

DIGITAL TWINS IN EDUCATION: CONCEPTUAL FOUNDATIONS, APPLICATIONS AND CHALLENGES

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Abstract: Although originally developed as part of an industry, digital twin (DT) technologies are now being adapted for education. Digital twins (DTs) can integrate artificial intelligence, Internet of Things technologies, learning analytics and immersive environments to model learners, learning processes and educational settings in a dynamic and data-informed manner. This paper conducts a review of academic articles between 2020 and 2026 to ascertain definitions, application areas, and areas regarding integration between humans and technology to better understand how DTs can be integrated in educational settings. Personalised learning, simulation-based training and immersive learning settings created using DT technology have shown to provide benefits to both educators and learners in terms of enhanced adaptability, engagement and improved decision-making based on the results of research studies. There are several significant barriers to widespread adoption of DT in education, including the technical complexity of implementation, high implementation costs, data privacy issues, and lack of a research-based pedagogical framework. The paper contributes by proposing a classification of educational digital twins according to the entity being modelled. Although the potential for DTs to transform education is great, further research is needed to develop standardized models to ensure DTs are successfully integrated into the teaching and learning process.

Keywords: Digital Twin, Education, Adaptive Learning, Human–Technology Integration, Artificial Intelligence

1. Introduction

Digital transformation has increased the flexibility, accessibility and data-driven personalization of educational systems. In this context, digital twin (DT) is emerging as a viable technology because of its ability to create data that dynamically models or represents a physical system based on real-time data [1-3].

Originally created in the industry for the monitoring and optimization of physical processes, DT technology is increasingly being explored as an educational tool capable of transforming how learning processes are designed, monitored and

adapted. [1, 3].

The primary relevance of using DTs in education is due to the convergence of numerous enabling technologies, principally artificial intelligence (AI), the Internet of Things (IoT) and extended realities (XR), as they provide the capability for continuous data collection and real-time data analysis that allows the educational system to dynamically reflect learners' needs. As compared with traditional e-learning systems, which generally employ static content and linear progression, DT-based educational systems provide learners with continuous feedback, predictive analytics and adaptive learning

pathways over time [6, 13].

While there may be potential, the field remains conceptually fragmented and has multiple implementations. There are many publications that only examine specific instances of a digital twin in education. This does not assist in establishing a common definition for a digital twin in education and describing how a digital twin differs from simulations and virtual labs or other similar technologies [2, 12]. In addition, there is very little application of pedagogical theory, which makes it difficult to apply a digital twin in an educational environment [3].

The purpose of this paper is to address the above-mentioned gaps by synthesizing the theoretical support for a digital twin in education, focusing on conceptual

foundations, the application of digital twins, the interaction of humans with technology, and challenges associated with digital twins.

2. Conceptual Foundations of Digital Twin in Education

Digital Twins (DTs) are virtual representations of real-world entities or processes that are continuously "refreshing" via ongoing collection of data from and between systems. This definition of a DT in education is not limited to only the physical aspects of the systems, but includes learners, their instructional environments, as well as the systems that support the educational process [4]. Figure 1 illustrates the conceptual foundations of digital twins in education.

