LEARNING OUTCOMES OF DIGITAL TWINS IN ENGINEERING EDUCATION: A SYSTEMATISED REVIEW

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ABSTRACT

Interest in educational applications of Digital Twins (DTs) is growing, but translation of theoretical benefits to measurable student experiences has not been investigated in depth. This systematised review evaluates empirically measured learning effects caused by Digital Twins in engineering education, in comparison to traditional teaching methods. It aims to identify key learning outcomes and experiences caused by DTs across cognitive, behavioural, and affective dimensions, and to assess current strength of evidence supporting their use in education. A keyword search of Scopus, Web of Science, and IEEE Explore yielded twenty-six papers. Strength of evidence was found to be tentative for behavioural outcomes, but more promising for cognitive outcomes, especially when DTs are used as an enabling technology for new ways of teaching and learning. Affective outcomes were found to be under-researched. Other research gaps include formalised qualitative outcomes, long-term effects, and experiences of marginalised students. To prevent misconceptions about technological feasibility and benefit, greater transparency is required when defining and describing Digital Twin implementations.

KEYWORDS

Digital Twins, Engineering Education, Experiential Learning, Standards: 2, 6-8

INTRODUCTION

Digital Twins (DTs) are gaining popularity in industry and academia (Kaur & Bhatia, 2025). Beyond their original context of product management, DTs are now expanding into increasingly diverse fields both within and outside of engineering. One such area is engineering education, where Digital Twins offer several theoretical benefits.

Interaction with a DT can encourage students to be agents of their own learning, aligning with constructivist principles of meaning-making (Piaget, 1971). Support for active and experiential learning also aligns with the Conceive, Design, Implement, Operate (CDIO) framework for engineering education (*Worldwide CDIO Inititative*). Kolb's Experiential Learning Cycle (Kolb, 1984) proposes that the ideal process of learning occurs in a cycle of experiencing, reflecting, thinking, and acting. Digital Twins bridge the theoretical and practical worlds (Grieves, 2005), which may encourage a more natural transition from thinking to acting. Furthermore, because virtual models may not have the same resource and safety constraints as physical environments, use of DTs to support laboratory activities can overcome barriers to the "acting" stage of the cycle (Ağca, 2023). Finally, DTs involve real-time data and provide immediate feedback (Madni et al., 2019), prompting reflection and allowing learners to repeat the learning cycle multiple times during an activity.

However, whether these theoretical benefits translate to learning is unclear. Evidence that a Digital Twin approach improves learning outcomes is largely through case studies. This review aims to evaluate strength of literature at this early stage, identify the most promising outcomes for targeted application, and highlight research gaps.

BACKGROUND

The idea of a Digital Twin was introduced in a lecture series in 2002 by Michael Grieves as part of the Product Lifecycle Management concept, and expanded in later literature (Grieves, 2005, 2011; Grieves & Vickers, 2017). In this context, it denotes a high-fidelity virtual copy that is linked to a physical product in real-time. Historical data are collected and stored by the DT throughout the product's lifecycle in order to "de-silo" the manufacturing process. This equips engineers with information to monitor an existing object and to explore hypothetical future scenarios. The virtual model is an extension of humans' ability to construct mental models, and visualisation is an integral part of the DT. Expansion into other domains has led to a greater variety of definitions, reflected in academic literature (Jones et al., 2020) and standards (Wang et al., 2024). Varying aspects include fidelity, nature of the physical entity, and level of connection between virtual and physical entities. Current usage of the term "Digital Twin" can often overlap with the established concept of a virtual simulation or digital model. This paper acknowledges all interpretations of the term, but explores these during analysis.

