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Enhancing Site Logistics Learning through 3D Printing and Augmented Reality

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Enhancing Site Logistics Learning through 3D Printing and Augmented Reality Demonstrations

Abstract

Understanding and planning construction site logistics can be challenging for students, as it's often hard to visualize 3D spaces from 2D drawings. In a Construction Means and Method course at a U.S University, a pilot instructional framework was developed to integrate 3D printing with instructor-led augmented reality (AR) for teaching construction site logistics planning. Twenty-four students participated in this pilot implementation. Students used 3D-printed building models fabricated at a university makerspace to physically design and discuss alternative site layout plans. To supplement the tactile experience, AR computer visualizations were demonstrated on iPads to project construction progressions and equipment placements. This dual-media setup supported an interactive, immersive environment in which construction phases could be visualized as well as spatial constraints. A pre- and post-test assessment was conducted to measure student learning outcomes related to spatial reasoning and construction planning accuracy. The assessment illustrated the pedagogical emphasis of real-world simulation to understand practical applications of concepts. Preliminary findings indicate improved comprehension of spatial relationships, higher engagement, and increased confidence in logistics decision-making compared with traditional 2D plan exercises. The project is representative of the way that blending hands-on and computer visualization tools can enhance the quality of spatial reasoning and communication that construction professionals will need in the future. While the pilot's limited sample size and single-semester scope constrain broad generalization, the results provide promising evidence that combining tactile and digital visualization tools enhances students' spatial cognition and communication skills. Continued data collection and cross-course integration are planned to strengthen the assessment base.

Introduction

The planning and management of construction site logistics are critical competencies for future construction professionals, with direct implications for project safety, productivity, and cost efficiency. Site layout decisions influence material flow, equipment movement, workforce coordination, and spatial safety constraints throughout the construction process. Despite their importance, these concepts remain challenging to teach effectively in undergraduate construction curricula. Students frequently struggle to translate two-dimensional (2D) drawings into the complex, three-dimensional (3D) spatial environments of active construction sites, particularly when multiple construction phases and dynamic constraints are involved [1]–[4]. Traditional instructional approaches largely based on static plans, lectures, and limited visual aids, which often fail to provide the experiential context necessary for developing strong spatial reasoning and logistics-related decision-making skills [1], [5], [6]. This gap highlights a deficiency in spatial reasoning skills required for logistics planning.

Recent advances in visualization and fabrication technologies have introduced new opportunities to address these pedagogical challenges in construction education. Tools such as 3D printing and augmented reality (AR) enable students to interact with spatial information in more intuitive and immersive ways. Physical 3D-printed models offer tactile engagement, allowing learners to manipulate building components and explore alternative site layout configurations collaboratively [7]–[10]. In parallel, AR technologies can overlay digital information—such as construction sequencing, equipment placement, and site constraints—onto physical representations, supporting the visualization of temporal and spatial relationships that are difficult to convey through 2D drawings alone [2], [4], [11]–[13].

While prior studies have explored the use of 3D printing or augmented reality individually in engineering and construction education [7], [9], [12], [14], relatively few have examined the use of hands-on 3D-printed physical models specifically for teaching construction site logistics. In addition, there remains limited empirical evidence on how such physical modeling activities can be supported by complementary, instructor-led augmented reality demonstrations to further enhance students' understanding of site logistics concepts [4], [11], [15]. In particular, there remains a need for empirical evaluation of instructional approaches that simultaneously examine cognitive learning outcomes and students' perceptions of technology-supported learning environments. Many existing studies emphasize descriptive observations or student satisfaction alone, without explicitly aligning learning outcome assessment with established educational or technology acceptance perspectives [6], [16]. Addressing this gap is essential for advancing pedagogically grounded, evidence-based instructional strategies that move beyond isolated technology demonstrations.

This paper presents a pilot study conducted in a construction methods course at a U.S. university that investigates a hybrid instructional framework integrating 3D-printed site models with instructor-led AR visual demonstrations. The framework was designed to support active learning in construction site logistics planning by enabling students to physically manipulate site layouts while simultaneously observing digitally augmented construction progressions and equipment movements. Rather than positioning the technologies themselves as the primary contribution, this study focuses on how the combined use of tactile and digital visualization tools influences student learning and perception within a structured instructional context.

