2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #52075

Improving Engineering Students' Sustainable Design Decisions with a Digital-Twin Pedagogical Model: An HBCU Case Study

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Abstract
Engineering students are usually required to consider sustainability, yet few demonstrate measurable gains in sustainable design decision quality. Without clear metric goals, many students who intend to achieve sustainability simply add one or more elements without analyzing the impact of those choices on other components of the design or on the environment. A digital twin is a valuable tool that can help students visualize the effect of each design option with immediate, scenario-based feedback and explore alternatives. By making outcomes measurable and comparable, digital twins turn sustainable intent into evidence-based optimization. Thus, digital twins can be an important tool for learning sustainable design.

This research describes an instructional approach that explores an existing building to help students understand how design decisions impact overall design and subsequently make more informed design decisions. We outline a teaching module that pairs simple model states, such as alternative envelopes, systems, and layouts. To understand learning, we propose a practical evaluation plan centered on decision tasks, brief rationales, and transparent, instructor-editable scoring, all aimed at documenting the change observed. This case study emphasizes improving the quality of engineering students' sustainable design decisions and helping them incorporate environmental and societal considerations into design. Its contribution is a replicable teaching pattern and adoption materials that enable programs to move beyond considering sustainability toward teaching, practicing, and evidencing sustainable design decisions.

Keywords: Digital twin, virtual reality, sustainable design, engineering education, decision quality, evidence-based pedagogy, sustainability metrics, HBCU.

Introduction

Sustainability has become a critical component of engineering education, and design programs increasingly emphasize that students should include environmental and societal impacts in their design processes [1]. One of the most important aspects of sustainable design education today is bridging the conceptual-level awareness of sustainability and competence in making sustainable decisions [1], [2]. Studies have shown that pedagogies rooted in project-based and immersive learning are more efficacious in combining conceptual knowledge with competence in the actual world, especially in the case of "complex dynamic interactions," such as the role of digital twins in design [1], [3]. Digital twin has been a tool used to link abstract learning and analytical problem-solving in engineering-related applications to allow users to view and analyze designs in an active setting [4], thus providing a platform for engineering students to train themselves on a virtual copy that will symbolize a realistic physical copy from any industry.

Digital twins have begun to appear in education environments with a view to facilitating immersive and project-based learning. In manufacturing classes, digital twins have been applied to teach students about sustainable processes through the integration of virtual models and resource utilization, energy, and waste [5] [6]. Nevertheless, there exists considerable potential in conducting further research regarding digital twins in engineering education, especially regarding their usage for assessing the impact on the quality of decision-making for sustainability by engineering students. This study employed a design-based instructional approach to examine how a digital twin can support engineering students' sustainable design decision-making.

Background and Literature Review

Sustainable Design Education in Engineering

Sustainable design, which integrates ideas from environmentally responsible practices, socially responsible practices, and financially feasible design, has become a paradigm for the engineering profession in response to the increasing effects of climate change, resource depletion, and environmental ecosystem deterioration, which has made sustainable design evolve from a trend to a critical imperative that is integral to engineering design and practice, particularly in response to the environmental effects and, specifically, climate change [7], [8]. Merely imparting broad notions of sustainability concepts to students does not constitute effective sustainability design education. Rather, it involves students applying systems-thinking processes among students and learning the trade-offs between the various goals to be met within design [9]. Consequently, the use of design-based learning, project-based learning, and experiential learning has been extensively advocated for, which can help to move students from conceptual awareness to competent, system-level decision-making [9], [10].

In particular, it is important to remember that engineering students' capacity for anticipating the outcome of design decisions, ranging from energy needs or environmental influences to carbon emissions, requires that they be provided with appropriate tools that enable them to see such outcomes at the design level. Relying solely on traditional lecture-based discussions of sustainability often fails to engage students meaningfully, especially when emerging technologies can illustrate how specific choices influence key performance indicators [7].

Digital Twin and Immersive Technologies in Engineering Education

A digital twin (DT) can be defined as a virtual representation of a physical system, enabling simulations, analyses, and feedback mechanisms to be comprehended by the learners with respect to system behavior in alternative scenarios without cost or risk for physical prototypes [11], [12]. DTs have been researched to be effective in bridging the gap between classroom theory and practice, offering authentic contexts for design thinking, experimentation, and decision-making [4]. Fig. 1 shows three levels of integration of digital depiction of physical systems, which are referred to as the digital model, digital shadow, and digital twin. The main difference between these levels is the way in which the digital and actual systems are connected. While in the digital model, there is no interchange of data, in the digital shadow, the flow of data is only from the actual model to the digital model. The digital twin, however, allows for data flow in both ways [13].

