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The Potential of Digital Twins in Higher Education: Exploring the Benefits and Drawbacks of Utilising Technology, Can It Be Used to Assist in The Creation of Sustainable Environments?

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Abstract

This dissertation examines the potential of Digital Twin technology in higher education, with a particular focus on the Architecture, Engineering and Construction sector. It investigates how Digital Twins, which are defined as dynamic digital replicas of physical assets, can bridge the persistent gap between static academic models and the developing, data-driven requirements of contemporary professional practice. Through literature reviews, case studies and qualitative interviews with students and practitioners, the research analyses the benefits and limitations of integrating DTs into architectural courses, addressing issues such as sustainability, cost, technical complexity and digital literacy.

The study is structured around assessing how educational institutions can move from static BIM models to real time, predictive, and eventually autonomous digital environments using Digital Twins. Case studies, including DigiLab/BE, Aachen West and Georgia Institute of Technology, to show diverse, accessible approaches to DT adoption, emphasising the value of open-source platforms and affordable hardware. The research also explores how experiential learning models and joint, studio-based teaching can improve digital skills, foster teamwork across courses and better prepare graduates for Industry 4.0.

Findings show that while significant barriers remain, particularly around cost, expertise, and institutional silos, the integration of DTs can support the development of sustainable, safe, and efficient built environments, concluding that embedding DT principles into higher education is essential for equipping future experts with the skills and environmental accountability required to meet the challenges of the modern AEC industry.

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Introduction

Digital Twin (DT) technology is often defined by its data collection, sensor integration, and real-time monitoring features. However, the main argument of this dissertation is that while these technical aspects are essential, they risk obscuring architecture's deeper educational role in learning, experimentation, and environmental accountability. The integration of Digital Twins into architectural education presents a unique opportunity to realign technology's purpose with the discipline's foundational values of performance and precision.

Despite advances, many learning environments stay fixed, where software is usually seen as a static drafting tool, data remains in isolated modules, and the link between digital models and real buildings is often unclear (Deng, Menassa and Kamat, 2021). While Building Information Modelling (BIM) has been adopted, it is often taught as a still frame in time rather than reflecting the always changing state of a building design (Dai and Brell-Çokcan, 2022). Courses are shaped by strict standards, tight budgets, and a focus on established methods over new technology (Hazrat et al., 2023).

In contrast, Digital Twins within the industry adopt methods, such as manufacturing and aerospace sectors utilising Digital Twins to improve efficiency and sustainability, aiming for ongoing optimisation through real-time synchronisation (Yang et al., 2024). Sensors, live weather data, and analytics can bridge design intent with real performance (IBM, 2023). Therefore, the models act as adaptive systems, not static forms (Dai and Brell-Çokcan, 2022). Industrial engineering shows digital replicas can boost efficiency and cut carbon and waste, with the potential to save the non-residential sector hundreds of millions in operational costs (Rafsanjani and Nabizadeh, 2023).

This difference raises a key question, if performance driven industries prioritise sustainability and data, why do educational institutions struggle? One reason may be how digital tools are taught. Some universities introduce them as separate subjects, while others add these tools superficially to traditional design studios not designed for them (Dai and Brell-Çokcan, 2022). This issue goes beyond software access, highlighting a deeper tension in education where balancing creative intuition with the need for data-literate professionals who can build sustainable, smart environments (Forcael et al., 2020).

This dissertation advances the argument that Digital Twins have the potential to reshape architectural education by integrating technical proficiency with environmental responsibility. It assesses the advantages and limitations of applying Digital Twin tools through a "five-level ladder" of maturity (Deng, Menassa and Kamat, 2021) to foster sustainable environments

within higher education. While acknowledging the distinct pressures of the classroom and construction site, it argues that Digital Twin principles, such as live feedback, lifecycle mapping, and predictive simulation, are critical to enhancing the environmental performance of future buildings and should be central to architectural education (Onstein et al., 2026).

Through literature reviews, case studies, and analysis of academic frameworks, such as David Kolb's Experiential Learning Model (ELM) (Omrany, 2025), this study identifies which aspects of professional Digital Twin applications may be successfully integrated into the university classroom. The underlying question driving this research is how architectural education can use Digital Twins not just as tools, but to address urgent needs critically and effectively for sustainability, safety, and technical precision (Forcael et al., 2020).

This research is motivated by the recognition that technology and the environment are linked. This is shown by the widespread adoption of digital tools for mapping historical sites and managing complex urban systems (Appendix B; Onstein et al., 2026). Yet, university discussions often stop at basic software use. Digital Twins go further, acting as systems with real social and environmental impact, such as supporting the "Golden Thread" of information required for building safety (Build UK, 2026).

For many students, the digital model is the only 'building' they fully realise during their studies. Unlike other academic work, these models are revisited throughout the design process, allowing students to better understand their designs (Zeng et al., 2025).

Aims and Objectives

The aim is to understand and examine both the concept and potential of Digital Twin technology in higher education, specifically focusing on the Architecture, Engineering, and Construction (AEC) sector, and to evaluate the benefits and drawbacks of integrating these tools into the course and explore how their use can assist in the creation of sustainable and smart environments.

The objective of this paper is to investigate the transition from traditional, static building models toward Digital Twins. This study aims to define how virtual replicas move beyond simple geometry to synchronise with real-world buildings through real-time data.

To critically evaluate the potential benefits and drawbacks of integrating these digital tools into architectural education. This includes exploring how the technology can assist in creating sustainable environments and meeting safety standards, while identifying the financial and technical hurdles that currently restrict its use in the classroom.

To assess potential learning methods that can bridge the gap between classroom theory and the technical demands of the modern construction industry. The research seeks to examine ways to make this technology more accessible through affordable hardware and open-source platforms, determining how these tools can help students meet professional competency standards for building safety and environmental responsibility.

Methodology

This paper adopts a qualitative research approach to explore the complex relationship between emerging technology and architectural education. A qualitative method is appropriate as it focuses on understanding individual experiences, professional perspectives, and the educational change required for Digital Twin adoption, rather than relying solely on numerical data.

The research is grounded in the idea that buildings are dynamic systems formed by constant data flow, requiring an analysis into how people, both students and professionals, interact with these systems (RIBA, 2020; Yang, et al. 2024).

The paper utilises the following to gather data and information to form its overall conclusions: A literature and framework review of existing research to provide the foundation for the study, case studies that analyse different academic implementations of the technology, to illustrate the practical applications of Digital Twins in a learning context, and lastly, interviews and qualitative responses to draw on views from students and experts in the field.

Selection of Case Studies

The selection of case studies for this research is based on a strategic need to demonstrate how Digital Twin technology can be practically integrated into higher education. The chosen case studies were selected for their unique ability to represent diverse geographical contexts, varied technological entry points, and distinct educational frameworks. The primary reason for choosing these specific cases was their focus on overcoming the three main hurdles identified in the literature, being the prohibitive costs, technical complexity, and the separation of professions in AEC education.

By selecting cases from different countries, the research demonstrates that the transition to DT is a globally explored requirement, where each case study utilises different core technologies to prove that DT implementation is not reliant on a single expensive software but can be achieved through various means.

DigiLab/BE (Norway and Spain)

This project was selected to justify the feasibility of low-cost and open-source frameworks. It uses affordable Arduino sensors and open-source data exchange platforms like Speckle, proving that DT can be accessible to institutions with limited budgets.

Aachen West (Germany)

This site highlights the use of game engines (Unreal Engine and Unity) and the MQTT protocol. It is uniquely significant for its focus on bridging the gap between classroom theory and the interactive, live environment of a modern construction site.

Georgia Institute of Technology (USA)

This case study represents a collaborative and technological approach. By using 3D laser scanning and 360-degree cameras to document campus buildings, it demonstrates how reality capture can foster communication and experience in the learning cycle.

These case studies prove that Digital Twins can act as more than just planning tools, and allows students to access and navigate real-time data, historical records, and complex data exchange protocols, providing justification for how universities can adjust their courses to produce knowledgeable professionals who can design and manage sustainable and safe building lifecycles.

CHAPTER 1 The Origins and Maturity of Digital Twin Technology in AEC

The term 'Digital Twin' (DT) was coined by Michael Grieves (2016), introducing the framework in 2002 during a Product Lifecycle Management presentation at the University of Michigan.

Grieves is an American scientist, writer, and business executive (Lawton, 2023), who defined the concept as a "digital equivalent to a physical product," being composed of three main parts; a physical object in a real space, a virtual object in a virtual space, and the data linking them together (Grieves, and Vickers, 2016). At its beginning, the technology was developed to manage complex engineering data throughout a product's lifecycle, ranging from early designs to manufacturing and ultimately its disposal (Deng, Menassa and Kamat, 2021), expected to reduce costs and operational risks in the processes of industrial manufacturing (Madubuike, Anumba, and Khallaf, 2022; Ma, Zhang, and Liu, 2025).

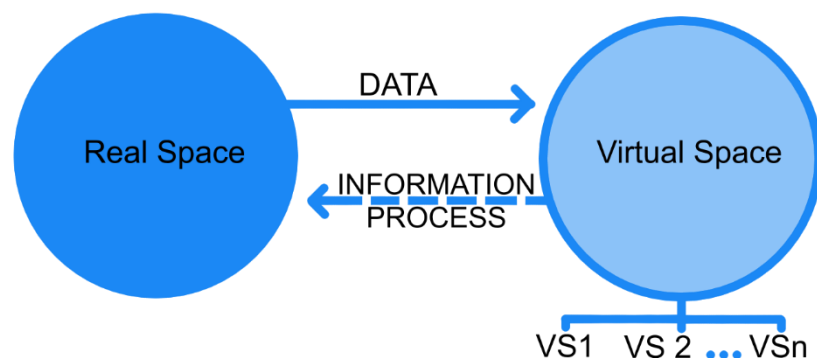


Fig 1. Diagram Showing Flow of Data Between Real Space, Virtual Space and Virtual Sub-Spaces, Based Off Grieves, and Vickers (2016) 'Concept For PLM'

In the 1960s, NASA used basic twinning ideas by creating physically duplicated systems at ground level to match the systems in space to troubleshoot spacecraft, an example of this being for the Apollo 13 mission to simulate onboard conditions (Miskinis, 2019) (Ma, Zhang, and Liu, 2025).