The primary objective of this study is to examine the educational impact of this dual-media instructional approach on students' spatial reasoning, engagement, and confidence in construction site logistics planning. To guide this investigation, the following research questions are addressed:

Research Question 1(RQ1): How does the use of hands-on 3D-printed physical models, supported by instructor-led augmented reality demonstrations, influence students' spatial reasoning and cognitive learning outcomes related to construction site logistics planning?

Research Question 2(RQ2): How do students perceive the usefulness, engagement, and overall learning support provided by 3D-printed models supplemented with augmented reality demonstrations, compared with traditional 2D plan-based learning activities?

Research Question 3(RQ3): How does the hybrid instructional approach influence students' confidence, collaboration, and readiness to make construction site logistics and layout decisions?

The remainder of this paper describes the development and implementation of the instructional framework, the assessment methodology used to evaluate student learning outcomes and perceptions, and the preliminary results from pre- and post-test measures and student surveys. By examining the synergy between hands-on tactile tools and digital visualization technologies, this study contributes to the growing body of research on experiential learning strategies in construction and engineering education, with an emphasis on instructional approaches that are replicable, scalable, and aligned with the spatial competencies required of future construction professionals.

Literature Review

Teaching construction site logistics requires students to reason about spatial configurations, construction sequencing, and resource interactions that evolve throughout the project lifecycle. Prior research has consistently reported that students experience significant difficulty interpreting construction schedules and site layouts when instruction relies primarily on two-dimensional drawings and abstract planning documents [1]–[3]. These challenges arise because learners must mentally associate 2D representations with construction activities and then visualize the progression of work over time, a cognitively demanding process that is especially difficult for students with limited field experience [1], [4].

Visualization-based instructional approaches have been widely explored to address these challenges in construction education. Early studies on four-dimensional (4D) modeling demonstrated that integrating construction schedules with three-dimensional representations can significantly improve students' understanding of time–space relationships and construction sequencing [2], [4], [11]. Interactive and web-based 4D models have further been shown to help students identify logical conflicts and spatial issues in construction plans more effectively than traditional CPM schedules alone [2], [11].

More recent research has examined immersive visualization technologies, including virtual reality and augmented reality, as tools for construction education. Empirical studies comparing immersive visualization environments with conventional 2D-based instruction have reported improvements in students' comprehension of construction sequencing, spatial awareness, and error detection [12], [13], [15], [17], [18]. These findings suggest that dynamic visualization plays a critical role in supporting learning in construction planning and site logistics contexts. However, many immersive visualization studies emphasize virtual or screen-based environments and rely primarily on post-activity perception surveys or engagement measures to evaluate instructional effectiveness [6], [15], with fewer investigations incorporating structured assessments of cognitive learning outcomes related to spatial reasoning and decision-making.

In parallel with advances in digital visualization, hands-on physical modeling has been recognized as an effective experiential learning strategy in engineering and construction education. Studies involving student-built or instructor-provided physical models have shown that tactile interaction can enhance spatial understanding, engagement, and collaborative learning [7], [8], [9]. The introduction of additive manufacturing technologies has expanded the use of physical models by enabling rapid fabrication of customized instructional artifacts, allowing learners to explore alternative layouts and construction configurations in a tangible manner [8]–[10]. Prior work in construction and related engineering domains has further suggested that hands-on engagement with physical artifacts can promote deeper cognitive processing than demonstration-based or observation-only activities, particularly when students are actively involved in manipulating and evaluating alternatives [7], [9].

Despite the demonstrated benefits of both immersive visualization and physical modeling, the literature indicates that these approaches are most often investigated independently. Research on augmented or immersive technologies typically emphasizes virtual environments without physical manipulation, while studies on 3D printing and physical models focus on tactile engagement without explicitly addressing temporal construction processes and dynamic site conditions [6], [9], [14]. As a result, there remains limited empirical evidence on instructional frameworks that intentionally integrate physical modeling with augmented visualization to support construction site logistics education.