In education, reviews by Alghamdi et al. (2025) and Bachmann et al. (2024) highlight Digital Twins as an emerging but promising technology. However, they also identify a lack of empirical validation, particularly through long-term studies, and note security, privacy, and scalability as challenges. In engineering education, reviews by Kotecha et al. (2025) and Shaikh et al. (2024) both conclude that DTs have potential, while a bibliometric review (Chamorro-Atalaya et al., 2024) demonstrates growth in this area. These papers analyse DTs' applications, but their coverage of learning outcomes and experiences is very limited. Assessment of specific learning outcomes is important to understand how theoretical potential translates to students. In specific engineering fields (Kumar Karanam & Hartman, 2025; Omrany et al., 2025) DTs' effects on measured learning outcomes have been identified. To the authors' knowledge, no reviews consider this area within engineering education as a whole.

Literature reviews in this area also tend to evaluate educational tools based on outcomes only. Meanwhile, this review adopts a constructivist approach, arguing that measurable teaching and learning *experiences* are as important as the outcomes they lead to, as argued by a previous review in a similar area (Sellberg et al., 2024). Both qualitative and quantitative measures of learning are therefore considered.

This review builds on previous literature by examining how the proposed benefits of DTs in engineering education translate to tangible student learning outcomes and experiences. It aims to address the following research questions:

- How strong is the evidence to support use of Digital Twins in engineering education?
- What learning outcomes and experiences (cognitive, behavioural, and affective) emerge from the literature when Digital Twins are compared to traditional teaching?
- What gaps, challenges and barriers limit the strength of evidence?

METHODS

To address the research questions, the PICO framework (Richardson et al., 1995), was used to clarify eligibility criteria. Two comparison points were considered eligible under the umbrella of "traditional teaching" stated in the research questions; campus management applications were not considered. The "Outcome" section was left open for investigation (see Table 1).

Table 1: PICO framework to define eligibility criteria

Category	Eligibility	Method
Population	Students and teachers in higher engineering education	Search strategy, inclusion strategy
Intervention	Intervention must be described as a "Digital Twin"	Search strategy, inclusion strategy
Comparison	Physical laboratories (experiments, demonstrations, practical coursework)	Inclusion strategy
	Theoretical teaching (lectures, worksheets, theory-based exams)	Inclusion strategy
Outcome	To be investigated; at least one measured effect required	Inclusion strategy

Search Strategy

A systematised review approach was taken for this study (Grant & Booth, 2009). This follows a similar process to a systematic review, but omits steps that require multiple independent reviewers. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) reporting methodology was used to describe all stages transparently (Page et al., 2021). Figure 1 illustrates the review process.

To constrain population and intervention, the search strategy ("digital twin" OR "virtual twin" OR "digital shadow") AND engineer* AND (educat* OR curricul*) was obtained through an iterative search. This was conducted on 9th December 2025 through Boolean search in Scopus, Web of Science, and IEEE Xplore, with minor syntax adjustments for each, on title, abstract and keywords. Literature reviews were excluded through databases' filtering tools.

Three papers were also found by hand search. All results were saved and manually deduplicated.

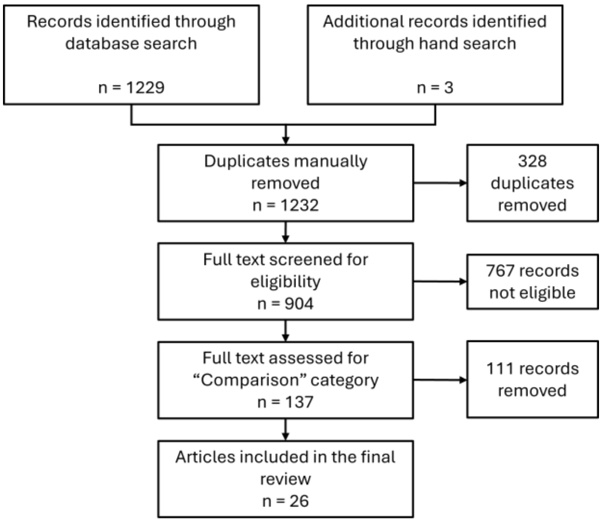

Figure 1: PRISMA flowchart for literature search and inclusion in this study

The following inclusion and exclusion strategies were applied manually to the full text of deduplicated literature. No constraints were put on date of publication; pre-print papers were also included. Though inclusion criteria aim to be as objective as possible, ambiguous cases remain where the primary researcher's judgement was required. The lack of independent review to validate these decisions is acknowledged as a limitation of the study.

