Enhancing Graduate Engagement in Sustainable and Resilient Infrastructure through Digital Twin Simulation: An ICAP- and SDT-Informed Living-Lab Study at an HBCU

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Abstract

Addressing challenges related to climate change and infrastructure resilience requires engineering graduates who can reason about sustainability, data-driven performance, and complex system trade-offs. Digital Twin (DT) technologies, which provide virtual representations of physical assets through modeling and simulation, offer opportunities to support experiential learning in sustainability-focused engineering education.

This study presents an exploratory, post-module investigation of student engagement within a Digital Twin–enabled living-lab module implemented in a graduate Sustainable and Resilient Infrastructure course at a Historically Black College and University (HBCU). The module was centered on an existing residential building, which served as a real-world case study for sustainability and retrofit analysis. Students developed retrofit strategies using SketchUp, simulated energy and carbon performance using OpenStudio powered by EnergyPlus, and interpreted results through performance visualization dashboards.

The study is grounded in the Interactive-Constructive-Active-Passive (ICAP) framework as the primary lens for cognitive engagement, with Self-Determination Theory (SDT) and the Technology Acceptance Model (TAM) used as supporting perspectives to contextualize motivation and technology use. Student engagement, motivation, technology acceptance, and perceived learning outcomes were examined using a post-module survey, with analysis limited to descriptive statistics and internal consistency measures.

Results indicate moderate to high levels of cognitive engagement across ICAP modes, with notable constructive and interactive engagement despite the short duration of the activity. Students also reported positive perceptions of learning relevance, interest in sustainable building design, and the usefulness of Digital Twin tools for understanding sustainability concepts. While exploratory in nature, the findings demonstrate the feasibility of using Digital Twin representations of existing residential buildings to support meaningful engagement in sustainability-focused graduate engineering education. The study also highlights the potential of HBCUs as contexts for innovation in digital pedagogy within engineering education.

Keywords: Digital Twin, Graduate Engineering Education, Sustainable and Resilient Infrastructure, Experiential Learning, Self-Determination Theory, ICAP Framework, Student Engagement, Technology Acceptance, Sustainability Pedagogy.

Introduction

Engineering education has increasingly shifted toward active, student-centered learning approaches that emphasize real-world problem solving and applied decision-making, particularly in science and engineering disciplines [1], [2]. Large-scale evidence indicates that active learning strategies significantly improve student performance compared to traditional lecture-based instruction, underscoring the need for instructional designs that move beyond passive content delivery [3].

In sustainability-focused engineering education, students are often required to evaluate complex trade-offs involving energy performance, carbon emissions, and design decisions, which are difficult to convey effectively through conventional teaching methods [4]. Digital Twin technologies, including building information modeling (BIM), building energy simulation, and performance visualization tools, offer new opportunities to support experiential learning by enabling students to interact with realistic system representations, test design alternatives, and observe performance outcomes [5], [6].

However, prior research has shown that the educational value of instructional technologies does not depend solely on their availability or frequency of use, but rather on how students cognitively engage with technology-supported learning activities [7]. To examine this engagement, the Interactive-Constructive-Active-Passive (ICAP) framework provides a theory-driven model that categorizes learning activities according to the level of cognitive engagement they elicit. The framework posits that constructive and interactive activities, where learners generate or co-construct knowledge, are more strongly associated with deep learning than passive or purely active engagement [7].

Beyond cognitive engagement, student motivation and technology adoption are critical factors influencing learning effectiveness in technology-rich environments. Self-Determination Theory (SDT) emphasizes that learning environments supporting autonomy, competence, and relatedness are more likely to foster intrinsic motivation and sustained engagement [8]. In parallel, the Technology Acceptance Model (TAM) explains how perceived usefulness and perceived ease of use shape users' intentions to adopt and meaningfully use technology, including in educational contexts [9].

Despite the relevance of these complementary perspectives, limited classroom-based research in engineering education has examined cognitive engagement, motivation, and technology acceptance together within Digital Twin-enabled learning modules. This paper addresses this gap by presenting an exploratory study of a Digital Twin-enabled living-lab module centered on an existing residential building. Using a post-module survey grounded in ICAP theory and informed by SDT and TAM, the study examines student engagement patterns and perceived learning outcomes in a sustainability-focused instructional context.

Theoretical Framework

This study is informed by three complementary theoretical perspectives that together explain student engagement in a Digital Twin-enabled learning environment: the Interactive-Constructive-Active-Passive (ICAP) framework for cognitive engagement, Self-Determination Theory (SDT) for student motivation, and the Technology Acceptance Model (TAM) for technology adoption. Each framework addresses a distinct but interrelated dimension of learning in technology-rich engineering education settings.

ICAP: Cognitive Engagement Framework

The primary analytical framework guiding this study is the ICAP framework, which categorizes learning activities based on the level of cognitive engagement they elicit: passive, active, constructive, and interactive [7]. Passive and active engagement involve receiving information or practicing given procedures, whereas constructive and interactive engagement require learners to generate new understanding individually or through collaboration. ICAP theory posits that learning outcomes improve as engagement shifts from passive toward constructive and interactive modes, reflecting increasingly generative cognitive processes [7].