Furthermore, prior studies differ considerably in how instructional effectiveness is assessed. Many investigations emphasize student perceptions, engagement, or qualitative feedback, while relatively fewer studies systematically examine cognitive learning outcomes using structured outcome-based frameworks [6], [16]. Recent work in construction-related education has highlighted that technology acceptance and perceived usefulness do not necessarily correlate with deeper learning or higher-order cognitive development, particularly when students' interaction with technology is limited to observation rather than active use [6]. This methodological inconsistency underscores the need for instructional research that simultaneously evaluates learning outcomes and student perceptions within a coherent assessment framework.

Addressing these gaps, the present study evaluates a hybrid instructional approach that integrates 3D-printed physical site models with instructor-led augmented reality demonstrations. By examining both cognitive learning outcomes and student perceptions, this work contributes empirical evidence to support the design of experiential, technology-enhanced instructional strategies for construction site logistics education.

Methods

Study Context and Participants

This study was conducted in a senior-level undergraduate Construction Means and Methods course at University of Delaware in the United States. The course is typically taken by students in their final year of the construction engineering and management program and focuses on construction operations, site planning, and logistics decision-making. The experiment was conducted in this course involving senior students who had completed several weeks of industry internships, providing them with exposure to real-world job-site situations. Additionally, completion of the core construction management coursework ensured that participants possessed the necessary skills to assess key aspects of construction projects, including safety, personnel, and others making them an appropriate sample for this study.

A total of 24 senior-level students enrolled in the course participated in the study. All participants had prior exposure to construction drawings, scheduling concepts, and fundamental site planning principles through prerequisite coursework. Students were organized into 6 groups of 4 students each, consistent with collaborative learning activities commonly used in upper-level construction courses. Demographic characteristics such as gender were not analyzed or reported in this study, as the research did not aim to examine demographic-based differences in learning outcomes or technology perceptions. Participation in the instructional activities was part of normal course requirements. Survey responses were collected from 22 of the 24 enrolled students, resulting in a response rate of approximately 92%. Analyses of survey data were conducted using responses from these 22 participants. This study was reviewed by the University’s Institutional Review Board and determined to be exempt from federal human subjects’ regulations under Exemption Category #1.

Project Description and Instructional Task

Students were provided with a complete set of construction site plans for a local construction project selected to reflect realistic site conditions and logistical complexity (Figure 1). The assignment required each group to design a comprehensive construction site logistics plan, addressing key considerations such as building placement, equipment locations, material storage areas, access routes, workforce circulation, and site safety constraints.

The same project, drawings, and task requirements were used across all instructional phases to ensure consistency and allow direct comparison of student performance and perceptions across instructional conditions, while augmented reality content was used solely as a supplemental, instructor-led visualization resource.

Figure 1. Construction site plan provided to students for the site logistics assignment

Instructional Design and Experimental Procedure

A within-subject pre- and post- instructional design was employed, in which the same student groups completed the site logistics assignment under two instructional conditions.

Phase 1: Traditional Plan-Based Instruction (Pre-Test): In the first phase, students completed the site logistics assignment using traditional instructional methods. Students relied exclusively on two-dimensional (2D) construction drawings, site plans, and classroom discussion to develop and submit their site logistics solutions. No physical models or augmented visualization tools were provided during this phase. This phase served as the pre-test condition, capturing baseline performance and perceptions associated with conventional plan-based instruction. Fabrication time for the complete set of physical models typically ranged from several hours to approximately one day, depending on printer availability and model complexity, reflecting a manageable one-time preparation effort.

Phase 2: Physical Modeling–Supported Instruction (Post-Test): Following completion of the pre-test assignment, students were asked to redesign the same site logistics plan using a physical modeling–supported instructional approach. Prior to this phase, the instructor prepared a complete set of 3D-printed physical mockups using the university's makerspace facilities. The mockups included the primary building under construction, surrounding existing structures, and representative construction equipment relevant to the project.

