving abilities, design thinking, and technical skills. From the literature review, we identified that empirical studies are needed to assess how digital twins influence student engagement, retention, and knowledge transfer to real-world scenarios. Additionally, researchers should explore the long-term impacts of digital twins on students' career readiness, particularly in industries that are increasingly adopting digital twin technology.

Moreover, engineering educators should engage in professional development to equip themselves with the knowledge and skills necessary to integrate digital twins into their curricula effectively. This includes exploring best practices for using digital twins in classroom settings, developing interdisciplinary projects incorporating digital twins, and fostering collaborative learning environments where students from different engineering disciplines can work together on virtual models. Educators must also address the barriers to adoption, such as the cost of software, the complexity of creating high-fidelity models, and the lack of access to adequate computational resources in some institutions. Future efforts should focus on creating open-source or low-cost solutions for digital twin implementation to democratize access for all students, regardless of their institution's resources.

While the potential benefits of digital twins in education are clear, several challenges and barriers to their widespread adoption remain. One of the primary obstacles is the cost and complexity of developing high-fidelity digital twin models. As Kinsner [27] notes, creating accurate and detailed virtual models requires significant investment in both hardware and software. In many cases, institutions may lack the necessary resources to develop or maintain these models, especially when the focus is on high-fidelity simulations. Another challenge is the need for faculty members to acquire the skills necessary to teach digital twins effectively. Many instructors may not be familiar with the technology or may lack the experience required to integrate it into their teaching methods. Training faculty to use digital twin technology effectively is essential for ensuring successful implementation. As noted by Grieves [6], integrating digital twins into the curriculum requires a shift in teaching philosophy, where instructors move from traditional lecture-based teaching to more interactive, student-centered approaches.

This systematized literature review leads to an opportunity for more scholars to research the context of digital twins in engineering and design education, such as at the pre-college level and in industry. The scope of this review is restricted to studies published within the past decade and thus may not fully capture the breadth of research over a longer time frame. We encourage the broader engineering education research community to expand upon this work by exploring additional studies outside this temporal boundary. Additionally, the review was conducted using a selection of only four databases. The inclusion of more databases may uncover further relevant studies, thereby enriching the insights derived from this review. It is also worth noting that we did not incorporate a formal quality appraisal step, which could potentially introduce biases. However, we mitigated this risk by adhering to a strict inclusion and exclusion protocol, designed to minimize any such biases.

Conclusion

Digital twin technology has the potential to transform engineering education by providing students with interactive, immersive, and data-driven learning experiences. This systematized review highlights the various ways digital twins are being integrated into engineering curricula, from bridging the gap between theory and practice to supporting remote learning and enabling immersive, hands-on experiences. We observed that digital twins offer significant advantages in design education, particularly in project-based learning and capstone projects, where students can experiment with virtual models, refine their designs, and simulate real-world scenarios without the constraints of physical prototypes. Furthermore, digital twins foster cross-disciplinary collaboration and industry-academia integration, preparing students for the demands of the modern engineering workforce. As digital twin technology continues to evolve, it holds the potential to enhance collaboration, improve student engagement, and provide valuable insights into complex systems. However, challenges such as high implementation costs, faculty training, and access to necessary resources must be addressed for widespread adoption.

For future work, both engineering education researchers and educators should focus on evaluating the effectiveness of digital twins in improving learning outcomes and career readiness, as well as exploring ways to make technology more accessible to institutions of all sizes. As digital twin technology becomes more prevalent in industry, its integration into engineering education will not only equip students with cutting-edge skills but also prepare them to drive innovation in the future of engineering design and technology.

