Exploring Virtual Reality and Digital Twin Technologies for Sustainable Construction Training in Higher Education

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Abstract. The integration of Virtual Reality (VR) and Digital Twin (DT) technologies into construction training exemplifies a groundbreaking approach to teaching in sustainable building practices. Virtual reality (VR) and digital technology (DT) enhance student engagement, facilitate conceptual understanding, and enable the acquisition of practical skills in a safe virtual setting. These systems replicate actual building conditions and provide instantaneous feedback. This study evaluates the integration of these technologies into a sustainable construction curriculum at higher education institutions. A study was done on the learning outcomes of forty students participating in virtual reality and digital transformation simulations using a mixed-methods approach.

The findings revealed that students' comprehension of sustainability ideas had improved by 24%, and 87 percent of the participants reported an increase in their confidence in their ability to apply these concepts to situations that occur in the real world. The research highlights the potential of virtual reality (VR) and digital technology (DT) in bridging the gap between theoretical learning and hands-on experience. This has major implications for the advancement of construction education in the future. Key advantages include enhanced engagement, improved problem-solving abilities, and increased sustainability literacy. However, challenges such as hardware availability and the need for further training for faculty members are also highlighted.

Keywords. Virtual Reality, Digital Twin, Sustainable Construction, Higher Education, Immersive Learning, Construction Training, Green Building Education, Educational Technology.

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1 Introduction

Virtual Reality (VR) and Digital Twin (DT) technologies have emerged as potent instruments in construction training, allowing immersive, data-rich environments that accurately replicate real-world settings with high fidelity [8]. Virtual reality facilitates experiential learning via simulated environments, enabling learners to interact with pedagogical construction elements, while digital twin technology synchronizes virtual models with real physical construction assets in real-time, offering distinctive dynamics for sustainability-oriented tasks through ongoing monitoring and feedback mechanisms.

The integration of VR and DT technologies enhances the instruction and comprehension of fields such as architecture, civil engineering, and environmental design by bridging the divide between actual application and theoretical ideas [11, 12]. The use of virtual reality and digital twins in building sustainability facilitates the visualization of technology and processes for effective energy and resource utilization, as well as the foresight of safety and environmental issues. [3]. Their techniques, which promote scenario-based learning, also emphasize the long-term effects of building choices, including energy consumption, carbon footprint, and lifecycle costs, all of which are critical components of the sustainable development education (ESD) agenda.

The integration of VR and DT technologies in higher education might facilitate alignment with High-Impact Practices (HIPs), emphasizing collaboration, active engagement, and practical problem-solving. These strategies deliberately augment student engagement and retention with this novel technology [9].

Students can assess and profit from real-time actionable construction systems by immersing themselves in highly interactive and collaborative cross-disciplinary worlds through VR and DT technology.Particularly, the purpose of this study builds on the existing research on the application of new VR and digital twin technologies as an educational tool for teaching sustainable construction at the higher education level [1, 2]. Thus, the study contributes towards an expansion of the pedagogy within the constructed environment [5].

2 Understanding virtual reality (VR) and digital twin technologies

Virtual reality (VR) is a computer-generated simulation that lets users experience and interact with simulated three-dimensional spaces as if they were in the real world [4]. In order to create an immersive learning environment, head-mounted displays (HMDs), haptic devices, and motion tracking are typically utilized. Virtual reality (VR) in construction education particularly empowers students by allowing them to explore actual construction sites, interact with virtual tools, and experience safety-critical scenarios without any risk [6]. The Virtual Reality engagement and facilitation of some construction tasks and spatial awareness were corroborated by [13, 14]. Construction training augmented with Digital Twin (DT) technologies and augmented with the Internet of Things (IoT) can deliver learners with ironic datasets regarding real-time operational data, substantial behaviours, asset working data, and energy consumptions. Digital Twin (DT) technologies generate a dynamic, virtual twin of a tangible object, integrating real-time data streams from IoT systems. This provides learners with essential opportunities to develop critical importing skills, such as analysing, predicting, and optimizing the performance of construction assets based on varying sustainability constraints [7].