Since this review focuses on outcomes, articles must include at least one empirical learning measure. This must be primary (e.g. not literature reviews) and must relate to students' learning (e.g. not system performance data alone). Both qualitative and quantitative measures of learning were accepted.

To remove superficial search results, articles that did not address the population or intervention were excluded. Only literature that referred to its intervention as a Digital Twin was included, regardless of implementation level, but evaluation of the varying definitions of Digital Twin in an educational context forms part of the analysis.

In some cases, Digital Twins featured in the learning outcomes themselves (for example, to prepare students to use DTs in industry). It was decided to exclude these papers from the study, and to focus on use of DTs as a teaching tool, not as a learning objective. Finally, fifteen papers that were not available in the authors' native language (English) were excluded. This is acknowledged as a limitation of the study that may centre Western education approaches. Geographic analysis of included papers has been provided for transparency.

Because literature was evaluated only by a single reviewer (the primary researcher), a formal risk-of-bias screening stage was not conducted. This is common in systematised reviews (Grant & Booth, 2009). However, articles with obvious quality concerns were removed during the screening stage. All included articles were also critically appraised for strength of evidence, which forms part of the review. Screening for the Comparison category of the PICO framework also occurred at this stage. Studies comparing the intervention to either theoretical teaching or in-person laboratories were included and classified. Ideally, this would involve control and experimental groups. However, though considered less strong, studies where students compared their own perceived learning to a clearly defined reference were also included.

Analysis Methods

Outcomes were classified into three dimensions (Rogaten et al., 2019): cognitive (knowledge and understanding), behavioural (actions and skills), and affective (attitudes and emotions). This involves some simplification – for example, academic grades could be considered both cognitive and behavioural – but gives a general idea of the learning effects linked to DTs.

Due to ambiguity surrounding the term, many interventions described as a Digital Twin do not match Grieves' definition (Grieves, 2005). To understand how the term is used in education, interventions were classified into three levels, proposed by Kritzinger et al. (2018). This is not the only way to classify DTs, but its focus on information flow aligns with the philosophy of Grieves' original concept. A low-level Digital Model involves no real-time connection between virtual and physical entities. A Digital Shadow involves a one-way connection from the physical entity to its virtual twin, so that the twin updates in real-time to reflect its physical counterpart. A fully-realised Digital Twin is bidirectional, so that the virtual entity can also influence the physical twin. Many studies avoided defining their Digital Twins; where this caused uncertainty, the intervention was categorised as a low-level Digital Model.

RESULTS

Figure 2(a) demonstrates a balance of journal articles and conference papers. Figure 2(b) shows that recent literature dominates, which reflects the novelty of the Digital Twin concept in education, but does limit ability to separate studies from the social and historical context of this time period. Finally, Figure 2(c) shows that literature represents multiple geographical regions; however, European and Western education is centred, which impacts generalisability.