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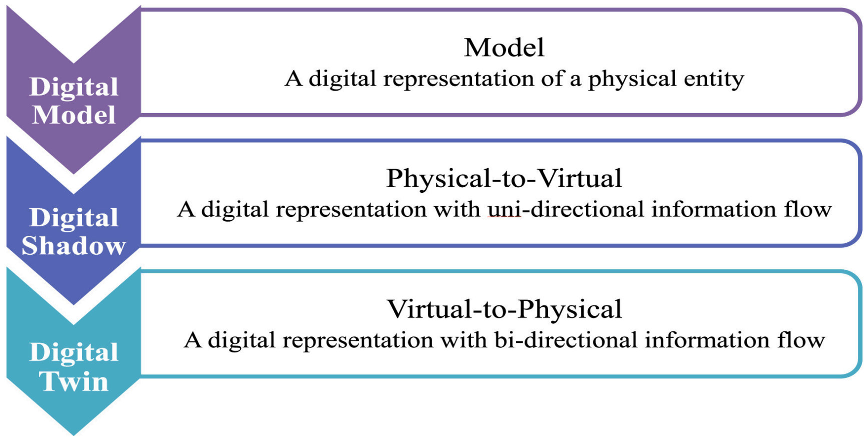

Fig. 1: Digital twin three levels of integration [13].

In engineering education, DTs have been applied to support hands-on learning across disciplines by allowing learners to visualize, manipulate, and analyze complex systems in virtual environments. By creating virtual replicas of real systems, DT technology enables students to simulate processes, experiments, validations, cost analyses, and performance outcomes within a controlled environment, thereby enhancing students' learning experience, critical thinking, and performance outcomes compared to traditional teaching methods. For example, rather than simply learning equations or reading static diagrams, learners can interact with a digital twin of a turbine to examine how its components function together, test design variations, and identify which factors most significantly influence performance outcomes [3], [4]. This deepens understanding and supports the transfer of learning to physical contexts.

Problem Statement

Despite growing enthusiasm for digital twins (DTs) in engineering education, the engineering literature still lacks outcome-focused evidence on whether the use of DTs improves learning outcomes and career readiness, as noted in a recent synthesis [4]. To address this gap, this study implements a DT workflow to evaluate the impact of immediate, data-driven feedback on sustainable design decision quality.

Methodology

Research Design

This study employed a design-based instructional approach to examine how a digital twin can support engineering students' sustainable design decision-making. Students were provided with a compiled digital twin-based instructional brief that presented multiple design scenarios alongside quantified sustainability performance indicators to support evidence-informed evaluation of design alternatives. Student learning was assessed through a post-instruction survey that captured design selections, decision rationales, and perceptions of the digital twin environment.

Digital Twin Development Process and Tools

A digital twin of the building was developed to replicate key physical, geometric, and performance characteristics. The development process followed a staged workflow commonly used in professional building performance analysis, shown in Fig. 2. To establish geometric and contextual fidelity, multiple sources of as-built information were collected and synthesized. These included site photographs, Google Earth imagery, and spatial data captured using Matterport technology. Fig. 3 illustrates representative examples of the source data used to develop the building geometry and context, which were triangulated to ensure consistency between the physical building and its virtual representation, providing a twin of the existing building.