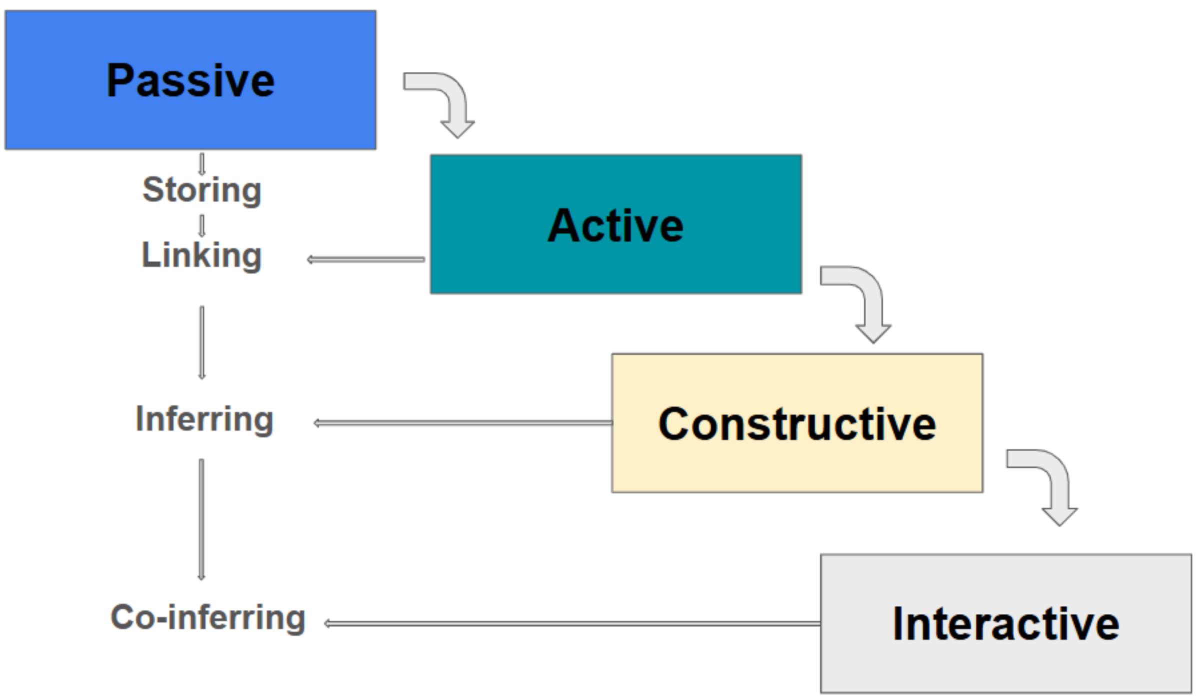

Fig 1. ICAP Framework

ICAP has been widely adopted in STEM and engineering education research to move beyond surface-level descriptions of instructional activity and instead characterize the quality of student engagement supported by learning environments [10]. In this study, ICAP provides the primary structure for examining how students engaged with Digital Twin tools during the living-lab module centered on an existing residential building. Engagement is operationalized through student self-reports describing how frequently digital tools were used to support each ICAP mode, allowing evaluation of cognitive engagement rather than simple tool usage.

SDT: Motivation Supporting Engagement

While ICAP explains how students engage cognitively, Self-Determination Theory (SDT) provides insight into the motivational conditions that support such engagement. SDT identifies autonomy, competence, and relatedness as fundamental psychological needs that foster intrinsic motivation, persistence, and meaningful learning [8]. Learning environments that support these needs are more likely to promote sustained engagement and deeper involvement in learning activities.

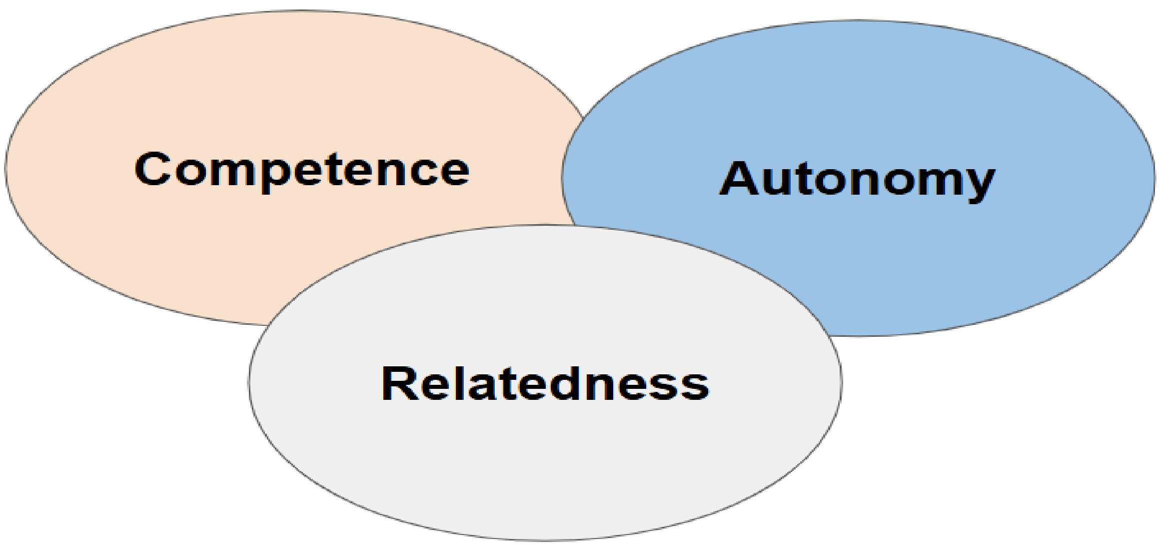

Fig 2. SDT Framework

Prior research in educational and engineering contexts has shown that instructional designs allowing students to make decisions, develop competence through feedback, and collaborate with peers are associated with increased motivation and engagement [8], [11]. In the present study, the Digital Twin living-lab module centered on an existing residential building incorporated exploratory tasks, open-ended decision-making, and collaborative discussion, which align with SDT principles. SDT is therefore used as a supporting lens to interpret students' willingness to engage in higher-order ICAP activities within the module.

