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Digital Twin Technology for Education, Training and Learning in Construction Industry: Implications for Research and Practice

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Abstract

Purpose

This study explores the potential of Digital Twin (DT) technology to enhance education and training in the construction industry. It aims to provide a clear understanding of how DT can be applied for educational purposes and proposes a framework to facilitate the adoption of DT in construction training.

Design/Methodology/Approach

A systematic literature review was conducted to examine the current applications of DT technology in construction education and training. A total of 19 relevant studies were identified and analysed to evaluate the educational objectives, tools, technologies and integration methods used in developing DT models for the construction sector. Based on this analysis, a conceptual framework was developed to guide the integration of DT technology into construction education, addressing gaps in the current literature and practices.

Findings

The analysis revealed a strong consensus on the effectiveness of DT technology in supporting education and training objectives within the construction industry. The study highlighted the fragmented nature of the current literature and proposed a comprehensive framework designed to facilitate the integration of DT in construction education. This framework offers a structured approach to bridging the gap between theoretical learning and real-world application.

Originality

The research presents a new systematic framework developed based on an in-depth review for utilizing DT in education, training and learning (ETL) processes in construction. The framework provides a novel and structured learning process to integrate theoretical knowledge with practical skills to support workforce development in the construction industry. This framework offers a structured roadmap for future research and practical applications.

Keywords: Digital Twin; Construction Workers; Education; Digital Technology; Construction Industry; Industry 4.0; Construction Employment; Social Sustainability; Migrant Workers.

1. Background

Migrants significantly contribute to global economic growth (Fassio et al., 2019), but managing their impact on infrastructure and resources requires careful planning. A recent report issued by the United Nations Department of Economic and Social Affairs in 2020 estimates 281 million migrants worldwide, highlighting the urgent need to develop effective strategies for managing global migration (UNDESA, 2020). The United Nations High Commissioner for Refugees (UNHCR, 2018) characterises a migrant as an individual who relocates from their country of usual residence, regardless of the reasons for moving or their legal status. Within this global context, Australia emerges as a prominent destination, attracting a substantial influx of migrants annually to support its industries. In particular, Australia recorded a net annual increase of 518,000 migrants during the period of 2022-23, representing an unprecedented 73% rise in migrant entries compared to previous years (Australian Bureau of Statistics, 2023). A large majority of this population targets the construction industry as a major source of employment due to its large size and extensive job opportunities available in this industry.

A recent report introduces the construction industry as the third most appealing sector in Australia attracting over 36,000 workers between 2023 and 2024 (Jobs and Skills Australia, 2024). This underscores the substantial allure of this industry for migrants, affirming its pivotal role in providing employment opportunities and contributing to the nation's economic growth. Nonetheless, the findings of recent studies (Loosemore et al., 2022; Hammad et al., 2023; Alkilani et al., 2024) revealed a reluctance within the Australian construction industry to accept newly arrived migrants. Amidst all, ‘lack of industry-specific experience’ and ‘difficulties in validating previous skills and qualifications’ were identified as the key challenges impeding migrants' employment in this industry (Loosemore et al., 2021; Loosemore et al., 2022; Alkilani et al., 2024).

Recent studies shed light on the challenges surrounding migrants’ employment in the construction industry, voicing a call for immediate action (Loosemore et al., 2022; Hammad et al., 2023; Alkilani et al., 2024). For example, Loosemore et al. (2022) identified a dearth of research on migrants’ experiences in securing work within the industry. Their findings revealed several barriers hindering migrants' job prospects, including the lack of local work experience, employer discrimination, failure to recognise migrants' qualifications and skills, and employers' lack of understanding of the challenges faced by migrants. Additionally, migrants perceived governmental employment agencies and systems as offering limited assistance in their job search endeavours. These findings are consistent with those reported by Loosemore et al. (2021), who identified the greatest barrier to employment as the lack of construction industry experience, followed by poor recognition of prior skills and experience.

Hammad et al. (2023) developed an equation model to analyse the factors influencing the job-seeking experiences of refugees and skilled migrants in the Australian construction industry. Their findings indicated that a candidate's familiarity with the local market positively affects their perceived support structures, which subsequently influences their work-related acculturation and opportunities for securing meaningful employment. The study concluded that policymakers should prioritise the better integration of skilled migrants and refugees into the local construction industry.

In the construction industry, digitalisation refers to the use of digital technology in day-to-day operations to deliver both tangible and intangible services within a construction organisation (Aghimien et al., 2019). Industry 4.0 is a term used to describe the rapid technological advancements of the 21st century. Chartered Institute of Building (2024) classified Industry 4.0 in construction into nine areas: Internet of Things (IoT), Artificial Intelligence (AI), Analytics, Robotics, Human-machine Interaction, Cloud Computing, Data (e.g., BIM data), Connectivity and DT. Industry 4.0 drives a shift towards automation, enabling the transition from low-skilled to high-skilled workers. However, the uptake of Industry 4.0 in the construction industry has been limited. Hence, a plethora of research has been carried out to solicit underlying reasons for the slow adoption of Industry 4.0. In a recent study, Mazurchenko and Zelenka (2022) identified several obstacles to construction 4.0 adoption, comprising (1) poor understanding of modern technologies, (2) negligence of construction workers to accept changes, (3) difficulties in describing the outcomes from the technology to the client, (4) complex nature of construction projects, (5) low technical know-how, (6) cost of construction 4.0 in terms of training, maintaining technologies.

To address these challenges, one promising approach involves advocating for the adoption of cutting-edge digital solutions. In recent years, digital twin (DT) technology has emerged strongly, demonstrating its versatility in various industries (Bakhshi et al., 2024 and Patel et al., 2024). The core of DT implementation depends on creating a digital representation of a physical entity using data to mimic its behaviours and functionalities in its actual context (Omrany et al., 2023). The DT technology utilises virtual replicas of physical assets, processes, and systems to provide immersive and interactive training environments for participants (Omrany and Al-Obaidi, 2024). Implementing a DT technology allows for forecasting potential problems, system feedback, and response based on simulation data (Xie et al., 2023). Among DT's potential applications is its capacity for education, training and learning (ETL), which holds particular promise for tackling the challenges mentioned afore (Sepasgozar, 2020).

The terms education, training and learning may often be used interchangeably, but they have different implications. Demystifying these terms would provide prospects to offer new skills for migrants and refugees in the local construction industry. Masadeh (2012) stated that education offers learners a foundation of knowledge that supports any activity they may engage with in the future, training tends to focus on skill development, while learning considers the results of both training-led and education-led approaches to development. In the context of literature, the adoption of DT can support optimising the ETL methodologies and facilitate smoother integration pathways for migrants within the construction industry. Through DTs, migrants may access tailored training modules and simulations, enabling them to acquire industry-specific skills and experience in a risk-free virtual setting.

Several studies demonstrated the application of DT in ETL. Speiser and Teizer (2024) provided personalised training scenarios to enhance construction safety training using digital twins. De

Los Santos Melo and Beriguete Alcántara (2024) presented a deeper understanding of complex processes and innovative solutions by integrating DT platforms to simulate real-world scenarios to improve immersive learning, real-time simulations and asset performance, and problem-solving skills. Zhang et al. (2024) developed a DT system using VR workstations, IoT sensors, 3D visualisation, and real-time feedback to develop engineering education in landscape architecture. Agostinelli and Nastasi (2023) used DT and MR for immersive training environments, integrating BIM data for real-time updates and remote collaboration to improve FM training and maintenance operations.

Despite its promising potential, the literature on DT technology for facilitating ETL in the construction industry remains fairly fragmented. Therefore, this paper aims to fill this gap by examining how DT can be effectively and systematically utilised to support ETL processes in construction. To achieve this, the paper sets two key objectives: i) to strengthen the understanding of DT's potential for ETL through a review of the relevant literature, and ii) to propose a conceptual framework to guide the effective integration of DT into construction ETL. This framework offers a structured roadmap for future research and practical applications, particularly in facilitating the assimilation of construction workers with diverse knowledge and cultural backgrounds into the host country’s industry. The ultimate goal of this study aligns with social sustainability goals, aiming to minimise inequality and promote inclusivity in the construction industry.

The outcomes of this study can benefit multiple target groups. First, researchers can use the findings of this study as a foundation for advancing knowledge and exploring new applications of DT in the construction industry for ETL purposes. Second, policymakers can also leverage the proposed framework to develop strategies that enhance inclusivity and workforce development. Lastly, practitioners in the construction industry can adopt the insights to improve training programs and effectively integrate diverse workers into the sector. The remainder of this paper unfolds as follows: Section 2 outlines the methodological approach adopted in this study, Section 3 presents the results of the literature review, Section 4 discusses the conceptual framework proposed, and finally, Section 5 offers concluding remarks.

2. Research Methods

This paper adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to systematically identify and retrieve publication materials (Figure 1). The PRISMA is one of the most commonly used approaches for performing systematic literature reviews across various disciplines (Page et al., 2021). The first step involved developing a search syntax to enable identifying materials related to the aim and scope of this paper. Consequently, the following syntax was developed and applied into the search engines of Web of Science (WoS) and Scopus on 9th of July 2024: ("construction industry" OR "building sector" OR "AEC" OR "architecture engineering and construction" OR "built environment") AND ("digital twin" OR "virtual twin" OR "digital replica" OR "virtual replica" OR "twin technology" OR "virtual simulation" OR "twin model" OR "cyber twin" OR "mirror model" OR "virtual model" OR "replica model" OR "virtual representation") AND ("education" OR "training" OR "learning" OR "skill development"). The initial search yielded a total of 223 documents, with 160 retrieved from Scopus and 63 from WoS. This paper proceeded by eliminating duplicate entries, excluding non-English materials, and employing filtering functions within these platforms to sift out sources deemed irrelevant, such as those pertaining to agriculture and medical science. As a result, 26 documents were excluded.

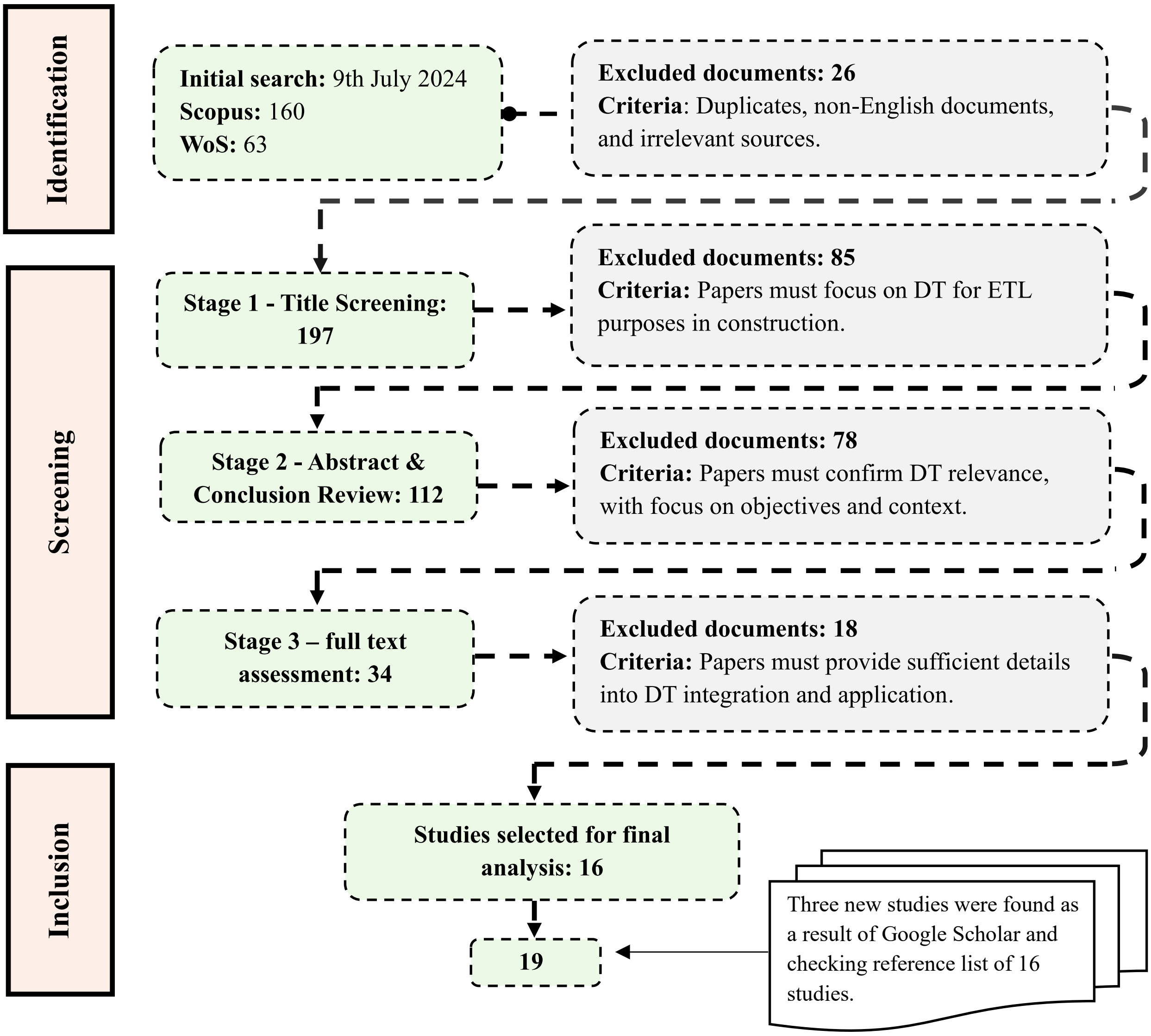

Figure 1. An overview of methodological approach

Afterward, three stages of screening were performed to ensure that the materials selected for the final analysis were all related to the aim and scope of this paper. In the first stage, the titles of shortlisted materials were carefully screened to ensure that documents were entirely related to the application of DT technology for ETL purposes within the context of the construction industry. This was followed by the second stage in which the abstracts and conclusions of the remaining documents were qualitatively checked for essential details such as the study's objectives, methodology, and findings. The key criterion considered during this phase was that studies must have implemented DT for ETL purposes. For example, studies employing other digital technologies such as Virtual Reality (VR), mixed reality (MR), or Augmented Reality (AR) to improve training in the construction context were excluded. This exclusion is justified by the study's specific focus on DT technology, which uniquely integrates real-time data and virtual replicas, offering distinct advantages over other digital technologies.