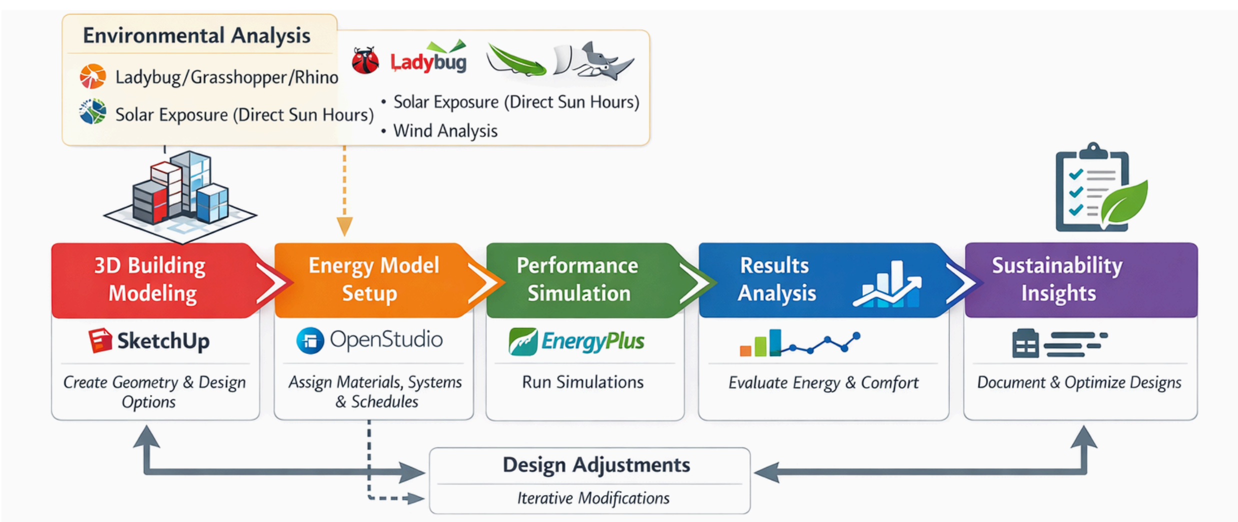

Fig. 2. Digital twin development workflow

Fig. 3. Source data used to develop the as-built building geometry for digital twin development, including site photographs, satellite imagery, scanned plans, and Matterport captures.

The building geometry was developed in SketchUp to create a three-dimensional representation of the baseline design. Fig. 4 shows the SketchUp model used as the geometric basis for the digital twin. SketchUp provides a lightweight and low-barrier environment to manipulate the physical characteristics of the twin, such as window-to-wall ratios and alternate designs, without the steep learning curve of more complex Building Information Modelling (BIM) platforms, thus making it suitable for this case study development. The 3D model was populated with the

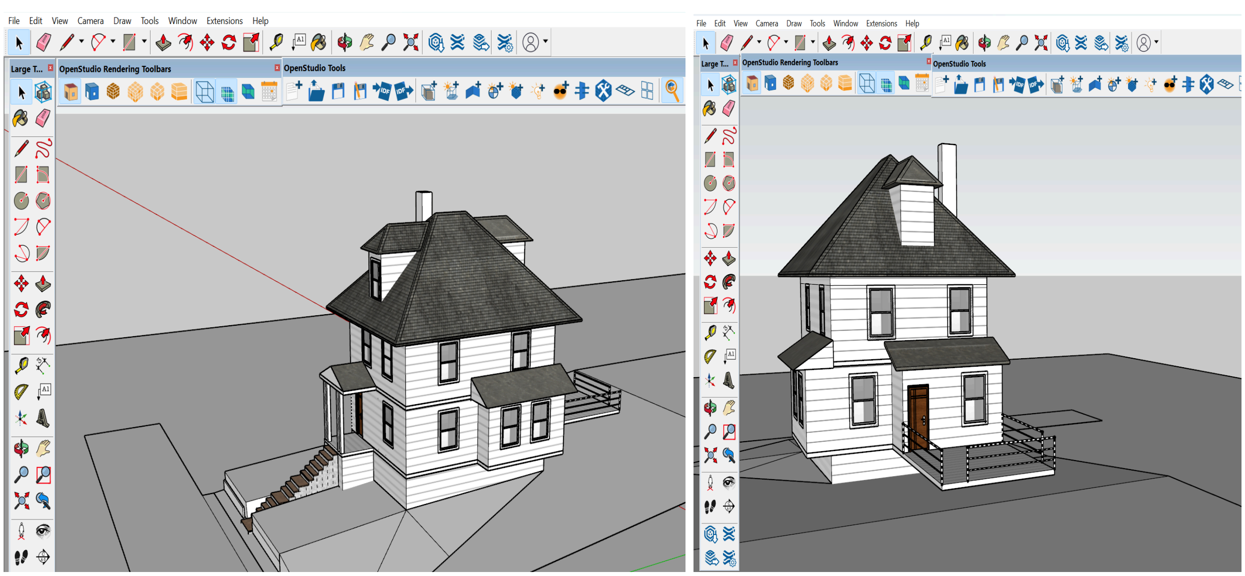

Fig. 4. Three-dimensional building geometry developed in SketchUp representing the baseline design configuration.

building information and site information, which were gotten from the Typical Meteorological Year (TMY) weather data. The integration of these data transformed the model from a mere 3D model to a twin of the physical building. The OpenStudio application, which is software in which EnergyPlus for energy model analysis is embedded, served as a major platform for managing alternative design scenarios, enabling systematic comparison of envelope, system, and layout options. In the OpenStudio application, the weather of the site and construction sets shown in Fig. 6, with a focus on the existing building envelopes, were defined to reflect realistic operating conditions.