TAM: Technology Acceptance Enabling Engagement

The Technology Acceptance Model (TAM) explains how users' perceptions of a technology influence their intention to use it. According to TAM, perceived usefulness and perceived ease of use are key predictors of technology adoption and continued use [9]. In educational settings, students are more likely to meaningfully engage with digital tools when they perceive those tools as beneficial for learning and manageable to use.

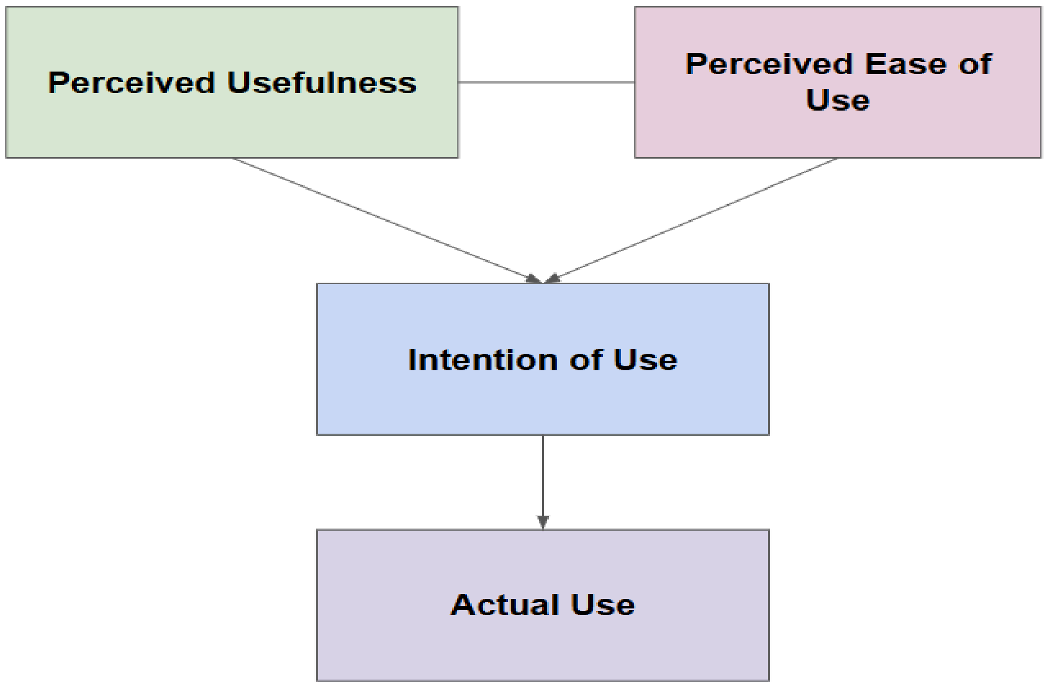

Fig 3. TAM Framework

TAM has been extensively applied in educational technology research to examine student adoption of learning technologies, particularly in contexts involving advanced or unfamiliar tools [12]. In this study, TAM provides context for understanding students' interaction with Digital Twin tools. Students' acceptance of modeling, simulation, and visualization technologies is expected to influence the extent to which they engage beyond superficial interaction, thereby enabling higher-order cognitive engagement as described by ICAP.

Integrated Perspective

Rather than serving as parallel descriptive lenses, ICAP, SDT, and TAM were positioned hierarchically within the analytical framework. ICAP functioned as the primary framework for categorizing and interpreting the level of cognitive engagement supported by the Digital Twin module. SDT and TAM were used to interpret enabling conditions underlying these engagement patterns. Specifically, SDT constructs (autonomy, competence, relatedness) were examined to understand motivational factors that may support or constrain higher-order ICAP engagement (constructive and interactive), while TAM constructs (perceived usefulness and ease of use) were used to contextualize how students' perceptions of the Digital Twin tools may influence the depth of engagement observed. This layered analytical structure allowed engagement patterns to be interpreted not only descriptively, but also in relation to motivational and technology-related conditions shaping those patterns.

Methodology

Instructional Context and Module Design

The study was conducted within a single graduate engineering class using a Digital Twin–enabled living-lab module centered on an existing residential building. Rather than a purpose-built laboratory facility, the residential building served as a real-world instructional case, allowing students to examine sustainability and retrofit decisions in an authentic built-environment context.

The module followed a structured yet interactive format. The session began with an instructor-led introduction and demonstration of baseline performance analysis. During the simulation of retrofit scenarios, students were prompted to propose alternative strategies, interpret emerging outputs, and discuss sustainability trade-offs. While much of the simulation was instructor-facilitated, several students directly manipulated model parameters and explored alternative configurations under guidance. Thus, engagement combined observation, discussion-based reasoning, and limited hands-on interaction with the Digital Twin environment.

Fig 4. Source data used to reconstruct the as-built building geometry for digital twin development, including site photographs, satellite imagery, scanned plans, and Matterport captures.

Students worked with a digital representation of the residential building and explored retrofit strategies using SketchUp for building modeling, OpenStudio powered by EnergyPlus for energy and carbon performance simulation, and data-visualization dashboards for interpreting results. The Digital Twin consisted of an integrated set of models and simulations that enabled students to evaluate alternative design and retrofit scenarios without physical intervention in the building.

