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Improving Spatial Reasoning in CAD and BIM Education through 3D Printing Integration

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Abstract

Developing spatial reasoning and projection skills is essential for success in computer-aided design (CAD)–related construction courses. However, visualizing three-dimensional (3D) structures from two-dimensional (2D) plans remains a challenging task for many construction students.

In this study, a 3D printing–supported instructional approach was introduced into an entry-level CAD course and evaluated using a control–test comparison across two academic years. Student learning outcomes from a prior course offering (control group), in which instruction relied on traditional screen-based CAD projection exercises, were compared with outcomes from a subsequent offering (test group) that integrated physical 3D-printed prototypes into projection-based learning activities. The instructional intervention included a CAD projection lab in which students who previously projected 3D views onto 2D drawings were provided with physical 3D-printed building elements corresponding to their digital models. By shifting from screen-based visualization to hand-based exploration, the intervention aimed to support students' comprehension of geometry, spatial relationships, and projection principles.

Following the projection-focused laboratory activities, students in the test group completed a collaborative design project in which they were allocated a plot of land and tasked with developing a 3D model of a single-family home, fabricating the model using the campus 3D printing facility, and working in teams to conceptualize a shared neighborhood environment with features such as a clubhouse, swimming pool, playground, and tennis court. This group project provided an applied context for evaluating spatial reasoning, collaboration, and engagement under the 3D-supported instructional condition.

Survey results from this pilot comparison indicate that the incorporation of 3D-printed models was associated with higher perceived spatial understanding, engagement, and teamwork when compared with the traditional CAD-based approach. Although the small-scale nature of this pilot study limits generalizability, the findings demonstrate the potential of blending digital modeling with physical fabrication to bridge the gap between abstract visualization and tangible spatial understanding in CAD and BIM education. Future work will expand the sample size, incorporate additional learning outcome measures, and explore the integration of augmented reality to further enrich spatial learning experiences in construction education.

Introduction

Spatial reasoning and projection skills are foundational competencies for students enrolled in computer-aided design (CAD) and building information modeling (BIM)–related construction courses. These skills support students' ability to interpret engineering drawings, visualize three-dimensional (3D) forms from two-dimensional (2D) representations, and translate design intent into constructible models. Prior research has consistently shown that construction and engineering students experience difficulty mentally reconstructing 3D geometry from 2D plans, sections, and projection views, particularly during early CAD and BIM instruction that relies heavily on abstract, screen-based representations [1], [2].

Although modern CAD and BIM platforms provide dynamic visualization capabilities such as rotation, zooming, and sectioning, effective use of these tools still requires well-developed internal spatial visualization skills. For novice learners, the cognitive demand associated with interpreting projection views and complex geometries may increase mental workload and hinder accurate understanding of spatial relationships [2], [3]. As a result, researchers have explored a range of visualization-based instructional strategies to better support spatial learning in construction education.

Recent studies have examined immersive and augmented visualization technologies, including BIM-enabled visualization, virtual reality (VR), and augmented reality (AR), as means to improve spatial comprehension and plan interpretation. Empirical evidence suggests that immersive and AR-supported environments can enhance students' understanding of spatial relationships, sequencing, and coordination tasks, particularly for complex building systems such as mechanical, electrical, and plumbing (MEP) plans [5]–[8], [13]. However, many of these approaches remain primarily screen-based or instructor-led, limiting opportunities for students to physically interact with spatial representations.

In parallel, physical modeling supported by additive manufacturing technologies has emerged as a complementary instructional strategy for spatial learning. Three-dimensional (3D) printing enables the rapid fabrication of tangible physical models directly from digital designs, allowing students to manipulate geometry, scale, and spatial relationships through hands-on exploration. Prior work has shown that physical models can enhance spatial understanding, engagement, and collaborative learning by reducing abstraction and supporting direct interaction with design artifacts [9]–[11].

Building on these advances, this paper presents a pilot instructional intervention implemented in an entry-level CAD and BIM course that integrates 3D printing into projection-based learning activities. Using a control–test comparison across two academic years, the study examines how the introduction of physical 3D-printed models influences students' spatial understanding, engagement, and collaborative learning experiences. The findings contribute empirical evidence to support blended digital–physical instructional approaches in CAD and BIM education.