Finally, the full texts of the selected documents were carefully reviewed to confirm they contained sufficient details on their adopted methodologies and reported results. This was particularly important for conducting a consistent content analysis across all the identified studies. The consideration of these filters led to the downsizing of the initial compiled database to 16 studies. Furthermore, two additional actions were undertaken to ensure the comprehensive identification of publications relevant to the scope of this paper. First, a separate search using the same keywords was conducted on the Google Scholar platform. Then, the reference lists of the selected 16 articles were meticulously reviewed. This subsequently led to the identification of three more articles, increasing the total number of shortlisted materials to 19.

Afterwards, a thorough content analysis was conducted on the selected papers to extract essential data. To this end, a Microsoft Excel spreadsheet was created to systematically extract information attributed to the studies' approach in the following areas: (i) tools and technologies employed for developing DTs, (ii) ETL objectives, (iii) methods utilised to integrate various models and technologies to construct an operational DT and (iv) evaluation of the effectiveness of using DTs for ETL purposes (See Table 1 and Table A of supplementary material). Each paper was reviewed in detail, and relevant information was categorised based on these criteria to ensure consistency. The collected data were thence synthesised to address the research objectives outlined earlier in the paper.

Reviewing the selected 19 studies as indicated in Table 1, Table A (supplementary material) and the eight examples in Section 4.1.5 helped in distinguishing common research areas to guide the framework development. McMeekin et al. (2020) established structured stages for framework development including three phases, which cover evidence from the literature to inform the methodological framework, build upon previous frameworks to create the foundations of the new methodological framework and use evaluation techniques to refine a proposed framework. As a result, this study adopted the approach in framework development by implementing three phases that include (1) identifying evidence to inform the methodological framework from previous studies, (2) developing the methodological framework through analysing the existing findings and (3) evaluating and refining the framework through a systematic development as shown in Figure 2.

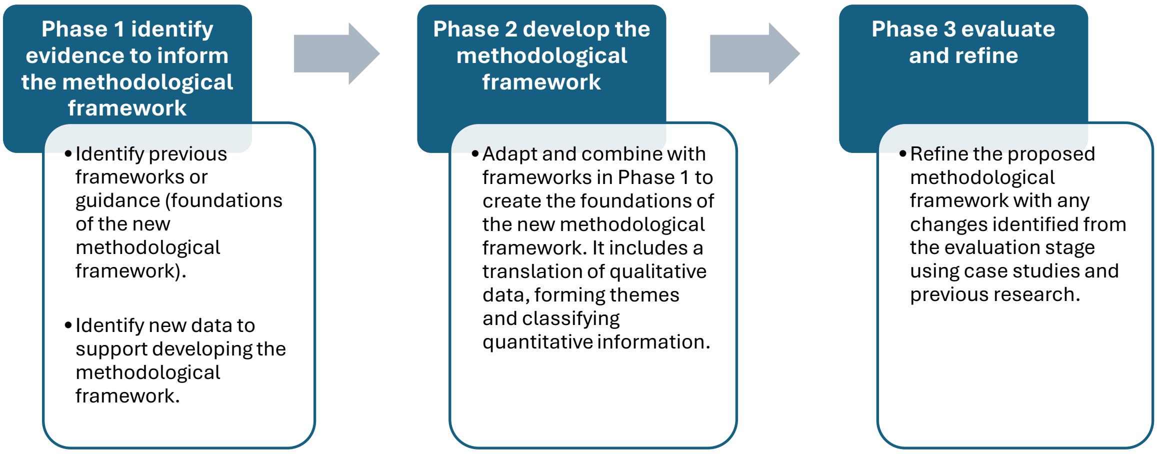

Figure 2. Steps for developing methodological frameworks as proposed by McMeekin et al. (2020).

The framework was developed by embedding theories, models and processes to support DT within ETL boundaries. In terms of theories, the development highlights a range of theoretical applications of digital technologies in education and the use of digital pedagogy to support the learning process. It considers a range of measurements including connectivity, scale, reflection, extension, embodiment, personalisation and creativity as mentioned in the Lunevich Model (Lunevich, 2021) and their connection to understanding the global framework of Digital Literacy Skills (UNESCO, 2018). For models, the framework investigated eight case studies, which exhibit various versions of DT in education. This examination highlighted key factors and workflows to understand design structures and research procedures. For processes, the framework inspected the features of the digital twin structure and applications. It helped the framework in defining the core components and their interactions including three areas: physical reality, virtual representation and interconnections between the physical and virtual elements.

Accordingly, the framework was structured to cover two key areas: DT Learning Phases and DT Application Phases. In the Learning Phases, the framework consisted of four distinct stages: the existing DT model for learners, fundamental aspects of physical reality, virtual exemplification and interconnectivity between physical and virtual environments. The Learning Phases were developed to provide a foundation for learners to understand theoretical concepts and practical applications before transitioning to the implementation phase. In the DT Application Phases, the framework demonstrates a technical approach to illustrating practical applications of DT using components, states and layers in two states, Intent (design/planning) and Status (real scenario). The details of framework development are presented further in section 4.2.

3. Exploring DT Applications in Construction Education

This section presents the findings of the systematic review on the application of DT technology for ETL purposes in the construction industry, organised by the key themes identified during the content analysis. Further details regarding content analysis can be found in Table A of supplementary material.

3.1 Educational and Training Objectives

The primary ETL objectives identified in the reviewed studies emphasise enhancing safety (Harichandran et al., 2021; Kamari et al., 2022; Wu et al., 2022; Speiser and Teizer, 2024), improving practical skills (Sepasgozar, 2020; Podder et al., 2022; Agostinelli and Nastasi, 2023; Martínez-Gutiérrez et al., 2023), and fostering interdisciplinary learning (Chacón et al., 2018; Wahbeh et al., 2020; Chacón, 2021; Gade et al., 2023; De Los Santos Melo and Beriguete Alcántara, 2024). Several studies focused on using DT technology to enhance safety training in the construction industry. Speiser and Teizer (2024) aimed to improve construction safety by creating realistic virtual training environments (VTEs) through the integration of DTCS frameworks with BIM and the Unity game engine. Similarly, Wu et al. (2022) combined DT with MR and DL algorithms to enhance hazard identification and real-time hazard awareness, thereby improving safety training outcomes. These studies underscore the significant role of DT technology in providing immersive and interactive environments that simulate real-world scenarios, substantially enhancing the effectiveness of safety training programs.

In addition to safety training, other studies targeted the development of multidisciplinary skills and digital literacy. Hazrat et al. (2023) and Gade et al. (2023) integrated DT with Industry 4.0 components, such as IoT sensors and data analytics tools, to foster human-centric decision-making and prepare students for future industry demands. This approach not only enhances technical skills but also encourages interdisciplinary collaboration and problem-solving. Similarly, Agostinelli and Nastasi (2023) and Podder et al. (2022) utilised DT in combination with AR devices, such as Microsoft HoloLens, and industry-specific tools to improve practical skills and operational efficiency. Sepasgozar (2020) also focused on enhancing construction management and engineering education by integrating DT technology with VR, AR, BIM, 3D models, and IoT sensors to create immersive learning experiences that engage students and develop their practical skills. These studies demonstrate the broad applicability of DT technology in meeting diverse educational objectives. By effectively addressing a range of needs—from enhancing safety training and improving practical skills to fostering interdisciplinary collaboration and learning—DT technology proves to be a multifaceted tool. Its ability to create immersive, interactive, and real-time learning environments not only engages students but also equips them with the necessary skills for real-world construction scenarios. This comprehensive approach underscores the transformative potential of DT technology in revolutionising construction education, making it more dynamic, effective, and aligned with industry demands. Table 1 outlines the main ETL objectives and research dimensions in exploring DT applications in construction education.

Table 1. Summary of ETL objectives and research dimensions on DT technology

Studies	**ETL Objectives**	**Research Dimensions**
Speiser and Teizer (2024)	Enhance construction safety training by creating realistic VTEs; provide personalised training scenarios.	Construction Workers DT Structure and Applications
De Los Santos Melo and Beriguete Alcántara (2024)	Enhances immersive learning, real-time simulations, design exploration, asset performance, and problem-solving skills.	DT Structure and Applications DT Models in Education

Zhang et al. (2024)	Enhance engineering education in landscape architecture.	Digital Dimensions Digital Education DT Models in Education
Martínez-Gutiérrez et al. (2023)	Enhance digital learning, improve skill transfer, increase safety and efficiency.	Construction Workers DT Structure and Applications
Hazrat et al. (2023)	Enhance engineering education by developing multidisciplinary skills, fostering human-centric decision-making, and preparing students for future industry demands.	Digital Dimensions Digital Education DT Structure and Applications DT Models in Education
Gade et al. (2023)	Develop digital literacy, DT technology understanding, foster interdisciplinary collaboration, and prepare students for future industry challenges.	Digital Dimensions Digital Education
Agostinelli and Nastasi (2023)	Improve FM training and maintenance operations, enhance problem-solving and decision-making, and foster interdisciplinary collaboration.	Digital Education DT Structure and Applications, DT Models in Education
Wu et al. (2022)	Improve construction safety by enhancing hazard identification, real-time awareness, and offering immersive training.	Construction Workers DT Structure and Applications
Podder et al. (2022)	Improve energy efficiency construction workforce training, enhance skills in operating Industry 4.0 components, and handling energy-efficient products in industrialised construction.	Construction Workers DT Structure and Applications, DT Models in Education
Kamari et al. (2022)	Improve hazard identification and risk assessment in construction sites, enhance safety protocols and disaster preparedness.	Construction Workers DT Structure and Applications
Hasan et al. (2022)	Enhance construction machinery operation training, improve project management and monitoring, increase safety, and facilitate remote operation and control.	DT Structure and Applications
Ogunseiju et al. (2021)	Improve self-management of ergonomic risks, enhance awareness of WMSDs, and provide real-time feedback on workers' postures.	Construction Workers DT Structure and Applications
Harichandran et al. (2021)	Enhance construction safety training by providing dynamic and realistic VR training environments; improve hazard awareness and safety compliance.	Construction Workers DT Structure and Applications
Chacón (2021)	Enhance civil engineering education through Construction 4.0 activities, promote STEAM education, and foster interdisciplinary skills.	Digital Dimensions Digital Education DT Models in Education
Wahbeh et al. (2020)	Enhance interdisciplinary learning in architecture, civil engineering, and geomatics; improve skills in VDC; promote practical application of DT technologies in academic settings.	Digital Education DT Models in Education
Sepasgozar (2020)	Improve construction management and engineering education through immersive learning experiences, enhance students’ engagement, and	Digital Dimensions Digital Education DT Models in Education

	develop practical skills in handling complex construction tasks.	
Liljaniemi and Paavilainen (2020)	Increase motivation for studying, improve learning outcomes, develop expertise in DT technology.	DT Structure and Applications DT Models in Education
Chacón et al. (2018)	Enhances civil engineering education with hands-on experiences, improves IoT understanding, and develops skills in sensors, data acquisition, and digital visualisation.	Digital Education DT Models in Education
Goedert et al. (2011)	Improve construction education and training by providing immersive, interactive simulations that enhance practical skills and decision-making.	Digital Education DT Structure and Applications