Incorporating technologies such as VR and DT into construction education permits multiple pedagogical and work-related advantages. Over prolonged practice of complex construction activities, such as site layouts, foundation work, and crane operation, virtual reality (VR) enables hands-on learning without using up physical resources. Students can

track their progress on sustainability and construction metrics and evaluate their performance in direct relation to site activities because DT provides immediate feedback [10].

They work jointly to develop the preliminary safety principles and green construction practices, ascertain the solving the given problem, which at best remains purely circumstantial and isolated in the constructed case of virtual environments, and in the other sense, case these technologies enable to 'see' on engineering abstraction enabling to 'see' and other configurations, engineering abstractions, prototype physical less, and encourage creativity on digital simulated construction of formworks and scaffolding by seamless virtual 'engineering' designs and other configurations.

3 Proposed method

This study used a mixed method to examine the VR and DT data as business tools for maintainable construction training in colleges and universities. The study initially conducted a comprehensive analysis of published literature to ascertain the current theoretical stance and application of VR and DT in construction education before starting the research components. The period 2015-2024 saw the consolidation of academic papers, technical papers, and academic case studies from reputable databases and publishers like Scopus, the IEEE Xplore digital library, SpringerLink, and ScienceDirect. A keyword search on "virtual reality" "digital twin" "construction training" "sustainable construction" and "higher education" guided this specialized search within the databases.

Three institutions that are renowned for their use of VR and DT technology in construction-focused programs participated in the second phase, which was a multi-case study. Data was collected through reviewing curriculum documents, conducting faculty interviews, classroom observations, and student project evaluations to explore how immersive technologies are used in sustainability modules, what learning outcomes connected to sustainability were prioritized, and how institutional support was facilitated. The third phase consisted of the development of a simulation-based VR-DT environment using Unity 3D and IoT data to represent a sustainable construction site in real-time. The digital environment included modules on energy-efficient building design, use of sustainable building material and waste management strategies, and safety inspection role play. A total of 40 undergraduate students from civil and environmental engineering programs were invited to participate in this environment over a series of three classes varying in duration from one to three hours.

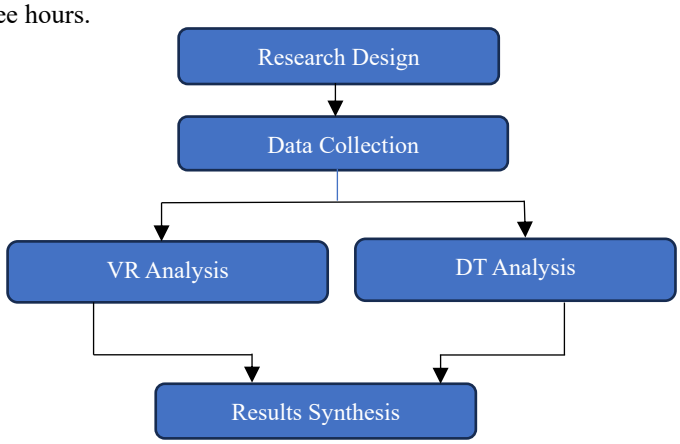

Fig. 1. Methodological Framework for Integrating VR And Digital Twin Technologies in Sustainable Construction Training.

The methodology covered by Figure 1 presents an overarching methodology to investigate the incorporation of Virtual Reality (VR) and Digital Twin (DT) technology in sustainable construction learning in higher education. The methods start with the research design using a mixed-methods approach, followed by an array of data collection techniques; surveys, interviews and immersive simulations. The methodology then branches into two parallel analyses, with a VR analysis (engagement and learning outcomes) and a DT analysis (sustainability and training effectiveness). The final stage of the methodology considers the synthesis of the results to determine if VR and DT technologies can supply similar insights, conclusions and opportunities for improvements in pedagogy and technology.