Literature Review

Spatial Reasoning Challenges in CAD and BIM Education

Spatial reasoning has long been recognized as a critical skill in engineering and construction education. In CAD and BIM courses, students are routinely required to interpret 2D drawings, orthographic projections, and sectional views while mentally reconstructing 3D geometry [1], [2]. Prior studies report that students often struggle with visualizing hidden elements, understanding spatial orientation, and interpreting projection relationships when instruction relies primarily on abstract representations displayed on screens [2], [3]. These challenges are especially pronounced among students with limited prior exposure to construction drawings or physical building components.

Visualization and Immersive Technologies for Spatial Learning

To address these challenges, visualization-based instructional approaches have been widely explored. Early work integrating 4D visualization and interactive models demonstrated that combining spatial and temporal representations can improve students' understanding of construction-related concepts beyond traditional plan-based instruction [3]. More recent research has focused on immersive visualization technologies, including VR and AR, in construction and engineering education. For example, studies evaluating BIM- and VR-supported instruction report improvements in students' comprehension of spatial layout, sequencing, and system coordination, particularly for MEP plan interpretation [5], [6], [15], [16]. AR-based learning tools have similarly been shown to enhance spatial awareness and contextual understanding in construction engineering and interior design education [1], [8], [13], [14]. Despite these benefits, many immersive visualization studies emphasize virtual or screen-based interaction and rely heavily on perception-based assessments, with fewer investigations incorporating physically interactive learning activities.

Physical Modeling and 3D Printing in Construction Education

Hands-on physical modeling has been widely recognized as an effective experiential learning strategy in engineering and construction education. Physical artifacts allow learners to directly observe geometry, scale, and spatial relationships without relying solely on mental reconstruction [9], [11]. Research involving student-built or instructor-provided physical models has demonstrated improvements in spatial reasoning, engagement, and collaborative learning, particularly in design-oriented courses [9]–[11].

Additive manufacturing technologies further expand the feasibility of integrating physical models into CAD and BIM instruction. Three-dimensional printing enables rapid fabrication of customized instructional artifacts that align directly with digital designs, supporting seamless transitions between virtual modeling and physical inspection [9], [10]. Prior studies suggest that combining digital modeling with physical fabrication can enhance conceptual understanding and promote active learning, especially when students are engaged in collaborative, hands-on tasks [10], [11].

Assessment of Learning Outcomes and Technology Acceptance

Recent construction education research highlights the importance of evaluating instructional effectiveness using coherent assessment frameworks that capture both cognitive learning outcomes and student perceptions. Prior studies grounded in Bloom's Taxonomy and the Unified Theory of Acceptance and Use of Technology (UTAUT) have shown that perceived usefulness, engagement, and technology acceptance do not always align with deeper levels of cognitive learning, particularly when student interaction with instructional technologies is limited to observation rather than active use [12], [17], [18]. These findings suggest that relying on either performance-based measures or perception-based surveys alone may provide an incomplete picture of instructional effectiveness.

Addressing these limitations, the present study evaluates a 3D printing–supported instructional intervention in CAD and BIM education using a comparative control–test design complemented by survey-based assessment. By combining outcome-based evidence with student perceptions measured through Bloom- and UTAUT-aligned instruments, this work examines spatial understanding, engagement, and collaborative learning in an integrated manner and contributes empirical evidence toward the effective integration of physical modeling within digitally mediated construction education environments. Given the pilot nature of the study and the limited number of survey items per construct, the Bloom- and UTAUT-aligned measures are intended as exploratory indicators to examine perceptual trends rather than as fully validated psychometric scales.

Research Methodology

Course Context and Participants

This study was conducted in an entry-level undergraduate CAD and BIM course offered in the construction engineering and management (CEM) program at University of Delaware. The course focuses on construction graphics, projection principles, and three-dimensional digital representation through in-person lectures and hands-on laboratories and has no formal prerequisites. A cross-year control–test comparison was employed, supplemented by survey-based data collected from the test group.