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Appendix

Scholarly Works Selected for Literature Review

No.	Article Title	Author(s)	Year	Document Type	Publication	Discipline
1	Digital Twins in a process engineering education environment	Virtanen	2020	Thesis	Acadia University	Engineering Education
2	Developing a Skilled Workforce for Future Industry Demand: The Potential of Digital Twin-Based Teaching and Learning Practices in Engineering Education	Hazrat et al.	2023	Article	Sustainability	Engineering Education
3	Educational Case Studies: Creating a Digital Twin of the Production Line in TIA Portal, Unity, and Game4Automation Framework	Balla et al.	2023	Article	Sensors	Industry - Production and Manufacturing
4	Digital Twin for Math Education: A Study on the Utilization of Games and Gamification for University Mathematics Education	Lee, J. Y., Pyon, C. U., & Woo, J.	2023	Article	Electronics	Mathematics Education
5	AutoDRIVE: A Comprehensive, Flexible and Integrated Digital Twin Ecosystem for Autonomous Driving Research & Education	Samak et al.	2023	Article	Robotics	Engineering (Cyber-Physical Systems)
6	Digital twins in MOOCs: exploring ways to enhance interactivity	Lexman, R. R. and Baral, R.	2023	Article	Development and Learning in Organizations	Target: Educational Institutions with MOOCs
7	Project-based learning in engineering education: Developing digital twins in a case study	Hagedorn, L., Riedelsheimer, T., & Stark, R.	2023	Conference Proceedings	International Conference on Engineering Design	Engineering Education
8	Low-Cost Digital Twin Approach and Tools to Support Industry and Academia: A Case Study Connecting High-Schools with High Degree Education	Acker et al.	2023	Article	Machines	Pre-College; K-12 Robotics & Automation
9	Developing a real-world scenario to foster learning and working 4.0 – on using a digital twin of a jet pump experiment in process engineering laboratory education	Boettcher et al.	2023	Article	European Journal of Engineering Education	Engineering
10	Digital Twinning and Remote Engineering for Immersive Embedded Systems Education	Hussein, R., Guo, M., Amarante, P., & Rodriquez-Gil, L.	2023	Conference Proceedings	Frontiers in Education Conference	Engineering Education (Electrical & Computer Engineering)
11	Using digital twins in education from an innovative perspective: Potential and application areas	Ağca, R.K.	2023	Article	Education Mind	n/a
12	Digital Twins and Their Role in Reengineering Engineering Education	Grieves, M.	2024	Book Chapter	Digital Twin: Fundamentals and Applications	Engineering Education

No.	Article Title	Author(s)	Year	Document Type	Publication	Discipline
13	Maximizing Learning Potential: Embracing the Power of Digital Twins in Architectural and Construction Education of the Twenty-first Century	De Los Santos, A. and Alacántara, E.B.	2024	Book Chapter	Teaching Innovation in Architecture and Building Engineering	Architectural and Construction Engineering
14	Towards Concepts for Digital Twins in Higher Education	Daineko et al.	2024	Conference Proceedings	International Conference on Extended Reality	Information Technology
15	The Effectiveness of a Digital Twin Learning System in Assisting Engineering Education Courses: A Case of Landscape Architecture	Zhang et al.	2024	Article	Applied Sciences	Architecture
16	Development and usability testing of a patient digital twin for critical care education: A mixed method study	Rovati et al.	2024	Article	Fronters in Medicine	Medicine
17	Use of Digital Twin Technology in the Teaching Learning Process, in the field of University Education: A Bibliometric Review	Chamorro-Atlaya et al.	2024	Article	International Journal of Learning, Teaching, and Educational Research	Engineering Education
18	Digital twin technology for blended learning in educational institutions during COVID-19 pandemic	Kartashova et al.	2024	Conference Proceedings	CTE Workshop 2024	Education
19	Digital Twins and Engineering Education: Current Status	Shaikh, M. K.	2024	Article	International Journal of Innovation in Science & Technology	Engineering Education
20	Immersive Digital Twins of an Industrial Forge in Engineering Education	Fleury, S., Baudouin, C., & Bondesan, P.	2024	Conference Proceedings	20th International CDIO Conference	Engineering Education
21	Digital Twins Empower Higher Education	Lei, J., Song, J.-Q., & Wang, J.-Y.	2024	Article	Journal of General Education and Humanities	Education
22	Application of the digital twin model in higher education	Selim, A., Ali, I., Saracevic, M., & Ristevski, B.	2024	Article	Multimedia Tools and Applications	Education
23	Applications of augmented reality (AR) in chemical engineering education: Virtual laboratory work demonstration to digital twin development	Zhou, Z., Oveissi, F., & Langrish, T.	2024	Article	Computers & Chemical Engineering	Chemical Engineering
24	Digital Twins Applications in STEM Education: Challenges and Implementation Opportunities in Developing Countries	Caribo et al.	2024	Conference Proceedings	IEEE Digital Education and MOOCS Conference	STEM Education
25	Digital twins in civil and environmental engineering classrooms	Chacón Flores et al.	2018	Article	Civil Engineering Education	Engineering Education