The 2010 roadmap on the other hand, formally established Digital Twins as vital for future vehicle development and management, marking a clear change in direction from traditional simulations, which used static models to explore set scenarios, while a Digital Twin is dynamic and receives real-time data.

The move from Virtual Reality and static modelling to a live virtual-physical connection made it possible for Digital Twin technology to expand beyond aerospace, where today it is applied in various sectors including industrial, educational, and the built environment. (Negri, Fumagalli and Macchi, 2017; Ma, Zhang, and Liu, 2025).

Tracing the Path of Progression from CAD to BIM to Digital Twins

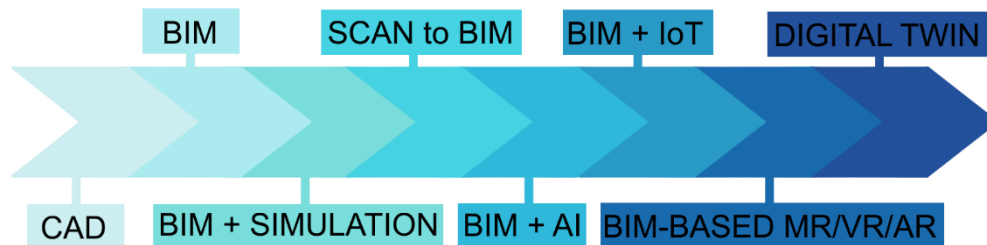


Fig 2. Evolutionary Diagram of Digital Twins in AEC from CAD to BIM to DT, Inspired by DIGITWIN4CIUE (2023)

The history of technical advancements in the Architecture, Engineering and Construction (AEC) sector is observable through a steady progression from geometric representations, towards more dynamic and data-centric information (Deng, Menassa and Kamat, 2021). This evolution is often framed within the context of 'Construction 4.0' (Forcael, et al. 2020), which represents a fundamental change in how physical assets are designed, delivered, and managed (Yang et al., 2024).

Construction 4.0 is a "transformative framework" that applies the principles of Industry 4.0 to the construction sector to improve productivity and efficiency. The term came about in 2016 and focuses on the digitisation of the industry and the industrialisation of construction processes. It integrates numerous technologies to achieve these goals, which includes Virtual Reality, 3D printing, Big Data, Robotics, etc. The core aim is to transition the industry from traditional methods toward a more automated and sustainable "intelligent manufacturing" environment (Forcael, et al. 2020).

This transition can be witnessed and categorised into three distinct stages; the first being the era of Computer-Aided Design (CAD), followed by the rise of Building Information Modelling (BIM), and lastly the emergence of Digital Twins (Deng, Menassa and Kamat, 2021; Aouad et al., 2012).

Setting The Foundations with Computer-Aided Design (CAD)

CAD has served as the primary tool for building design for many decades, shifting the industry from physical drawings to digitised environments. While the use of CAD revolutionised accuracy, its outputs remained primarily 'dumb' in a data sense (Deng, Menassa and Kamat, 2021), where CAD models focused primarily on 2D and 3D geometry such as lines, arcs, and surfaces, it lacked in definition (Autodesk, 2021; Aouad et al., 2012).

Lines representing a wall in a CAD file did not fundamentally understand its material properties, such as thermal conductivity or cost (Deng, Menassa and Kamat, 2021). It provided a visual guide for construction but could not support automated analysis, let alone complex decision-making, leading to information being isolated between architects and engineers on projects (Autodesk, 2021; Aouad et al., 2012).

Information Analysis with Building Information Modelling (BIM)

The term "Building Information Model" first saw use in the early 1990s, whereafter it evolved into the current system known as BIM (Deng, Menassa and Kamat, 2021), where digital components such as windows, walls, HVAC systems, are improved with metadata and parameters. This allowed for geometric and non-geometric data to be unified (Madubuike, Anumba, and Khallaf, 2022), such as material schedules and cost estimations, which can be stored in a shareable and consistent database (BS EN ISO 19650-1, 2018).

BIM enables the seamless collaboration across the AEC lifecycle, from energy simulations during design to scheduling during construction (Deng, Menassa and Kamat, 2021).

However, some sources identify a critical limitation to BIM, which is its static nature (Autodesk, 2021). Once the construction phase is complete, the model typically remains 'as is', showing design intent rather than a reflection of the completed building's actual status, lacking in the ability to update information real-time and automatically without the need for manual intervention or additional data sources (Yang et al., 2024; Madubuike, Anumba, and Khallaf, 2022).

The Introduction of Autonomous Data Utilising Digital Twins

The rise of Digital Twins represents the next clear step in this path, being enabled by the integration of BIM with the Internet of Things (IoT) (Deng, Menassa and Kamat, 2021). IoT is a network of physical objects embedded with sensors and software that allow them to connect and exchange data over the internet allowing these smart devices to collect real-time information to automate tasks and provide insights into how environments function (IBM 2023). A Digital Twin is defined as a virtual representation that achieves real-time synchronisation with its physical counterpart (Yang et al., 2024). Unlike BIM, which serves as

a static record, Digital Twins maintain a live two-way source of data by using sensors and communication protocols, such as Message Queuing Telemetry Transport (MQTT) (Dai, and Brell-Çokcan, 2022).

MQTT is an industry standard messaging protocol designed for efficient machine-to-machine communication, making it the ideal choice for IoT devices like smart sensors. Originally being linked to IBM's MQ Series, it was released as an open-source protocol in 2010 and later standardised by the Organisation for the Advancement of Structured Information Standards (OASIS) in 2013 (AWS 2024). Oasis Open are a trusted non-profit organisation that allows projects and open-source initiatives to achieve formal, and legal recognition (OASIS Open, 2026).

The virtual to physical connection of DTs allows the digital model to mirror the actual state of the physical asset constantly (Yang et al., 2024). The transition from BIM to Digital Twin is not a replacement but an extension, where BIM provides the essential geometric and descriptive foundation (Deng, Menassa and Kamat, 2021), while IoT and Artificial Intelligence (AI) provide the metaphorical 'brain' required for the real-time monitoring, maintenance prediction, and control of the building (Madubuike, Anumba, and Khallaf, 2022).

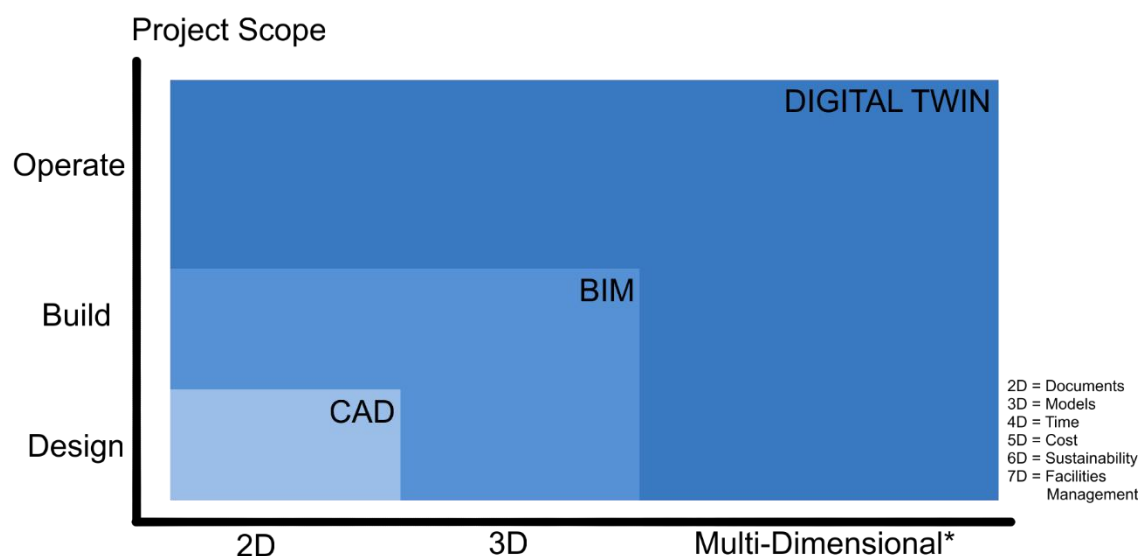


Fig 3. Diagram Showing the Capabilities of CAD, BIM and DTs and Their Uses, based off a diagram by Bentley Systems (2022)

Breakdown of The Five Levels of Digital Twin Maturity

To standardise the implementation of Digital Twins, researchers have developed maturity frameworks that can categorise these systems based on their analytic capabilities and amount of human intervention required (Rafsanjani and Nabizadeh, 2023). A ‘five-level ladder’ classification system has been proposed to reflect the current state of research in the Architecture, Engineering, Construction, and Facility Management (AEC-FM) industry (Deng, Menassa, and Kamat, 2021).

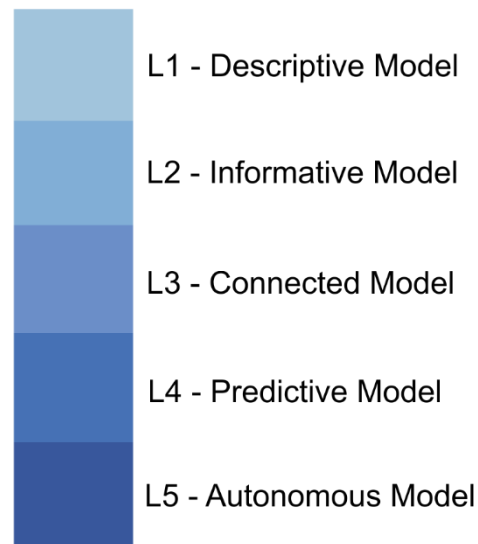


Fig 4. Diagram Visualising the Five Levels of Digital Twin Maturity

Level 1: The Descriptive Model (BIM Review)

At the base of the ladder, Level 1 is considered primarily by the establishment of the digital foundation through literature and model reviews. While not an active twin in the operational sense, this level involves the rigorous documentation of requirements and the standardisation of data exchange formats (Deng, Menassa, and Kamat, 2021). It represents the introductory phase where stakeholders define what information must be mirrored in the eventual digital replica (BS EN ISO 19650-1, 2018).