Table 1. Overview of Course Offerings and Study Groups

Item	Control Group	Test Group
Academic year	Fall 2024	Fall 2025
Instructional approach	Traditional CAD/BIM-based instruction	CAD/BIM-based instruction with 3D-printed physical models
Access to 3D-printed models	No	Yes
Number of students	*n* = 21	*n* = 25

Note: Both groups were drawn from the same entry-level CAD course offered at the University of Delaware, taught by the same instructor, and enrolled students from the same CEM major.

A comparative control–test design was employed across two consecutive course offerings (Table 1). Both offerings followed the same syllabus, learning objectives, project requirements, and instructional schedule, and were taught by the same instructor to students from the same academic major.

Both cohorts were enrolled in the same CEM major under identical admission criteria, with no curricular restructuring between academic years. While demographic and academic characteristics were not formally compared, baseline projection performance suggests comparable spatial preparation levels.

The primary instructional difference between the two groups was the integration of physical 3D-printed models into selected CAD projection and modeling activities for the test group, whereas the control group relied exclusively on traditional screen-based CAD instruction. While the control–test comparison leveraged data from both course offerings, survey-based measures of student perceptions and self-reported learning outcomes were collected only from the test group following the implementation of the 3D printing–supported activities. Given the exploratory nature of this pilot study and the limited sample size, the analysis focused on descriptive comparisons and trend identification rather than formal inferential statistical testing.

This study was reviewed and approved by the university's Institutional Review Board (IRB) and determined to be exempt under federal regulation exemption category #1, which applies to research conducted in established educational settings involving normal educational practices. All data were collected in accordance with approved IRB procedures, and student participation in surveys and reflections was voluntary and anonymized.

Instructional Framework and Learning Activities

The instructional framework was designed to support the development of spatial reasoning and projection skills by progressively integrating digital modeling with physical visualization. The course followed a structured sequence of lectures and laboratory activities that introduced construction graphics, CAD, and BIM concepts over a 17-week semester, with identical weekly topics, assignments, and pacing in both the control (Fall 2024) and test (Fall 2025) offerings.

During the early portion of the semester (Weeks 1–4), students completed a series of projection-focused laboratory assignments aimed at strengthening their ability to interpret and generate orthographic views from isometric representations. Initial activities required students to manually sketch orthographic projections using grid paper prior to formal CAD instruction. Subsequent laboratories transitioned to AutoCAD-based projection tasks in which students generated multi-view drawings of increasingly complex objects. In the test group, corresponding physical 3D-printed models were introduced during selected projection laboratories to supplement screen-based CAD visualization, allowing students to directly inspect and manipulate geometry while completing identical tasks.