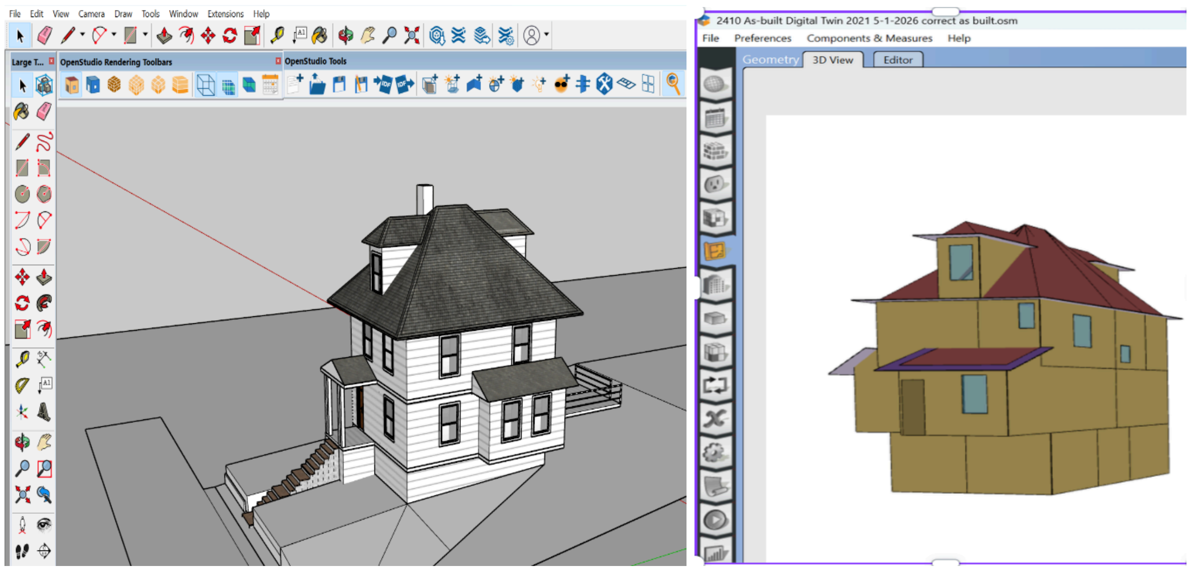

Fig 5. Sketch up and Open studio Three-dimensional building geometry

The module was delivered within a single class session and emphasized applied analysis, decision-making, and collaborative discussion. The instructional design intentionally supported exploratory learning, allowing students to evaluate multiple design alternatives and observe performance outcomes. This approach aligns with prior research highlighting the value of active and technology-supported learning in engineering education [3].

Unlike traditional case-based or simulation-based activities that rely on hypothetical scenarios or instructor-defined solution pathways, the living-lab approach used in this study centered on an existing, context-specific building with real-world constraints, data sources, and performance conditions. Students engaged in open-ended analysis of retrofit strategies, evaluated trade-offs using authentic performance outputs, and interpreted results in relation to the building's actual characteristics. This emphasis on contextual realism, exploratory decision-making, and iterative evaluation distinguishes the living-lab from structured simulation exercises with predetermined outcomes.

In this study, the term "living-lab" refers to a data-rich, real residential building used as a virtual experimentation environment for student learning, rather than a controlled physical laboratory.

Study Design and Participants

The study employed a post-only, cross-sectional survey design, which is appropriate for exploratory classroom-based research and instructional innovation studies [13]. Participants were students enrolled in the course who completed the Digital Twin module. Survey participation was voluntary, responses were collected anonymously, and no personally identifiable information was recorded.

The post-only design was selected to minimize disruption to instruction and to focus on students' engagement during the learning experience rather than on pre–post comparisons, which would be inappropriate given the single-session nature of the module.

ICAP Engagement Measure

Student cognitive engagement was measured using an adapted version of the ICAP Technology Scale, originally developed to assess technology-supported learning activities across the four ICAP engagement modes: Passive, Active, Constructive, and Interactive [14]. The adapted instrument consisted of 12 Likert-scale items, with three items corresponding to each ICAP mode. Students reported how frequently they used digital tools during the module for each described purpose using a five-point scale ranging from *Almost never* to *Almost always*.

Item wording was modified to reflect a student perspective and the Digital Twin residential-building context, while preserving the underlying cognitive actions defined by the ICAP framework. The original ICAP Technology Scale has demonstrated strong reliability and construct validity in technology-enhanced learning settings [14].

However, these items were included to capture students' perceived learning experiences rather than to serve as objective measures or proxies of learning gains.

Motivation and Technology Acceptance Measures (SDT and TAM)

To support interpretation of cognitive engagement patterns, the survey also included a limited set of items informed by Self-Determination Theory (SDT) and the Technology Acceptance Model (TAM).

Motivation-related items were aligned with SDT constructs of autonomy, competence, and relatedness, capturing students' perceived sense of choice, capability, and collaboration during the module. Technology acceptance items were informed by TAM constructs of perceived usefulness and perceived ease of use, reflecting students' perceptions of the Digital Twin tools used in the activity.