3.2 DT Tools and Technologies

The reviewed studies highlight a wide array of tools and technologies used to develop DT models that enhance ETL in the construction sector. These include BIM tools, IoT sensors, and various simulation and visualisation technologies for creating and deploying DT models. BIM tools allow for precise and comprehensive construction project modelling, while IoT sensors enable real-time data collection and monitoring (Opoku et al., 2021; Al-Obaidi et al., 2022; Omrany et al., 2024b). Simulation and visualisation technologies also contribute to developing immersive and interactive learning environments (Omrany et al., 2023). For example, Speiser and Teizer (2024) utilised DT for training safety in construction by developing a framework integrated with BIM and the Unity game engine to develop virtual training environments. Martínez-Gutiérrez et al. (2023) also employed a Robot Operating System, Unity for graphics, and Oculus Quest 2 VR glasses for creating immersive training experiences for users. Additionally, Hazrat et al. (2023) and Gade et al. (2023) incorporated DT with Industry 4.0 components and data analytics tools to cultivate multidisciplinary skills and digital literacy. Studies by Agostinelli and Nastasi (2023) and Podder et al. (2022) focused on using DT in conjunction with AR devices like Microsoft HoloLens and industry-specific tools such as the Pre Framer™ machine to improve practical skills and operational efficiency. This range of applications demonstrates the versatility and potential of DT technology to transform construction ETL by offering immersive, interactive, and real-time learning experiences tailored to various educational goals.

3.3 Methods of Integrating DT Technology

The reviewed studies employed various methods to integrate DT technology into construction ETL, demonstrating innovative approaches tailored to their specific educational objectives. Several studies, such as those by Speiser and Teizer (2024) and Wu et al. (2022), focused on creating immersive learning environments through the integration of DT with virtual and MR technologies. Speiser and Teizer (2024) integrated BIM models, schedules, resources, and hazard data into VTEs using the Unity game engine, enabling personalised training scenarios with minimal user interaction. Similarly, Wu et al. (2022) developed a real-time visual warning system combining DT with MR, DL algorithms, and IoT sensors to enhance hazard identification and safety awareness on construction sites. These approaches underline the potential of DT technology to create realistic and dynamic simulations that enhance practical learning experiences and safety training. By using advanced visualisation and simulation tools, these studies provide trainees with the opportunity to engage in lifelike scenarios that mirror real-world conditions, which helps in developing critical thinking and decision-making skills essential for managing actual construction projects.

Other studies highlighted the use of DT technology to foster interdisciplinary collaboration and digital literacy. For instance, Hazrat et al. (2023) and Gade et al. (2023) implemented DT-based labs and integrated DT tools into existing curricula and pedagogical frameworks. Hazrat et al. (2023) utilised Industry 4.0 components, such as IoT sensors and data analytics, to create multidisciplinary learning environments and prepare students for future industry challenges. Similarly, Gade et al. (2023) employed DT as semantic learning material in educational programs, conducted focus group interviews to assess student understanding, and incorporated practical workshops to enhance digital literacy and critical thinking skills. These studies highlight the versatility of DT technology in promoting comprehensive educational strategies that address both technical proficiency and interdisciplinary collaboration. The wide-ranging applications of DT technology indicate its potential to greatly enhance construction ETL by equipping students with practical, real-world skills and creating an environment that encourages innovative problem-solving. Figure 3 demonstrates areas to develop methods of integrating digital twins as identified by the selected 19 studies, further information can be found in Table A of supplementary material.

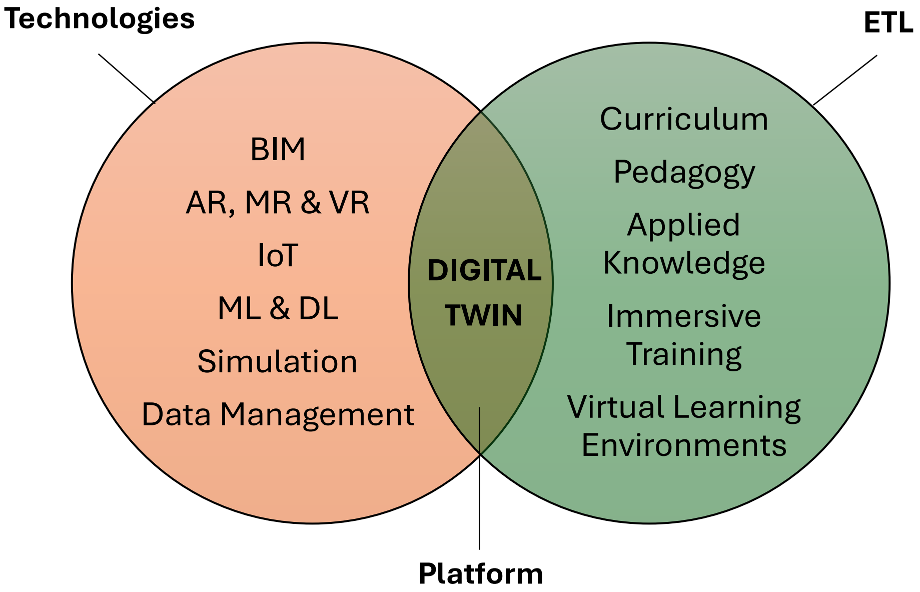

Figure 3. Illustration of identified areas to explore methods to integrate DT technology into ETL construction.

3.4 Evaluation of Effectiveness

The evaluation of effectiveness across the reviewed studies reveals a consistent positive impact of DT technology on construction ETL. Numerous studies reported enhanced learning outcomes, increased student engagement, and improved practical skills. For instance, Speiser and Teizer (2024) demonstrated the efficacy of their DTCS framework through three real-world projects and a case study, highlighting meaningful feedback provided to trainees using runtime data collection and analysis.

Studies focusing on interdisciplinary skills and digital literacy also reported positive outcomes. Liljaniemi and Paavilainen (2020) noted increased motivation and improved learning outcomes by integrating DT tools such as the NX Mechatronics Concept Designer in engineering education through practical projects and virtual learning environments. In another study, Hazrat et al. (2023) observed improved student engagement and skill acquisition through the implementation of DT-based labs and integration with existing curricula. Gade et al. (2023) highlighted the importance of digital literacy, creativity, critical thinking, and practical knowledge, noting that their DT technology integration in ETL programs effectively fostered these skills. Agostinelli and Nastasi (2023) found that using DT and MR for immersive training environments led to enhanced operational performance, reduced maintenance errors, and increased efficiency. Moreover, the application of DT technology in specific training scenarios also proved beneficial. Wu et al. (2022) validated the increased accuracy in risk assessment and improved safety behaviour through system tests in quasi-on-site scenarios. Podder et al. (2022) reported enhanced learning experiences, increased productivity, and improved task preparation and execution in energy-efficient construction workforce training. Hasan et al. (2022) also demonstrated improved safety, operation precision, and remote monitoring capabilities with their DT system integrated with AR, IoT sensors, and Cyber-Physical Systems.

Overall, the consistent positive feedback across various studies underscores the transformative potential of DT technology in construction education. Unlike other technologies such as VR, MR, or AR, DT technology provides a comprehensive and dynamic digital replica of physical assets, processes, and systems. This integration allows for real-time data synchronisation, predictive analytics, and advanced simulations that go beyond static or isolated virtual experiences. For example, Sepasgozar (2020) reported a significant improvement in student engagement and understanding of complex construction processes due to the integration of DT technology with VR, AR, BIM, 3D models, and IoT sensors. Similarly, Goedert et al. (2011) observed enhanced learning outcomes and improved decision-making skills in construction management education through the use of the Virtual Interactive Construction Education system, which employed DT technology along with 3D simulations and game-based learning. The ability of DT to offer continuous, real-time updates and feedback makes it a robust tool for training and education, ensuring that learners are not only immersed in realistic scenarios but also equipped with the latest data and insights to enhance their practical skills and decision-making abilities.

4. Conceptual Framework: Design and Application

This section outlines the details involved in developing a conceptual framework from a technical standpoint for implementing DT technology for ETL in construction. It includes two stages:

i) establishing framework's dimensions: In Stage 1, five key dimensions are derived from Section 3 and examined in the following sub-section (4.1). These dimensions were identified in Table 1, which include the characteristics of construction workers, digital (literacy, competence, skills and thinking), digital education, DT structure and applications, and DT models in education (Figure 4). This analysis was conducted prior to designing the conceptual framework.

ii) developing a systematic conceptual framework. In Stage 2, the identified dimensions were translated and developed into a comprehensive model to validate the proposed framework in the context of construction education.

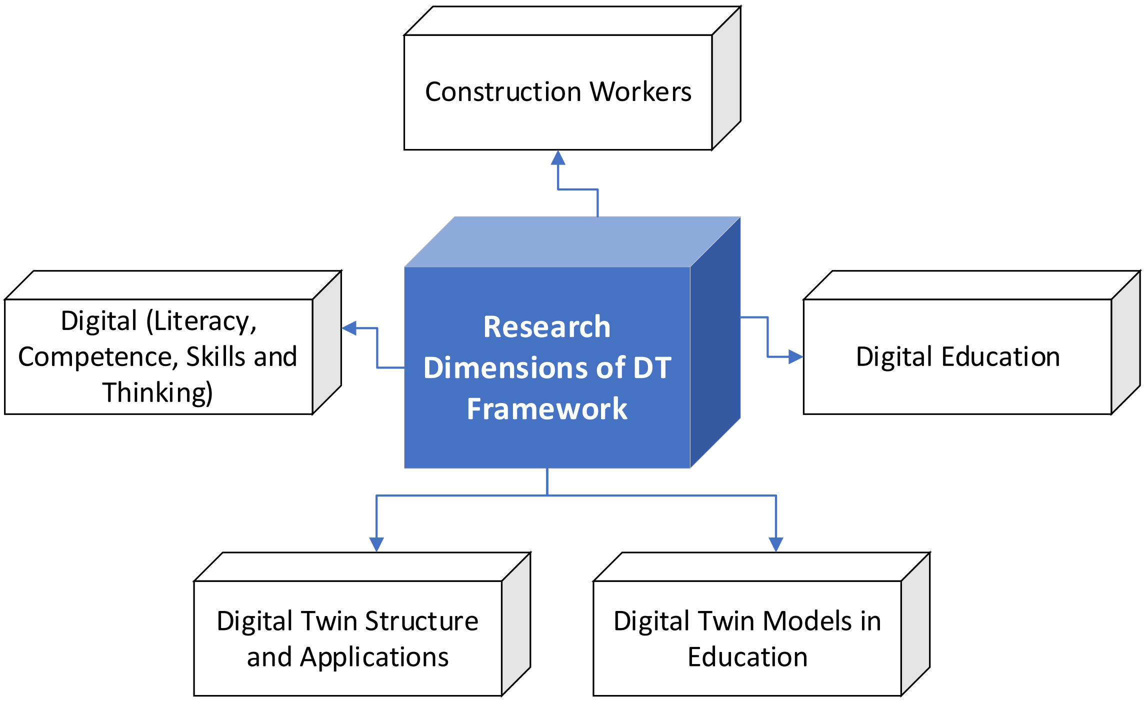

Figure 4. Model of research dimensions in developing DT framework.

4.1 Research Dimensions in Developing DT Framework

4.1.1 Dimension of Construction Workers

Construction workers in the 21st century encounter several challenges with promoting health and safety, training and skill formation and skills testing and certification (International Labour Organization, 2001; Kotera et al., 2020; Van Laar et al., 2020). Eaves et al. (2016) stated that construction workers confront high physical demands at construction sites. Fleishman and Mumford (1991) pointed out that cognitive, psychomotor, social, and sensory demands are needed beyond physical demands. Learning new tools adds new levels of demand and stress for construction workers due to constant updates on technical requirements.

Boschman et al. (2011) reported that construction supervisors reported their uppermost demands as inadequate staffing, a lack of competent personnel, poor communication, numerous regulations, frequent meetings, rapid task changes, financial management, paperwork stress, and complex decision-making. Rodriguez et al. (2020) also investigated Fleishman's job analysis using a survey. Their study revealed that the construction sector must acknowledge the demands of the cognitive and psychosocial domains, as a shortage in these areas could lead to an overload that negatively impacts workers' performance and the time management of projects. Figure 5 demonstrates the level of demand according to the Fleishman job analysis survey.