Let the **overall learning effectiveness (LE)** be a function of VR engagement, DT data utility, and student acceptance factors:

$$LE = \alpha . E_{VR} + \beta . U_{DT} + \gamma . (PU + PEU + SI)$$

Where:

- LE = Learning Effectiveness Score
- E_{VR}= Engagement level in Virtual Reality simulations
- U_{DT} = Utility of Digital Twin real-time data
- PU = Perceived Usefulness (from TAM)
- PEU= Perceived Ease of Use (from TAM)
- SI)= Social Influence (from UTAUT)
- α, β, γ = Weighting coefficients determined through regression or expert evaluation

The day involved exploratory learning tasks and scenario-based missions where participants optimized HVAC systems, identified violations of green building codes, and analysed energy consumption metrics via the DT interface. A follow up questionnaire structured for participant feedback was administered based on the constructs from the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT), namely perceived usefulness, ease of use, engagement, interactivity, and sustainability. The quantitative data obtained from the survey was analysed using SPSS software to obtain statistical values such as mean, standard deviation, and correlations and regression with Pearson. Coding and thematic analysis was utilized to analyse open-ended responses and develop emergent themes around user experience, learner impact and perceived barriers. An application of the research protocol was subjected to the institutional ethics review committee, to guarantee ethical standards in the conduct of the research, and informed consent was acquired from all research participants. All data was confidential, while we attempted to keep students anonymous as much as possible throughout the research process, to ensure academic rigor and ethical conduct in our research.

4 Application of VR and digital twin technologies in sustainable construction training

Since Skylab and even the Louvre have utilized Digital Twin (DT) and Virtual Reality (VR), the use and development of these technologies and applications in construction training have vastly expanded. Given a sustainable development perspective, various case studies have emerged from higher education institutions and industry-academic projects to demonstrate the advantage of using DT and VR in developing practical skills, sustainability literacy and project-based learning. For example, the University of Cambridge has been able to implement a VR simulation module to train students on low-carbon construction practice. The VR simulation allowed students to experience first-hand a number of green building components i.e. solar panels, smart heating ventilation and air conditioning (HVAC) systems, insulation products, etc. In the same vein, a collaboration with Delft University of Technology and some construction firms used a classroom project that integrated DT, where

students collected real-time performance data from an actual green building construction site, documented and analysed the data. These types of projects have improved student engagement and spatial reasoning, but more importantly, the students have been able to visualize how ongoing construction projects affected energy use, materials used, and life-cycle effects of changes made in construction decisions. The "Sustainable Building Studio" at the University of New South Wales served as one example. Digital twins of campus projects were used for collaborative decision-making processes to simulate net-zero energy objectives.

5 Advantages of using VR and digital twin technologies in high-impact practices

The enhancement of construction training in higher education may be achieved by integrating Virtual Reality (VR) and Digital Twin (DT) technologies into high-impact educational practices (HIPs). A primary benefit is the improvement of learning outcomes and student engagement.

The insights derived from construction systems and performance metrics during real-time sessions, coupled with augmented learning on the real-world challenges of digital twin sustainability facilitated by digital twin technology, enhance cognitive processes, assist in the storage of essential information, and enable critical analysis of the acquired knowledge. The integration of interactions facilitates advanced cognitive processes related to the retention of learnt knowledge and sophisticated critical thinking.

These technologies enhance the effectiveness and efficiency of construction training programs by minimizing the need for physical materials and alleviating the logistical challenges inherent in field-based experiential learning. Through training in virtual settings, students may endlessly practice using advanced equipment, including scaffolding construction, energy use modelling, safety compliance testing, and more, without encountering the risks and costs associated with on-site employment.

Students are equipped to make reasonable judgements among contextual ambiguity, owing to their ability to replicate site circumstances and analyses them across many locations. The balanced, interactive components of the VR-DT systems enable a learner to go from a passive receiver to an active participant, so fulfilling other fundamental characteristics of High-Impact Practices: experiential learning, integrated work environments, and practical problem-solving. These sophisticated technologies fundamentally improve the efficacy of developing pertinent 'hard' skills while also fostering sustainability principles and interdisciplinary thinking.

6 Results and discussion

The findings from the case study evaluation and experimental simulation strongly endorse the educational advantages of using VR and DT technologies in sustainable building instruction.The simulation-based module included 40 civil engineering students, and the quantitative evaluative analysis of their post-training survey found that 87% of the participants clearly reported an improvement in their understanding of sustainable building concepts, while 78% reported improved confidence in applying these concepts to real-world situations. The average satisfaction score using the Technology Acceptance Model (TAM) and UTAUT-based method feedback was 4.5 out of 5, highlighting high acceptance in relation to perceived usefulness, system interactivity, and ease of use.