Level 2: The Informative Model (BIM-Supported Simulation)

This level introduces the use of BIM models for accurate simulations based off static data. These simulations cover energy performance, thermal flow through computational fluid dynamics (CFD), or structural analysis, which allows designers to evaluate ‘what-if’ scenarios before a building is constructed (Deng, Menassa, and Kamat, 2021). At this level, the data remains disconnected from the physical assets performance, leaving the results to be based on assumptions and historical measures instead of real-time conditions (Autodesk, 2021).

Level 3: The Connected Model (BIM Integrated with Sensors)

The transition to Level 3 marks the start of a true Digital Twin, where integrating IoT sensors that measure temperature, occupancy, humidity, or carbon dioxide levels, into the BIM model allows it to become a live dashboard, focusing on real-time visualisation and monitoring, providing remote observation by facility managers of current building conditions (Deng, Menassa, and Kamat, 2021). The goal at Level 3 is to grant situational awareness and identifying that a fault has occurred as it happens (Yang et al., 2024).

Level 4: The Predictive Model (BIM Integrated with Sensors and Algorithms)

This level enhances the sensor data with predictive algorithms and Machine Learning (ML), instead of solely relying on reporting of the status of the building (Deng, Menassa, and Kamat, 2021). These twins can be used for forecasting potential performance, for example, a Level 4 twin can predict occupant thermal comfort or energy demands by analysing the live data alongside weather forecasts and historical patterns. This shifts facility management from a reactive approach where they fix things as they break to a more pre-emptive one by preventing identified failures before they occur (Madubuike, Anumba, and Khallaf, 2022).

Level 5: The Autonomous Model (Intelligent Digital Twin)

The peak of this technology's maturity is at the autonomous or 'Intelligent' Digital Twin, where at this stage the virtual and physical environments interact effortlessly through a closed-loop system (Deng, Menassa, and Kamat, 2021). The Digital Twin can not only predict a need before its required but also executes the solution automatically through actuators and building management systems (Rafsanjani and Nabizadeh, 2023).

For example, the twin can detect an anomaly in energy consumption or a spike in carbon dioxide levels, where it then independently adjusts HVAC settings or lighting without human intervention to optimise its performance. This level represents the ultimate desire of Construction 4.0, where a self-learning and self-optimising built environment can exist (Forcael et al., 2020).

While the research into Levels 2 and 3 is extensive, very few studies have managed to reach Level 4, and none have fully managed to reach the 'Ideal Digital Twin' at Level 5 (Deng, Menassa and Kamat, 2021). Currently, 'Digital Twins' in the industry primarily function as integration platforms for real-time monitoring rather than fully autonomous systems (Yang et al., 2024).

Identifiable knowledge gaps include issues with data sensing, such as data loss and lack of consistency, and a lack of real-time predictive simulations, still relying on continued human intervention for control strategies (Madubuike, Anumba and Khallaf, 2022).

The Industry and Its Drivers for Digital Twin Technology

The main driving reason behind the rapid adoption of Digital Twins can be linked to economic, and environmental factors including regulations (Forcael et al., 2020), with the industry demanding these tools as vital components for existence in a complex modern global market (Rafsanjani and Nabizadeh, 2023).

The AEC industry has a major impact on global carbon emissions and depletion of resources; hence sustainability is a main leading factor for the adoption of Digital Twin technology in the sector to improve sustainability (Forcael et al., 2020).

By providing an in depth and real-time view of energy use, Digital Twins allow for precise efficiency improvements that standard static models cannot match (Deng, Menassa and Kamat, 2021). Digital Twins support the idea of a circular economy by tracking the lifecycle of materials from their foundation to end, ensuring that a building's components can be repurposed or recycled at the end of their operational life, enabling a future with sustainable approaches for the built environment (Rafsanjani and Nabizadeh, 2023).

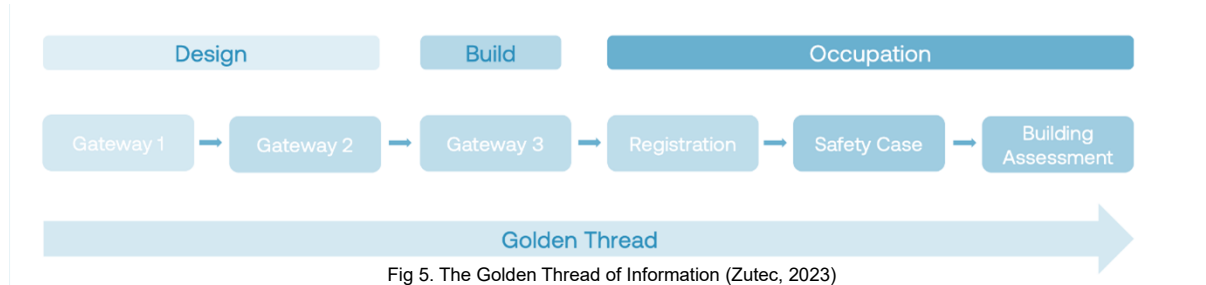
Predictive Maintenance and Operational Cost Savings

Economic efficiency is a powerful motivating factor for a more sustainable built environment, with research suggesting that by 2025 the global demand for advanced digital technologies to aid in the design and construction phase, and Operation and Maintenance (O&M) for the non-residential sector could lead to cost savings of around \$950 million (£700 million) and \$400 million (£295 million) respectively (Rafsanjani and Nabizadeh, 2023).

Predictive maintenance which is enabled through Level 4 and 5 twins can reduce the Total Cost of Ownership (TCO) by extending the lifespan of mechanical assets all while reducing the frequency of emergency repairs (Deng, Menassa and Kamat, 2021).

The Golden Thread and Information Exchange

This is a mandatory requirement established by the Building Safety Act 2022 for Higher-Risk Buildings (HRBs), which aims to provide a 'single source of truth' or a Common Data Environment (CDE) (Build UK, 2026).



The 'Golden Thread' is the timeline of information from building design to assessment containing all the essential details required for a building's safety, including construction methods, materiality, and information regarding the operation and maintenance of the building, aiming to ensure that those responsible for a building's safety management have access to accurate and up-to-date data throughout the building's entire lifecycle (Build UK, 2026).

The legal requirement for 'Golden Thread' applies to any new HRBs, existing HRBs, and those under construction or using transitional arrangements. For new projects it is required for the thread to be set up before works begin and is a critical part of the Gateway Two and Three approval processes (Build UK, 2026).

Various stakeholders use this information which includes the designers and contractors during construction, the Principal Accountable Person (PAP) during the building's occupation, and emergency services to ensure they have access to exact building data for an effective response (Build UK, 2026).

While the term 'Golden Thread' is a regulatory requirement in areas like the UK, the fundamental concept of access to continuous and reliable information exchange across the entire lifecycle of a building is a global industry demand (Forcael et al., 2020). As found in the literature, buildings are required to superimpose information layers that aid in the collaboration between design teams, construction contractors, and facility managers (Yang et al., 2024).

Digital Twins can provide the framework for this 'Golden Thread' by ensuring that the digital record evolves alongside the physical asset to prevent the loss of critical safety and maintenance data that often occurs during the handover phase between the construction

and operation of a building (Autodesk, 2021), ensuring compliance with increasingly strict global regulations (Rafsanjani and Nabizadeh, 2023).

While the industry aims for the 'Ideal Digital Twin' at Level 5, the current reality is that it remains stuck in a foundation phase controlled by real-time monitoring rather than full autonomy and control (Deng, Menassa and Kamat, 2021). This barrier depends less on tools and more on people, in that construction needs workers who see buildings as dynamic systems, not fixed drawings, highlighted by a gap in academics where higher education needs to prepare graduates for smart, responsive environments shaped by constant data flow to meet the demands of Industry 4.0 (Dai and Brell-Çokcan, 2022).

CHAPTER 2 The Disconnect Between AEC Education and Industry 4.0

The evolution from CAD models to fully autonomous Digital Twins reflects the transition in the AEC industry from a focus on ‘how things look’ to the performance of a building (Deng, Menassa and Kamat, 2021). Respondents from a questionnaire, aimed at gathering the views and knowledge of DTs from experts to students can be found in Appendix B, define the Digital Twin as a "working computer model" capable of determining the real-life performance of a building, also describing it poetically as "a library in which every detail about a building is described, from a cornice detail to the manufacture date of a boiler." (Appendix B).

Building Information Modelling (BIM) provides the necessary data infrastructure for Digital Twins which provide the connectivity and intelligence required to act on said data in real-time. The adoption of the ‘Five Levels’ maturity framework allows the industry to move forward from the current ‘pilot phase,’ where simple descriptive twins move towards more autonomous systems (Deng, Menassa, and Kamat, 2021; Rafsanjani and Nabizadeh, 2023).

As these technologies mature they will enable the standard for achieving global sustainability targets, such as “net-zero carbon operations” (Appendix B), all while ensuring the safety of occupants through life-long documentation with the integration of AI, IoT, and BIM into a single Digital Twin ecosystem that is necessary for the future of the built environment (Forcael et al., 2020).

The rapid adoption of these technologies in the construction and design sector highlights a significant ‘academic gap,’ which has appeared within higher education institutions characterised by a ‘digital literacy gap,’ where students entering practices often lack the ability needed to manage the difficult data-driven environments of modern construction undertakings (Dai and Brell-Çokcan, 2022).

The disconnect between graduation and professional readiness is clear; as one respondent noted, “architectural education is lagging behind the industry” regarding advanced digital literacy (Appendix B). This gap is amplified by the split between the theoretical knowledge provided in traditional academic programs, which are still largely falling behind with outdated methods, that prioritise individual disciplines and static data models (Dai and Brell-Çokcan, 2022), all while lacking the digital skills required for current construction practices demanded by Industry 4.0, with the industry requiring trained professionals that are capable of managing these intricate connected systems (Forcael et al., 2020).