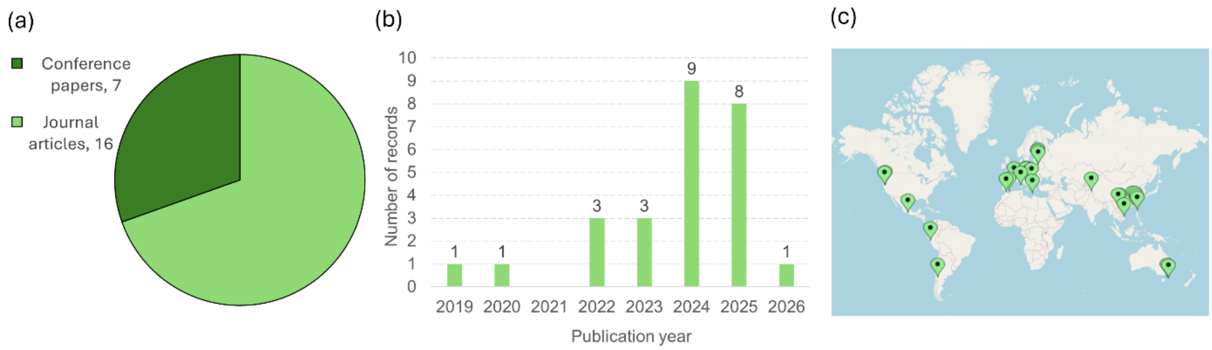

Figure 2: Analysis of included records by (a) type, (b) publication year and (c) location

Digital Twins Compared to Theoretical Teaching

Literature comparing Digital Twins to theoretical teaching (Table 2) focuses on improving understanding, providing real-world knowledge, and creating interactive learning experiences.

Table 2: Summary of literature comparing Digital Twins to theoretical teaching

Study	**DT Level**	**Strength of Evidence**	**Dimensions**
The Experience of Introducing Digital Twins Into the Educational Process on the Example of Training in the Repair of Aircraft Equipment Units (Ainakulov et al., 2023)	Model	Low	Behavioural
Effective Application of Operator Training Simulator in Experiential Education (Bělohlav et al., 2024)	Model	Low	Cognitive
Digital Twin-Enhanced Programming Education: An Empirical Study on Learning Engagement and Skill Acquisition (Lu & Hu, 2025)	Model	High	Affective, Behavioural, Cognitive
Exploration of the Application and Practice of Digital Twin Technology in Teaching Driven by Smart City Construction (Ning et al., 2024)	Model	Low	Behavioural, Cognitive
Digital Twin-Based Active Learning for Industrial Process Control and Supervision in Industry 4.0 (Ortiz et al., 2025)	Twin	Moderate	Behavioural
Digital Twin and Web-Based Virtual Gaming Technologies for Online Education: A Case of Construction Management and Engineering (Sepasgozar, 2020)	Twin	Low	Affective, Cognitive
Application of Digital Twin Technology in Mining Machinery Education (Su et al., 2025)	Model	Low	Behavioural, Cognitive
Interactive Application as a Teaching Aid in Mechanical Engineering (Weis et al., 2024)	Model	Low	Cognitive
The Impact and Diversity of Digital Twin Technology and Immersive Learning in Education: A Case Study of the University "Aleksandër Moisiu" (Zeneli & Cerma, 2026)	Model	Low	Affective
Research on Innovative Models of Industry-Education Integration to Promote Sustainable Education in Agricultural Machinery Majors (H. Zhang et al., 2025)	Model	Low	Behavioural
The Effectiveness of a Digital Twin Learning System in Assisting Engineering Education Courses: A Case of Landscape Architecture (J. Zhang et al., 2024)	Shadow	High	Affective, Behavioural, Cognitive
Design and Implementation of a Virtual Experimental Teaching System for Deep Energy Exploitation Based on Digital Twin Technology (Zhao & Zhu, 2024)	Model	Low	Cognitive

Behavioural Outcomes and Experiences

Improvement in academic results is reported by Su et al. (2025) and J. Zhang et al. (2024). Though the first set of results is inseparable from effects of Covid-19, the second is stronger; differences between experimental and control groups were significant to $p < 0.001$. More industry-oriented performance improvements were found by Ortiz et al. (2025) and H. Zhang et al. (2025).

Lu & Hu (2025) designed a smart classroom with virtual models for students in a first-year programming course. Students reflected on their experience, with questions targeting cognitive, behavioural, and emotional engagement. Behavioural engagement was found higher within the experimental group than the control, to significance of $p < 0.001$. Learning logs also reflect that students using DTs were able to use their time more efficiently.