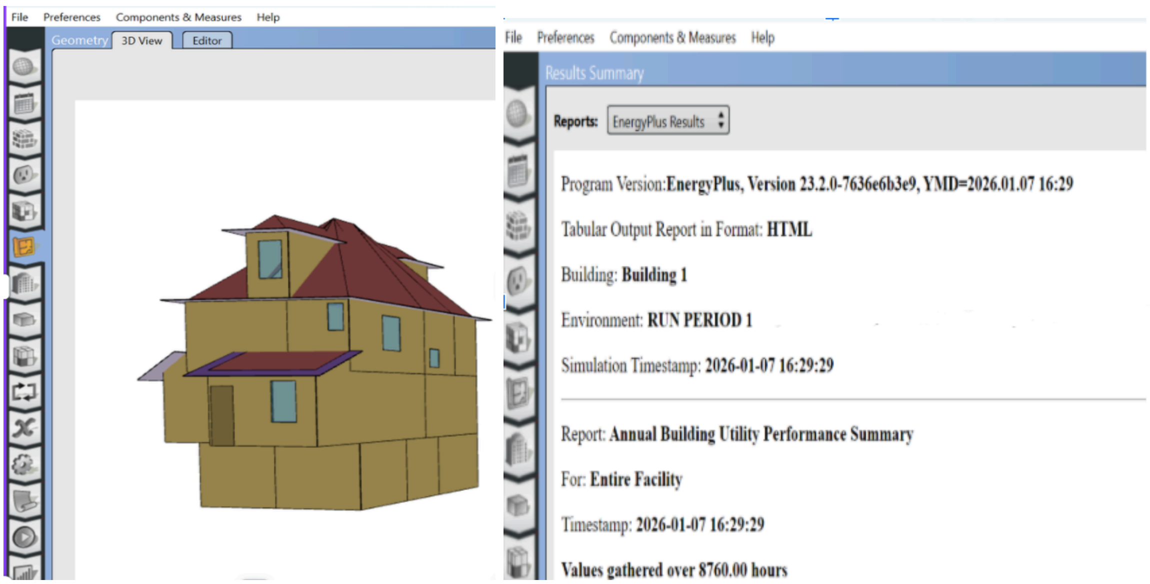

Fig. 5. OpenStudio interface illustrating the assignment of building systems, schedules, and construction properties for simulation scenarios.