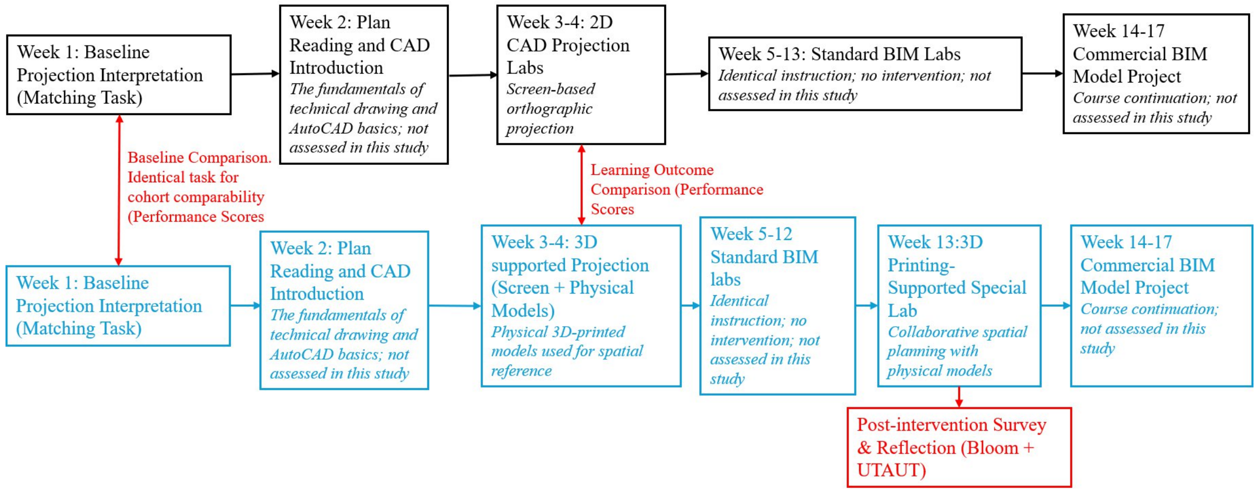

Figure 1. Overall instructional framework and study design overview. Color coding is used to distinguish between standard instruction for the control cohort (2024) shown in black, instructional interventions for the experimental cohort (2025) shown in blue, and assessment and comparison elements shown in red.

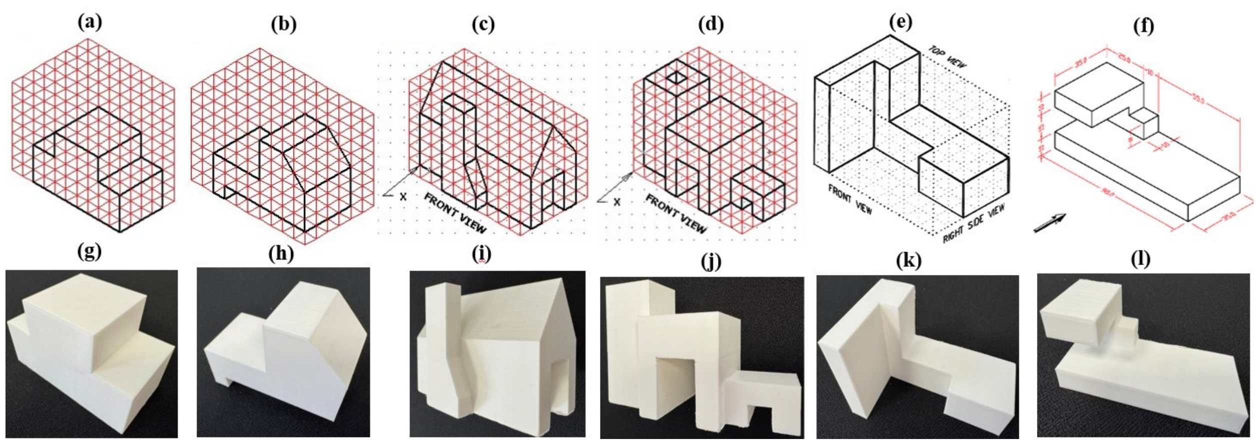

Figure 2. Examples of projection-based digital representations and corresponding 3D-printed physical models used in the CAD projection laboratories. (a) to (f) show representative objects in digital 3D views used for instruction; (g) to (l) show the corresponding 3D-printed physical models provided to students for hands-on spatial reference.

Following the foundational CAD and projection exercises, both course offerings continued with BIM-focused laboratories using Autodesk Revit, covering building elements, views, dimensions, structural components, and site modeling. These laboratories reinforced the relationship between 2D documentation and 3D digital models while maintaining consistent instructional content across both years.

A capstone instructional intervention was implemented only in the test group during the latter portion of the semester (Week 13). This special laboratory activity extended prior projection and modeling concepts into a collaborative, community-scale design task. Students were randomly assigned to teams and required to obtain institutional 3D-printing credentials to access the university makerspace. Each team developed or sourced a residential building design, prepared the digital model for fabrication, and produced a physical 3D-printed house model at a fixed scale. During an in-class session, teams used a large-format touchscreen display to mark up a site map and explore alternative neighborhood layouts. Physical models representing residential units and shared amenities were placed directly onto the marked-up layouts to support discussion, comparison of alternatives, and group decision-making.

(a) (b)

Figure 3. In-class BIM Cave session illustrating physical model placement and collaborative digital discussion. (a) Physical placement of 3D-printed building massing models on a site plan. (b) Collaborative in-class discussion integrating physical models with the BIM Cave digital environment.