Cognitive Outcomes and Experiences

There is a lack of consensus on several cognitive aspects. Improvement to self-reported understanding is reported by Weis et al. (2024), but Zhao & Zhu (2024), who created dynamic models to teach fracture processes, did not find significant differences in theoretical comprehension tests. Similarly, qualitative feedback in (Bělohlav et al., 2024) indicates increased creative thinking after use of a virtual distillation column, but J. Zhang et al. (2024) found no significant difference in creativity between experimental and control groups, although testing methods for this lack detail and cannot be assessed for construct validity.

Despite these conflicts, there is convincing evidence that Digital Twins can introduce new ways of thinking. Zhao & Zhu (2024) reported observations of increased confidence, more active learning, and greater practical understanding in students who were exposed to a DT, albeit in a very small sample. J. Zhang et al. (2024) found improvements in critical thinking, though testing methods remain undefined. Lu & Hu (2025) found that self-reported engagement in the cognitive dimension was significantly higher in the experimental group; through tests of cognitive skills, they also found significant improvement in syntax, algorithmic thinking, and debugging ability, with algorithmic thinking being particularly notable. Qualitative evidence suggests that this was due to DTs providing context to abstract concepts. Also of note, lower-performing groups demonstrated greater improvement; Lu & Hu suggest that DTs' alternative visualisation methods may act as an equalising technology. Whether any of these changes to thinking translate to long-term effects, however, remains unknown.

Affective Outcomes and Experiences

Little evidence is available on the affective impact of DTs compared to traditional teaching. Zhao & Zhu (2024) found that learning experience improved with use of DTs, while learning motivation was unchanged, but its measurement method is unclear. Lu & Hu (2025) found that DTs significantly improved self-reported emotional engagement; of note was their potential to reduce anxiety due to lower-stakes experiences of failure. Students reported that they could take risks because they were less afraid of causing errors, facilitating adventurous exploration of edge cases. Meanwhile, students in the control group reported frustration when receiving error messages without context. Reduction of anxiety is relevant to domains outside of this study's computer science application, and may warrant investigation in other contexts.

Digital Twins Compared to Physical Labs

Literature comparing Digital Twins to physical labs (Table 3) focuses on increasing availability of hands-on opportunities, improving efficiency, and attaching meaning to laboratory work.

Behavioural Outcomes and Experiences

Evidence for behavioural benefit is very tentative. Tang & Li (2023) replaced a physical controller with a virtual model and observed improvement in grade distributions between comparison and intervention years. However, this result lacks generalisability on its own, as the study is highly ecological. The only other study that measured academic outcomes compared to physical labs (Liljaniemi & Paavilainen, 2025) found no significant differences. Meanwhile, there is mild evidence that DTs improve accuracy and efficiency compared to physical labs. Azkarate Fernández et al. (2019) found that virtual commissioning increased self-reported learning efficiency in a programming exercise due to early error detection, reduction of downtime, and ability to work in parallel. This is limited by a lack of formal qualitative reporting combined with a small sample size, leading to polarised results.

Qualitative evidence from Deniz et al. (2022) suggests that DTs provide access to a greater range of experiences and roles than hands-on labs. Finally, Darejeh et al. (2025) found that use of virtual reality (VR) to teach composite manufacturing processes worsened task completion time, but Liljaniemi & Paavilainen (2025) found that this gap decreased over time.