The Current Restrictions of Static 2D and 3D Learning Methods

AEC education has focused primarily on the skill of 2D drafting for the last few decades, and more recently Building Information Modelling through 3D design (Deng, Menassa and Kamat, 2021). While BIM has widely been adopted on courses, it is often taught as a still frame in time rather than the ever-evolving state of a building (Dai and Brell-Çokcan, 2022; Forcael et al., 2020).

Participants noted that while students use these tools for "visually seeing the site," they often fail to treat models as "working models that are updated in real-time" (Appendix B). Current teaching methods often treat BIM models as fixed objects that are of a building's design, while not actually reflecting the real-world developing state of a project during its construction or operation (Rafsanjani and Nabizadeh, 2023; Yang et al., 2024).

The reliance on static models creates resistances in the academic world where students are taught to base their designs on basic environmental aspects where factors such as the material wear and site-specific conditions are often simulated using static and often idealised environments rather than live data from the site (Deng, Menassa and Kamat, 2021; IES 2023).

In contrast to this, a true Digital Twin allows for "heat loss assessments" and testing "occupant scenarios" before finalising designs (Appendix B), providing a virtual replica that is continuously linked and updated with its physical counterpart through sensors and IoT devices, which allows for constant monitoring and optimisations to take place (Feng, et al., 2021; Omrany, et al., 2025).

As one respondent observed, this gap is strongly defined by its failure to teach students how to navigate the flow of information; with current methods not providing the interactive environment necessary to understand the live details of a site (Appendix B), failing to teach students how to navigate and manage the flow of information between the digital and physical worlds.

Beyond the use of technical tools, the delivery of information and knowledge often uses passive learning methods, where in many cases a student only engages with construction site processes through lectures, site visits or educational videos and presentations. Although these methods can be informative, they are unable to provide the interactive data-driven environment that is necessary for students to understand the details of a modern construction site, resulting in a discrepancy between the theoretical knowledge provided in the classroom and the practical skills needed on-site (Sepasgozar, 2020).

Hurdles Regarding the Cost of Software and Technological Infrastructure

The emergence of technologies such as Digital Twins and their integration into the classroom is hindered mostly by technical and financial barriers, with the main among these being the prohibitive cost of accessing the software. This point is reinforced by responses that explain that “there could also be additional costs, Revit is seen as an industry standard but is one of the most expensive software and so you tend to find practice use software that can make it more difficult to implement a digital twin in its truest sense” (Appendix B).

Unlike traditional CAD/BIM software which is accessible through educational licenses at a decreased cost, the infrastructure for Digital Twins usually involves a complex ecosystem of software and hardware, which are in most cases too expensive for academic departments, especially those running with limited budgets (Hazrat et al., 2023; Bachmann et al., 2024).

This can include the use of; software to host real-time visualisation, communication protocols for IoT devices such as MQTT, and access to heavy data processing through cloud computing platforms (Omran, H., et al. 2025); Bachmann et al., 2024. This results in a financial strain due to requiring many licenses, which can extend to the students themselves, who may struggle to access the necessary tools outside of the university setting (Bachmann et al., 2024).

“The upfront initial cost of acquiring a digital twin set-up will seem too great as the monetary cost is judged against perceived value.” – Respondent 4 from questionnaire (Appendix B).

In addition to this, the lack of standardisation in Digital Twin software means that institutions often need to reinvent the metaphorical wheel by developing their own proprietary systems rather than using prepackaged educational products, causing a fragmentation of these tools which complicates the learning process for students who need to navigate these often incompatible platforms (Bachmann et al., 2024).

The hardware required for running Digital Twin models tends to be bulky and often requires high-end processing power to manage the large file sizes and the processing of real-time data from IoT sensors. The requirement for specialised equipment such as VR headsets, terrestrial laser scanners, and drone-mounted LIDAR cameras, as well as high-fidelity graphics cards to render information can create IT issues that certain educational institutions may not be equipped to manage (Hazrat et al., 2023; Bachmann et al., 2024).

The Silo Effect and The Separated Nature of AEC Teaching

The most persistent problem in the teaching methods of AEC is its separated nature where architects, engineers, and contractors are educated in isolation of each other, with these departments commonly being housed in different areas with their own courses and culture (Bachmann et al., 2024).

In contrast to this, the professional world varies greatly where the successful delivery of a project requires seamless information exchange between different professionals. However, academic structures often mirror the industry's historical silos, where these fields are taught in isolation from one another (Hazrat et al., 2023; Bachmann et al., 2024).

Information silos are a self-contained information management system that struggles to communicate with other systems, with information flowing vertically, making it difficult to share data between different teams or platforms. This can lead to problems with collaboration as students from different fields lack the required communication pathways during their time in education, whereas a Digital Twin environment is reliant on the interconnected nature of this technology and information (Sepasgozar, 2020; Hazrat et al., 2023).

Students are rarely taught to work together across different courses, with a professional describing it as the "whole design and delivery team needs to work together", including building services, structural designers, and contractors, to produce an accurate twin. Without this collaborative "Common Data Environment" (CDE), students enter the workforce ill-prepared for the shared realities of modern construction (Appendix B).

Digital Literacy Gap, Technical Complexity, and the Expertise Gap

The combination of technical barriers and disconnect between professions in education has resulted in a noticeable digital literacy gap, which is adversely affected by a shortage of expertise among faculty. Respondents highlighted a "lack of lecturers and professionals" who possess both industry experience and the technical proficiency to teach these new tools. There is also a significant "learning curve" when moving from traditional CAD to Digital Twins (Appendix B). Educators in AEC fields are experienced in traditional design and engineering but may lack the training required for technical tutorials with software, meaning that even when a university invests in the necessary hardware and software for the technology, it may not be used to its full extent. Research and respondents both indicate a lack of skilled people who can teach how to use this technology, with staff being "stuck in their ways" regarding the fundamental concepts of Digital Twins (Appendix B) (Omran, H., et al. 2025; Onstein et al., 2026).

The complexity of systems involving Digital Twins can in themselves be a hurdle, described as being on "another level" compared to just using CAD (Appendix B), they require knowledge of data science and computer programming, not normally found in AEC courses. Such as, ensuring that the security and privacy of real-time data from a building remains protected, and is a core concern in Industry 4.0, yet it is rarely talked about in courses related to architecture or civil engineering, requiring a shift toward programs that teach students the base logic of these technologies rather than just the use of specific software.

The rapid pace of technological change means it would be extremely challenging to get all parties, especially Small and Medium Enterprises (SMEs) to coordinate (Appendix B), and by the time a set of courses is revised to current standards, the industry has often moved on to newer approaches, leaving academia in a continuous state of catch-up (Hazrat et al., 2023; Onstein et al., 2026).

Bridging the Academic Gap Through Case Studies

To address these challenges in education new structures are beginning to emerge that prioritise experimental and collective learning. Projects like that of the DigiLab/BE project (funded by Erasmus+) focus on providing low-cost equipment for easy access, with an aim to lower the financial and technical barriers students face (Onstein et al., 2026).

Using free or low-cost software with accessible hardware, such as Arduino sensors allows for the capturing of dynamic climate data, while platforms also use open-source data exchange servers such as Speckle to support real-time data sharing via APIs (Application Programming Interfaces) without the requirement of large file downloads.

Speckle is an open-source data platform specifically designed for the AEC industry to solve the problem of fragmented software, allowing professionals to stream granular geometric and metadata directly between different software like Revit, Rhino, and Grasshopper. It enables real-time collaboration, version control, and automated data workflows, making complex project information accessible for all stakeholders without the need for specialised licenses or manual file exports (Dietmair, Esser, and Harder, 2024; Speckle, 2024).

For institutions that lack expensive equipment like laser scanners, the project provides open datasets from two primary demonstration sites located in Norway and Spain which allows them to focus on analysis and visualisation without the financial burdens (Onstein et al., 2026).

Another example of Digital Twins used in education is the Reference Construction Site Aachen West, that allows students to explore Digital Twin frameworks powered by game engines like Unreal Engine or Unity, enabling real-time interaction with site machinery and

processes that let students explore construction sites virtually through these platforms by using real-time data from site machinery via the aforementioned protocol (Dai and Brell-Çokcan, 2022; Omrany, et al. 2025).

By using game engines as a foundation, it allows these projects to bridge the gap between theory taught in a classroom to the practicality of a real-world construction site. Initiatives like these show that while the hurdles of cost and complexity are something to be considered, these systems can be put in place through structured academic models that emphasise the usefulness of real-world application (Hazrat et al., 2023; Omrany, et al. 2025).

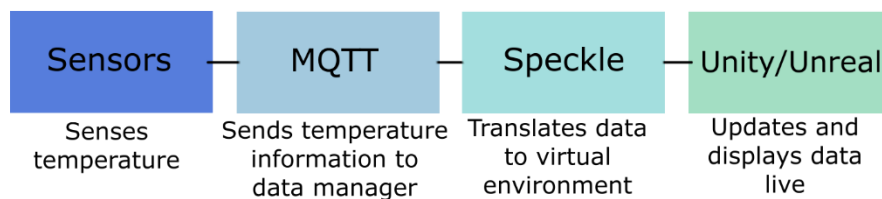


Fig 6. A Flow Diagram Illustrating the Connection of Components in a Digital Twin System, How Sensor Data is Sent to a Game Engine

Lastly the Georgia Institute of Technology implemented a collaborative Digital Twin project where graduate students from diverse backgrounds used 3D laser scanning technology and 360-degree cameras to document a campus building (Zeng et al., 2025).

These projects allow students to gain confidence using this technology and prepares them for professional success by supporting this direct approach, allowing students to experience the challenges of data exchange between platforms and why this necessitates clear paths of communication between professions that are currently seen to be lacking in traditional programs (Zeng et al., 2025).