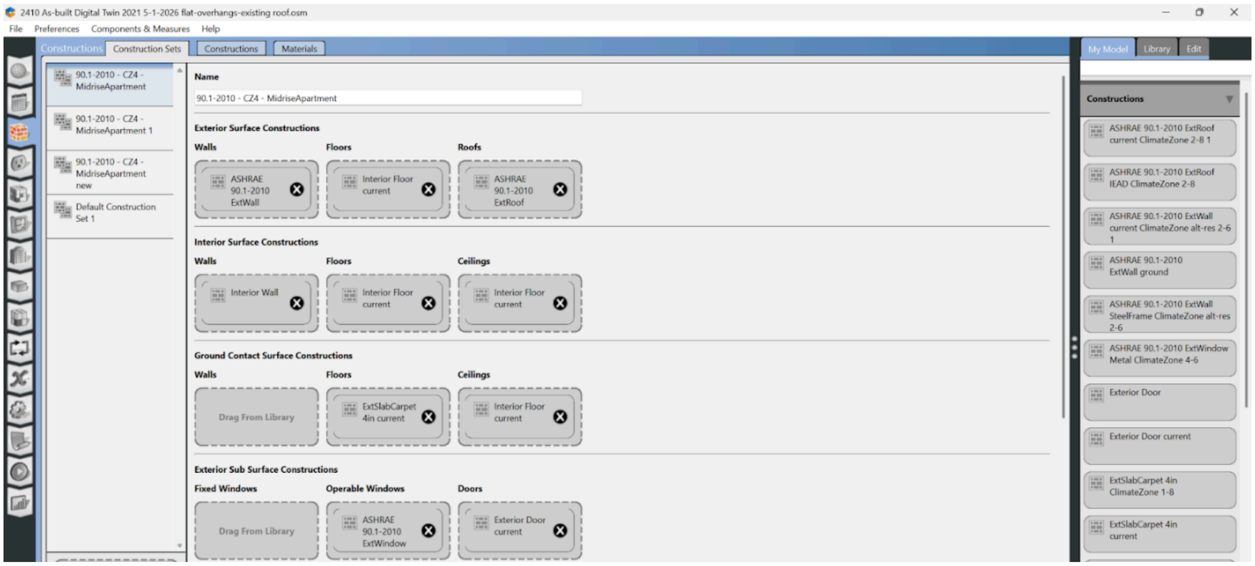

Fig 6. Definition of the alternative construction sets and materials interface

These SDT- and TAM-informed items were included for descriptive and contextual purposes only and were not used for predictive or causal modeling. Their role was to provide supporting insight into motivational and technology-related factors associated with student engagement.

Perceived Learning Outcomes

To contextualize engagement results, the survey included a focused set of items assessing perceived learning outcomes, including understanding of building sustainability concepts, confidence in interpreting simulation results, ability to connect theory to real-world sustainability problems, and interest in sustainable building design. These items provided descriptive insight into students' perceived educational experiences following participation in the module.

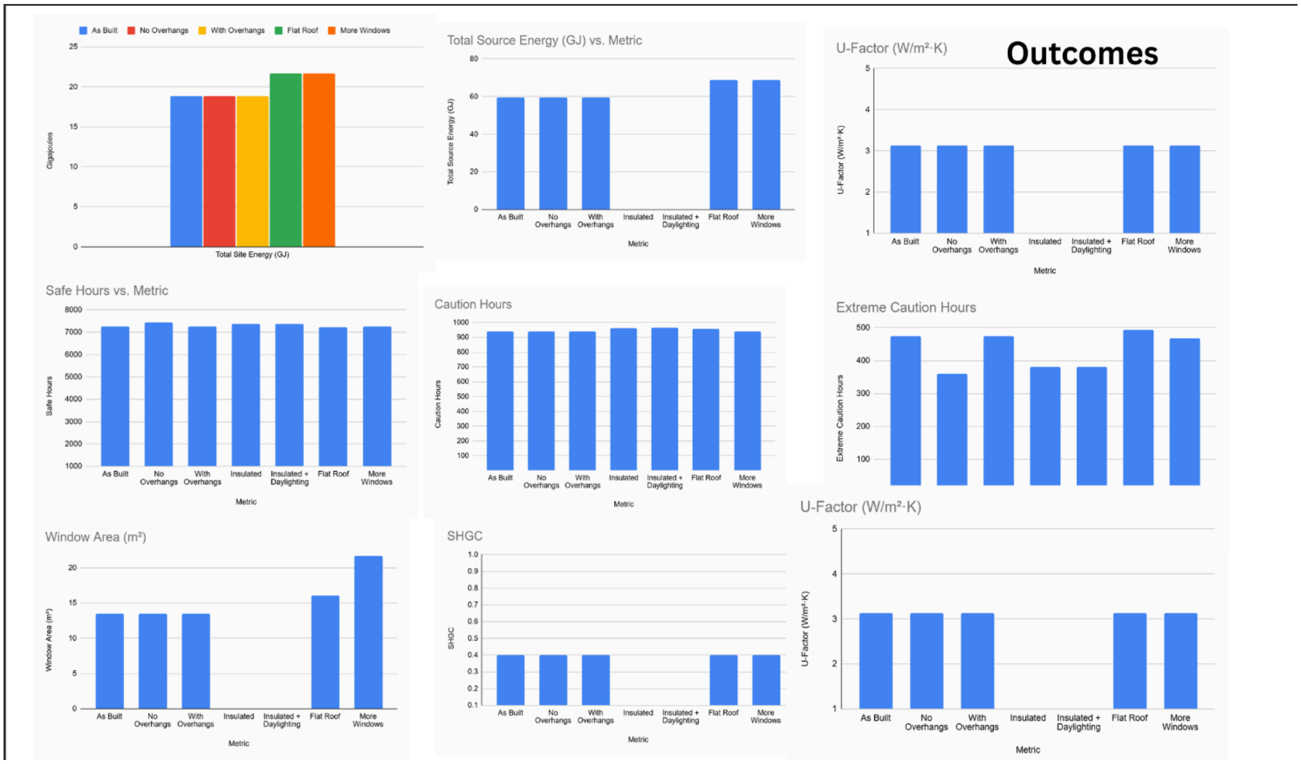

Fig 7. Graphical Representation of alternative construction sets and materials results

Table 1. Comparative sustainability performance metrics

Metric	As Built	No Overhangs	With Overhangs	Insulated	Insulated + Daylighting	Flat Roof	More Windows	Note
Total Site Energy (GJ)	18.84	18.84	18.84	—	—	21.67	21.67	Flat roof and more windows increase total energy use.
Total Source Energy (GJ)	59.65	59.65	59.65	—	—	68.63	68.63	Source energy follows the same trend as site energy.
Safe Hours	7258.47	7432.1	7258.47	7384.28	7383.61	7218.07	7252.07	Insulation and no overhangs slightly improve safe hours.
Caution Hours	941.69	941.62	941.69	962.56	963.87	957.82	941.51	Caution hours are stable across most scenarios.
Extreme Caution Hours	475.06	359.54	475.06	381.94	381.57	493.56	467.93	No overhangs reduce extreme caution hours most.
Envelope Convection (GJ)	570.2	580.9	570.2	568.19	568.21	572.12	492.12	More windows reduce convection but raise exfiltration.
Window Area (m²)	13.49	13.49	13.49	—	—	16.1	21.7	More windows increase solar exposure and daylight.
SHGC	0.401	0.401	0.401	—	—	0.401	0.401	SHGC is constant; performance changes come from area.
U-Factor (W/m²·K)	3.127	3.127	3.127	—	—	3.127	3.127	U-Factor is unchanged; insulation affects walls/roof.