Table 3: Summary of literature comparing Digital Twins to physical labs

Study	**DT Level**	**Strength of Evidence**	**Dimensions**
Reimagine Lab: Bridging the Gap Between Hands-On, Virtual and Remote Control Engineering Laboratories Using Digital Twins and Extended Reality (Alsaleh et al., 2022)	Shadow	Moderate	Affective
Virtual Commissioning of a Robotic Cell: An Educational Case Study (Azkarate Fernandez et al., 2019)	Model	Moderate	Behavioural, Cognitive
Photogrammetry as a Method of Educational Innovation. Civil Engineering Student Case Study (Ballinas-González et al., 2024)	Model	Low	Affective, Cognitive
Virtual Reality and Digital Twins for Mechanical Engineering Lab Education: Applications in Composite Manufacturing (Darejeh et al., 2025)	Model	Moderate	Behavioural, Cognitive
Combining Virtual Reality With Mixed Reality for Efficient Training in Battery Manufacturing (Denisart et al., 2024)	Model	Low	Behavioural, Cognitive
Online (Remote) Teaching for Laboratory Based Courses Using "Digital Twins" of the Experiments (Deniz et al., 2022)	Model	Moderate	Affective, Cognitive
User Acceptance of a Modular Interactive Digital Twin of the Production Department for Virtual Reality (Dvořák et al., 2022)	Shadow	Moderate	Cognitive
RHL-Butterfly: A Scalable IoT-Based Digital Twinning Platform for Embedded Systems and Remote Laboratories (Guo et al., 2025)	Model	Low	Affective
Digital Twinning and Remote Engineering for Immersive Embedded Systems Education (Hussein et al., 2023)	Model	Low	Affective, Cognitive
Enhancing Engineering Education Through Immersive Environments – A Study of the Holodeck VR System in Hydraulics and Pneumatics (Liljaniemi & Paavilainen, 2025)	Model	Moderate	Affective, Behavioural, Cognitive
Educational Metaverse (Martínez-Gutiérrez et al., 2024)	Model	Low	Affective
Integrating Digital Twins of Engineering Labs Into Multi-User Virtual Reality Environments (Norambuena et al., 2025)	Shadow	Moderate	Affective, Cognitive
Research And Practice of PLC Experiment Teaching Based on OBE and Digital Twin (Tang & Li, 2023)	Shadow	Moderate	Behavioural
Virtual Labs for Higher Education in Industrial Engineering (Terkaj et al., 2024)	Shadow	Low	Affective, Cognitive

Cognitive Outcomes and Experiences

Evidence for cognitive outcomes is mainly, but not wholly, positive. Ballinas-González et al. (2024) and Hussein et al. (2023) found improvement in self-reported understanding, while Denisart et al. (2024) and Dvořák et al. (2022) found improvement in post-tests of comprehension and recall. However, lack of statistical analysis obscures significance, especially as several studies have small samples. There is also a possible improvement in cognitive load: Darejeh et al. (2025) found that mental and physical demand was lower in the experimental group, though lack of distinction between VR and DTs is a limitation. Thematic analysis by Hussein et al. (2023) identified that a virtual parking lot helped with design approach and was more intuitive than traditional breadboards, but was harder to debug.

The potential of DTs to enable new ways of thinking is evident here. Qualitative responses in (Deniz et al., 2022) found that students could easily repeat virtual experiments, and could vary parameters to edge cases, echoing findings by Lu & Hu (2025) in theoretical teaching. Liljaniemi & Paavilainen (2025) observed more active engagement, spatial awareness, and confidence in students using virtual laboratory exercises, though these themes were not formally reported. In (Norambuena et al., 2025), students interacting with a virtual engine reported greater self-reported safety, participation, and communication, although lack of counterbalance may introduce recency effects. However, there is also evidence that aspects of physical labs are missing from DTs. Terkaj et al. (2024) used Digital Twins of physical labs within industrial engineering courses, and the limited feedback available suggests that students would miss access to physical instruments. Deniz et al. (2022) also found that simplifications in the DT could prevent learning experiences caused by making errors.

Affective Outcomes and Experiences

There is a moderately strong body of evidence for DTs' ability to engage and motivate students. Ballinas-González et al. (2024) and Liljaniemi & Paavilainen (2025) found improvements in self-reported engagement with Digital Twins. In (Norambuena et al., 2025), self-reported interest in a virtual engine was higher than a physical experiment, and 80% of students favoured the intervention. Using the System Usability Scale, Alsaleh et al (2022) found that usability was noticeably higher for a Digital Twin of a 3D crane than for traditional desktop experiments. However, these measures are vulnerable to the influence of novelty effects, especially as most were not counterbalanced. Meanwhile, several studies evaluate feelings of immersion and realism, with varying results. Qualitative feedback in (Deniz et al., 2022) indicated that a virtual experiment platform decreased feelings of realism, but Guo et al. (2025) and Martínez-Gutiérrez et al. (2024) reported that virtual and physical experiences did not feel different to students. Note that this measure is also prone to publication bias.