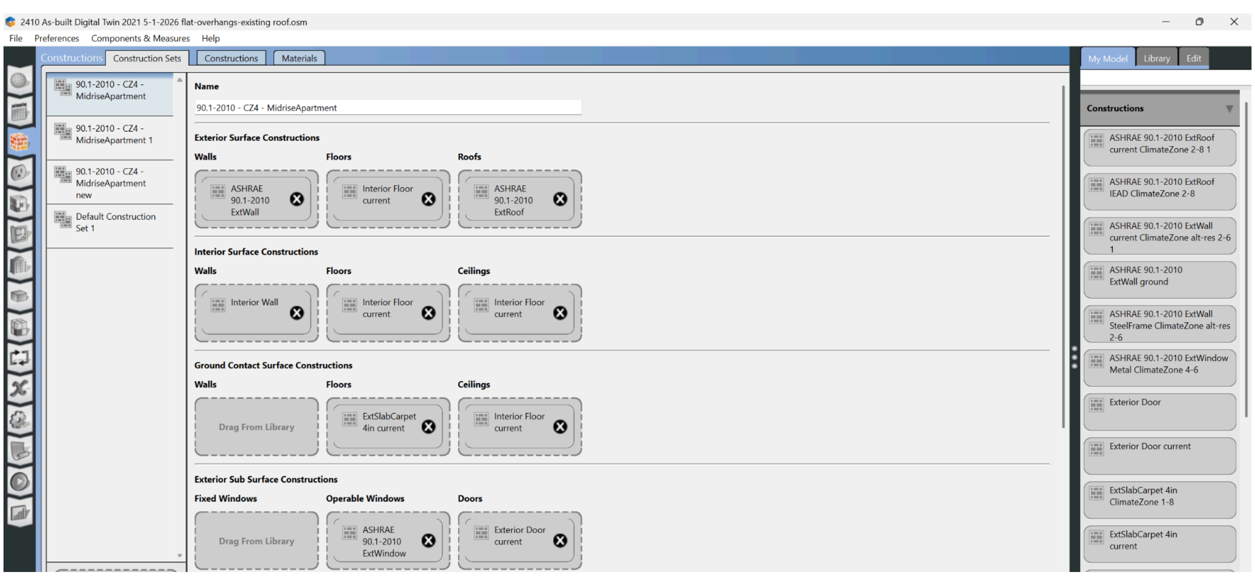

Fig. 6. Definition of the alternative construction sets and materials interface

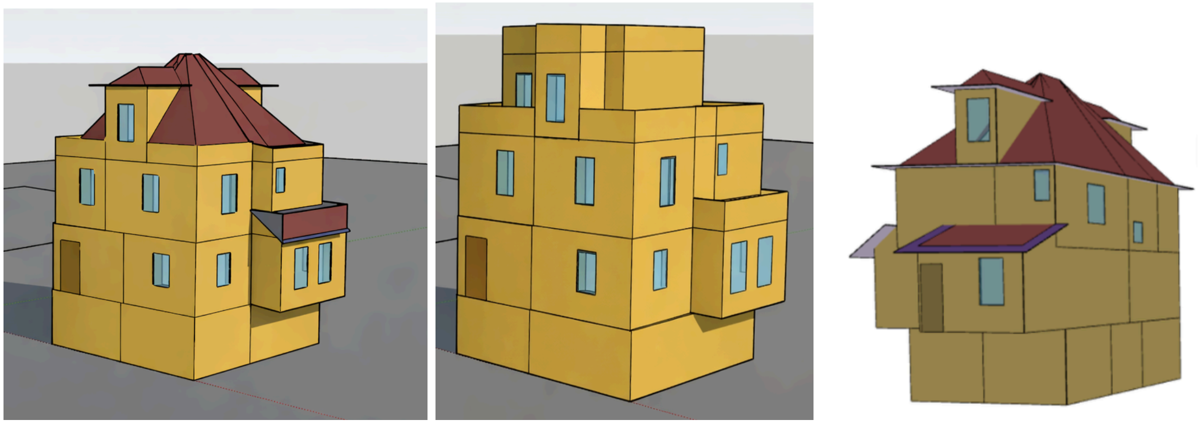

Fig. 7. Digital twin scenarios illustrating alternative building envelope and system configurations presented to students.

The results from the analysis were combined into instructional material that showed students how different design choices affect sustainability, an excerpt shown in Table 8. By looking at energy use alongside wind and solar data, students could see the 'trade-offs.' For example, the EnergyPlus results showed that switching from a hip roof with a total energy use of 18.84 GJ to a flat roof with a total energy use of 21.67 GJ increased the building's total energy use by 15%, as shown in Table 1. By comparing these two sets of data, students learned to make 'trade-off' decisions—such as realizing that while 'More Windows' might offer better views, they also increased the energy demand to 21.67 GJ

Table 1: Comparative sustainability performance metrics

Metric	As Built	No Overhangs	With Overhangs	Insulated	Insulated + Daylighting	Flat Roof
Total Site Energy (GJ)	18.84	18.84	18.84	—	—	21.67
Total Source Energy (GJ)	59.65	59.65	59.65	—	—	68.63
Safe Hours	7258.47	7432.1	7258.47	7384.28	7383.61	7218.07
Caution Hours	941.69	941.62	941.69	962.56	963.87	957.82
Extreme Caution Hours	475.06	359.54	475.06	381.94	381.57	493.56
Envelope Convection (GJ)	570.2	580.9	570.2	568.19	568.21	572.12

Results and Discussion

This section presents the results of the post-instruction survey administered following the digital twin–based sustainability module. Analyses focused on summarizing learning and decision-support outcomes, examining relationships among key constructs related to digital twin use and sustainable design decision-making, and interpreting student reasoning through qualitative responses. Together, these analyses provide a multi-dimensional view of how the digital twin supported sustainable design decision-making.