This sequence of activities was designed to move students from individual, projection-based reasoning toward collaborative spatial decision-making, providing an applied context for examining spatial understanding, engagement, and teamwork under the 3D printing–supported instructional condition.

***Study Design and Data Collection**:*

A mixed-method study design was employed to evaluate the instructional intervention, combining a cross-year control–test comparison with survey-based data collection. The control–test component leveraged data from two consecutive course offerings taught by the same instructor, following the same syllabus, learning objectives, assignments, and instructional schedule. The control group (Fall 2024, $n = 21$) completed all activities using traditional CAD and BIM instruction, while the test group (Fall 2025, $n = 25$) completed identical activities with the addition of physical 3D-printed models during selected laboratories and the capstone community layout exercise.

Learning outcome comparisons were informed by students' performance on common projection-based laboratory assignments completed by both cohorts, particularly early-semester tasks designed to assess baseline spatial reasoning and projection interpretation skills prior to the introduction of advanced modeling content. These baseline assignments served as a reference point for examining cohort comparability and were not used to evaluate the effects of the instructional intervention.

Survey-based data collection was conducted only with the test group following completion of the 3D printing–supported instructional activities. One week after the capstone community layout session, students completed an individual survey and written reflection. The survey captured self-reported learning outcomes and perceptions of the instructional approach using Bloom's Taxonomy–aligned cognitive measures and UTAUT-based technology acceptance constructs. The written reflection prompted students to articulate their decision-making processes, challenges, and perceived value of combining 2D drawings, digital models, and physical 3D-printed artifacts. An overview of the instructional activities and associated data sources for both the control and test groups is summarized in Table 2.

Table 2. Summary of instructional activities, data sources, and timing for control and test groups

Activity	Timing	Description	Group(s)	Primary Purpose	Data Used in Study
Lab Assignment 1	Early semester (week 1, prior to CAD instruction)	Orthographic view matching based on isometric representation	Control & Test	Baseline spatial reasoning and projection skill comparability	Performance scores
CAD Projection Labs	Early–mid semester (week 3-4)	Screen-based CAD projection tasks (multiple views)	Control & Test	Learning outcome comparison under different instructional conditions	Performance scores
Capstone Community Layout Activity	Late semester (Week 13)	Fabrication of physical models from BIM designs and collaborative spatial planning using physical	Test only	Instructional intervention to support spatial visualization and collaboration	Bloom's Taxonomy–aligned survey, UTAUT-based survey, and open-ended reflections

		models			

Given the pilot nature of the study, data collection emphasized instructional consistency and clarity of comparison rather than experimental randomization. Performance-based comparisons and survey evidence were used to provide complementary perspectives on student learning and engagement.

Data Analysis:

Data analysis was conducted to examine differences in student learning outcomes between the control and test groups and to characterize student perceptions of the 3D printing–supported instructional activities. Given the pilot and exploratory nature of the study, the analysis emphasized descriptive comparison and trend identification rather than confirmatory statistical inference.

Table 3. Summary of Assessment Instruments and Constructs

Instrument	**Analysis Construct**	**Number of Survey Items**	**Related Bloom Categories / Example Focus**
UTAUT	Performance Expectancy	2	Task efficiency, productivity
	Effort Expectancy	2	Ease of learning and use
	Social Influence	2	Instructor and peer support
	Facilitating Conditions	2	Availability of resources and assistance
	Technology Anxiety (reverse-coded)	1	Risk perception and hesitation
	Engagement (Hedonic Motivation)	1	Learning interest and engagement
	Behavioral Intention	1	Intention to use similar tools in the future
Bloom's Taxonomy	Core Cognitive Learning	4	Understanding & Application (Q1–Q3); Analysis (Q4)
	Higher-Order Reasoning	3	Synthesis & Evaluation (Q5–Q6); Critical Thinking (Q9)
	Collaboration & Motivation	2	Teamwork and learning motivation (Q7–Q8)

Student performance on common projection-based laboratory assignments was summarized using descriptive statistics (means and standard deviations) for each cohort. Where appropriate, between-cohort comparisons were examined to identify directional performance trends, with formal hypothesis testing applied conservatively due to the limited sample size and quasi-experimental, cross-year design.