Data Collection Procedure

The survey was administered immediately after completion of the Digital Twin module. All survey items were required to prevent missing data. Prior to deployment, the instrument underwent face and content review by a small group of students and faculty to ensure clarity, relevance, and alignment with the instructional activities, consistent with recommended practices for survey-based educational research [15].

Data Analysis Approach

Data analysis was intentionally limited to descriptive and reliability-based methods, consistent with the exploratory nature of the study, the single-class context, and the modest sample size. Mean scores and standard deviations were calculated for each ICAP engagement mode to characterize student engagement patterns. Internal consistency of the ICAP subscales was assessed using Cronbach's alpha.

No inferential statistical testing or causal modeling was conducted. This decision aligns with best practices for small-sample instructional studies and avoids overinterpretation of results beyond the scope of the data [13]. Findings are therefore interpreted as descriptive indicators of engagement within the implemented Digital Twin module, rather than as generalizable or causal outcomes.

Results and Analysis

This section presents descriptive results from the post-module survey administered following the Digital Twin-enabled living-lab activity. Consistent with the exploratory nature of the study and the small sample size, analysis is limited to descriptive statistics and internal consistency measures.

Participant Overview

A total of 15 students completed the survey. Respondents represented a mix of graduate-level programs, including PhD, MEng, and MSc engineering tracks. All survey items were completed, resulting in no missing data. Responses were recorded on a five-point Likert scale (1 = strongly disagree / almost never, 5 = strongly agree / almost always).

ICAP Engagement Patterns

Student cognitive engagement was examined using the four ICAP engagement modes: Passive, Active, Constructive, and Interactive. Table 1 summarizes the mean scores, standard deviations, and internal consistency values for each ICAP subscale.

Table 2. ICAP engagement descriptives and reliability (N = 15)
Note: Items were measured on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree)

ICAP Mode	Items	Mean	SD	Cronbach's
Passive	3	3.87	0.66	0.77
Active	3	3.31	1.33	0.93
Constructive	3	3.62	1.13	0.92
Interactive	3	3.62	1.30	0.87

Students reported the highest levels of engagement in Passive activities, followed closely by Constructive and Interactive engagement. Active engagement was comparatively lower, though still above the scale midpoint. This pattern suggests that students frequently engaged in understanding, interpreting, and discussing sustainability concepts, while hands-on procedural practice occurred less consistently within the single-session module.

Internal consistency values for all ICAP subscales exceeded commonly accepted thresholds for exploratory educational research, indicating acceptable to strong reliability across engagement modes.

Item-level results further indicated that students most frequently reported developing an understanding of building performance and sustainability trade-offs and observing energy and carbon performance outputs. Lower-scoring items were associated with procedural practice and independent creation of retrofit strategies, reflecting the limited duration and scope of the activity.

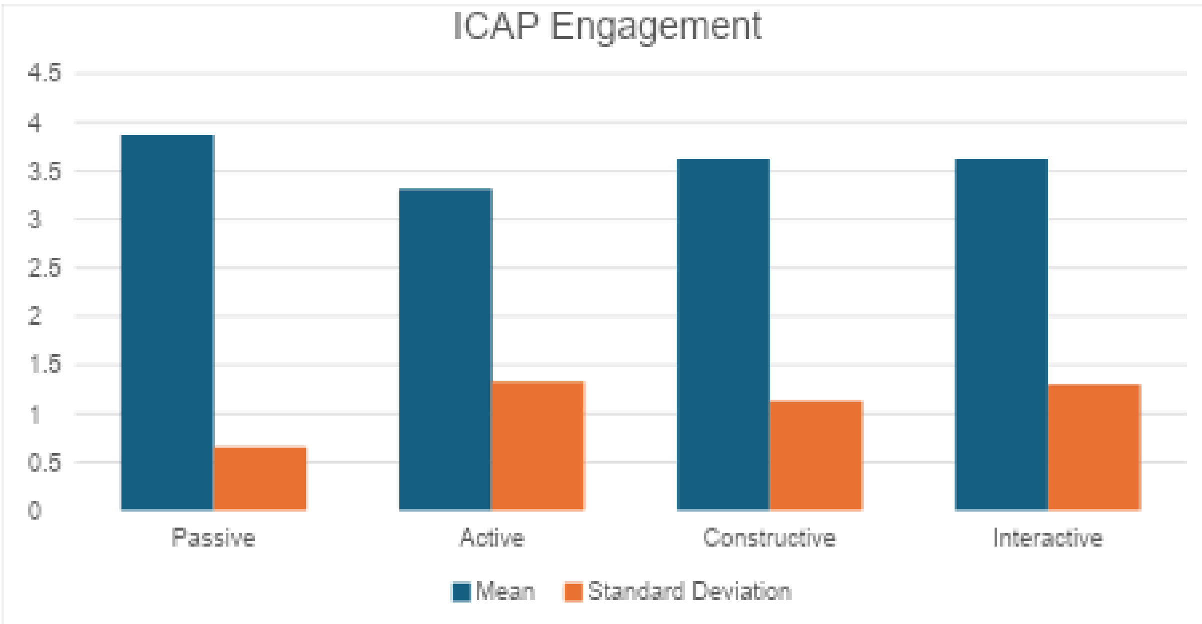

Fig 8. Bar Chart of ICAP Engagement Mean and Standard deviation

Motivation and Technology Acceptance

To contextualize ICAP engagement patterns, descriptive statistics were computed for motivation-related (SDT-informed) and technology acceptance (TAM-informed) survey items. These measures were included to support interpretation rather than to test predictive relationships.