A large-format interactive touchscreen display (Samsung WA75D 75-inch UHD 4K Touchscreen) was arranged horizontally in the classroom to function as a shared tabletop workspace. The display presented a scaled site map of the project area. Students physically placed and rearranged the 3D-printed components on the site map to explore alternative site logistics configurations (Figure 2). Across the instructional setup, the primary implementation costs consisted of a reusable 75-inch interactive touchscreen display (approximately $2,100) and a tablet device for instructor-led augmented reality visualization (approximately $1,000), both of which are commercially available and not per-student consumables.

Eight student groups participated sequentially in this activity, with each group allotted 12 minutes of structured discussion time to collaboratively evaluate spatial constraints, equipment placement, material flow, and safety considerations. The activity was conducted primarily in a standard classroom, with student groups sequentially invited to an adjacent BIM laboratory that could accommodate the tabletop display and group interaction. The only spatial requirement was sufficient room for group members to gather around the shared display, rather than a dedicated or specialized facility. This sequential rotation model also supports scalability to larger class sizes without requiring additional hardware.

(a) (b)

Figure 2. Use of 3D-printed physical models for construction site logistics planning: (a) examples of 3D-printed physical mockups, and (b) students collaboratively redesigning site logistics on a shared interactive site map.

The instructional intervention was implemented over a two-week period. During the first week, student groups were given one week to complete the initial site logistics assignment using traditional plan-based methods outside of class. In the second week, students were provided with the 3D-printed physical models and asked to prepare for the in-class collaborative redesign activity. The physical modeling–supported discussion and redesign were conducted during a scheduled class session, where each group was allotted structured time to explore and revise their site logistics solutions.

Order Effect and Instructional Sequencing Considerations

The authors acknowledge that the fixed instructional sequence where students completed the traditional 2D site logistics planning task prior to the physical modeling–supported activity may introduce a potential order or learning effect. This sequencing was intentionally selected to reflect typical construction education and professional practice, in which site logistics planning is conventionally introduced through two-dimensional drawings before more advanced visualization or representational tools are applied.

The objective of this study was not to compare two instructional methods under cold-start conditions, but rather to examine whether the introduction of hands-on physical modeling could enhance students' spatial reasoning and decision-making after an initial plan-based interpretation had been established. Importantly, the physical modeling activity did not introduce new procedural skills requiring repeated practice; instead, it functioned as a representational scaffold to externalize spatial relationships and site constraints. Therefore, the observed improvements particularly in higher-order cognitive dimensions such as synthesis, evaluation, and justification are unlikely to be attributable solely to task repetition or a generic learning curve.

Role of Augmented Reality Demonstrations

Augmented reality (AR) was used only as an instructor-led visualization supplement during the post-test phase (Figure 3). The instructor employed AR demonstrations using an iPad and the Revizto application [19] to illustrate construction sequencing and changes across different project stages when relevant. The iPad represented the primary AR-related hardware cost, while the Revizto software was available through an educational license at no additional cost. Students did not directly operate AR tools or applications. The AR demonstrations were intended to support conceptual understanding of temporal progression rather than serve as a primary hands-on learning tool.

(a) **(b)**

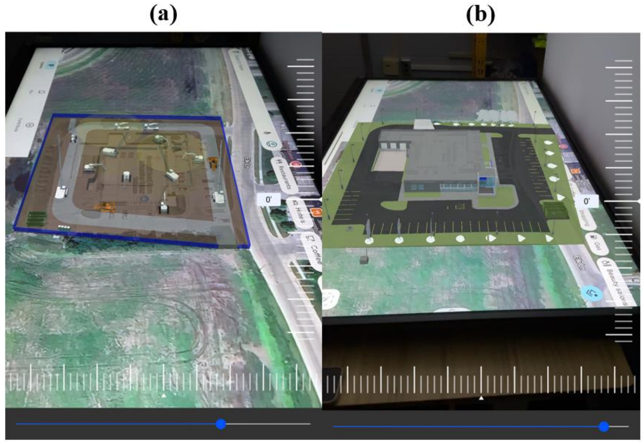

Figure 3. Instructor-led augmented reality demonstration using a tablet to illustrate construction sequencing as a supplemental visualization aid, shown using a representative project example: (a) construction phase illustration; (b) completed project visualization.