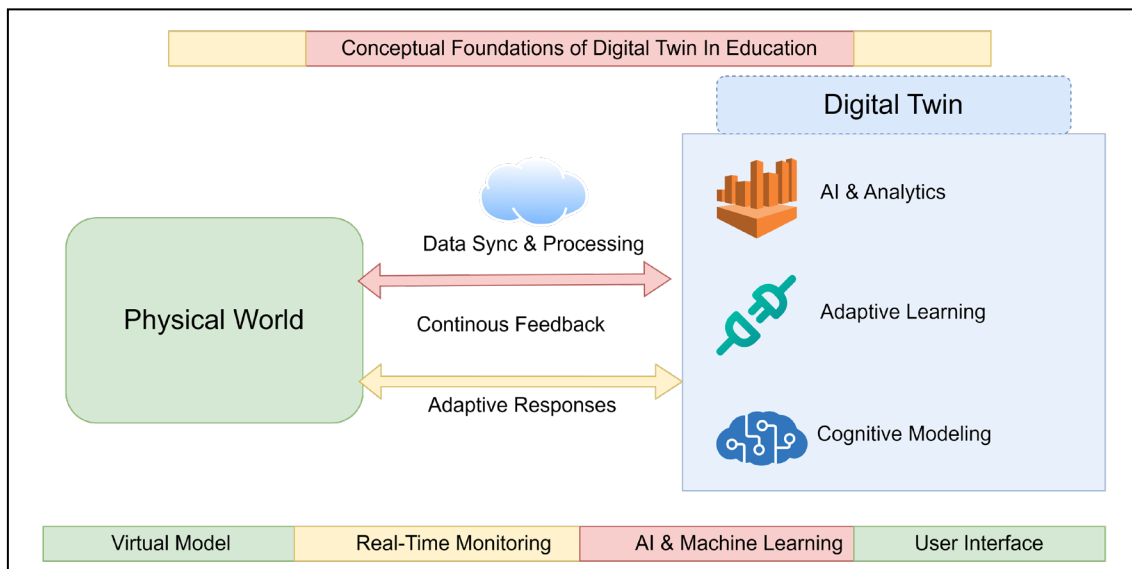


Figure 1. Conceptual Foundations of Digital Twin in Education

DTs have a few defining characteristics, but one is that they provide continual two-way connectivity between the physical and digital worlds. As a result, DTs provide for real-time communication between the two worlds and also permit for real-time monitoring, anticipating, and providing responses. From a learner's perspective, a digital twin of that learner could evolve as a function of that learner's behaviour and performance data, and the DT system could then adapt its instructional approach accordingly [6, 10, 12].

The typical architecture of educational DTs consists of several core building blocks:

- A physical counterpart (e.g., student, lab system, or environment)
- A virtual model representing that entity
- Data pipelines enabling real-time synchronization
- Analytical components powered by AI or machine learning
- User interfaces that support interaction and visualization

Together, these elements form a closed-loop system that continuously refines itself based

on incoming data [1-3].

It is necessary to differentiate digital twins from other closely related technologies. Although simulations and virtual laboratories provide excellent methods for learning, they do not contain real-time, ongoing synchronization found in digital twins. Smart learning environments use technology to improve learning; however, are frequently not integrated as well as able to adapt to changing conditions when compared to digital twins. The basic difference between all of these technologies is that digital twins evolve with their physical counterparts as a dynamic, living solution as opposed to being simple, stand-alone, static solutions.

Additionally, in evolving to include cognitive digital twins that integrate artificial intelligence (AI) with reasoning

and decision-making abilities, digital twins open up additional opportunities to use them in education. Not only can cognitive digital twins' model physical processes, but they can also model cognitive or brain-based behaviours allowing for more complex types of adaptive learning [16].

Based on the reviewed literature, DTs in education can be grouped according to the entity being modelled and the pedagogical function they serve. The following classification is added to clarify the contribution of the review and to make the conceptual synthesis more explicit. The categories presented in Table 1 were derived inductively from the thematic coding of the included studies, with the modelled entity used as the primary classification criterion and the pedagogical function used as a secondary interpretive criterion.

Table 1. Proposed classification of educational digital twins

Type of DT	Entity and educational role	Studies supporting the category
Student DT	Individual student; supports personalization, prediction, feedback and misconception detection	[1], [6], [10], [13], [14]
Laboratory DT	Laboratory system or equipment; supports safe experimentation and procedural training	[4], [5], [7], [8], [11], [15]
Classroom DT	Learning environment; supports monitoring of interaction, engagement and classroom conditions	[1], [2], [6], [10]
Curriculum DT	Learning pathway; supports adaptive sequencing and curriculum optimization	[7], [10], [14]
Institutional DT	Educational organization; supports planning, resource allocation and decision support	[1], [2], [13]

Cognitive digital twins extend this concept by integrating artificial intelligence, reasoning and decision-making capabilities. In education, this opens opportunities not only to model physical processes, but also to represent learning behaviour, progress, misconceptions and adaptive support needs [16].