Respondents have suggested that one way to overcome resistances, is through "studio-based" work and "live site" modules. By bringing in people from practice to lead workshops, it allows universities to help students, all while seeing how the technology aligns with industry and fitting in during the design process. One student noted that using DT for historical restoration made it possible to "twin in and assess" buildings that were otherwise too dangerous to enter, proving that the technology has immediate, practical value in a learning context (Appendix B).

Closing this gap in AEC education requires a fundamental rethinking of how digital technologies are implemented into the classroom, where it is no longer enough just to teach students how to create static 3D models, but they must be prepared to manage the full lifecycle of a building through the dynamic data-driven nature of Digital Twins, investing not only in technology but also in enhancing the skills of teachers, while creating or using standardised and open-source frameworks to increase access and reduce economic barriers (Onstein et al., 2026; Hazrat et al., 2023).

Through the promotion of digital literacy that shows the significance of the connection between the physical and virtual world, it will allow AEC programs to ensure that their graduates are both proficient in current tools and are also prepared for the continuous change required within the profession and of Industry 4.0 (Onstein et al., 2026).

CHAPTER 3 Experiential and Collaborative Approaches to Digital Literacy in Construction Education

The integration of Digital Twin technology into AEC programs represents a fundamental shift from a static and retrospective approach to teaching, towards a dynamic and direct learning style (Onstein et al., 2026; Bachmann et al., 2024). Previously, AEC education has relied heavily on BIM as its technological peak, with participants highlighting a distinction, in that while BIM is often used by students for “visually seeing the site” or creating “scaled, convincing models,” a true Digital Twin is a “working model” that reflects the actual operation of a building (Appendix B).

The existence of an academic gap is evidence that students are frequently taught to create designs that remain disconnected from the reality of site dynamics, behaviour of materials, and collaboration between different professions.

The transition toward a Digital Twin framework permits educators to move more so toward a “deep consideration” of how a building is intended to work (Appendix B), allowing students to interact with the built environment in a manner that mirrors Industry 4.0 standards (Onstein et al., 2026; Omrany, et al. 2025).

Academic Implementation and Kolb’s Experiential Learning Cycle

Digital Twins could be applied in education through David Kolb’s Experiential Learning Model (ELM), where he suggests that the process of learning is dynamic and knowledge is made through the transformation of experience (Al-Obaidi, 2024; Zeng, Q., et al. 2025).

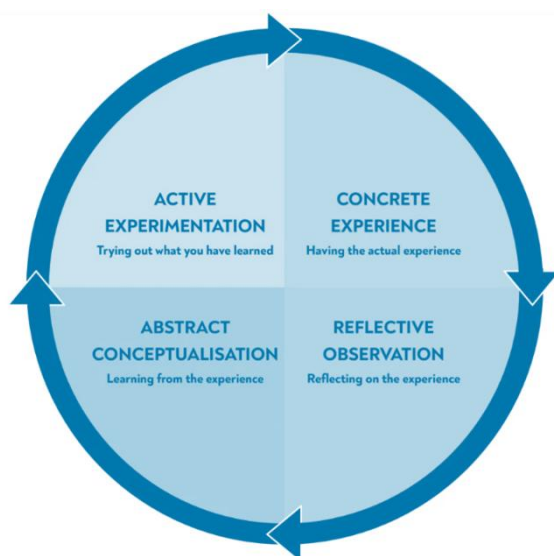


Fig 7. Diagram Showing Kolb's Experiential Learning Cycle, a Four-stage Model How People Learn Through Experience (McLeod, 2023)

The Experiential Learning Model would allow for theory and reality to be linked through the guiding of students in its four proposed stages: Concrete Experience (CE), Reflective Observation (RO), Abstract Conceptualisation (AC), and Active Experimentation (AE) or simply put, Feeling, Watching, Thinking and Doing (Kolb, and Fry, 1975; Kolb, 1984).

In the process of Concrete Experience, students can engage in direct documentation, detailed in the Georgia Institute of Technology case study, reality capture technologies such as 3D laser scanning (LiDAR) and 360-degree cameras allow for the creation of high-fidelity 'as-built' models. These models represent the visual data of a site and are spatially accurate data sets that students can navigate (Zeng et al., 2025).

In regards to this, a student respondent who had previously worked with Digital Twin technology noted that using this information allowed them to "accurately comprehend the terrain and topography" of a space far more effectively than 2D maps (Appendix B), enabling a core understanding of spatial and geometric data that would otherwise be difficult to access, significantly enhancing their ability to comprehend site conditions.

During Reflective Observation students can utilise Digital Twins as a tool for controlled inspection and visualisation of a case study as to why certain site conditions are occurring, for instance, observing how temperature fluctuations in a virtual room relate with HVAC sensor data compared to their initial expectations, all while identifying challenges, such as misaligned reference points or data exchange inconsistencies, which is able to be further enriched by feedback from facility managers, prompting students to analyse the real-world operational relevance of their digital counterpart (Onstein et al., 2026; Zeng et al., 2025).

The Abstract Conceptualisation stage would grant students access to understand these concepts regarding building performance, such as through sustainable design, energy efficiency, or potential "heat loss assessments" (Appendix B), aided by lectures on Construction Operations Building Information Exchange (COBie) data standards and DT principles (Onstein et al., 2026; Omrany, et al. 2025). COBie is a standardised data format, typically delivered as a spreadsheet, used to capture and share essential information about a building's assets, such as equipment lists, maintenance schedules, and manufacturer details allowing for a smooth handover from the construction team to the building owner (Hamil, 2018).

Active Experimentation allows Digital Twins to function as a risk-free 'sandbox' environment, where the Reference Construction Site Aachen West provides this environment, enabling students to use game engines to interact with site machinery in real-time. This allows for the simulation of maintenance routines and operational changes without the risk or cost of physical trial and error. This cycle can boost technical proficiency and has been shown to increase student motivation and perceived learning outcomes significantly (Dai and Brell-Çokcan, 2022; Omrany, et al. 2025).

Virtual Site Visits by Bringing the Site to the Student

One of the most immediate applications for Digital Twins in the classroom is its capabilities for virtual site visits. Traditionally, site visits are challenging to organise both logistically and cost wise, often being restrictive due to safety concerns (Yang et al., 2024).

In a virtual site visit, a student can walk through a mechanical room that would be otherwise too dangerous or cramped for larger classes of people, while also providing features such as 'time-travel' to see development progress. For example, how a specific structural joint was installed before it was covered by drywall, providing a level of transparency that is otherwise impossible in a physical site visit (Yang et al., 2024; Dai and Brell-Çokcan, 2022).

Real-Time Data Streams and Global Connection

The Reference Construction Site Aachen West project demonstrates the power of integrating IoT communication protocols, such as MQTT into these virtual visits, streaming live data from site machinery and environmental sensors directly into a game-engine based Digital Twin (such as Unreal Engine) (Dai and Brell-Çokcan, 2022).

Students can observe live construction activities from thousands of miles away, allowing for this to be particularly advantageous for international collaborations, as seen in the DigiLab/BE project, where students from across Europe could simultaneously explore the same virtual site, discuss progress, and identify issues in real-time (Onstein et al., 2026).

This access to a virtual model breaks the traditional geographical barriers of AEC education, by providing students with sites that have different environmental conditions, allowing for the undertaking of unique projects increasing the scope of AEC education (Onstein et al., 2026; Dai and Brell-Çokcan, 2022).

Scenario Testing and Learning through Virtual Failure

A key aspect of the academic gap is the inability of students to see the long-term consequences of their design decisions. In a traditional course, a student submits a design, it gets graded, and they move on. There is no feedback loop where they can assess their building to see where it fails (Omran, et al. 2025; Bachmann et al., 2024).

Digital Twin based scenario testing changes this by providing a safe and low-cost environment for testing while also allowing students to conduct complex simulations that go beyond the capabilities of a standard BIM model. Using predictive analytics students can simulate 'what-if' scenarios, as an example, highlighted in the research by IES (Integrated Environment Solutions) on performance digital twins testing refurbishment options on a

digital twin predicted a 14% estimated savings in energy (Yang et al., 2024; Onstein et al., 2026; IES, 2023).

This allows students to bridge the ‘performance gap’ between design intent and actual operation, being able to manipulate variables such as occupancy levels, extreme weather events, or structural loads to see the immediate data reaction (Onstein et al., 2026; Hazrat et al., 2023).

Professional feedback emphasises that DTs can “dramatically help with weather predictions and how a building or structure will fare over long periods of time.” Students can assess if a structure is “weatherproof” or if it can be adapted for “different building uses” in the future (Appendix B).

By manipulating variables like occupancy or extreme weather, students gain an awareness of “longevity” and building performance that typically takes years of professional experience to develop. This type of virtual failure would provide an essential academic tool, allowing for the active experimentation during the learning cycle, where students can make mistakes in a risk-free environment (Omrany, et al. 2025; Onstein et al., 2026).

Collaborative Environments and The Common Data Environment

The separated nature of AEC education is one of the biggest obstacles to student success. Using a CDE in the classroom would be a key strategy for breaking these barriers. A CDE, as defined by the ISO 19650 standard, is a sole source of truth where all project information is gathered, managed, and shared (Negri, Fumagalli and Macchi, 2017; Omrany et al., 2025).

In a DT enabled classroom, students from various fields must collaborate on a single project. As one professional observed, the “whole design and delivery team needs to work together” to create a precise model. The introduction of a “BIM expert” role within student groups can serve as a “bridge between architects and assistants” reflecting the new professional environment where specialised data managers connect designers and contractors. This setup promotes teamwork and makes sure that the Digital Twin is a useful tool for integrated project delivery (Appendix B) (Omrany et al., 2025; Zeng et al., 2025).

A Digital Twin hosted in a CDE, like Autodesk Construction Cloud or a custom-built DigiLab platform, mirrors the real-world professional workflow. If an architecture student changes a partition wall in the virtual model, the structural engineering student sees the change and can calculate the new load requirements. This synchronised collaboration helps students communicate and negotiate, preparing them for the connected nature of Industry 4.0 (Negri, Fumagalli and Macchi, 2017; Forcael, E., et al. 2020).