Participant Overview

Fifteen graduate students majoring in engineering filled out the survey. Most of the participants had been taught sustainability in various capacities for relatability and comprehension of the instructional module and questionnaire, as shown in fig. 8.

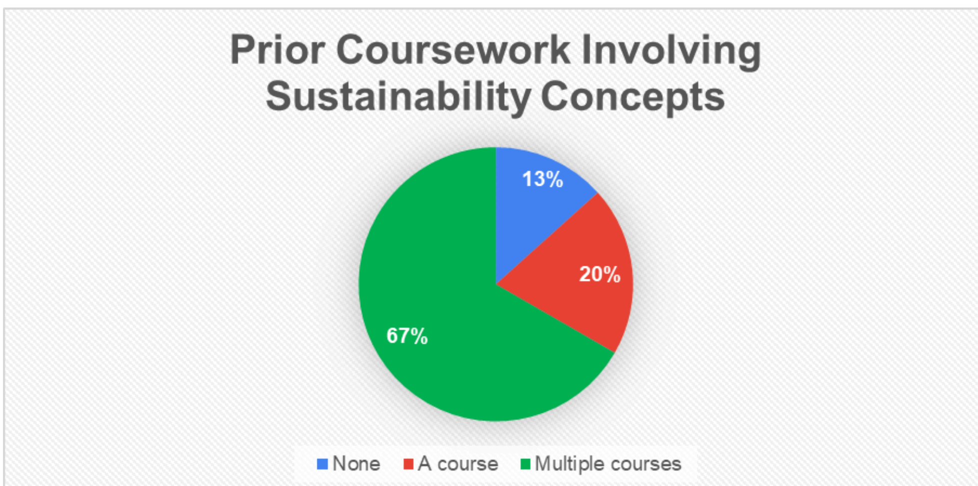

Fig. 8. Participants' Knowledge of Sustainability Concept

Learning and decision-support outcomes

Students' perceptions of the digital twin were measured using a four-point Likert scale (1 = Strongly Disagree, 2 = Disagree, 3 = Agree, 4 = Strongly Agree) addressing understanding, trade-off reasoning, visual influence, evaluation of alternatives, and perceived improvement in decision quality.

Table 2. Descriptive statistics of learning and decision-support outcomes

Outcome Measure	Mean	SD
Understanding the sustainability impact of design decisions	3.53	0.52
Considering sustainability trade-offs	3.33	0.49
Influence of the digital twin simulation results on decisions	3.53	0.52
Evaluation of multiple design alternatives	3.33	0.62
Improved quality of sustainable design decisions	3.47	0.52

Mean values across all items exceeded 3.3 on a 4-point Likert scale used, as shown in Table 2, indicating consistent agreement that the digital twin supported sustainable design reasoning, with the highest agreement observed for understanding sustainability impacts and visual feedback influence. Meanwhile, sustainability trade-offs and evaluation of design alternatives having the lowest average scores imply some nuance and reflect that even though participants generally agreed that the digital twin supported these processes, they were less confident here compared to understanding and influence. This reflects the greater cognitive complexity required in balancing multiple competing objectives, where learners need to synthesize several variables more actively rather than respond to a single metric, suggesting that a different or active environment can increase the impact of this learning method, an environment that can be provided for students daily.

Qualitative Analysis

Responses to the open-ended design decision question were analyzed using thematic coding to identify recurring patterns in students' reasoning. This qualitative analysis was intentionally used to complement the Likert-scale responses and to mitigate known limitations of self-reported data, including acquiescence bias and the Dunning–Kruger effect, in which participants may unintentionally overestimate their competence or align responses with perceived researcher expectations [14], [15]. Although the 4-point Likert items yielded average scores of approximately 3.0, the quantitative results were corroborated by open-ended responses, strengthening confidence that the reported learning gains reflected substantive technical understanding rather than response bias.

Five dominant reasoning themes emerged from the qualitative analysis, summarized in Table 3, each reflecting a distinct way in which the digital twin module influenced students' design decision-making.

Table 3. Themes identified in student design reasoning

Reasoning Theme	**Frequency**	**Interpretation**
Energy performance considerations	High	Emphasis on simulation outputs
Material and envelope decisions	Moderate	Linking design choices to performance
System-level efficiency	Moderate	Evidence of systems thinking
Data-driven revision of assumptions	Moderate	Reflective decision-making

The most prevalent theme was energy performance considerations, which appeared frequently. Students frequently justified their design choices using explicit simulation outputs generated by the digital twin. For instance, one participant explained their preference for a hip roof over a flat roof by citing a measurable performance difference between 18.84 GJ and 21.67 GJ, noting that the selected option "*reduced heat gain and improved overall performance under local weather conditions.*" The use of precise quantitative metrics suggests that students were not merely observing simulation results but actively interpreting performance data to support evidence-based decisions.