Survey data collected from the test group were analyzed using descriptive statistics and aggregated at the construct level, as summarized in Table 3. Open-ended survey responses and written reflections were reviewed using qualitative content analysis to identify recurring themes related to spatial understanding, collaboration, and instructional value.

Student Learning and Perception Assessment Instruments*:*

Student learning outcomes and perceptions were assessed using a combination of performance-based measures, structured survey instruments, and open-ended written reflections. Performance-based measures included projection-focused laboratory assignments completed by both cohorts, while survey and reflection data were collected from the test group following the 3D printing–supported instructional activities.

Cognitive learning outcomes were measured using survey items aligned with Bloom's Taxonomy and analyzed at the construct level to capture perceived improvements in understanding, application, analysis, and higher-order reasoning related to spatial visualization and projection tasks.

Student perceptions of the instructional approach were measured using a survey instrument grounded in UTAUT. UTAUT-based items assessed perceived usefulness, ease of use, facilitating conditions, engagement, and behavioral intention to use similar tools in future coursework or professional practice. All survey items employed a seven-point Likert scale (1 = strongly disagree; 7 = strongly agree). Construct definitions are summarized in Table 3, and the full survey items are provided in Appendix Tables A1 and A2.

In addition, students completed an open-ended written reflection following the capstone community layout activity. Reflection prompts invited students to compare 2D and 3D planning approaches, describe how physical models influenced spatial understanding and decision-making, and comment on perceived benefits and challenges of integrating 3D printing into construction education.

Results and Discussion

Baseline Comparability of Student Cohorts

Baseline comparability between the control and test cohorts was assessed using the automatically graded multiple-choice component of the first projection laboratory (Lab 1, Part 1), which evaluated students' projection-matching ability prior to any instructional intervention. Because this component was graded automatically by the learning management system Canvas, it was not subject to teaching assistant grading variability. As summarized in Table 4, no statistically significant difference was observed between the Fall 2024 (control) and Fall 2025 (test) cohorts, indicating comparable baseline spatial reasoning and projection-matching ability.

Table 4. Baseline comparison using Lab 1, Part 1 (auto-graded)

Cohort	n	Mean (out of 8)	SD
Control (Fall 2024)	21	7.89	0.22
Test (Fall 2025)	25	7.93	0.21

Note: Scores reflect the automatically graded multiple-choice component of Lab 1, completed prior to any instructional intervention. Welch's t-test indicated no statistically significant difference between cohorts ($p = 0.53$).

Performance on Projection-Based CAD Laboratories

Student performance on projection-based CAD laboratories was compared between the control (Fall 2024) and test (Fall 2025) cohorts following the baseline projection task. Summary statistics for the two related labs are presented in Table 5.

The test cohort achieved higher average scores on Lab 3, indicating stronger performance on drawing and modification tasks using screen-based CAD tools. For Lab 4, performance differences between cohorts were smaller and not statistically significant.

Table 5. Performance comparison on projection-based CAD laboratories

Lab	Cohort	n	Mean (out of 20)	SD
Lab 3 – CAD Projection 1	Control (Fall 2024)	21	19.29	0.68
Lab 3 – CAD Projection 1	Test (Fall 2025)	25	19.92	0.71
Lab 4 – CAD Projection 2	Control (Fall 2024)	21	19.07	2.47
Lab 4 – CAD Projection 2	Test (Fall 2025)	25	19.92	0.40

Note: Welch's t-tests were used for between-cohort comparisons. Lab 3: $p = 0.016$, Cohen's $d = 0.74$; Lab 4: $p = 0.134$, Cohen's $d = 0.48$. Statistical results are reported for completeness and interpreted descriptively given the exploratory nature of the study.

Because both laboratories were completed prior to the introduction of the 3D printing–supported instructional activity, these differences are interpreted as cohort-level variation rather than instructional effects. Accordingly, the results provide contextual background for the perception-based and qualitative findings reported in subsequent sections, rather than serving as evidence of causal impact.