Education through a CDE helps close the digital skills gap by showing students how to manage file structures and stick to consistent naming rules. Instead of focusing only on design visuals, attention shifts toward managing live building data. The Digital Twin lives in a shared online space, making it easier for universities to get past costly equipment needs, allowing students to reach the model using regular internet browsers, allowing for the viewing of core details, leaving the heavy computational tasks to be overseen by cloud servers or specialised lab workstations (Hazrat et al., 2023). Working together like this turns Digital Twin from a flashy demo into something practical, shaping real teamwork through a functional tool for integrated project delivery (IPD) (Omrany et al., 2025).

Overcoming the Hurdles Through Technical and Academic Implementation

Free access matters when schools face soaring prices for commercial software. Instead of paying, educators now choose tools such as Unreal Engine or Unity, that often provide free licenses, allowing for real-time rendering and physics simulations that outperform traditional AEC software. Often, these systems pair with open-source, low-budget hardware like Arduino or Raspberry Pi for IoT sensor integration. With these tools, students can assemble 'mini-DTs' using affordable parts rather than expensive industrial sensors, resulting in cost dropping sharply while allowing direct experience to grow (Onstein et al., 2026; Omrany et al., 2025).

The 'expertise gap,' with participants noting a "lack of lecturers and professionals" who can teach these advanced systems (Appendix B), can be addressed through 'Train the Trainer' initiatives, such as the 'OpeBIM' sessions for teachers (Suwal, Jäväjä, and Salin, 2014).

OpeBIM (or TeacherBIM) is an educational initiative launched by the Metropolia University of Applied Sciences in Finland designed to provide training for teachers on BIM processes and technologies (Suwal, Jäväjä, and Salin, 2014).

The program was developed as part of the European Credit Transfer and Accumulation System (ECTS), which allows for credits to be easily transferred between different institutions and countries to support academic mobility (European Commission, 2022), with this program providing 5 credits to bridge the gap between traditional 2D/3D drafting and the modern, collaborative BIM requirements of the construction industry (Suwal, Jäväjä, and Salin, 2014). OpeBIM provides the essential foundation for teaching digital twins in the AEC profession, since a digital twin is a BIM model evolved with live data. Because OpeBIM focuses not just on design, but also real-world uses like managing buildings or testing workflows, it gives educators both firsthand practice and deeper understanding, providing

the foundations that allows them later to guide students in working with digital replicas of physical systems (Onstein et al., 2026; Omrany et al., 2025).

Success in Digital Twin adoption hinges on equipping teachers with skills in data science, IoT standards, and VR systems, pushing universities to value hands-on innovation over conventional research output, where change emerges when institutional goals begin favouring the development of 'Living Lab' infrastructures and technical competency over paper-based achievements (Omrany et al., 2025).

The following strategies could be considered for adoption based on participant recommendations (Appendix B):

- **Studio-Based Learning:** Moving away from isolated lectures toward integrated workshops.
- **Contextual Learning:** Giving students “space to learn new tools in the context of their projects” rather than as a separate software class.
- **Early Adoption:** Encouraging use “as quickly as possible” to help students keep that edge ahead of industry standards.

The Future of the Integrated AEC Professional

The implementation of Digital Twin technology in AEC education allows for exploring different strategies where students explore virtual sites that respond dynamically, instead of relying only on fixed 2D/3D models. These simulations allow learners to assess different conditions, observing how changes affect structures over time, through collaborative CDEs, offering teams to work together much like they would onsite, allowing data to flow continuously, turning each session into an active experience, supporting a deeper understanding through live feedback rather than theory alone (Sepasgozar, 2020; Omrany et al., 2025).

As one respondent concluded, Digital Twins are “on another level to just using CAD” (Appendix B), and by providing students with the tools necessary to experience the construction site virtually and to test the limits of their designs in a safe digital environment. Therefore, graduates emerge with the ability to adapt quickly when challenges arise and are ready to cooperate alongside a team.

The goal behind these methods lies in building digital literacy by making sense of intricate data patterns within the complex data flows of the modern built environment, ensuring that the “better models” they create today “lead to more testing and better design” tomorrow (Appendix B).

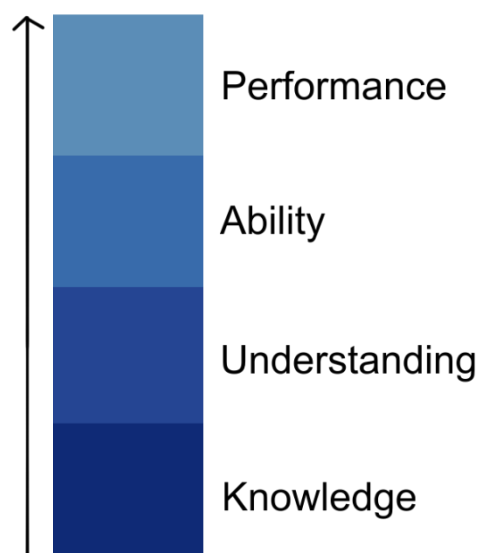
The transition into Construction 4.0 is as much a cultural shift as it is a technical one. Shifting from separate, fixed training methods to connected, evolving systems like Digital Twins in AEC programs can assist in dissolving traditional barriers among architects, engineers, and contractors. The goal is to produce graduates who do more than simply operate software, instead they learn to guide real-time information across projects, required of the modern built environment. As a result, the industry ensures that future structures are more sustainable, efficient, and above all, safe for their occupants (Hazrat et al., 2023; Omrany et al., 2025).

CHAPTER 4 Aligning Digital Twin Education with ARB and RIBA Competency Frameworks

Integrating Digital Twin technology into educational frameworks aligns with competency standards set by bodies such as the Architects Registration Board (ARB) and Royal Institute of British Architects (RIBA). When woven into coursework, these models prepare coming generations of architects to respond to environmental crises. Safety for communities gains strength through precise simulations shaped by live data inputs. Ethical practice evolves when students learn to navigate information flows responsibly during design phases (ARB, 2023a/b; RIBA, 2020).

Application of Digital Twins in Architectural Education

Digital Twins transform the traditional studio experience, by shifting it from a theoretical design environment into an active workshop for data-driven experimentation. Unlike static simulations like CAD/BIM, Digital Twins give students live dashboards which enable real-time monitoring of conditions, which include occupancy, carbon dioxide levels, and thermal performance. Digital Twins provide an immersive, real-time experience of a building's lifecycle, and through a Level 3: Connected Model, students can observe building conditions remotely using IoT sensors (Deng, Menassa and Kamat, 2021).



This approach advances learning from 'Knowledge (Knows)' to 'Understanding (Knows how)' to 'Ability (Shows how)' and lastly 'Performance (Does/Is)' as explained in the ARB's adaptation of Miller's Triangle, engaging with live models that allow students to connect theory with practice and immediately see environmental impacts (ARB, 2023a; RIBA, 2020).

Fig 8. Diagram Illustrating the Stages of Learning Adopted by the ARB, Based off Miller's 'Triangle'. Inspired by ARB (2023a)

Digital Twins serve as a CDE, supporting the 'Golden Thread' of information mandated by safety legislation. In educational settings, this fosters collaboration between professions and reflects the ARB competency outcomes regarding the architect's role. Students collaborate with engineers and contractors in a unified virtual space, managing complex data and directing real-time information across projects, building digital literacy, all while preparing graduates to work as a team and adapt to site challenges within the digital twin (Omrany et al. 2025; Build UK, 2026).

Relevance to ARB Competency Outcomes

The ARB's 'Tomorrow's Architects' framework defines five core competency areas: Contextual and Architectural Knowledge, Design, Research and Evaluation, Management Practice and Leadership, and Professionalism and Ethics. Digital Twins can address multiple threshold competencies within this framework (ARB, 2023a).

ARB Outcome D12 requires students to 'use appropriate digital systems for creating, modelling, processing, presenting, and sharing design, building and project information.' Digital Twins are the most advanced of these systems, with Digital Twin technology allowing students to go beyond basic 3D geometry and develop designs that integrate artistic, spatial, environmental, social, and experiential aspects with the technical requirements of construction (Outcome D4). Digital Twins enable students to appraise and refine building briefs using actual performance data, rather than solely on design intent (Outcome D2) (ARB, 2023a; Omrany et al., 2025).

Sustainability is a key reason for adopting Digital Twin technology. The ARB asks architects to understand the 'principles of climate change and biodiversity' (CK4). It also asks them to know the 'implications and benefits of regenerative design solutions' (D9). Digital Twins provide the in-depth, real-time view of energy use that students need. This helps them understand 'life-cycle costs to the environment' (Outcome D7). When tracking material lifecycles, Digital Twins support the circular economy, letting students meet standards for ethical sourcing and supply chains throughout a project (ARB, 2023a; Omrany et al., 2025).

The ARB has prioritised 'Fire and Life Safety' in response to events like the Grenfell Tower fire. Outcome D11 requires students to address 'fire safety, life safety and wellbeing.' Digital Twins simulate what-if scenarios for emergency evacuations or fire spread. This lets students evaluate safety strategies in a safe digital environment before construction, with such an approach helping to ensure buildings are safe to construct, use, and maintain (Outcome CK7) (ARB, 2023a; Omrany et al., 2025).

Relevance to the RIBA Education Framework

The RIBA's (2020) "The Way Ahead" brochure emphasises a focus on core knowledge and professional behaviours. The framework introduces 'Mandatory Competences,' including Climate Literacy and Health and Life Safety, which Digital Twins can support.

RIBA Past President, Alan Jones, says education must address the climate emergency and the mediocre performance of the built environment. Digital Twins provide students with the research literacy needed to demonstrate expertise, allowing students to use predictive algorithms and machine learning (Level 4 Digital Twins) to forecast building performance. This evidence-based method is needed to build public confidence in chartered architects (RIBA, 2020; Deng, Menassa and Kamat, 2021).