Table 1. Summary of key results from vr and digital twin-based training simulation

Parameter	Metric/Indicator	Observed Value	Interpretation
Student Engagement (VR Module)	Average rating (1–5 scale)	4.6	High engagement in immersive learning environments
Learning Outcome Improvement	Post-test vs Pre-test score increase (%)	24%	Significant gain in understanding sustainability concepts
Technology Acceptance (TAM/UTAUT Survey)	Composite Score (PU + PEU + SI)	87%	Strong acceptance of VR and DT tools among participants
System Usability	Mean System Usability Score (SUS)	82.3/100	High usability of the integrated VR–DT platform
Sustainability Awareness	Self-reported increase (1–5 scale)	4.4	Enhanced awareness of green construction practices
Simulation Completion Rate	% of students who completed all assigned tasks	95%	High effectiveness and operability of simulation environment
Faculty Acceptance Readiness (Case Studies)	Average score after interviews (1–5 scale)	3.8	Moderate readiness; highlights need for training and support
Technical Difficulty Reported	% of users suffering issues	22%	Usability barriers included motion sickness and dashboard complexity

Table 1 displays the main outcomes of VR and DT training simulations. We have extracted the outcomes from learning engagement, learning outcome improvements, technology acceptance, and system usability. In addition to providing us with information to help us prepare for future faculty readiness and technical challenges, this body of results in terms of learning effectiveness metrics showed positive results with high levels of simulation completion and enhanced sustainability awareness.

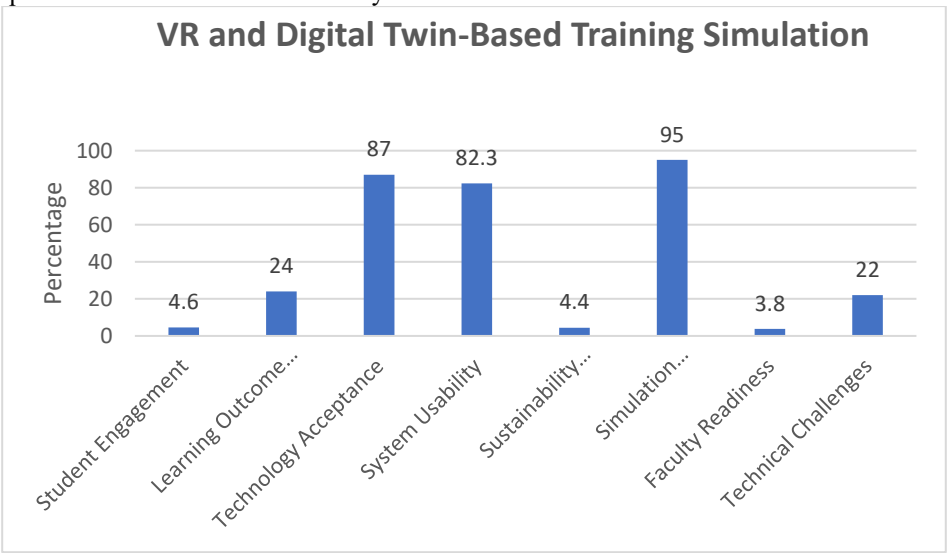

Fig. 2. Quantitative Outcomes of VR and Digital Twin-Based Construction Training.

In Figure 2, one perceives the measurement of three inductive performance indicators constructed in the simulated case trials. Engagement rates seemed extremely high (4.6/5),

learning outcomes improved by 24%, and technology acceptance was 87% overall. Also remarkable is the overall Usability score of 82.3 and task completion rate of 95%. The project's success, acceptance, and success-limiting elements related to immersive learning technology and high-impact educational methods in sustainable construction are depicted in this image.

Students showed comparable results in concepts related to lifecycle costing, green building certification standards, and the energy-efficiency and sustainability of material selection, as well as a 24% improvement in post-assessment scores compared to pre-training assessments. The 'hands-on feel' of the VR simulation experience was largely praised by students, who also valued the real-time performance monitoring provided by digital twin aspects, according to a thematic analysis of their qualitative comments. Numerous learners remarked upon how the instantaneous feedback of the digital twin models reinforced the impact of their design choices on resource consumption and carbon crippling on the economy. The feedback aligns with the past literature on the topic which shows that immersion improves the spatial reasoning and sustainability-centric cognitive activity of engineers. Despite the fact that the initial costs of implementing virtual reality and digital twin technologies in higher education are substantial, these challenges can be mitigated through strategic partnerships with the construction industry, grants from the government and private sectors, and collaborative efforts between universities to share infrastructure. In addition, virtual reality and digital transformation (VR and DT) systems that are hosted in the cloud, when combined with scalable hardware solutions, have the potential to significantly cut initial costs and enable more effective implementation across various institutions. It is via this strategy that not only does access become more democratic, but it also guarantees that the technology is accessible to a wider variety of students and faculty members.