Cognitive (21 scales)	Oral Comprehension, Written Comprehension, Oral Expression, Written Expression, Fluency of Ideas, Originality, Memorization, Problem Sensitivity, Mathematical Reasoning, Number Facility, Deductive Reasoning, Inductive Reasoning, Sorting Information, Category Flexibility, Speed of Closure, Flexibility of Closure, Spatial Orientation, Visualization, Perceptual Speed, Selective Attention and Simultaneous Information Processing.
Psychomotor (10 scales)	Control Precision, Multiple Limb Coordination, Response Orientation, Rate Control, Reaction Time, Arm-Hand Steadiness, Manual Dexterity, Finger Dexterity, Wrist-Finger Speed and Speed of Limb Movements.
Physical (9 scales)	Static Strength, Dynamic Strength, Strength Endurance, Trunk Strength, Extent Flexibility, Dynamic Flexibility, Gross Body Coordination, Gross Body Equilibrium and Stamina.
Sensory-perceptual (12 scales)	Near Vision, Far Vision, Colour Discrimination, Night Vision, Peripheral Vision, Depth Perception, Glare Sensitivity, Hearing Sensitivity, Auditory Attention, Sound Localization, Speech Recognition and Speech Clarity.
Speech clarity Social (21 scales)	Friendliness, Behaviour Flexibility, Coordinating, Reliability, Expressing Opinion, Negotiating, Persuasion, Communicating with Others, Social Compliance, Social Sensitivity, Emotional Control, Self-Confidence, Training Others, Oral Fact-Finding, Motivation, Openness, Assertiveness, Persistence, Resistance to Premature Judgment, Debating and Stress Tolerance.

Figure 5. Areas and scales covered in the Fleishman job analysis survey.

Examining Fleishman’s criteria and research by Rodriguez et al. (2020), the study found that construction workers often deal with tasks that necessitate appropriate interaction. Industry 4.0 established avenues to enhance interactions and increase productivity using physical and digital technologies. Sacks et al. (2020) defined areas of digital technologies for monitoring construction, including distance measurement, global positioning systems, computer vision, audio and sonar, tag identification systems, communication networks and smart sensors and sensors networks. Calvetti et al. (2020) demonstrated models of interaction between construction workers and technology (physical and digital). The study was divided into two areas: a sensored construction site and human data generated. The area of a sensored construction site equips construction workers with various technologies including tools, software, communication and hardware. The human data domain encompasses worker conditions, human factors, and outputs. These areas represent an approach to enhancing the performance of construction workers in the 21st century.

Table 2 summarises two key areas that categorise the main technologies within each domain, as demonstrated by (Calvetti et al., 2020). Through the analysis of research conducted by Rodriguez et al. (2020), Sacks et al. (2020) and Calvetti et al. (2020), a theoretical perspective was developed to establish the relationship between Fleishman’s job analysis and the increasing demand for digital technologies. The results showed that proper training is essential for equipping construction workers with the skills to effectively use both physical and digital technologies, particularly DT.

Table 2. Criteria of worker 4.0 – areas of sensored construction sites and human data generated.

Sensored Construction Site		**Human Data**	
Technologies	Drones, CCTV, Mixed Vision Glasses, Smartwatches, Physiological sensors, Cameras, Point cloud motion 3D camcorders, environmental sensors, automated equipment, automated machines, smart phone, GPS and QRcode.	**Conditions**	Brain activity, Oxygen saturation, location path, respiration rate, heart rate, body motion, blood pressure, body orientation, body temperature, muscular effort, body transpiration, repetitive strain and environmental sensors.
Software	Embedded and Interface	**Human Factors**	Skill, Fatigue, Motivation
Communication	Bluetooth, Wi-Fi, Ethernet and 3G-4G-5G	**Performance**	Data and Statistics
Hardware	IoT, Local Storge and Cloud	**Outcome**	Safety, Training and Productivity

Preparing workers for Industry 4.0 requires actions to define their digital skills. Bergson-Shilcock (2020) classified digital skills in the industry into 4 types including (1) **No digital skills**: this group fails to meet one or more of the baseline criteria, such as completing at least four out of six basic computer tasks, proper computer usage, or willingness to take a computer-based assessment. (2) **Limited digital skills**: this group is capable of completing only simple digital tasks and steps that involve a basic, generic interface. (3) **Proficient digital skills**: This group possesses some digital knowledge but encounters difficulties with tasks that involve both generic and specialised technology applications. (4) **Advanced digital skills**: This group is proficient in navigating various online platforms and applications and can successfully perform multiple steps within a given task. These classifications provide a foundation for the industry to assess workers' readiness and for educational institutions to design their pedagogical models.

4.1.2 Dimension of Digital (Literacy, Competence, Skills and Thinking)

As defined before, digitalisation is an approach to integrating digital technologies into the work process (Aghimien et al., 2019). Understanding the concepts and applications of digitalisation is critical in helping construction workers assess their technological and communication skills. Clearly defining these concepts also enables employers and educators to evaluate workers' readiness for this evolving digital landscape.

Tinmaz et al. (2022) provided a systematic approach to understanding digital applications in different educational settings. The study identified four areas: digital literacy, digital competence, digital skills and digital thinking. Studies have shown that while the term 'digital literacy' has not been explicitly introduced as a formal concept, it is referenced in the literature as the understanding and practical use of information through digital technologies in daily life (Canchola-Gonzalez and Glasserman Morales, 2020; Cetindamar Kozanoglu and Abedin, 2021; Reyes and Avello-Martínez, 2021). Dimitrakopoulou (2022) defined digital literacy as the capability to exhibit knowledge and skills using a wide range of technological tools and communicate across different digital platforms. In another study, Marín and Castaneda (2023) stated that digital literacy is a concept that encompasses skills and practices involving fluency, literacy, and competence, integrating knowledge, skills, and attitudes in a cohesive manner.

Digital competence is another critical aspect of digitalisation that must be taken into consideration when assessing the skills needed by construction workers. Ilomäki et al. (2016) defined digital competence as the proficiency individuals need to master in today's digital society, while digital literacy refers to the integration of multiple literacies, including information, computer, and media. Studies have shown that digital competence and digital literacy are often used interchangeably, although they have distinct meanings. In contrast, digital skills and digital thinking are typically defined separately in the literature. Van Laar et al. (2017) described digital skills as proficiency in using information and communication technology (ICT) applications, as well as skills related to cognitive processes and higher-order thinking. From the authors' perspective, digital skills can be divided into essential (social media, video conferencing, digital marketing, digital research analytics, spreadsheets, digital collaboration, data communication, video editing, design, data visualisation and project management) and advanced (user experience design, coding, AI, cloud computing and app development). Nonetheless, Sundarrajan (2016) and Neeley and Leonardi (2022) stated that digital thinking or digital mindset is a set of attitudes and behaviours possessed by individuals to understand data and technologies.

An analysis of the stated definitions reveals that digitalisation has been studied from various perspectives since its emergence over the past decades (Esteve-Mon et al., 2020). However, all definitions encompass attitudinal, technological, and cognitive components aimed at questioning, exploring, understanding, communicating, and expressing ideas (Avello Martínez et al., 2013). Accordingly, the study identified two key frameworks for understanding digital literacy and digital competence. Ferrari and Punie (2013) introduced a research project initiated by the European Union that established the first framework for understanding digital competence in Europe. Later in 2018, UNESCO developed a global framework to address Digital Literacy Skills (UNESCO, 2018). As a result, Figure 6 summarises the digital dimensions based on the key findings from these frameworks and analysed studies in retrospect (Sundarrajan, 2016; Van Laar et al., 2017; UNESCO, 2018).

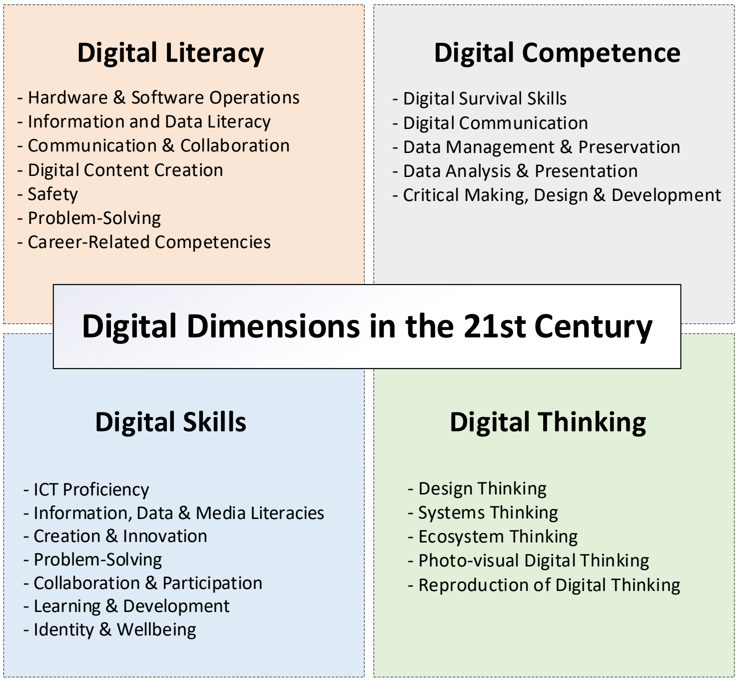

Figure 6. Digital Dimensions in the 21st Century

From the construction perspective, the World Built Environment Forum by RICS hosted a talk in 2023 to discuss the construction education skills gap: Training the Next Generation (RICS, 2023). Helen Taylor, the Director of Scott Brownrigg, highlighted specific skills required by the industry from new graduates (RICS, 2023). The required skills covered five key areas: (1) BIM skills (an extension of digital design proficiency), (2) digital collaboration, (3) sustainability, (4) project management, and (5) health and safety (RICS, 2023). It was further noted that behaviour and attitude, such as a proactive mindset, willingness to learn, flexibility, and self-motivation, are necessary. Additionally, the importance of graduates bringing fresh ideas and new software knowledge, which are considered valuable to practitioners, was emphasised.

The World Economic Forum (2020) highlighted that the rapid evolution of the labour market necessitates new sets of emotional, social, digital, personal development, and learning skills. Furthermore, it noted that workers with limited expertise or a singular skillset will struggle to maintain long-term employment. This shift has already gained momentum in the industry, as it transitions from routine-based, low-skilled jobs to greater automation and digitalisation (Morandini et al., 2020). The digital transformation is advancing towards both soft skills, such as teamwork, leadership, and problem-solving, and hard skills, including programming, simulation, and machine learning (Jurczuk and Florea, 2022). As a result, existing teaching and learning methods require fundamental shifts and developments to meet employers' increasing demand for digital skills. The need for such changes is further supported by the European Strategy for Universities, which emphasises the importance of maintaining high standards and resilience in adapting to unpredictable and evolving conditions (European Commission, 2022).

4.1.3 Dimension of Digital Education

The globalisation of learning and teaching has increased the demand for using digital technologies in education. The current age of information, data economy and communication technologies are the new currency for ETL. The changes in workforce and technological needs are shifting the environment of practice, demanding broad competencies than conventional norms in technological and scientific disciplines.

In the context of the construction industry, the learning approach requires a distinct delivery style that integrates both physical and digital environments. The conventional education models mainly rely on using theoretical and practical methods through physical environments. However, the shift in digital learning has provided new opportunities to develop learners' performance in terms of structured thinking, problem-solving and process comprehension (Hernandez-de-Menendez and Morales-Menendez, 2019). Haleem et al. (2022) discussed the significance of digital technologies and their applications in education. Table 3 tabulates the significance of bridging physical and digital technologies in education within four areas: Learning, Productivity, Resources and Skills.

Table 3. Areas and advantages of digital technologies in education (Haleem et al., 2022 & Hernandez-de-Menendez and Morales-Menendez, 2019).

Areas	Advantages
Learning	Innovative Way of Learning, Inclusive Learning Environments, Dynamic Education, Expand Knowledge, Flexible Education, Virtual Learning and Promote Education for Exceptional Needs.
Resources	Improved Access to Educational Resources, Online Resources & E-Books, Promote Distance Learning and Develop Online Libraries.
Skills	Addresses Learning Gaps, Increase Knowledge and Understanding Skills, Teamwork and Communication Skills and Gain Self-Learning Abilities.
Productivity	Quickly Gain Information, Access Up-To-Date Material, Breakdown all Educational Barriers, Evaluating Students in Real-Time, Increased Educational Opportunities and Improve Students' Performance.