No.	Article Title	Author(s)	Year	Document Type	Publication	Discipline
26	Platform for industrial internet and digital twin focused education, research, and innovation: Ilmatar the overhead crane	Autiosalo	2018	Article	IEEE World Forum on Internet of Things	Engineering Education (Industrial Engineering)
27	Experimentable Digital Twins—Streamlining Simulation-Based Systems Engineering for Industry 4.0	Schluse et al.	2018	Article	IEEE Transactions on Industrial Informatics	Engineering Education (Industrial Engineering)
28	Learning Experiences Involving Digital Twins	David et al.	2018	Article	IEEE Industrial Electronics Society	Engineering Education (Electrical & Computer Engineering)
29	Early Stage Digital Twins for Early Stage Engineering Design	Jones et al.	2019	Article	International Conference on Engineering Design	Engineering Design
30	Digital Twins for Education and Study of Engineering Sciences	Zacher	2020	Article	International Journal on Engineering, Science and Technology	Engineering Education
31	Digital Twin and Web-Based Virtual Gaming Technologies for Online Education: A Case of Construction Management and Engineering	Sepasgozar	2020	Article	Applied Sciences	Engineering Education
32	Using Digital Twin Technology in Engineering Education – Course Concept to Explore Benefits and Barriers	Liljaniemi and Paavilainen	2020	Article	Open Engineering	Engineering Education
33	Digital Twins: State-of-the-Art and Future Directions for Modeling and Simulation in Engineering Dynamics Applications	Wagg et al.	2020	Article	ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems	Mechanical Engineering
34	A Theoretical Analysis Method of Spatial Analytic Geometry and Mathematics under Digital Twins	Wang	2021	Article	Advances in Civil Engineering	Civil Engineering
35	Engineering Education and Cloud-Based Digital Twins for Electric Power Drive System Diagnostics	Rassudov et al.	2021	Article	International Workshop on Electric Drives: Improving Reliability of Electric Drives	
36	A review of digital twin in product design and development	Lo et al.	2021	Article	Advanced Engineering Informatics	Engineering Design

No.	Article Title	Author(s)	Year	Document Type	Publication	Discipline
37	Digital Twins by Study and Engineering	Zacher	2021	Article	South Florida Journal of Development	Engineering Education
38	Education as a way to create skills in the knowledge economy using the example of BIM technologies in the era of digital twins and digital pedagogy (EDTECH)	Pokusaev et al.	2021	Article	International Journal of Open Information Technologies	Engineering Education
39	Digital Twins Enabled Remote Laboratory Learning Experience for Mechatronics Education	Guc et al.	2021	Article	International Conference on Digital Twins and Parallel Intelligence	Engineering Education (Mechatronics)
40	Digital Twins for Personalized Education and Lifelong Learning	Kinsner	2021	Article	Canadian Conference on Electrical and Computer Engineering (CCECE)	Engineering Education
41	STEAM activities for civil engineering curricula. From Calculus to Digital Twins	Chacón and Estela	2021	Article	IEEE Frontiers in Education Conference (FIE)	Engineering Education
42	Digital Twins of Building Physics Experimental Laboratory Setups for Effective E-learning	Johra et al.	2021	Article	Journal of Physics	Engineering Education
43	Digital Visual Sensing Design Teaching Using Digital Twins	Lian and Yan	2022	Article	Advances in Civil Engineering	Engineering Education
44	ReImagine Lab: Bridging the Gap Between Hands-On, Virtual and Remote Control Engineering Laboratories Using Digital Twins and Extended Reality	Alsaleh et al.	2022	Article	IEEE Access	Engineering Education
45	Digital Twins in Contemporary Education: Virtual Workshop	Balyakin et al.	2022	Article	Perspectives and Trends in Education and Technology	Engineering Education
46	Applying Digital Twin Technology in Higher Education: An Automation Line Case Study	Eriksson et al.	2022	Article	Advances in Transdisciplinary Engineering	Engineering Education
47	The role of Digital Twin technology in transforming engineering education	Maksimović and Davidović	2022	Article	Technics and Informatics in Education Conference	Engineering Education
48	Online (Remote) Teaching for Laboratory Based Courses Using "Digital Twins" of the Experiments	Deniz et al.	2022	Article	Journal of Engineering for Gas Turbines and Power	Engineering Education
49	Transformation of education through Big Data: digital twins case study	Andreasyan and Balyakin	2022	Article	Journal of Physics	Engineering Education

No.	Article Title	Author(s)	Year	Document Type	Publication	Discipline
50	Digital twins as education support in construction: a first development framework based on the Reference Construction Site Aachen West	Dai and Brell-Çokcan	2022	Article	Construction Robotics	Engineering Education
51	Common Educational Teleoperation Platform for Robotics Utilizing Digital Twins	Kaarlela et al.	2022	Article	Machines	Engineering Education
52	Using mixed reality based digital twins for robotics education	Orsolits et al.	2022	Article	International Symposium on Mixed and Augmented Reality Adjunct	Engineering Education