Compared to cognitive experiences, very few studies examine emotional experiences during the learning process. Qualitative feedback in (Deniz et al., 2022) highlighted a possible detriment to collaboration and social aspects, and similar feedback in (Liljaniemi & Paavilainen, 2025) expressed that virtual experiences did not give the same feeling of achievement from creating a physical product. These fragmented negative aspects point to a possible neglect for emotional experiences, which could be explored in future research.

DISCUSSION

Evidence supporting educational applications of Digital Twins is positive but tentative. No single quantitative outcome is conclusively linked to DTs, and though positive results dominate, this may be due to publication bias. Contradiction within several measures also indicates that consensus has not been reached. However, evidence of improved cognitive outcomes and experiences is most promising, especially where combination with curriculum reform stimulates different ways of thinking. The fact that DTs can enable students to learn actively, in context, and through failure is supported by diverse qualitative evidence. It is proposed that Digital Twins can be used as a platform to introduce ways of learning that may not otherwise arise naturally, but that benefit also depends on underlying teaching values.

Main gaps and barriers to research are identified as follows. Affective outcomes and experiences are particularly underrepresented. Very few studies compare affective outcomes between DTs and theoretical teaching, and though there are more affective outcomes reported for laboratory applications, almost all of these are limited to motivation and perceived realism. Meanwhile, a breadth of emotional experiences during learning could merit research, as well as development of emotionally charged outcomes such as empathy and collaboration.

Many qualitative results are not directly reported. This limits understanding of the student experience, as indirect data involve an extra degree of interpretation. Since several papers mention student feedback, qualitative data appear to be available, but they are not translating to publication. This highlights an opportunity to draw from these data in more depth using formal qualitative analysis techniques.

Lack of clarity over the term “Digital Twin” limits homogeneity. Realisation level varies between studies, with only two studies implementing a full Digital Twin, and many studies implementing a low-level Digital Model. Several papers do not clearly define their own Digital Twin, and greater transparency in future research would prevent misconceptions about technological feasibility. Furthermore, several learning benefits identified in this review can be achieved by low-level Digital Models alone. Whether benefit improves with level of realisation, or whether simpler tools are sufficient, could be a topic for future review.

As found by Alghamdi et al. (2025), lack of long-term analysis remains a limitation. It is unknown whether benefits are retained in subsequent years, or whether they translate to professional environments. Not all benefits must be long-term; some immediate impacts, such as reduced anxiety and increased autonomy, are notable on their own. However, many of the behavioural and cognitive outcomes in this review would benefit from longitudinal evaluation.

Finally, most included studies do not state the gender balance of participants. Where it is stated, all studies use a male-majority sample, and so averages will bias towards the male experience. While this may reflect the current makeup of engineering students, learning requirements of female students may be different due to gendered experiences, expectations, and challenges in a male-dominated field. Future work could investigate whether benefits and disadvantages of DTs are equally received by all students.

CONCLUSIONS

While Digital Twins are not conclusively linked to any quantitative learning measure, there is evidence that they offer a platform for new learning experiences. When informed by pedagogical values and student needs, cognitive benefits can be realised, especially by prompting active, contextualised, and reflective thinking. Behavioural aspects are not as convincingly evidenced. Meanwhile, there is a gap to research emotional learning experiences and emotionally charged skills. In future work, there is also a need to understand experiences of marginalised groups, to conduct longitudinal research on outcomes, to be transparent about the level of technology implemented, and to consider formalising qualitative feedback.

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Artificial intelligence usage

Generative AI (Microsoft Copilot) was used to translate syntax of Boolean search strings between databases. All syntax was manually reviewed before use. No AI tools were used at any other stage in the research and writing of this review.

Data access

No new data were generated or analysed in this study.

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