Assessment Instruments and Data Collection

To evaluate the educational impact of the instructional intervention, data were collected using a combination of performance-based assessments and student surveys.

Performance-Based Assessment (Pre vs. Post): Student group submissions from both instructional phases were evaluated using a consistent grading rubric developed by the instructor. The rubric assessed key dimensions of site logistics planning, including spatial organization, equipment placement, material flow, access planning, and safety considerations. Pre- and post-intervention scores were compared to examine changes in student performance related to spatial reasoning and site logistics decision-making.

Survey Instrument Design: Following completion of the post-test activity, students completed a structured questionnaire consisting of three integrated components. All close-ended items used a 7-point Likert scale, where 1 = Strongly Disagree, 4 = Neutral, and 7 = Strongly Agree.

Part 1: Unified Theory of Acceptance and Use of Technology (UTAUT): Students completed a UTAUT-based survey for both instructional methods (2D and 3D). Items were grouped into the following sub-constructs as shown in Table 1.

Table 1. UTAUT-based survey items and associated sub-constructs (2D vs. 3D comparison).

UTAUT Construct	Measurement Focus	Survey Items
Performance Expectancy	Perceived effectiveness of the planning method in supporting task completion and productivity	Q1. Using this method allows me to accomplish tasks efficiently and accurately. Q2. Using this method increases my productivity.
Effort Expectancy	Perceived ease of use and ease of skill development	Q3. I would find this method easy to use. Q4. It would be easy for me to become skillful using this method.
Social Influence	Perceived social and disciplinary support for the planning method	Q5. People who influence my behavior think I should use this method. Q6. In general, my field has supported the use of this method.
Facilitating Conditions	Perceived availability of resources and institutional support	Q7. My program has the resources and knowledge necessary to use this method. Q8. Resources are available for assistance with method difficulties.
Technology Anxiety / Risk Perception	Perceived concern or hesitation related to making errors	Q9. I hesitate to use the method for fear of making mistakes I cannot correct.
Engagement and Behavioral Intention	Perceived engagement and intention to use the method in future practice	Q10. The method makes learning more interesting. Q11. I predict I would use the method in my future career.

Part 2: Cognitive Learning Outcomes (Bloom's Taxonomy–Aligned): Students also completed a Bloom's Taxonomy–aligned survey for both 2D and 3D instructional conditions. Items were organized into hierarchical cognitive categories as shown in Table 2:

Table 2. Bloom's Taxonomy–aligned cognitive learning and confidence survey items.

Bloom's Taxonomy Category	Measurement Focus	Survey Items
Understanding & Application	Ability to recall, explain, and apply site logistics concepts	Q1. I believe the proposed task improved my ability to remember important concepts or principles relevant to the main topics. Q2. I believe the proposed task improved my ability to explain core ideas in my own words. Q3. I believe the proposed task improved my ability to use the methods or formulas learned to solve typical problems or exercises.
Analysis	Ability to distinguish components and identify spatial or logical relationships	Q4. I believe the proposed task improved my ability to distinguish between the different components or elements of a complex problem.
Synthesis & Evaluation	Ability to integrate ideas and justify reasoning in complex or ambiguous situations	Q5. I believe the proposed task improved my ability to integrate ideas from multiple sources or topics to develop innovative approaches to problems. Q6. I believe the proposed task improved my ability to defend or justify my reasoning when evaluating a controversial or ambiguous issue in this course.
Collaboration & Motivation	Perceived improvement in teamwork, communication, and motivation to learn	Q7. I believe the proposed task improved my ability of working within a team through improved communication and collaboration skills. Q8. I believe the proposed task increased my motivation to learn through utilizing hands-on applications.
Higher-Order Thinking	Perceived development of critical and reflective thinking skills	Q9. I believe the proposed activity improved my intellectual and critical thinking skills.