The RIBA framework prioritises ethical practice and risk and liability management. By combining Digital Twins with a CDE to support the recording of this single source of truth, it helps students to keep this golden thread of information, and reinforces their duty to the environment, society, and the well-being of future generations. This is outlined in ARB Professionalism outcomes (PE5), changing education from solely creative work to a focus on leadership, responsibility, and competence (ARB, 2025; RIBA 2020; Omrany et al., 2025).

Through the integration of Digital Twins, educational institutions can support compliance with the "Standards for Learning Providers" established by the ARB, where standard five states that providers must maintain appropriate digital resources to deliver the Outcomes. As the industry moves toward Level 5 Autonomous Models, educational providers must invest in digital infrastructure, this includes IoT sensors and BIM-integrated platforms, helping to teach advanced competencies (ARB, 2023a; Feng, Chen and Garcia de Soto, 2021; Deng, Menassa and Kamat, 2021).

The ARB understands not all students can show every competency in a physical environment; therefore, it allows assessment through simulated scenarios (ARB, 2023a). Digital Twins offer an ideal platform for such simulations, providing authentic situations where students navigate many constraints and complexities (Grieves and Vickers, 2016). This ensures equal access to quality learning resources for all students (Standard 5.2) (ARB, 2023b).

Integrating Digital Twins in architectural education is a strategic must, not only is it just a technological upgrade, but Digital Twins bridge traditional static models and the dynamic, data-driven buildings of the future (Negri, Fumagalli and Macchi, 2017). They provide the sharpened focus that RIBA seeks, all while supporting the reaching threshold competencies required by the ARB (RIBA, 2020; ARB, 2023a). Through direct learning, real-time sustainability assessments, and safety simulations, Digital Twins can prepare architects to face climate challenges and the needs of Construction 4.0. Their main value is building the skills, ethics, and responsibility of tomorrow's architects (Haahr, et al. 2026; Forcael, 2020; RIBA, 2020).

CHAPTER 5 Reflections and Conclusions on Digital Twin Adoption in AEC Education

Digital Twin (DT) technology in the AEC sector marks a shift from static building representations to dynamic, data-driven models. Building on this technological transformation, in the era of Construction 4.0, this evolution prioritises building performance over appearance by synchronising physical and digital assets. Digital Twins address challenges in sustainability, safety, and operations, but a lack of alignment with higher education limits their effective use in practice.

This transition unlocks significant opportunities for performance and safety. The main advantage of Digital Twins is their real-time, two-way connection between buildings and digital replicas. Unlike static BIM models, Digital Twins use IoT sensors and protocols such as MQTT to reflect an asset's current state, enabling immediate fault detection (Level 3) and predictive maintenance (Level 4).

Alongside performance improvements, Digital Twins play a key role in achieving net-zero carbon targets by providing real-time information on energy consumption and occupant behaviour, consequently supporting targeted efficiency improvements. They facilitate tracking of materials' life cycles, supporting recycling and repurposing efforts in support of a circular economy.

Furthermore, Digital Twins improve safety by ensuring compliance with requirements like the Building Safety Act 2022. By serving as a single source of evolving information, they keep crucial safety data and enable simulations for emergency scenarios, especially in high-risk buildings.

Despite these advantages, achieving full Digital Twin maturity remains rare. Many projects do not advance beyond basic levels, with few achieving predictive functions and none attaining full autonomy. The considerable costs of software, hardware, and specialised equipment including LiDAR and VR often render Digital Twins not accessible to many firms and academic institutions.

Adding to these technical and financial barriers, a siloed approach in AEC education limits collaboration and hinders the adoption of Digital Twins. Lack of cross-disciplinary training and educators with both industry and technical expertise heightens the problem.

Additional technical challenges consist of data loss, platform incompatibility, and rapidly outdated courses. Data security and privacy are also insufficiently addressed in current academic programs.

To close these gaps, AEC education should adopt experiential learning models, provide direct experimentation with tools like Unreal Engine, and integrate practical digital twin projects. This approach strengthens technical skills and engages students directly with industry-relevant challenges.

Initiatives such as DigiLab/BE demonstrate that using affordable sensors and open-source platforms makes the digital twin experience accessible. Virtual site visits using 3D scans empower students to explore complicated environments safely and remotely. Expanding the use of such practical, cost-effective approaches increases digital twin adoption.

Institutions should enhance faculty skills through programs like OpeBIM, implement studio-based, industry-led learning, and integrate lifecycle management within courses. Such measures enable graduates to manage building lifecycles rather than simply operate software.

Adopting Digital Twin technology requires viewing buildings as dynamic, data-driven systems. Success in Construction 4.0 depends on collaboration and strong data management throughout a building's life. To advance Digital Twin adoption, prioritising investment in digital skills and open-source tools ensures courses support climate knowledge, safety, and ethics to promote an environment of collaboration.

For all users and designers, implementing these actions and ideologies can enable and nurture a more sustainable, efficient, and safe built environment; or more eloquently put by a respondent in Appendix B; "Do it yay!"

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APPENDIX A: Glossary of Terms

AEC: Architecture, Engineering, and Construction

API: Application Programming Interface

AR: Augmented Reality

ARB: Architects Registration Board

BIM: Building Information Modelling (also referred to as "Building Information Model")

CAD: Computer-Aided Design

CDE: Common Data Environment

CFD: Computational Fluid Dynamics

DT: Digital Twin

ECTS: European Credit Transfer and Accumulation System

ELM: Experiential Learning Model

HRBs: Higher-Risk Buildings (mentioned in the context of building safety legislation)

HVAC: Heating, Ventilation, and Air Conditioning

IoT: Internet of Things

IPD: Integrated Project Delivery

LIDAR: Light Detection and Ranging

ML: Machine Learning

MQTT: Message Queuing Telemetry Transport

MR: Mixed Reality

O&M: Operation and Maintenance

OASIS: Organisation for the Advancement of Structured Information Standards

PAP: Principal Accountable Person

PLM: Product Lifecycle Management

RIBA: Royal Institute of British Architects

SMEs: Small and Medium Enterprises

TCO: Total Cost of Ownership

VR: Virtual Reality

APPENDIX B: Questionnaire Responses

Can you describe your role and experience with digital twin technology, particularly within architecture or education?

1. I have used a digital twin for a historical restoration scheme. It was hard to enter the building in its state, so it was used to twin in and assess it digitally.
2. I have just started utilising digital twin technology in my studies. I am currently learning how it can be utilised in architectural design.
3. I work with project design and delivery teams to help ensure the buildings they are delivering for clients operate as net zero carbon. I also work with organisations to advise on ways to decarbonise their operations. I don't have a lot of experience of digital twins, other than being aware that they are talked about within architectural projects as being used to track project progress through design, construction and building operation.
4. Student who has used digital twinning technologies for a University project which needed understanding and deep consideration on a historical site. The ability to use a digital twin for the project not only helped myself and colleagues to visually see the site from different perspectives in a 3D scope but also it allowed us to accurately 3D model and render our schemes and contextual images. Working an entry level job utilising digital twin systems again for understanding the site and being able to accurately comprehend the terrain and topography of the space. The general tasks were to create scaled, convincing models for architectural practices to use to persuade the council for planning permission as well as gaining public backing... I used the digital twin, pointcloud scans, to design, mass and detail a digital 3D model on Revit or autoCAD, before utilising that information to design a physical model.
5. I work with students and professionals to aid in their use of point clouds in their projects. Using Revit, I import point clouds and use them as a template for creating digital twins of existing buildings. One of our biggest projects being the digital twin of the Lampeter campus and surrounding grounds, which took several hundred scans with the terrestrial laser scanner and LIDAR camera mounted on a drone. I also work with local architecture practices to deliver as built models for their projects, creating digital twins.

How would you define a “digital twin” in the context of architectural practice or education?

1. An asset! Yay!
2. A digital twin is a digital recreation of an existing context for use in design. The form I know it in is point clouds and lidar scanning.

3. In the context of architectural practice, I would define a digital twin as being a working computer model of a building, which can be used at design stage to assess building performance, for clash detection, etc. It will then be updated as a project progresses from design to construction and occupation, and should be capable of determining real-life building performance, as well as making it easier to find and rectify faults, to highlight any abnormalities, such as unexpected high energy use of a particular system, identify when systems/equipment are broken, flag when items are approaching end of life, etc. In theory, a digital twin should provide more certainty about a building's performance, should be used to improve facility management, and is capable of managing energy consumption and generation to ensure the building operates as efficiently and effectively as possible.
4. From my experience I have been using digital twinning systems to enhance and speed up the process of digitally designing within the construction industry. This creates the breathing space for building projects under tight time constraints to develop new schemes for a sustainable future in built environment. These tools can be used to revolutionise the way we plan, design and build new towns, cities and other key elements of infrastructure, whilst also making it possible to reach bigger goals like sustainable practices. From what I can see when discussing projects with the architectural practices I work with there has been examples of a production plant twin to represent manufacturing facilities, procurement and supply chain, or infrastructure twins that represent physical infrastructure like a building, stadium or a network of roads. Aside from structural development it can be used to present to clients and the general public to convey schemes and help them visualise what the architect or contractor is trying to convey.
5. One of my presentations contains a quote that I believe helps answer this question: 'A digital twin is a library in which every detail about a building is described', meaning that everything from the micro to macro, a cornice detail to the manufacture date of a boiler.

In what ways do you think digital twins could enhance architecture students' understanding of complex building systems, design processes, or sustainability principles?

1. It would be much easier to understand how buildings work, as you have a digital copy you can zoom into, mess around with etc. Especially derelict buildings, or for things like heat loss assessments.
2. It can aid students in providing a consistent visual tool for understanding a site and its context. It can provide consistent accurate measurements that students may not be able to find or survey, e.g. floor heights. It may be used as a tool for understanding building construction.