3. Research Methodology

The study adopts a scoping review design because DT applications in education represent an emerging and conceptually fragmented research area. A scoping review was considered appropriate because the aim of the study is not to measure the

effectiveness of a single educational intervention, but to map the existing literature, clarify key concepts, identify application areas and synthesize the main challenges associated with the adoption of digital twins in educational contexts.

The search for literature involved searches on various major academic databases, namely, IEEE Xplore, ScienceDirect, SpringerLink, and MDPI, with the addition of Google Scholar. Peer-reviewed studies that were published in 2020 through 2026 were the only studies included in the examination. The search strings combined the expression “digital twin” with education-related terms, including “learning”, “training”, “higher education”, “education”, “engineering education”, and “virtual laboratory”.

Eligible sources consisted of conceptual, empirical, technical or pedagogical contributions, particularly studies connecting digital twins with AI, IoT, XR, adaptive learning, virtual laboratories or learning analytics.

The process used in the study to select the studies used for analysis used a multi-stage approach:

- Initial identification of relevant publications using keyword-based searches
- Screening based on titles and abstracts
- Full-text evaluation for relevance and quality
- Final inclusion of 16 peer-reviewed studies

The study selection process is summarized in Figure 2. The initial search returned 2,123 records, identified through database searching. After removing 600 duplicate

records, 1,523 records were screened by title and abstract. Of these, 1,423 records were excluded because they did not meet the inclusion criteria. Subsequently, 100 full-text articles were assessed for eligibility, and 84 articles were excluded predefined exclusion criteria, mainly because they focused on industrial digital twins without educational relevance, used the term digital twin superficially, or described generic simulations without digital twin characteristics such as real-time data synchronization. Finally, 16 peer-reviewed studies were retained for thematic synthesis. Data were extracted from each included study using a structured extraction matrix. The extracted information included: author and year of publication, type of study, educational domain, type of digital twin addressed, enabling technologies, pedagogical function, type of evidence, reported benefits, reported challenges and relevance to the research questions.

The research questions include:

- What conceptual foundations define digital twin technology in education?
- What are the primary application areas?
- How does DT influence human–technology interaction?
- What challenges limit adoption and scalability?

Findings were analysed thematically; findings were classified according to three dimensions (conceptual, technical, and pedagogical). This method provides a structured summary of the findings but also demonstrates some limits due to the small number of studies available and the fact that this area of research is still emerging.