Part 3: Open-Ended Reflection: An open-ended question invited students to reflect on their experiences with 2D and 3D site logistics planning. Students were guided to address the following prompts:

1. Differences observed between planning construction sites in 2D and 3D

2. Impact of each method on understanding spatial layout, sequencing, and site logistics
3. Aspects of each approach that were easier or more challenging
4. Project types or situations where 2D or 3D planning would be most effective
5. Recommendations for future construction education or practice

Alignment of Survey Constructs with Research Questions: To ensure coherence between assessment instruments and study objectives, survey components were aligned with the research questions as summarized in Table 3.

Table 3. Alignment between research questions and survey sub-constructs.

Research Question	Assessment Instrument	Related Survey / Assessment Items
RQ1	Pre-post performance-based assessment; Bloom's Taxonomy–aligned cognitive learning outcomes	Pre-test vs. post-test site logistics assignment scores; Bloom Q1–Q5 *(Understanding & Application: Q1–Q3; Analysis: Q4; Synthesis & Evaluation: Q5)*
RQ2	UTAUT-based student perception survey	UTAUT Q1–Q10 *(Performance Expectancy: Q1–Q2; Effort Expectancy: Q3–Q4; Social Influence: Q5–Q6; Facilitating Conditions: Q7–Q8; Technology Anxiety: Q9; Engagement: Q10)*
RQ3	Confidence, collaboration and decision-making measures (integrated)	Bloom Q6, Q9 *(confidence and higher-order thinking)*; Bloom Q7–Q8 (collaboration and learning motivation); UTAUT Q11 *(behavioral intention to use the method in future practice)*

Data Analysis: Quantitative data from performance assessments and Likert-scale survey responses were analyzed using descriptive statistics, including means and standard deviations. Comparisons between 2D and 3D instructional conditions were examined at the group level. Open-ended responses were reviewed qualitatively to identify recurring themes related to spatial understanding, engagement, and instructional effectiveness. Responses were analyzed using thematic analysis, with recurring ideas coded and grouped into higher-level themes.

Given the exploratory nature of this pilot study and the limited sample size, results are reported using descriptive statistics to highlight overall trends and directional differences rather than inferential statistical testing.

Results and Discussions

RQ1-Focused Results: Cognitive Learning and Spatial Reasoning

Pre–Post Performance Comparison in Site Logistics Planning

A paired-samples t-test was conducted to examine the effect of the intervention on total scores by comparing pre- and post-experiment results for the same groups (n = 6). The mean pre-experiment score was 46.67 (SD = 10.33), while the mean post-experiment score increased to 80.83 (SD = 14.63). The analysis showed a statistically significant improvement in scores following the experiment, $t(5) = -7.23$, $p = 0.0008$. This large increase in mean scores, combined with the very low p-value, indicates that the observed improvement is unlikely due to chance and suggests that the intervention had a strong positive effect on overall performance.

Perceived Learning Outcome 2D vs 3D Comparison

As shown in Table 4, mean ratings were higher for the 3D condition than the 2D condition across the RQ1 categories. The largest improvement was observed for Synthesis & Evaluation, suggesting that the physical modeling–supported activity may have been particularly helpful when students were asked to integrate ideas and develop more innovative approaches in site logistics planning. In contrast, Analysis showed no difference between conditions, indicating that students perceived similar gains in their ability to distinguish components of complex problems under both 2D and 3D planning approaches. Understanding & Application showed a modest increase in the 3D condition relative to the 2D condition.

Table 4. Bloom's Taxonomy–Aligned Learning Outcome Ratings (2D vs. 3D)

Bloom Category (RQ1)	Included Items	Mean (2D)	Mean (3D)	Δ (3D–2D)
Understanding & Application	Q1–Q3	5.22	5.44	+0.22
Analysis	Q4	6.00	6.00	0.00
Synthesis & Evaluation	Q5	6.00	6.67	+0.67
Overall (RQ1 items)	Q1–Q5	5.53	5.83	+0.30

At the item level (Q1–Q5), the 3D condition produced higher mean ratings in most areas, with the strongest directional increase occurring for remembering key concepts (Q1) and integrating ideas to develop innovative approaches (Q5). Some items showed minimal or no difference (e.g., certain application/analysis-related items), indicating that the added value of the 3D-supported approach may be more pronounced for selected learning outcomes rather than uniformly across all cognitive dimensions.