Given the evolving educational environments and technological advancements, digital pedagogy in teaching and learning demands careful consideration of purpose, methods, learning formats, teaching tools, and content (Lunevich, 2021). Several studies revealed that new educational models encompass aspects such as experiential learning, personalised instruction, community engagement, and the integration of technology, all while addressing equity, diversity, and inclusivity (Gottschalk and Weise, 2023). As such, there is a necessity to understand learners and their needs in digital pedagogy. Lunevich (2021) classified learners into verbal (linguistic), visual (spatial), physical (kinesthetic), aural (auditory), logical-mathematical learning style, interpersonal and solitary. Each learner has special needs and demands to learn effectively. For instance, visual learner prefers learning by observing, logical-mathematical learning style learner prefers learning face-to-face/online, physical learner prefers learning with their hands via face-to-face/workshops/classroom, etc. In digital pedagogy, there are several digital platforms and tools for delivering teaching and obtaining knowledge. Examples of learning tools in virtual environments include web-based learning platforms, robots, digital games, virtual labs/simulations and smartphones. Teaching tools also encompass web-based platforms, social networks, Building Information Modelling (BIM), Internet of Things (IoT) technologies, and simulations. Each tool or approach owns distinct characteristics that necessitate tailored implementation strategies. Therefore, a thorough understanding of digital pedagogy is essential for effectively integrating these methods into the development of a framework for DT. Table 4 demonstrates the areas of critical digital pedagogy, as adopted from Lunevich (2021).

Table 4. Critical Digital Pedagogy - Lunevich Model (Lunevich, 2021)

Measurements	Methods
Connectivity	Crossover Learning, Personal Tools, Flipped Learning and Seamless Learning.
Scale	Massive Open Online Courses, Crowed Learning, Rhizomatic Learning, Citizen Inquiry and Social Learning.
Reflection	Learning Analytics, Learning to Learn, Learning Design Informed by Analytics, Assessment for Learning and Learning Through Argumentation.
Extension	Geo-Learning, Learning from Gaming, Event Based Learning, Computational Thinking, Threshold Concepts, Context Based Learning and Incidental Learning.
Embodiment	Embodied Learning, Bricolage and Maker Culture.
Personalisation	Personal Inquiry Learning, Dynamic Assessment, Analytics of Emotions and Adaptive Teaching.
Creativity	Problem Solutions and Group Work.

Pugacheva et al. (2020) provided an example to demonstrate the application of a digital paradigm in educational management using a virtual construction site. The study offered training based on digital resources to demonstrate the construction process and provided a glimpse into understanding the application of training using virtual environments. The research applied five functions to validate the steps in the educational process for learners: interactive, integrative, competence, methodical and control. They classified criteria and indicators as (i) meta-subject criterion, (ii) digital criterion, (iii) relevant criterion and (iv) complex criterion. The study found that pedagogical management increased with digital literacy and enhanced when practices and innovations are linked in learning.

Hazrat et al. (2023) explored the role of DT in developing a skilled workforce to meet future demands in engineering education, focusing on employability strategies in Australia. The study examined Industry 4.0 education across four key areas: (1) learning methods, (2) competencies, (3) infrastructure, and (4) ICTs. Learning methods include approaches such as learning by doing, challenge-based, and problem-based learning, as well as face-to-face, online, and hybrid modalities. Competencies are divided into soft skills (critical thinking, collaboration, communication, creativity, and innovation) and hard skills (training, research, and emerging technologies). Infrastructure is classified into classroom and institutional levels, covering virtual platforms, smart learning environments, and innovative tools. Finally, ICTs are categorised into technology-based solutions (IoT, AI, ML, cloud computing, cyber-physical systems, data analytics, and MR) and tools/platforms-based solutions (learning management systems, web conferencing, collaborative virtual environments, and cyber-physical labs). The results suggest that leveraging new technologies enhances training, skill development, and employability.

4.1.4 Dimension of Digital Twin Structure and Applications

To understand the structure and applications of DT, it is essential to examine its core components and their interactions. VanDerHorn and Mahadevan (2021) and Tuhaise et al. (2023) classified DT into three components: physical reality, virtual representation and interconnections between the physical and virtual elements. VanDerHorn and Mahadevan (2021) provided a further classification for each part: (1) physical reality incorporates system, environment, and processes, (2) virtual representation comprises system, environment and process, and (3) interconnections between the physical and virtual elements includes physical to virtual, data fusion and virtual to physical. In another research, Tuhaise et al. (2023) classified DT applications into several layers: data gathering, digital modelling, data transmission, data/model integration and service layers. Javaid et al. (2023) also reviewed DT applications and discussed their needs in Industry 4.0. The study identified eight features of DT in industry 4.0: (1) data collection, (2) analysis, (3) opportunities, (4) maintenance history, (5) operational history, (6) product behaviour, (7) learning and (8) collaboration network. Chartered Institute of Building (2024) published an AI Playbook that demonstrated the benefit of DT in the construction industry. Table 5 summarises the main features and applications of DT extracted from the literature and highlighted by previous studies (Javaid et al., 2023; Chartered Institute of Building, 2024).

Table 5. List of DT features and applications identified in previous studies

Features	Applications
Learning and Collaboration Network	Provide better knowledge, develops a virtual replica, digital representations of real-world product and update virtual representation.
Data Collection	Real-time monitoring, monitor equipment and systems, structural health monitoring and environmental impact assessment.
Analysis	Determine performance level, enable system for prediction, process simulation, optimised scheduling and visibility in manufacturing.
Maintenance	Enables maintenance, enables engineers to identify any fault, detect possible problems, automatic inspection and maintenance scheduling.
Operation	Improved visibility of building utilisation, enhance machine's self-awareness, reduce errors during manufacture, user-friendly and efficient services, automate procedures and operations, enhance the processes and material handling system.
Product Behaviour	Development of innovative products, mimic the physical asset and operation, improve product quality, simulate reality, minimise human decision-making and sustainable design.
Management	Immersive information management system, strong information management solution, resource management, safety management, lifecycle management, energy management and supply chain management.
Opportunities	Encompasses automation, design cost reduction, opportunities for innovation, efficient manufacturing, opportunities for new and superior goods and save development time.

Zhang et al. (2022) investigated DT data, focusing on methods and hierarchical structure. They categorised DT data into four configurations: physical entity (status, conditions, environment), virtual model (parameters, processes, simulation conditions, outcomes), services (prognosis, quality, scheduling, algorithms), and domain knowledge (industry standards, expert experience, predefined rules). They also proposed seven types of empowering technologies for DT data: (1) data gathering (modelling tools, transfer learning, validation), (2) data storage (format transformation, database management, security), (3) data interaction (consistency evaluation, redundancy removal, transmission), (4) data association (spatial-temporal alignment, knowledge reasoning, data mining), (5) data fusion (algorithms, anomaly detection, granularity transformation, distributed fusion), (6) data evolution (network modelling, visualization, information analysis), and (7) data servitisation (optimisation, resource encapsulation, demand decomposition, AR/VR visualization). Figure 7 illustrates the types and hierarchy of DT data sources.

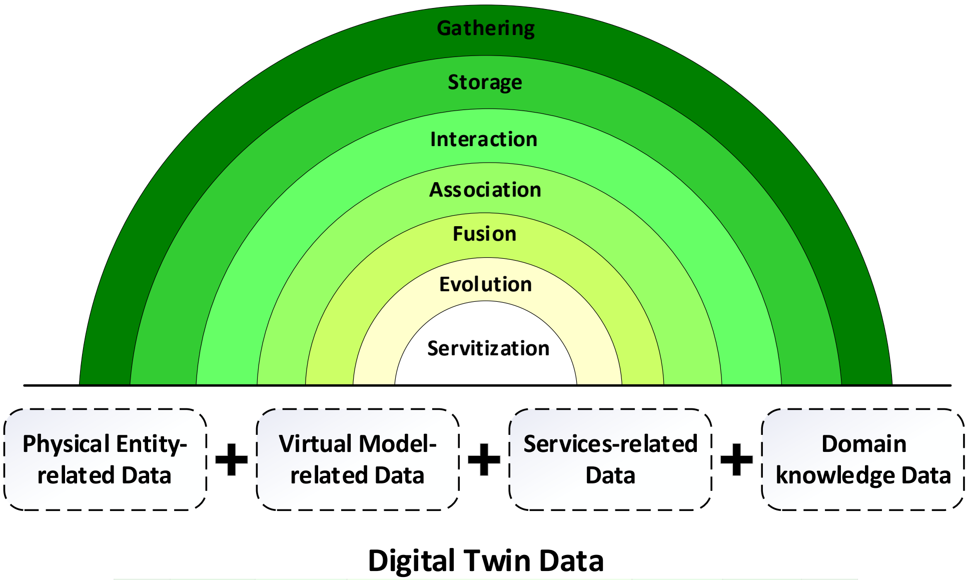

Figure 7. Types and hierarchy of DT data.

Tao et al. (2019) classified DT technologies into six levels: (1) virtual product (CAD and 3D model), (2) analyse, integrate and visualise data (data analytics, data integration, data visualization, AI), (3) simulate behaviour (VR, simulation), (4) control behaviour (actuator and AR), (5) communicate with virtual product (security, cloud computing, cloud platform, connectivity) and (6) measure data (software and sensors). Madubuike et al. (2022) developed a model using Siemens technologies to outline the dimensions of DT in construction. The model includes: (1) IoT devices such as sensors, drones, wearables, and mobile devices; (2) Big Data encompassing both static and dynamic data; (3) AI with applications in machine learning and DL; and (4) cloud-based access for data processing and connectivity. As a result, Figure 8 demonstrates the connection between DT dimensions and technologies.

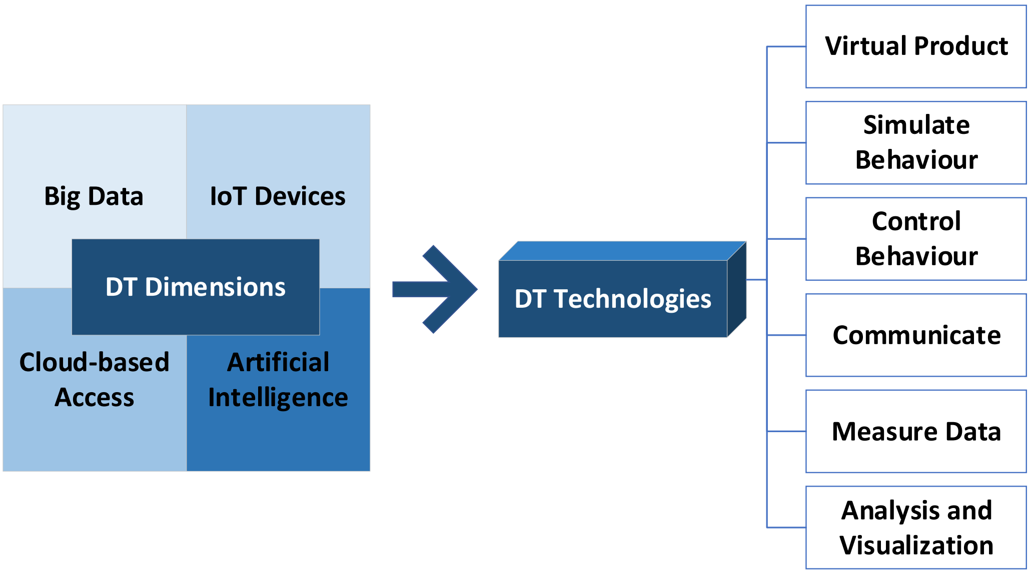

Figure 8. DT dimensions and DT technologies

4.1.5 Dimension of Digital Twin Models in Education

This section analyses eight models from various educational disciplines, which form the foundation for the DT framework presented in Section 4.2. The models were selected based on criteria such as experimental content, educational relevance, and recent publications showcasing the latest advancements.

Bucchiarone (2022) introduced a DT-based approach integrating VR and gamification to enhance training and learners' engagement. The study developed a conceptual model with six key elements: (1) a game dashboard (login, profile, status), (2) a VR learning tool (tasks, events, updates), (3) a game master (monitoring, API integration, player status), (4) quality assessors (task validation), (5) a gamification design framework (artefact design, game elements, mechanics, deployment), and (6) a gamification engine (game status, execution). The model is highly adaptable, supporting various applications such as lesson planning, instructional design, and user diversity (Figure 9.a).