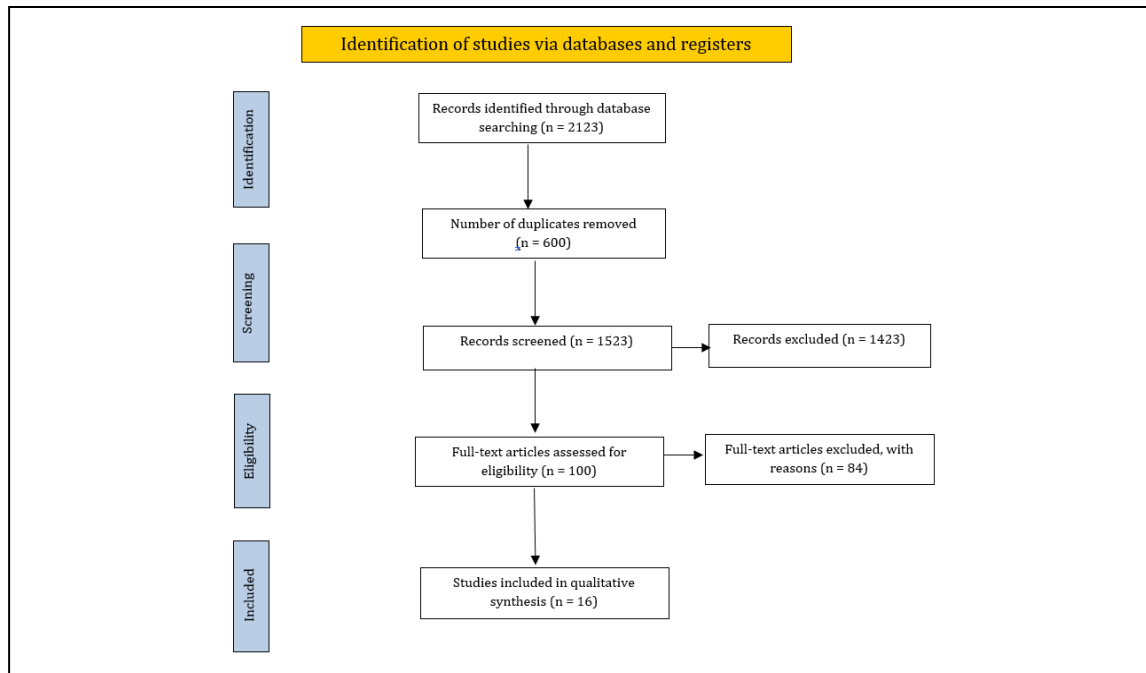


Figure 2. Identification of studies via databases and registers

4. Applications and Human–Technology Integration

The education sector has primarily adopted digital twin technology for multiple areas within education. Digital twin technology has a long history of application within education, illustrating potential to enhance and change the way individuals learn and how institutions operate as a whole. One of the biggest advantages of DT technology is in its use to support personalised and adaptive learning [10, 12]. Digital twins of learners can develop continuously throughout the course of their learning. By being able to access data from the digital twin in real time, the instructor can adjust the learner's learning content, pace, and method as necessary. This enables a more effective and individualised learning experience [8]. Another key application of DTs in education is situational learning for both engineering and medical curricula. By utilising a digital twin, students can gain access to realistic representations of complex systems while engaging in experiential learning (via the use of realistic representations). Where large amounts of investment are required, or

where there are concerns related to the safety of the learner, this use of DTs is most beneficial [11].

Furthermore, digital twins are increasingly being implemented in workforce development and industry-specific training programmes through their ability to simulate real-world processes and better connect theoretical coursework with practical skills, helping to prepare students for an Industry 4.0 setting [11]. Additionally, the integration of immersive technologies such as AR, VR, and XR into DT-based educational applications creates an immersive, interactive learning environment that further enhances the development of the students [4, 14].

Overall, applications of digital twin technology have the potential to reshape how humans relate to technology in education. This change can be understood through various changes that occur along the way:

- Students move from passive recipients of information to active participants in adaptive learning systems

- Educators evolve from being instructors; they become facilitators through their access to timely and reliable information
- Technology becomes an intelligent mediating layer that supports feedback, personalization and instructional decision-making.

In this process, AI plays a central role by analyzing learner data, identifying patterns and transforming them into feedback and instructional support. Figure 3 summarizes the relationship between digital twin technology, AI and adaptive educational processes.