SDT Constructs

Table 3 summarizes descriptive results for SDT constructs of autonomy, competence, and relatedness.

Table 3. SDT descriptive statistics
Note: Items were measured on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree)

Construct	Items	Mean	SD
Autonomy	2	3.63	0.95
Competence	2	3.37	1.06
Relatedness	2	3.50	1.35

Students reported moderate-to-high levels of autonomy and relatedness during the module, indicating perceived freedom to explore design alternatives and comfort collaborating with peers. Competence scores were slightly lower and exhibited greater variability, suggesting differences in students' confidence when using Digital Twin tools.

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TAM Constructs

Descriptive results for technology acceptance constructs are shown in Table 4.

Table 4. TAM descriptive statistics
Note: Items were measured on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree)

Construct	Items	Mean	SD
Perceived Usefulness	2	3.90	0.85
Perceived Ease of Use	2	3.53	0.79
Behavioral Intention	2	3.93	0.80

Students generally perceived the Digital Twin tools as useful for learning and expressed positive intentions to engage with similar tools in the future. Ease-of-use ratings were moderately positive, indicating that while the tools were accessible, some cognitive or technical effort was required.

Perceived Learning Outcomes

Students' perceived learning outcomes were examined using four post-module survey items focused on understanding, interpretation, relevance, and interest. These items were analyzed at the item level, consistent with their intended use as descriptive indicators rather than as a single latent construct. Table 5 summarizes descriptive statistics for each learning-outcome item.

Table 5. Perceived learning outcome item descriptives (N = 15)
Note: Items were measured on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree)

Perceived Learning Outcome Item	Mean	SD

I better understand how building retrofits affect energy performance.	3.73	1.10
I can interpret simulation results to support design decisions.	3.53	1.13
The module helped connect theory to real-world sustainability problems.	3.93	0.96
This activity increased my interest in sustainable building design.	4.07	0.96

Students reported the strongest agreement with increased interest in sustainable building design and improved connection between theory and real-world sustainability problems. Perceived understanding of how building retrofits affect energy performance and the ability to interpret simulation results were rated positively but with greater variability, reflecting differences in prior experience and familiarity with modeling tools.

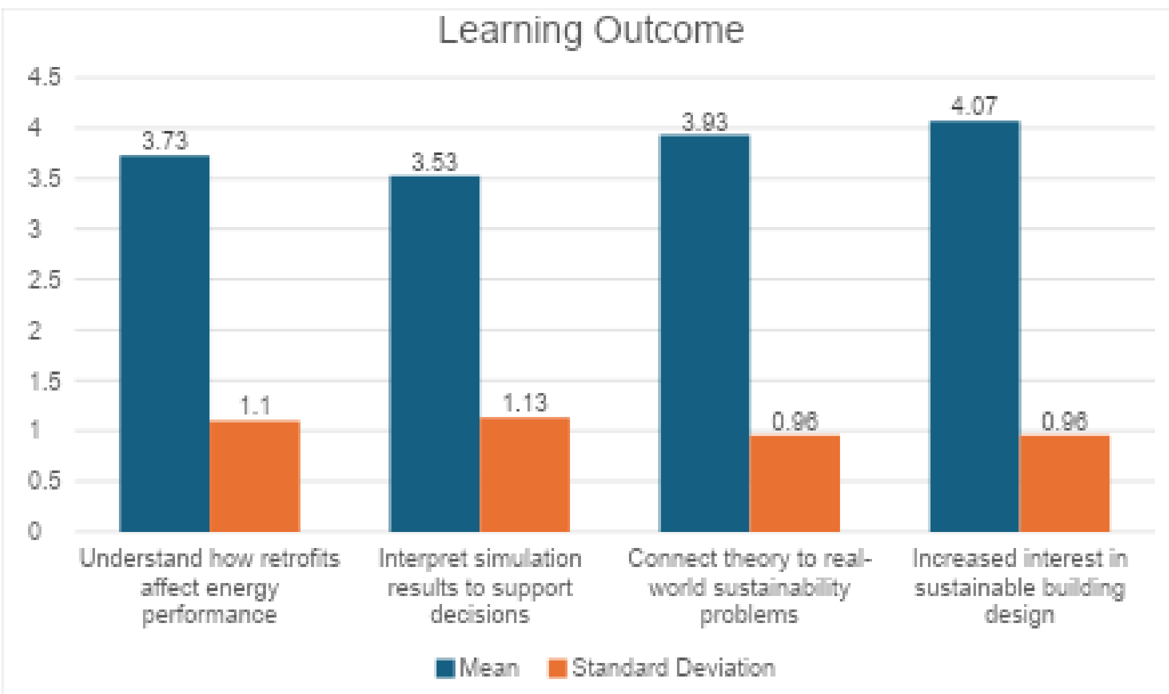

Fig 9. Bar chart of Perceived Learning outcome Mean and Standard Deviation

Discussion

This study examined student engagement and perceived learning outcomes within a Digital Twin-enabled living-lab module applied to an existing residential building, using ICAP as the primary analytical framework and SDT and TAM as supporting perspectives. The results provide descriptive insight into how students engaged cognitively with Digital Twin tools and how they perceived the learning experience in a sustainability-focused engineering context.