Komninos and Tsigkas (2022) developed a DT prototype for environmental education using a smart birdhouse model to facilitate learning. The birdhouse integrates IoT sensors (sound, temperature, humidity, light, motion) with a Raspberry Pi 4B microcontroller, an MQTT server, and a dashboard accessible via mobile and screen interfaces. The prototype was designed to monitor environmental data and collect historical data for bird identification, the prototype enhances real-time learner engagement. Although simpler than construction industry applications, it still effectively demonstrates DT application in an educational context (Figure 9.b).

Martínez-Gutiérrez et al. (2023) introduced an approach integrating VR and DT technologies for Industry 4.0 training. The study utilised a mobile robot on a predefined course to minimise errors and complete tasks efficiently, offering insights into potential future applications for construction workers. The proposed model includes six interconnected components: (1) the real environment (robot), (2) the virtual environment (3D modelling, collision physics, server connection, VR glasses), (3) DT (Robot Operating System, Navigation), (4) a web server (interface), (5) a graphical user interface (data collection, joystick control), and (6) a GUI manufacturer. The study showed improvements of 28% with the computer application, 38% with VR, and 47% through hands-on learning (Figure 9.c).

Sacks et al. (2020) proposed a DT information system for monitoring construction processes, highlighting limitations in BIM models for integrating raster graphics and point clouds. The study introduced virtual–physical and status–intent regions, distinguishing between physical aspects (e.g., site and prototype) and virtual aspects (e.g., Project Intent and Status Information). The DT construction workflow integrates physical and digital twins, with the physical twin focused on monitoring, while the DT operates across four levels: Project Intent Information, Project Status Information, Project Intent Knowledge, and Project Status Knowledge. These levels were able to interpret, evaluate, and predict performance through continuous feedback from the physical twin, enabling real-time monitoring and historical data storage. The workflow outlines a clear process but remains purely theoretical (Figure 9.d).

Zhang et al. (2024) proposed a framework for facilitating learning in engineering courses, incorporating horizontal and vertical learning experiences across four components: (1) project preparation (learner analysis, scenario creation, task allocation), (2) project implementation (design, embodied experience, collaborative inquiry, scheme verification), (3) project summary (presentation, evaluation, expansion), and (4) the DT learning system, which integrates vertically with the other components (data collection, model creation, simulation, intelligent teaching analysis). The study also introduced a six-dimensional DT model, including physical learning space (teacher, student, environment, sensors), virtual space (AI tutor, virtual partner, devices), cloud services (learning monitor, intelligent analytics), front-end display (AR/VR), digital data, and connection. Results showed improvements in cognitive load, critical and creative thinking, academic performance, and learning experience (Figure 9.e).

Hazrat et al. (2023) introduced a DT framework for an existing HVAC system, comprising five elements: (1) physical asset system (building structure, HVAC), (2) IoT (control system, data acquisition), (3) cloud (data from HVAC and other sources), (4) simulation space (3D model, optimisation, validation), and (5) virtual space (AI-based analysis, fault finding, diagnostics) (Figure 9.f). The study emphasised integrating DT in engineering education to develop multidisciplinary skills and support human-centric decision-making. Hazrat et al. (2023) also highlighted the importance of industry collaboration and professional development for educators to effectively use DT technologies. In another study, Wahbeh et al. (2020) proposed a DT model for project-based learning in architecture, incorporating scanning, BIM modelling, IoT, data management, and visualisation (Figure 9.g). The proposed DT model introduced a straightforward theoretical concept to bridge three key areas: context, physical twin, and DT model.

Fonsati et al. (2024) introduced a DT model for educational purposes, integrating BIM and a building management system (BMS) in a Stockholm educational building. The study focused on data capture, connection, and communication (Figure 9.h). Real-time data was captured using BIM models and IoT-enabled BMS devices. Data connection was achieved through two workflows: (1) Visual Programming Language (VPL) via Dynamo in Revit to link BIM with physical assets, and (2) the online platform 'Styrportalen' to stream sensor data from BMS. These workflows bridged BIM and BMS, further connected through VR using Unity. Data communication involved two workflows: sensor data was analysed in Revit via VR and AR applications on mobile devices allowing flexible communication without a BIM environment.

Figure 9 presents the assessment of eight DT case studies, highlighting key factors and workflows to better understand design structures and research processes. The assessment revealed inconsistencies in DT implementation for ETL in the construction industry, with varied models leading to divergence in practice. These inconsistencies make it challenging for educators to standardise approaches and effectively integrate DT into learning environments. The next section aims to develop a comprehensive framework tailored for effective teaching and learning.

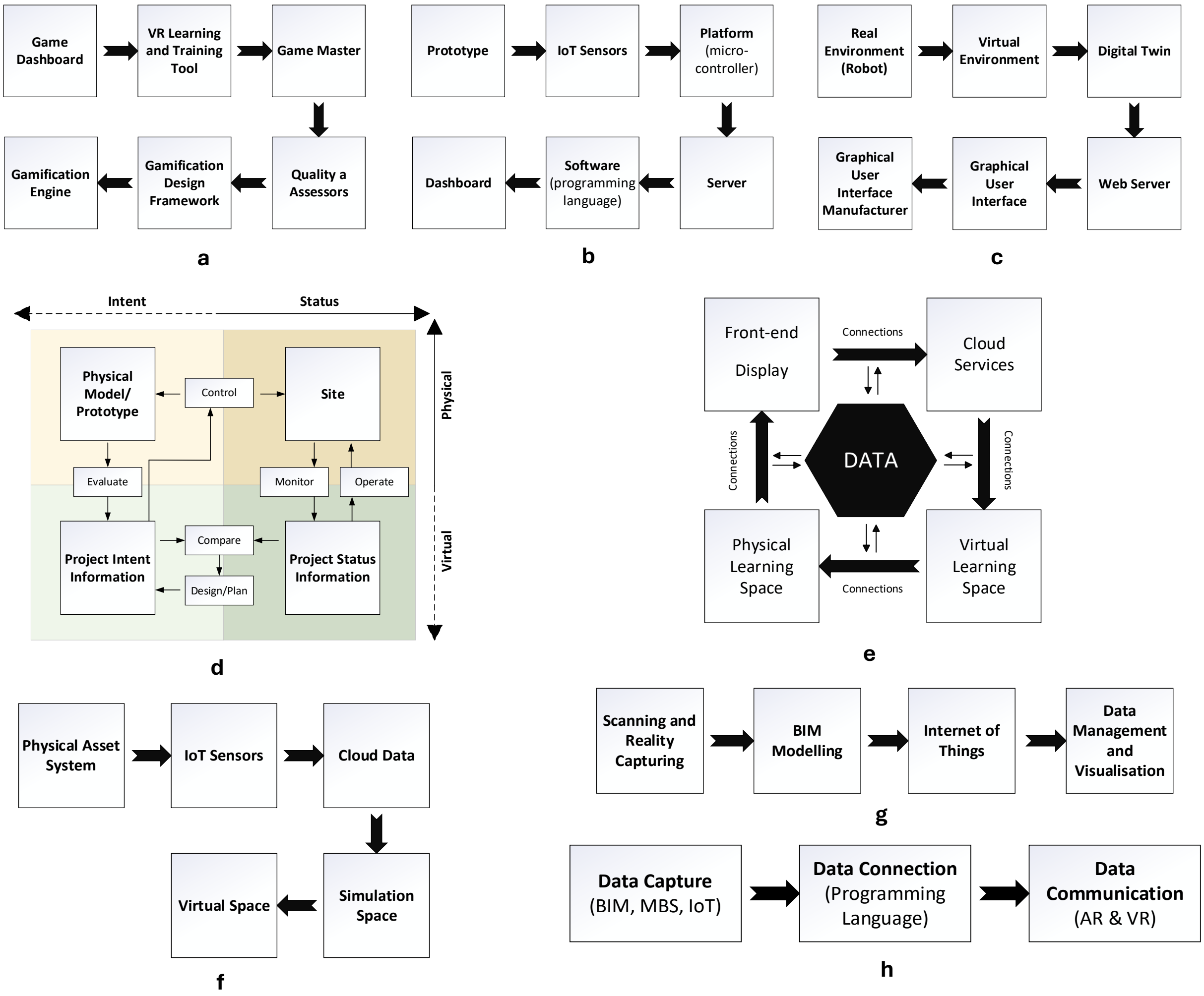

Figure 9. Visual summary of the main DT workflow in previous research developed by the authors.

4.2 Proposed Conceptual Framework

This section elaborates on the development of the DT conceptual framework tailored for ETL purposes in construction, drawing on several dimensions outlined in Figure 4. The framework aims to provide a structured approach to facilitating the effective use of DT technology for ETL purposes within the construction industry. It is designed to achieve four key objectives: (1) to facilitate the application of DT in construction education, (2) to integrate teaching and research perspectives in defining DT boundaries, (3) to address fragmented knowledge and clarify educational challenges, and (4) to support construction workers within the industry context. This framework is developed based on specific theories, models, and case studies analysed in this study, and was designed to accommodate diverse learners by incorporating both Bottom-up and Top-down learning models. The use of DT for ETL aligns well with Kolb's learning styles—Active Experimentation, Abstract Conceptualisation, Concrete Experience, and Reflective Observation—which have been applied in virtual learning environments for teaching construction in higher education (Wang et al., 2020). The development focuses on two key areas: DT Learning Phases and DT Application Phases as shown in Figure 10.

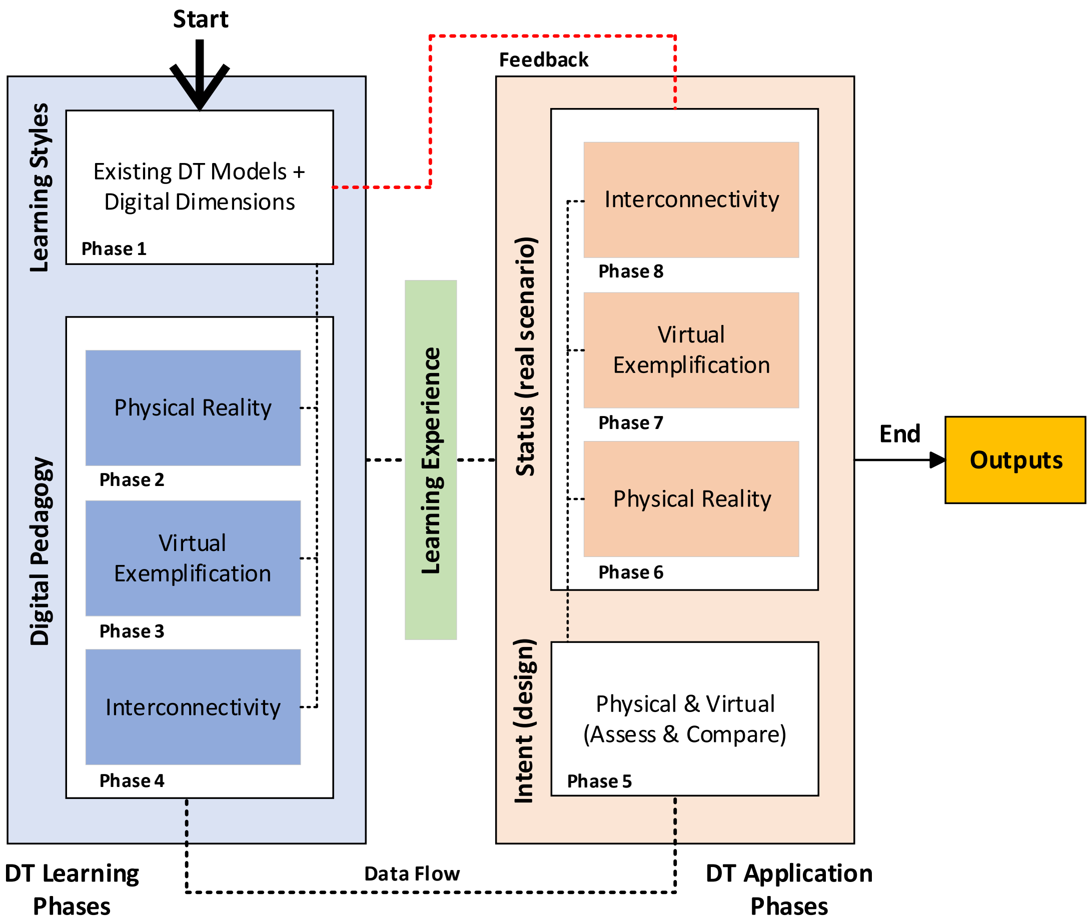

Figure 10. Conceptual structure of learning and application phases in the proposed DT framework.