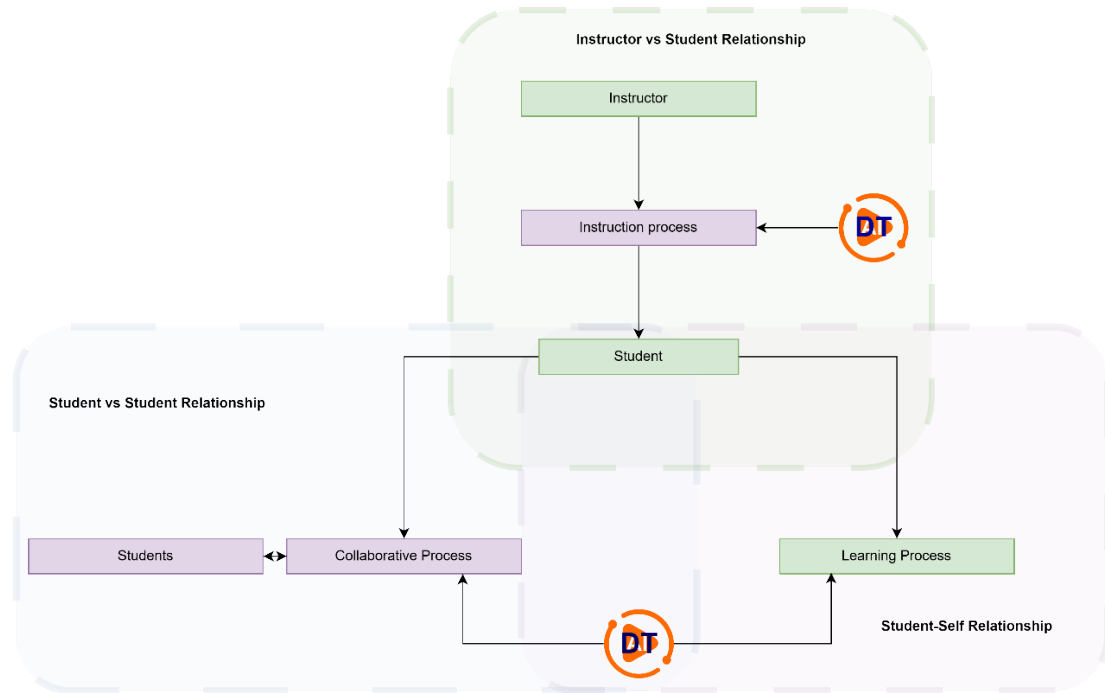


Figure 3. Digital Twin and AI in education

This AI-supported interaction between learners, educators and digital environments helps explain why DTs can be applied not only in typical traditional classroom environments but also remote and hybrid environments; therefore, making education much more resilient against disruptions [4, 5].

In addition to supporting various educational environments, DT create cyber-physical educational ecosystems with connected physical and digital components; therefore, making learning an ongoing experience based on continuous interaction through the use of real-time data and intelligent systems rather than simply existing in predetermined structures [4, 6, 7].

5. Challenges, Discussion, and Future Directions

Digital twins have the potential to

revolutionize education, but presently numerous factors limit their broad application. A major technical challenge concerns the integration of heterogeneous data sources and the maintenance of real-time synchronization between physical and virtual educational environments. The accuracy of a digital twin can be indirectly affected by the efficiency and capabilities of technology infrastructure used by the school system and whether or not there is sufficient technical expertise available within the educational community to build and maintain these systems [3, 9].

Another obstacle to implementing digital twins is cost. Initial costs associated with digital twin hardware, software and systems are high, which often create concerns regarding equity because the initial costs cannot be absorbed by under-resourced

educational institutions. Finally, the use of student data to create and maintain digital twins raises significant ethical questions related to the collection, storage, use and dissemination of individualized student data [10, 14].

From a pedagogical point of view, one of the major limitations of DTs in the classroom is the non-existence of an instructional model to guide teachers toward effectively integrating DTs into coursework. While there are many examples of DTs that successfully employ emerging technologies, they do not necessarily reflect the integration

of well-established learning theories into their implementations [11, 12]. Addressing this development gap in implementation is necessary to guarantee that DTs will enhance educational outcomes and not just add to the complexity of using technology in education.

The barriers discussed above are closely interconnected and indicate that the integration of digital twins into educational contexts remains challenging. Figure 4 summarizes the main technical, economic, ethical and pedagogical challenges associated with their implementation.