The living-lab framing was pedagogically significant because it positioned students not merely as users of simulation tools, but as decision-makers engaging with a specific real-world system characterized by contextual constraints and authentic performance metrics.

When interpreted alongside ICAP results, SDT and TAM measures provide insight into why constructive and interactive engagement remained relatively strong despite the single-session format. Moderate-to-high autonomy and relatedness scores suggest that students experienced sufficient psychological support to engage in generative discussion and interpretation, consistent with ICAP's higher-order modes. Similarly, strong perceived usefulness ratings (TAM) may explain sustained engagement with simulation outputs, even when ease-of-use ratings were more moderate. Thus, SDT and TAM constructs functioned analytically as explanatory layers that contextualize how and why specific ICAP engagement patterns emerged.

ICAP Engagement in a Digital Twin Learning Environment

The ICAP results indicate that students reported moderate to high engagement across all four ICAP modes, with particularly strong engagement in constructive and interactive activities. These findings suggest that even within a single-session module, a Digital Twin–based instructional design can support higher-order cognitive engagement, consistent with ICAP theory's emphasis on generative and collaborative learning.

Passive engagement was reported at the highest level, reflecting the presence of demonstrations, explanations, and observation of simulation outputs within the activity. However, constructive and interactive engagement were also prominent, indicating that students went beyond observation to interpret results, discuss alternatives, and reason about sustainability trade-offs. Active engagement, while still above the scale midpoint, was comparatively lower, likely reflecting the limited time available for repeated procedural practice within a single class session.

Taken together, these patterns align with the instructional intent of the module: to prioritize understanding, interpretation, and discussion over extended hands-on practice. From an ICAP perspective, the results suggest that Digital Twin representations of real residential buildings can effectively support higher-quality engagement, even when the physical system itself is not directly manipulated.

Motivation and Technology Acceptance as Enabling Conditions

Although not analyzed as predictive factors, SDT- and TAM-informed measures provide useful context for interpreting the engagement results. Students reported relatively strong perceptions of autonomy and relatedness, suggesting that the exploratory and collaborative structure of the module supported motivational conditions associated with deeper engagement. Competence ratings were more variable, indicating that while some students felt confident using the tools, others experienced challenges, an expected outcome when introducing advanced modeling and simulation software.

Similarly, students generally perceived the Digital Twin tools as useful for learning, while ease-of-use ratings were moderately positive rather than uniformly high. This pattern suggests that perceived usefulness may have encouraged students to persist and engage meaningfully with the tools, even when usability demands were nontrivial. In combination, these findings support the conceptual framing in which motivation (SDT) and technology acceptance (TAM) act as enabling conditions for ICAP-level cognitive engagement rather than as direct determinants of learning outcomes.

Perceived Learning Outcomes and Educational Implications

Students reported positive perceptions across all four learning-outcome items, with the strongest agreement observed for increased interest in sustainable building design and improved connection between theory and real-world sustainability problems. These outcomes suggest that using an existing residential building as the Digital Twin case study enhanced the perceived relevance of course content and supported interest development.

Perceived understanding of how building retrofits affect energy performance and the ability to interpret simulation results were also rated positively, though with greater variability. This variability likely reflects differences in prior experience with modeling and simulation tools and reinforces the importance of scaffolding and repeated exposure in future implementations.

While not claiming superiority over lower-tech approaches, Digital Twin enabled real-time visualization, iterative testing, and immediate feedback on sustainability outcomes. These affordances supported dynamic exploration of trade-offs and system-level reasoning. Future studies should compare this approach with alternative instructional formats.

While the study does not examine institutional effects, the HBCU context is relevant in demonstrating the feasibility of integrating advanced Digital Twin technologies within historically underrepresented engineering environments. The findings should therefore be interpreted as context-specific but potentially transferable pending future multi-institutional studies.

Overall, the findings indicate that Digital Twin-enabled modules grounded in real residential buildings can support engagement, relevance, and interest in sustainability topics, even when implemented within limited instructional time.

Limitations

Several limitations should be acknowledged. First, the study involved a small sample size (N = 15) from a single class, which limits generalizability. Second, the post-only design relies on self-reported perceptions and does not allow for measurement of learning gains over time. Third, the module focuses on a single existing residential building, and engagement patterns may differ in other building types or instructional contexts.

Importantly, perceived learning outcomes should not be interpreted as direct evidence of learning gains. The study did not include pre-post testing or objective assessment measures. Future work may incorporate performance-based or longitudinal measures to examine learning outcomes more directly.

Because the study was conducted within a single HBCU context, engagement patterns may reflect institutional characteristics such as class size, collaborative norms, or prior exposure to digital tools. Future research across institutional types would help assess broader transferability.

These limitations are consistent with the exploratory nature of instructional innovation studies and provide direction for future work rather than detracting from the present findings.

Conclusion

This study presented an exploratory examination of student engagement within a Digital Twin-enabled living-lab module applied to an existing residential building, using the ICAP framework as the primary analytical lens and SDT and TAM as supporting perspectives. Descriptive results indicate that the module supported moderate to high levels of cognitive engagement, with notable constructive and interactive engagement despite the short duration of the activity.

Students also reported positive perceptions of learning relevance, sustainability interest, and understanding of energy-performance concepts, suggesting that real-building digital twin representations can effectively connect theory to practice in engineering education. Motivation and technology acceptance measures further contextualized these findings, highlighting the role of autonomy, collaboration, and perceived usefulness in supporting engagement with advanced digital tools.

While exploratory in scope, this study demonstrates the feasibility and educational value of integrating Digital Twin technologies into sustainability-focused engineering instruction using existing residential buildings as learning contexts. Future work may extend this approach through multi-session implementations, pre-post designs, and comparative studies across building types to further examine learning outcomes and engagement dynamics.

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