In the DT Learning Phases, the framework is primarily educational, aimed at helping learners grasp both theoretical concepts and practical applications. This phase consists of four distinct stages, including:

- ***Phase 1*** starts with demonstrating an existing DT model for learners to establish a foundation to engage with different digital dimensions (Digital Literacy, Digital Competence, Digital Skills and Digital Thinking).
- ***Phase 2*** provides learners with the fundamental aspects of Physical Reality in construction industry, including Physical Systems, Physical Environments and Physical Processes.
- ***Phase 3*** explores Virtual Exemplification in the industry, including Virtual Systems, Virtual Environments and Virtual Processes.
- ***Phase 4*** demonstrates the Interconnectivity between physical and virtual environments, including Physical to Virtual, Information Fusion and Virtual to Physical.

Phases 2, 3 and 4 are established based on critical features of Digital Pedagogy that are adopted from the Lunevich Model (Lunevich, 2021), including Connectivity, Scale, Reflection, Extension, Embodiment, Personalisation and Creativity (See Table 4). In Phases, 2, 3 and 4, digital pedagogy plays an important role in paving the understanding of DT components in physical and digital applications. Considering learner diversity as verbal, visual, physical, aural, logical-mathematical learning style, interpersonal and solitary (Lunevich, 2021), the phases include consideration of learning methods, competencies, infrastructure, and ICTs. The learning and training in these phases are interactive, integrative, methodical and controlled. Pugacheva et al. (2020) utilised these approaches in educational management using a virtual construction site. In addition, the pedagogy for DT includes learning by doing, problem-based learning, challenge-based, and hybrid modalities to improve engagement, training, skills and personal development. Considering the variety of competencies including soft and hard skills based on applicable infrastructure that could be delivered using labs, virtual platforms and the use of innovative tools. Finally, the pedagogy integrates ICTs via tools/platforms-based solutions and technology-based solutions. Examples of these aspects are covered by Hazrat et al. (2023), the study explored the role of DT in developing a skilled workforce in engineering education in Australia.

In the DT Application Phases, the framework aims to demonstrate a connected model composed of components, states and layers. This phase offers a technical approach to illustrate the practical applications of DT. First, this phase covers two states: Intent (design/planning) and Status (real scenario). The Intent state allows learners to develop and test approaches prior to construction, while the Status state enables them to monitor and respond to real-world scenarios. Both states define the system's condition in relation to its development and improvement. Second, in the status condition, the model consists of three components and three layers. These aspects demonstrate the main structure and core complexity of the DT application. Each element is explained within the three components (Physical Reality, Virtual Exemplification, and Interconnectivity between physical and virtual) and the three layers (Data Transmission, Services, and Operation), as outlined below.

- First, physical reality consists of three parts including (a) physical system, (b) physical environment, and (c) physical processes. (a) ***physical system*** consists of interrelated entities that establish its purpose and structure, defining the system's boundaries in relation to other systems. It may range from a single unit, component, or system to an interconnected system of assets, such as a room, floor, building, or entire site. (b) ***physical environment*** represents the conditions in which the system is positioned and operates. It influences the physical system and shapes its processes. For example, the surrounding environment includes technologies and environmental conditions such as natural elements, climate and weather, living organisms, physical properties, natural resources and human-made products. (c) ***physical process*** reflects the behaviour of a physical system and its responses within the physical environment, including aspects such as consumption, emissions, comfort, and performance.
- Second, virtual exemplification represents the idealized form of physical reality in virtual space. This process abstracts real-world data into parameters, characteristics, states, and

variables, which are then interpreted through data models like data structures or computational models (e.g., physics laws). The abstraction process converts physical elements into virtual ones, a step called interpretation, and it requires three components: (a) virtual system, (b) virtual environment, and (c) virtual process. (a) The ***virtual system*** includes data and models of the physical system represented by tools like BIM (Revit, ArchiCAD, Navisworks, etc.) allowing various abstraction levels. These models may not always be interconnected. (b) The ***virtual environment***, tailored to the DT model's needs, can be non-immersive VR, semi-immersive VR, fully immersive VR, augmented reality, or collaborative VR, depending on the task. (c) ***Virtual processes*** simulate the system's functionality and behaviour at different abstraction levels, reflecting physical changes. They demonstrate input-output relationships and can be enhanced using AI techniques.

- Third, interconnectivity between physical and virtual elements is the key stage in DT, enabling bi-directional data exchange (Jones et al., 2020). This process involves three aspects: (a) physical to virtual, (b) information fusion, and (c) virtual to physical. (a) The ***physical to virtual*** connection transmits information from the physical world to update the virtual model. It follows three steps: (i) collecting data via sensors, IoT, or offline methods like inspections, (ii) interpreting the data based on abstraction, and (iii) updating the virtual model to reflect the current state, verified by system identification. (b) ***Information fusion*** minimises redundancy and uncertainty through: (i) data association to reduce volume, (ii) state estimation for system monitoring, diagnosis, and control, and (iii) decision fusion to enhance decision-making (Castanedo, 2013). (c) The ***virtual to physical*** process transfers insights from the virtual model to the physical world for visualisation, assessment, and decision-making.

The framework also incorporates three key layers to support the DT process: the Data Transmission Layer, the Service Layer, and the Operate Layer. Each of these layers plays a distinct role in facilitating communication, service provision, and the interaction between physical and virtual systems.

- The ***Data Transmission Layer*** facilitates the transmission and processing of raw data from data acquisition systems like IoT, employing wired, wireless, and hybrid technologies. It also utilises protocols and technologies such as Hypertext Transfer Protocol (HTTP), Message Queuing Telemetry Transport (MQTT), Universal Resource Identifier (URI) and Azure blockchain platform.
- The ***Service Layer*** provides users with essential services derived from the DT, helping them identify specific needs to accomplish tasks. Examples include monitoring construction progress, site activities, machine and worker operations, structural health, material safety, movement, and working conditions.
- The ***Operate Layer*** is crucial for closing the loop between physical and virtual twinning, enabling virtual actions to be implemented in the physical system. It involves two steps: (1) making necessary changes to the physical state, and (2) executing procedures to modify the physical process.

Figure 11 demonstrates the detailed steps of the proposed conceptual framework of DT in construction. The DT conceptual framework developed in this study consists of two main sections: learning and application encompassing eight interconnected phases. The framework provides a systematic, organised approach to tasks, offering a structured model to help learners develop construction-related knowledge and skills through the application of DT technology. education.

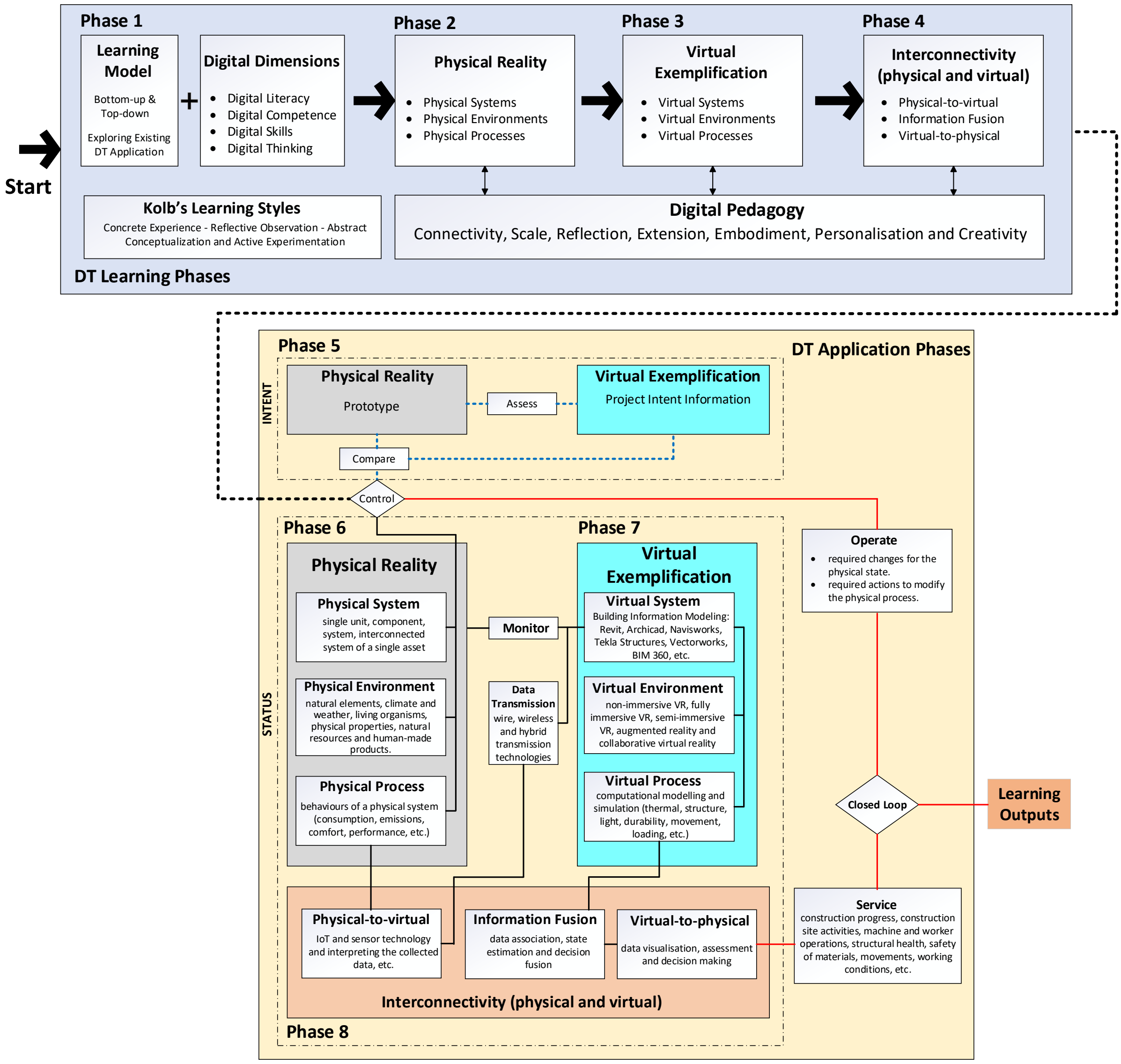

Figure 11. Conceptual framework to facilitate the adoption of DT in construction education.

The framework structure is adaptable for application across various sectors of the construction industry. The framework could be applied in real-world ETL settings to improve lesson planning and instructional design while taking into consideration user diversity. For example, the framework would effectively support learning to understand and apply Modern Methods of Construction (MMC) such as off-site construction in terms of planning, design, fabrication, and assembly. The framework provides a systematic configuration to equip learners with skills to use standardised industrial practices. Also, the DT framework could be implemented during the retrofitting stage to equip learners with effective skills to deal with real scenarios to assess and monitor consumption and efficiency. Furthermore, the DT framework could be implemented to demonstrate the practice of facilities and asset management to examine the practices of post-occupancy evaluation of building performance in use. Using the proposed framework in architectural and construction pedagogy has the potential to provide integrated learning to equip learners with a perspective of overseeing construction stages and identify the impact of embodied and operational carbons to understand the pragmatic and realistic actions to reach net zero by 2050. In future research, this framework has the potential to transition from learning and training to establishing new models for construction companies and developers, particularly for new construction and retrofitting projects.

The full implementation of this framework can promote inclusivity within the industry by addressing the unique challenges faced by underrepresented groups, such as women, migrants, and individuals from diverse backgrounds. The framework is intended to integrate tailored learning modules and simulation-based training, which offer a safe and controlled environment for participants to develop industry-specific skills without fear of judgment or discrimination. This is particularly beneficial for migrant workers, who may lack local experience, familiarity with industry standards and practices or struggling with understanding the native language including industry-specific terminology and jargons. The proposed framework also incorporates adaptable learning pathways that accommodate varied educational backgrounds and digital literacy levels. By doing so, it helps bridge the skills gap and assures that participants can progress at a pace suited to their abilities which could potentially result in fostering a more equitable learning experience.

The implementation of this framework can also play a pivotal role in helping women integrate into the construction industry. It provides access to virtual learning environments that mitigate potential biases or barriers present in traditional training settings, as evidenced by previous studies (Agyekum, et al. 2024; Lekchiri and Kamm, 2020) and encourages active participation and skill development in areas where women have historically been underrepresented. Adding to these, the framework would also enable leveraging the immersive and interactive features of DT technology to offer hands-on engagement and experiential learning. This approach not only helps underrepresented groups build confidence and practical competence but also equips them with skills essential for real-world scenarios.