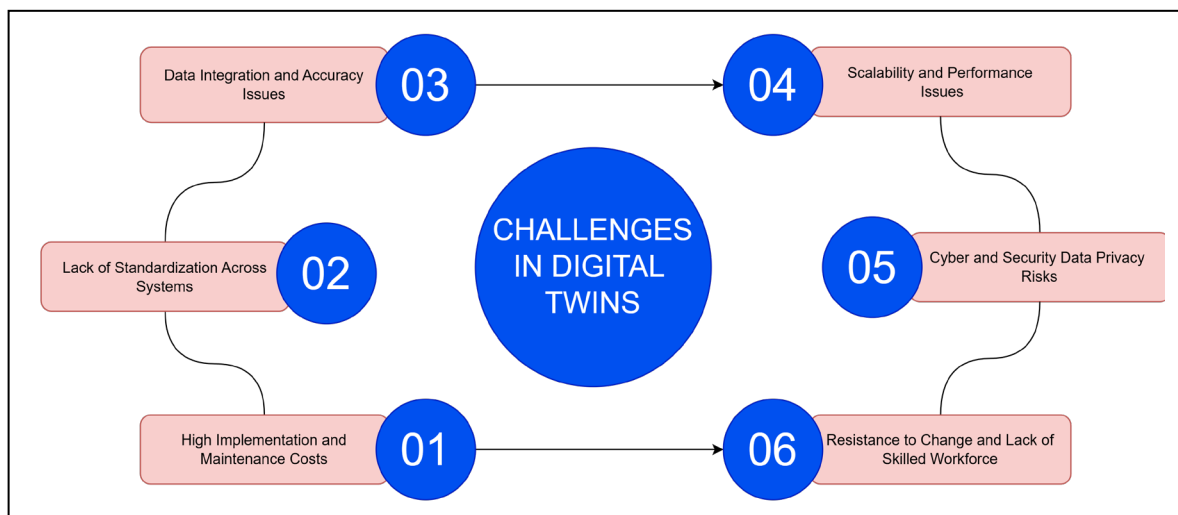


Figure 4. Challenges in Digital Twins

Currently, the integration of DTs into educational practices is inconsistent in relation to levels of maturity exhibited in each of the application areas. Some examples of more mature use of DTs are:

- Simulation-based learning in engineering and healthcare
- Virtual laboratories and training environments
- Industry-aligned workforce development

While cognitive digital twins and metaverse-based education are still relatively new concepts; they are yet to show any significant empirical evidence of being successful [14, 16]. Digital twins add value by integrating data, modelling, analytics, and feedback into a cohesive adaptive

system. This distinctive property supports the argument that digital twins may become important components of future learning environments. There is a lot of potential for future research related to digital twin technology (e.g., developing a clear definition and description of digital twin operation; potential avenues for including artificial intelligence processing in the model; and finally, building an educational base or frame of reference for the use of these novel technologies) [13, 14]. Moreover, researchers must work together as teams across different types of disciplines when attempting to solve the complex problems involved with implementing digital twins.

6. Conclusions

This paper mapped the emerging literature on DTs in education and clarified their conceptual foundations, application areas, pedagogical implications and adoption challenges. The findings indicate that digital twin technology is an emerging area in innovation for education that has potential to create adaptive, data-driven and interactive learning environments. Digital Twins (DT) provide real-time data connections between the physical and digital systems to support personalization, simulation-based training and greater levels of human-technology integration within the context of personalizing the educational experiences for the learners [14].

A central contribution of this paper is the classification of educational digital twins according to the entity being modelled. The proposed classification distinguishes between student digital twins, laboratory digital twins, classroom digital twins, curriculum digital twins and institutional digital twins. This classification helps clarify the conceptual diversity of the field and provides a basis for future research, design and implementation.

Although there are many advantages to using DTs, there are still many challenges at this stage of development within this emerging area of educational technology; such as the complexity of DTs, affordability,

data privacy and pedagogically aligned learning resources will impede their potential development [15]. Collaborations between technology, education and policy are required to overcome these challenges [16].

As digital technologies evolve over time, digital twins will increasingly be critical for shaping the future of education. DTs are able to integrate data, intelligence and interaction, which places them in a position to be one of the most influential components of next-generation learning systems.

Future research should move beyond technologically optimistic descriptions and provide empirical evidence regarding learning outcomes, teacher use, student engagement, skill development, privacy protection and scalability.

In conclusion, digital twins should be understood as promising but still developing educational technologies. Their value lies not simply in creating virtual replicas, but in integrating data, modelling, analytics and feedback into learning systems that can support more adaptive, interactive and evidence-informed education. However, their successful adoption depends on responsible implementation, pedagogical alignment and critical evaluation of both benefits and risks.

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