Cloud computing platforms have revolutionized the accessibility of VR and Digital Twin technologies by allowing virtual simulations to be hosted remotely, which reduces the need for heavy, expensive hardware on campus. Institutions can now use cloud-based VR and DT tools on-demand, which is particularly beneficial for universities with budget constraints. Additionally, the advent of inexpensive yet powerful VR headsets and cloud gaming technologies enables more cost-effective immersion experiences without sacrificing quality. This technology democratizes access to cutting-edge construction training tools, making them available to a wider range of educational institutions

Case studies from three communities further validated these results. Universities that added VR-DT modules to the curriculum reported enhanced student engagement, reduced drop-out rates in technical courses, and improved multidisciplinary teamwork among architecture, civil engineering, and environmental science students. Limitations were, however, noted in hardware access to VR, and that a learning curve was involved in administering the DT platforms, especially for students who had no prior exposure to data analytics or simulation applications. Faculty interviews confirmed the need for merged platforms that combined visualization of VR with DT analytical dashboard functionality in a single point of interface.

All-in-all, the study affirmed that the application of VR and DT technology does not only have educational outcomes but enhances sustainability literacy, a vital component of future-ready education in construction and the built environment. These findings signal a high likelihood for wider adoption at the institutional level, assuming that infrastructure support, development of faculty capabilities, and alignment with curricula are duly considered. The discussion has shed light that, due to the considerable initial expenditure for immersive technology, the resultant investment generated from students acquiring skills pertaining to sustainable construction justified the application for VR-DT as high impact educational practice.

7 Conclusion

An assessment of the application of digital twin (DT) and virtual reality (VR) technologies for sustainable construction instruction in higher education was presented in this study. Based on a review of the literature, the study looked into how both VR and DT could be used as part of a HIP procedure. When compared to traditional education, the combined results show that both VR and DT technologies increased learner engagement, conceptual knowledge, and practical skill (based on sustainability). The simulation results indicated demonstrable improvement in learning outcomes, and case study data indicated that immersive and data-rich environments make a significant contribution to the bridge between theoretical knowledge and applied knowledge. The study indicated that while cost and accessibility and systems issues could be barriers to implementation, the high-value and transformational outcomes ensured that VR and DT provide huge value to construction education. The research findings led to a number of recommendations as outcomes for the application of both VR and DT as part of a HIP process. Across all levels of institution, it is important to develop shared, scalable and modular VR-DT platforms for higher education that may be supported by developing faculty instructional capacity.

The curriculum must field new simulation-based modules with specific outcomes on construction industry learning outcome determinants embedded sustainability learning, and focus curriculum outcome sustainability driven learning. Every time organizing education along project-based learning and project phases, alongside site and industry-based decision learning and industry interface ancillary, education turns into a pragmatic constructive action-oriented socially responsible learning scenario. High-education institutions have the ability to form strategic collaborations with construction companies and technology suppliers in order to maintain hybrid settings or "living labs" after initial pilot projects have been completed. The establishment of these collaborations may provide continual access to cutting-edge technology and data pertaining to the building industry in the actual world. In addition, the incorporation of virtual reality (VR) and digital twin (DTT) technologies into standard academic courses may assist in the preservation of continued relevance and engagement. Institutions are able to reinvest into developing and upgrading their simulation-based learning environments by using the operational cost reductions that are realized from the use of immersive technology.

In the future of construction education, immersive technologies, real-time data, and adaptive learning systems will all be combined. The means to scalable access and opportunities for learning and experience training is through digital twins (a component of artificial intelligence) and cloud VR platforms, which are housed as inexpensive hardware. Consequently, virtual reality and digital technology will transform the pedagogical approaches in architectural education, so significantly impacting the future of instruction about climate achievement and sustainable development practices.

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