RQ2-Focused Results: Student Perceptions of Learning Support

Overall, students reported more favorable perceptions of the 3D-supported planning method across all UTAUT constructs compared with the traditional 2D approach (Table 5). The largest differences were observed for Performance Expectancy, Engagement, and Technology Anxiety, indicating that the 3D-supported activity was perceived as more effective, more engaging, and less error-prone during site logistics planning. Students rated the 3D approach higher in terms of perceived productivity and ease of use, suggesting that students reported that hands-on interaction with physical models helped reduce cognitive and operational barriers associated with complex spatial tasks. Perceptions related to Social Influence and Facilitating Conditions also favored the 3D approach, though differences were smaller, indicating that institutional support was viewed as adequate for both methods. Taken together, these results suggest that the 3D-supported instructional approach enhanced perceived learning support, increased engagement, and reduced anxiety, complementing the cognitive learning gains observed under RQ1 and supporting greater student receptiveness to 3D-based planning methods in construction education.

Table 5. UTAUT Construct Ratings for 2D and 3D Planning Methods (n=22)

UTAUT Construct	Mean (2D)	Mean (3D)	Δ (3D–2D)
Performance Expectancy (Q1–Q2)	5.32	5.91	+0.59
Effort Expectancy (Q3–Q4)	5.11	5.52	+0.41
Social Influence (Q5–Q6)	4.89	5.05	+0.16
Facilitating Conditions (Q7–Q8)	5.02	5.18	+0.16
Technology Anxiety / Risk Perception (Q9)*	4.43	3.86	−0.57
Engagement (Q10)	5.48	6.09	+0.61

Note: Lower values indicate lower perceived anxiety or risk.

RQ3-Focused Results: Confidence, Collaboration and Decision-Making

As shown in Table 6, results from Bloom items related to decision-making confidence and higher-order thinking (Q6 and Q9) indicate higher perceived gains for the 3D-supported condition than for the 2D approach, suggesting improved confidence in justifying site logistics decisions and applying critical reasoning. Students also reported higher perceived gains in collaboration and learning motivation (Bloom Q7–Q8) when using the 3D-supported method, reflecting enhanced teamwork, communication, and engagement during the planning activity. Consistent with these trends, students expressed a stronger behavioral intention to use the 3D-supported planning method in future professional practice (UTAUT Q11), indicating greater readiness to apply the approach beyond the classroom. Collectively, these findings demonstrate that the hybrid instructional framework supported not only cognitive learning outcomes (RQ1) and positive learning perceptions (RQ2), but also students' confidence, collaborative readiness, and decision-making preparedness for construction site logistics.

Table 6. Confidence, Collaboration, and Decision-Making Readiness Outcomes (2D vs. 3D, n = 22)

Outcome Dimension	Survey Items	Mean (2D)	Mean (3D)	Δ (3D–2D)
Decision-making confidence & higher-order thinking	Bloom Q6, Q9	6.57	6.86	+0.29
Collaboration & learning motivation	Bloom Q7–Q8	6.64	6.77	+0.13
Behavioral intention (future use)	UTAUT Q11	5.91	6.50	+0.59

Qualitative Themes from Open-Ended Student Reflections

Table 7 summarizes the dominant themes aligned with the five guiding reflection prompts, followed by a brief discussion of each theme.