A second theme, material and envelope decisions, emerged with moderate frequency. Participants linked material selection and envelope configurations directly to energy outcomes, with statements such as "*Materials used are a great influence on the energy used in a design*" and "*Different types of roofs affect the energy efficiency of buildings.*" These responses demonstrate an ability to associate component-level design choices with system-wide sustainability performance, reinforcing the digital twin's role as a decision-support tool rather than a passive visualization aid.

The system-level efficiency theme also appeared at a moderate frequency, reflecting evidence of systems thinking. Responses in this category demonstrated awareness of interactions among building subsystems, such as roof geometry, envelope performance, and climate conditions, indicating that students were reasoning beyond isolated design variables.

Another moderately frequent theme was data-driven revision of assumptions, which captured reflective decision-making. Students described revising initial design assumptions after reviewing performance feedback, highlighting an iterative design process grounded in simulation evidence. This theme is particularly important, as it suggests that the module encouraged students to engage in adaptive reasoning rather than fixed or confirmatory thinking.

Taken together, the alignment between moderate-to-high Likert scores and metric-linked qualitative explanations supports the validity of the findings. The triangulation of quantitative and qualitative data indicates that students' perceived learning gains were grounded in technical reasoning and performance-based justification. Overall, the results suggest that the digital twin functioned not only as a visualization platform but also as an active cognitive support system that enabled students to compare alternatives, synthesize multiple criteria, and justify design decisions using quantitative evidence. In educational contexts, such performance-linked feedback is known to promote deeper learning by explicitly linking design actions to measurable consequences [1], [2], [3].

Limitations and Future Directions

The findings of this study should be interpreted within the context of some limitations that provide opportunities for the ongoing work. Primarily, the current sample size was relatively small and drawn from a single instructional context at a specific institution, which naturally constrains the broad generalizability of the results. Furthermore, the existing digital twin implementation is intentionally narrowed to a few key sustainability metrics, such as energy intensity and thermal resilience. While these are fundamental to high-performance building design, they do not yet capture the full complexity of environmental, economic, and social variables, such as lifecycle cost analysis, embodied carbon footprints, or regional policy constraints that often dictate professional engineering decisions.

Another significant limitation involves the mode of delivery, which utilizes a pre-compiled, asynchronous instructional module rather than direct, synchronous physical interaction with learners, potentially limiting the overall pedagogical impact. Although the module was meticulously structured with detailed models and clear analytical explanations and provided direct contact channels for researcher support, the absence of real-time, instructor-led guidance remains a notable constraint.

To address these limitations, future research directions will focus on expanding data collection across multiple. A major technological leap for the next phase of this work involves the integration of real-time, multi-user Virtual Reality (VR) environments. This transition will allow students to inhabit the digital twin synchronously, enabling them to manipulate building parameters, such as adjusting geometry or material properties, and observe the immediate impact on performance metrics through immersive data overlays. By expanding the digital twin's capability to include broader metrics like embodied carbon and social impact, future iterations will move beyond simple energy modeling toward a comprehensive decision-support system that reflects the multi-disciplinary reality of modern sustainable engineering.

Conclusion

This study examined the use of a digital twin–based instructional module to support sustainable design decision-making among engineering students. Although exploratory in scope, the findings indicate the pedagogical value of integrating digital twin simulations into sustainable design education, as it can bridge the gap between theoretical sustainability concepts and applied design decisions. By embedding performance metrics within a visual and interactive modeling environment, students can be better positioned to connect cause and effect in their design choices. As digital twin technologies continue to mature, their thoughtful integration into engineering education holds significant potential for strengthening sustainable design competencies and preparing future engineers to make informed, responsible decisions in complex real-world contexts. However, while this study supports insight generation, future iterations involving real-time VR interaction and broader life-cycle metrics, where students can systematically compare alternatives and explicitly articulate trade-offs, could further strengthen this aspect of learning. Nevertheless, this work contributes a practical and adaptable pedagogical model that leverages widely available tools and can be extended across disciplines and institutional contexts.

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