3. Digital twins could significantly enhance understanding of complex building systems, design processes, sustainability principles and the impact of occupants on buildings and their operation. This would be through enabling different materials, service strategies and user/occupant scenarios to be tested within the digital twin, during design development, before finalising designs. This would be incredibly useful for informing designs and helping students design truly sustainable buildings, with more confidence that they will perform as anticipated in reality.
4. Because they give a thorough and through example of the site and existing building fabric as well as assisting in the digital, geolocated, structural progression of designs and schemes.
5. I believe that students can grasp a buildings context and probe its inner workings more when there is a solid and accurate data set to work with. It can be used as a starting ground for interrogating condition of existing buildings, (without being tied to site, though can be argued as an important part of the process) develop informed responses to site conditions and test ideas using an accurate representation of the site. Greater accuracy can lead a more tailored response to site i.e less waste during construction.

How could digital twins be incorporated into architectural curricula (e.g. design studios, construction technology, or environmental systems)?

1. through technology modules perhaps. Or any historical scheme.
2. A digital twin of a project site may be supplied by the university as an optional tool for students to exploit. It can be used as a tool for introducing sites if a site visit is not currently possible.
3. These could be developed as a follow on from the Revit models that students produce within their design studios. Teaching modules within construction technology could be included on digital twins, using the models developed by students to enhance understanding, i.e. backing up theory with practice.
4. by using them to conduct site analysis or to develop different architectural or structural schemes throughout educational development
5. Yes, definitely. I recently talked at the BIM in Series event held in Leicester, it was highlighted that architectural education is lagging behind the industry when it comes to advanced digital literacy. I believe that schools should consider incorporating BIM and as an extension, digital twins, to the curriculum, as they are valuable tools in the understanding and accuracy of data when it comes to building information. It shouldn't detract from good, sound design or replace design thinking but be enhanced by it.

What teaching models might best support the use of digital twins in architectural education (e.g. studio-based, problem-based, work-integrated, etc)?

1. Studio based.
2. The technology must be introduced in workshops as it's too niche to be self taught, however afterwards it would be best utilised in long term projects in a studio based model to allow students to experience how the digital twin can aid each step in the design process.
3. I think students would gain a full understanding of digital twins by developing them through their studio work. Once developed, different scenarios, representing real-world scenarios and challenges, could be tested using the model. This would enhance learning, as the theory of digital twins would be tested in practice, which would make the theory more memorable and be more reflective of real-world issues.
4. studio based work - using examples from work integration - all sound good !!!!!
5. Any combination of models could work as an approach to teaching, however, by integrating digital twins into a studio-based project, where students are working with them from the start to achieve a design, has worked well. I can also envision a problem-based task in which students are given a goal such as to model a specific detail based on a given point cloud or to populate an asset with manufactures details also working well.

How might experience with digital twin technology improve students' employability or readiness for professional practice?

1. It is something they will probably use in practice, so having that prior knowledge is great.
2. As newer technologies are becoming more available, students with experience in these technologies will become much more valuable in practice.
3. It would prepare students to design for real challenges faced in practice and to understand the implications of design changes during construction of projects.
4. its relevant to the future of architecture and construction - and is a relevant and will only be more relevant skill to have
5. Having proficiency working on digital twins is becoming more important as regulation and standards continue to improve and new technology emerges that are able to lead to better informed and more accurate design decisions. The rise of AI in the industry is also a highlight and so students should be ready, by the end of their education, to rise to the challenges of the fast moving working world.

What skills related to digital twins do you believe future architects should develop to meet industry demands?

1. The ability to design sustainably - etc heat loss and passive house standards.
2. Experience in synthesising, utilising and understanding how they can be used across the building sector.
3. Viewing design models as working models that are updated in real-time as projects progress. Often design models are not updated during construction phases and as-built drawings/models do not always represent what was actually built. This is not just an issue for architects to face. The whole design and delivery team needs to work together to coordinate efforts to produce accurate digital twins, which can be handed over to clients at project completion.
4. I don't know enough to say sorry xxx
5. In recent times, I have seen that BIM, not just CAD skills, are important to the industry. Being able to detail buildings to such a level that every brick, MEP, asset etc. are designed, enables a 'one truth' in which everyone, from the contractor to the designer, is clear on how a building is built. In the hopes that it leads to a building that performs better, with tighter tolerances and with fewer mistakes/mistranslations. So, students that have a good grasp of these concepts would be ahead of others.

How can universities collaborate with industry to ensure that digital twin applications in education align with real-world practices?

1. Restoration projects.
2. Universities are the places where these technologies can be experimented with and in collaborating with industries on current projects, students can see how their use of the technology aligns with the industries use during the design process.
3. Liaising with organisations to find out what they are doing, how they use them, issues they face or foresee, what skills need to be developed to improve, etc. Working with design and construction companies and/or shadowing construction projects would provide a good view into real-world practices, although this can be difficult to implement in reality, due to time, logistics, access to projects, etc. Maybe a good start would be to invite industry into the university to take part in an open workshop to discuss, in the first instance - this may lead to partnerships developing with organisations. It would be a good way to gain some insight into the issues, in the first instance.
4. incorporating modules at live sites that can utilise the facilities that the practices have - therefore learning the industry standard and getting students work ready
5. It isn't easy to marry academic and professional practice together, given how busy professionals tend to be! But by bringing in people from practice that work with digital twins and BIM, this could help students get a better understanding.

What challenges or barriers might institutions face when implementing digital twin technologies (e.g. cost, expertise, infrastructure)?

1. Cost is the main one, and a lack of people who can teach how to use them.
2. There may be a lack of lecturers and professionals with both experience in the industry and experience with the technology. Funding for such people within universities may be lacking.
3. Cost and expertise are big challenges. Also, the desire and time of construction teams to maintain digital twins throughout a project and ensure they are reflective of the building once complete, and usable for facilities management.
4. Generally (I would presume) the overall demographic of common practicing architects and construction professionals find it difficult to use the technology associated with digital twinning and would need training. That in itself is expensive for companies to do and put into practice. I would also imagine that whilst digital twinning can provide so much more information, if people don't perceive the information to be useful (stubborn stuck in their ways) then the upfront initial cost of acquiring a digital twin set up will seem too great as the monetary cost is judged against perceived value.
5. There is always a learning curve when going from CAD to digital twins and it would take time for designers to adapt to the complexities involved. There could also be additional costs, Revit is seen as an industry standard but is one of the most expensive software and so you tend to find practice use software that can make it more difficult to implement a digital twin in its truest sense i.e BIM.

Are there any ethical, data privacy, or environmental concerns related to the use of digital twins in education or practice?

1. Unsure - depends if the neighbouring properties are captured.
2. N/A
3. There shouldn't be any personal information involved, so I wouldn't think so.
4. If AI is used it isn't the most sustainable environmentally. I would imagine people may have issues with data capture as their homes or private spaces will be included...?
5. This is a good question! The responsibility of managing a digital twin once a project is completed is a key issue, as buildings need maintenance and will change over time, who is responsible for maintaining digital twins, the architects? Owners? The rise of AI in the generation of models, including digital twins, is also a concern, there is a lot of energy and water that is used in those systems and it would be interesting to see how this impacts our environment.

How might institutions overcome resistance or uncertainty about adopting this technology?

1. I think going into universities and workplaces and showcasing how they can be used, getting people involved could clear up uncertainty.
2. If universities fall behind the industry, students will become less valuable after leaving education. In order to stop this, we can showcase its potential through collaboration with people in the industry.
3. All new systems take a while to be adopted, but over time and with increased use, knowledge increases and they become the norm. Therefore, I think if students are taught to develop them, they will continue this through into practice. However, the industry needs to ensure all members of a design and delivery team adopt the technology. The biggest challenge is getting all parties to coordinate efforts - building services, structural, civil designers, and contractors. It will be the job of main contractors to coordinate with all their subcontractors, which is extremely challenging as many of them will be SMEs and not used to this technology.
4. Seeing examples of what it can do and how it can enhance architectural schemes positively. Also watching people use and create with it.
5. Education. Most professionals or lecturers that are resistant to the adoption of new technologies often have misconceptions or outdated understandings, or are stuck in their ways and so it is key for everyone to continue to develop their knowledge, be willing to learn and adapt, as well as students.

How do you see digital twin technology evolving in architectural education and practice over the next 5–10 years?

1. I think it will play a massive part. Its the most accurate way to survey.
2. I see it becoming a staple part of design, overtaking normal surveying.
3. I think it will become more widely adopted.
4. I would imagine it would become more popular as the demand increases and trends decrease the overall price tolerances will drop so it will become more financially accessible.
5. I would expect there to be a rise in its use, especially in practice. Many of the big practices are already miles ahead of academia when it comes to the adoption of digital twins and BIM. It will continue to be difficult for smaller practices to adapt, but with the help of architecture schools, we can equip students with both traditional and digital skills to use a tools for achieving good design.

What future roles do you envision for digital twins in fostering sustainable and resilient design thinking?

1. I think they will be paramount - you will be able to identify heat loss, inconsistencies within insulation, broken cavities etc and then design accordingly instead of guessing.
2. More care and accuracy for designing around existing fabric and incorporating it in design for a reduced carbon footprint.
3. They could play a fundamental part, if used properly.
4. Digital twin can dramatically help with the weather predictions and how a building or structure will fare over long periods of time. The longevity of building and structures are just as important, if not more, than other additive sustainable measures so being able to test if a structure is going to be kept with the client for different building uses but also so that it is weather proof and can stand the test of time.
5. For the near future, the role I have in practice, where I assist practices with digital twin creation, a BIM expert, would be a bridge to architects and assistants later down the line. I don't think new roles should replace old ones, just the methods and ways in which architects /assistants interact with projects in the future, with the hope that better models lead to more testing and better design.

What recommendations would you give to universities considering adopting or expanding digital twin initiatives?

1. Do it yay!
2. Encourage it's use as quickly as possible to edge ahead of the industry.
3. Start with finding out how the construction industry is currently using them, research areas that could be improved and focus on them.
4. Test it out and try it...?
5. Give yourself time to learn and understand what a digital twin is, as it on another level to just using CAD. If you can teach students how to learn, giving them space to learn new tools in the context of their projects, it would make it easier for them to adapt to new tools.