Table 7. Summary of Qualitative Themes from Open-Ended Student Reflections (n = 22)

Reflection Prompt	Dominant Themes	Representative Insights (Paraphrased)
1. Differences between 2D and 3D planning	Spatial clarity; Tangibility; Iterative exploration	3D planning made site constraints and spatial conflicts more visible and easier to understand; physical models allowed rapid rearrangement of site elements.
2. Impact on spatial layout, sequencing, and logistics	Improved spatial awareness; Clearer sequencing; Better constraint recognition	Students reported that 3D models helped them visualize equipment movement, material flow, and phased construction more clearly than 2D drawings.
3. Easier or more challenging aspects	2D: faster but abstract; 3D: intuitive but time-intensive	2D planning was quicker for documentation, while 3D planning required more setup but reduced confusion during decision-making.
4. Suitable project types	2D: simple or repetitive projects; 3D: complex or constrained sites	Students preferred 3D planning for projects with tight sites, multiple phases, or heavy equipment interactions; 2D was seen as sufficient for small or repetitive projects.
5. Recommendations for education and practice	Hybrid approach; Early exposure to 3D tools	Students recommended combining 2D and 3D methods in coursework and introducing physical or 3D-based planning earlier in construction education.

In general, students consistently reported that the 3D-supported planning activity provided clearer spatial understanding than traditional 2D drawings, particularly in visualizing equipment movement, site constraints, and construction sequencing. Many students noted that they reported that the ability to physically manipulate site elements helped reduce ambiguity and supported more confident decision-making during layout development.

Students described the 2D approach as faster and more familiar, especially for documenting final layouts, but also as more abstract and prone to misinterpretation when spatial complexity increased. In contrast, the 3D-supported approach was perceived as more intuitive and engaging, though somewhat more time-intensive during the planning process. Despite the additional time required, students frequently reported that the 3D method reduced confusion and facilitated more effective group discussion.

Reflections further suggested that students viewed the 3D-supported approach as particularly beneficial for complex or constrained projects involving multiple construction phases, heavy equipment interactions, or safety-sensitive logistics, while 2D planning was considered sufficient for simpler or repetitive projects. Many students recommended adopting a hybrid instructional strategy that integrates both 2D and 3D planning methods in construction education, with several suggesting earlier exposure to 3D-supported activities to strengthen spatial reasoning skills. These qualitative insights reinforce the quantitative findings by highlighting how hands-on physical modeling can enhance spatial understanding, engagement, and collaborative learning in construction site logistics education.

Conclusion

Site logistics is essential for the success of any project. To maintain efficiency, safety, and better circulation on the job site, a well-designed site logistics is a must. This study designs and implements a pilot instructional framework integrating hands-on physical modeling supported by instructor-led augmented reality demonstrations to train senior construction engineering and management students in designing site logistics.

The results show a clear and consistent improvement in site logistics planning quality through students' overall performance. In addition, using hands-on physical modeling supported by digital visualization improves the delivery of topics that require a specific set of spatial reasoning and decision-making skills to be fully understood, similar to those in this research. These findings suggest that combining tactile interaction with visual augmentation can enhance students' ability to externalize, discuss, and justify site logistics decisions in collaborative settings.

On the other hand, the study has several limitations, such as being conducted as a pilot with a relatively small sample size drawn from a single course and institution. As a result, findings are reported using descriptive statistics to identify trends and directional differences rather than to support broad generalizations. Accordingly, the primary instructional contribution of this study lies in the use of physical modeling as a representational aid for spatial reasoning, rather than in AR-based learning. Augmented reality was used as an instructor-led demonstration rather than a hands-on student-operated tool, which limits conclusions regarding individual AR interaction effects but aligns with the intended instructional scope of this pilot implementation.

Also, the observed improvements are unlikely to be attributable solely to a learning curve, as the physical modeling activity did not introduce new procedural or operational skills requiring repeated practice, but instead functioned as a representational aid that externalized spatial relationships and constraints, thereby supporting reasoning rather than skill acquisition. Rather, the activity served to externalize spatial relationships and constraints, enabling more effective discussion and comparison of alternative site logistics solutions.

For future work, this work could cover a larger sample and be multi-institutional. Future studies may also explore longitudinal integration across multiple courses or semesters, incorporate hands-on student interaction with augmented reality tools, and examine the use of large-format interactive displays for real-time markup and iterative site logistics refinement. Such extensions would further evaluate the scalability and long-term instructional value of the proposed framework within construction engineering and management curricula.

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