4.3 Characteristics of the Proposed Framework

This section aims to briefly highlight the unique characteristics of the proposed framework in juxtaposition to the analysed studies. First, it bridges the gap between theoretical learning and practical application by structuring the process into two interconnected phases learning and application each comprising tailored stages that systematically progress from understanding digital dimensions to applying them in real-world scenarios. This holistic approach is absent in the majority of analysed studies such as Wu et al. (2022) and Martínez-Gutiérrez et al. (2023), which primarily focused on single-phase implementations or isolated aspects of DT technology.

Second, the framework is intended to take into consideration the scalability and adaptability by incorporating bi-directional data exchange layers and critical pedagogical dimensions. Unlike the rigid models employed by previous studies (Agostinelli and Nastasi, 2023; Kamari et al. 2022), the proposed framework targets integration across diverse learning contexts, catering to varied user groups, including those with different levels of digital literacy.

Lastly, the framework uniquely addresses socio-technical dimensions by embedding features that promote inclusivity and industry readiness, particularly for underrepresented groups. The review identified studies like Hazrat et al. (2023), which explored multidisciplinary learning environments. However, the proposed framework builds on this by incorporating tailored pathways designed for migrant workers, facilitating equitable skill development through adaptive simulation-based training.

Overall, these characteristics collectively position the framework as a comprehensive, multi-dimensional tool that resolves fragmentation in the existing literature and provides a structured roadmap for integrating DT technology into construction education.

5. Conclusions

The implementation of DT technology in the construction industry has been widely investigated in previous studies. However, the current body of literature remains fairly fragmented when it comes to the use of DT for ETL purposes. Correspondingly, this study approached the literature aiming to bridge the gap by first providing a clear understanding of the current application of DT technology for ETL in construction. To this end, the paper conducted a comprehensive systematic literature review and identified 19 studies that applied DT technology for ETL in construction. These studies were analysed in detail to understand their approach to adopting the technology. The findings indicated a strong consensus among the studies regarding the effectiveness of DT in achieving ETL objectives within the construction sector.

Furthermore, this study proposed a conceptual framework based on the outcomes of the literature review analysis, aimed at providing a structured approach to facilitate the adoption of DT technology for ETL in the construction industry. The proposed framework consists of five key dimensions: the characteristics of construction workers, digital literacy (competence, skills, and thinking), digital education, DT structure and applications, and DT models in education. The framework is designed with both Bottom-up and Top-down learning models and seeks to achieve four key objectives: (1) to facilitate the application of DT in construction education, (2) to integrate teaching and research perspectives in defining DT boundaries, (3) to address fragmented knowledge and clarify educational challenges, and (4) to support construction workers within the industry. The proposed framework can potentially assist educators, policymakers, and industry stakeholders in adopting innovative training methodologies that improve the inclusivity and effectiveness of construction training programs.

The implications of this study reach beyond the educational sphere, offering substantial value for both industry and policy development. The findings pave the way for creating more inclusive and effective training programs, benefiting not only migrant workers but also individuals from diverse backgrounds, women, and other underrepresented groups. This supports workforce development and advances social sustainability within the industry. Policymakers and industry stakeholders can leverage these insights to streamline worker upskilling, enhance industry readiness, and reduce barriers to entry for underrepresented groups.

Despite the efforts undertaken to ensure the robustness of this study's methodological approach, certain limitations must be acknowledged. First, the study is limited to emerging developments of DT technology in construction and engineering education, which may not necessarily encompass all emerging advancements in DT technology, particularly given the rapid-pacing nature of technological innovation in this field. This reliance on secondary data might limit the ability to fully capture the recent trends and practices, which subsequently may affect the generalisability of the findings. Therefore, future studies can target conducting primary research, such as surveys, interviews, or case studies with industry professionals, to capture real-time advancements and practical applications of DT technology. This approach would provide a more comprehensive understanding of current trends and their implications for construction education.

Second, the proposed framework has not been practically tested in real-world scenarios, leaving its applicability and effectiveness in actual educational settings unverified. This highlights the need for empirical validation to assess how well the framework supports learning objectives and addresses the challenges faced by underrepresented groups, including migrant construction workers. The next stage of this research will focus on addressing this gap by implementing the framework in educational settings, evaluating its performance, and gathering insights to refine its components for practical application. Third, this study primarily focuses on the theoretical dimensions of integrating DT technology into education and training without delving deeply into practical barriers that could possibly arise during implementation. For instance, factors such as the high costs associated with DT infrastructure, the readiness of construction organisations to adopt such technologies, and the availability of skilled personnel to manage and operate DT systems are not fully explored. These limitations may impact the feasibility and scalability of applying the framework across diverse contexts. Future research should address these issues by incorporating empirical studies and examining the broader industry-specific challenges to provide a more robust understanding of DT's potential in construction education.

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Table A. Summary of findings on DT technology in construction ETL

Studies	Tools/ Technologies applied	Methods of Integration	Evaluation of Effectiveness
Speiser and Teizer (2024)	DTCS framework integrating BIM, schedules, resources, and hazard data via Unity game engine.	Integrating BIM models, schedules, resources, and hazard data into VTEs with minimal user interaction; using Unity game engine for scenario generation.	Efficacy demonstrated through three real cases; meaningful feedback to trainees was provided via runtime data collection and analysis.
De Los Santos Melo and Beriguete Alcántara (2024)	Not enough info provided.	Integrates DT platforms to simulate real-world scenarios and foster interdisciplinary collaboration among students.	Deeper understanding of complex processes and innovative solutions were discussed; addresses challenges, e.g., data integration and ethical considerations.
Zhang et al. (2024)	DT, VR, AR, IoT, 3D Visualisation.	Developed DT system using VR workstations, IoT sensors, 3D visualisation, and real-time feedback.	Improved academic performance, critical thinking, and cognitive load. No significant impact on creative thinking was reported.
Martínez-Gutiérrez et al. (2023)	DT framework using Robot Operating System (ROS) for simulation and control, Unity for graphics engine, Oculus Quest 2 VR glasses.	Convergence of DT and VR for immersive training; ROS for simulating navigation and control of industrial robots; Unity for realistic graphics and physics simulation; Oculus Quest 2 VR glasses for immersive interaction.	47% improvement in skill transfer via real training, 38% via VR, and 28% via computer application; immersive environments for training were highly effective.
Hazrat et al. (2023)	DT integrated with Industry 4.0 components, including IoT, data analytics, and simulation technologies.	Implements DT-based labs, integrates with curricula and pedagogy, collaborates with industry for real-world projects, and uses virtual models to simulate real systems.	Improved student engagement and skill acquisition, cost-effectiveness, resource management, and enhanced learning; challenges include IT infrastructure, data quality, privacy, and security.
Gade et al. (2023)	DT technology using BIM software, IoT sensors, and data analytics tools.	Use of DT as semantic learning material in educational programs, focus group interviews to assess student understanding, integration into existing curricula, and practical workshops.	Highlighted the importance of digital literacy, creativity, critical thinking, and practical knowledge; identified challenges like structured data collection and curriculum integration.
Agostinelli and Nastasi (2023)	DT framework using BIM, MR (e.g., Microsoft HoloLens), IoT sensors, and cloud-based CDE platforms.	Use of DT and MR for immersive training environments, integrating BIM data for real-time updates and remote collaboration, implementation of hybrid learning spaces via MR devices.	Enhanced operational performance, reduced maintenance errors, improved collaboration, and increased efficiency; challenges include IT

			infrastructure, data quality, and integration complexities.
Wu et al. (2022)	DT combined with MR, Deep Learning (DL), IoT sensors, and the Unity game engine.	Creation of a real-time visual warning system using MR devices (e.g., Microsoft HoloLens), DL algorithms (YOLOv4-Tiny), and IoT sensors; integrating BIM data to develop virtual construction sites.	Increased risk assessment accuracy and improved safety behaviour, validated through quasi-on-site tests; challenges include network latency, data accuracy, and real-time integration complexity.
Podder et al. (2022)	Immersive Industrialised Construction Environments (IICE) using DT, VR, IoT sensors, and the Pre Framer™ machine.	Develops IICE for training; uses VR for immersive learning, virtual time-and-motion studies, and VR headsets for interacting with DT models and simulating real-world construction scenarios.	Findings showed enhanced learning, productivity, and better task preparation and execution; challenges include comprehensive data systems and addressing technical and non-technical constraints.
Kamari et al. (2022)	DT integrated with vision-based DL techniques and IoT sensors.	Using DT for modelling jobsites; DL algorithms for visual data analysis from satellite imagery and Google Street View; IoT sensors for real-time data collection and monitoring.	Improved accuracy in risk assessment of windborne debris impacts; validated through real-world case studies; challenges include data accuracy, managing large datasets, and integrating multiple data sources.
Hasan et al. (2022)	DT system integrated with AR, IoT sensors, and Cyber-Physical Systems (CPS) utilising Arduino Microcontroller Units (MCUs) and Unity3D.	Developing DPL using AR and DT for real-time interaction with construction machinery; Arduino MCUs for sensor and actuator control; Unity3D for 3D models and AR interfaces; server for data management and communication.	Demonstrated improved safety, operation precision, and remote monitoring capabilities; challenges include data accuracy, latency issues, and the complexity of integrating various technologies.
Ogunseiju et al. (2021)	DT framework utilising wearable IMUs, LSTM networks, and AR HMDs (e.g., Microsoft HoloLens).	Implementing DT system for real-time posture tracking using wearable IMUs; LSTM networks for posture classification; AR HMDs to display virtual feedback on ergonomic risks.	Demonstrated potential for reducing ergonomic risks through increased awareness; experimental study showed feasibility but highlighted the need for scalability and extensive field works; challenges include high computational costs and data accuracy.

Harichandran et al. (2021)	DT technology integrated with VR games using BIM data, safety regulations, and historical data.	Developing VR training scenarios dynamically updated through information streams from DTs, including project intent information, project status knowledge, and safety regulations; creating immersive learning experiences using VR headsets.	Improved safety performance by providing realistic training scenarios; challenges include technology readiness in construction and data quality for creating realistic training environments.
Chacón (2021)	DT technology integrated with BIM, 3D printing, robotics, TLS, and IoT sensors.	Developing STEAM-rich activities and workshops; integrating DTs in cornerstone and capstone projects; use of open-source and affordable hardware/software; creating immersive learning experiences.	Implemented several demonstrators, increased student engagement, and improved understanding of Construction 4.0; challenges include maintaining up-to-date content and scalability of resources.
Wahbeh et al. (2020)	DT technology integrated with BIM, 3D laser scanning, IoT sensors, and mobile mapping systems.	Project-based learning with the "DT Campus Muttenz" project; integrating DTs in various courses and workshops; use of scanning, reality capturing, IoT, and data management technologies to create a comprehensive DT of the campus.	Improved students’ engagement and interdisciplinary collaboration; effective teaching of VDC and DT technologies; challenges include managing large datasets, ensuring data accuracy, and maintaining up-to-date content.
Sepasgozar (2020)	DT technology integrated with VR, AR, BIM, 3D models, IoT sensors, and gaming engines like Unity3D.	Developing interactive virtual modules (VTBM, PAR, Excavator DT); using VR and AR for remote learning; integrating DTs with BIM and IoT for real-time visualisation; use of gaming engines for realistic ETL contents.	Increased students’ engagement and understanding of complex construction processes; challenges include data accuracy, managing large datasets, and maintaining the technology infrastructure.
Liljaniemi and Paavilainen (2020)	NX Mechatronics Concept Designer, physics-based modelling and simulation.	Integrates DT tools in engineering education through practical projects and virtual learning environments.	Increased motivation and improved learning; benefits include expertise development; barriers include IT issues and limited teacher expertise.
Chacón et al. (2018)	DT technology integrated with IoT devices, sensors, DAS, GUIs using Arduino and Processing.	Developing portable DT artifacts for classroom demonstrations; use of open-source hardware/software for creating interactive educational tools.	Increased student understanding of physical-to-digital integration; positive feedback on applying theoretical concepts; challenges include data accuracy, managing complexity, and providing sufficient support for complex learning.

Goedert et al. (2011)	Virtual Interactive Construction Education (VICE) system using 3D technologies, simulation, modelling, and game-based learning.	Developed the VICE system to simulate whole construction processes using real project data; a game-based framework for experiential learning with 3D technologies for realistic visuals, integrated with problem-solving and situational simulations.	Enhanced students’ engagement, improved learning outcomes in construction management; challenges include maintaining the technology infrastructure and ensuring system scalability.