Student Perceptions of Learning and Engagement (Survey Results)

Student perceptions of learning outcomes and engagement associated with the 3D printing–supported instructional activity were examined using a post-activity survey completed by 22 students. Survey items were aligned with Bloom's Taxonomy and the Unified Theory of Acceptance and Use of Technology (UTAUT), as summarized in Table 3.

Descriptive results aggregated at the construct level are presented in Table 6. Overall, students reported positive perceptions across both UTAUT-based technology acceptance constructs and Bloom-aligned cognitive learning constructs. Higher ratings were observed for facilitating conditions, collaboration and motivation, and higher-order reasoning, suggesting that students perceived the instructional environment and the use of physical 3D-printed models as supportive of collaborative learning and complex spatial thinking. Low levels of technology anxiety further indicate that the instructional approach did not introduce undue hesitation or perceived risk.

Table 6. Summary of student survey responses by assessment construct (n = 22)

Instrument	Analysis Construct	No. of Items	Mean	SD
UTAUT	Performance Expectancy	2	5.38	1.55
	Effort Expectancy	2	5.26	1.31
	Social Influence	2	5.59	1.33
	Facilitating Conditions	2	6.15	1.06
	Technology Anxiety (reverse-coded)	1	5.82	1.48
	Engagement (Hedonic Motivation)	1	5.35	1.13
	Behavioral Intention	1	5.41	1.54
Bloom's Taxonomy	Core Cognitive Learning	4	5.29	1.39
	Higher-Order Reasoning	3	5.59	1.39
	Collaboration & Motivation	2	5.63	1.37

Taken together, the survey results suggest that students viewed the integration of physical 3D-printed models as a beneficial complement to traditional CAD-based instruction, supporting engagement and perceived learning without increasing cognitive or technological burden.

Although performance comparisons were conducted on projection-based laboratories earlier in the semester, these assessments were completed prior to the implementation of the 3D printing–supported capstone activity. Therefore, the study does not include a direct quantitative comparison of post-intervention graded performance that would isolate the transfer effects of the 3D printing activity on subsequent coursework. As a result, findings related to later-stage impact are interpreted primarily through survey responses and qualitative reflections rather than through measured post-intervention performance differences.

Qualitative Insights from Student Reflections

To complement the performance-based comparisons and survey findings, written reflections were collected from 23 students following the capstone community layout activity supported by 3D-printed physical models. The reflections provided qualitative insight into how students perceived the role of physical models in supporting spatial understanding, collaboration, and decision-making during construction site logistics planning.

Qualitative content analysis revealed three recurring themes across student reflections: (1) enhanced spatial comprehension through physical representation, (2) improved collaborative discussion and consensus-building, and (3) increased confidence in evaluating and revising layout alternatives. A summary of the identified themes and representative expressions is presented in Table 7.

Table 7. Summary of themes identified from student reflections (n = 23)

Theme	Description	Representative Expressions
Enhanced spatial comprehension	Physical models helped externalize scale, proximity, and spatial relationships that were difficult to interpret from 2D drawings alone	“easier to visualize,” “see how everything fits together,” “understand spacing better”
Collaborative discussion	Shared physical artifacts supported group discussion and alignment during layout decisions	“everyone could point to the same model,” “helped us agree faster,” “made discussion clearer”
Decision-making confidence	Ability to test and revise alternatives increased confidence in layout decisions	“move buildings around,” “compare different options,” “more confident in our final layout”

Note: Themes were identified through qualitative review of student-written reflections following the capstone activity.

Students frequently emphasized that the physical models served as a shared reference point that facilitated communication among team members, enabling spatial conflicts and constraints to be identified and discussed more efficiently. Several reflections also highlighted the value of physically manipulating site elements, which supported rapid comparison of alternative layouts and iterative decision-making.

To further contextualize these qualitative themes, a keyword frequency visualization was generated based on terms identified during qualitative review of student reflections (Figure 4). The visualization reinforces the prominence of concepts related to physical models, spatial visualization, layout reasoning, and collaboration, providing additional support for the thematic findings.

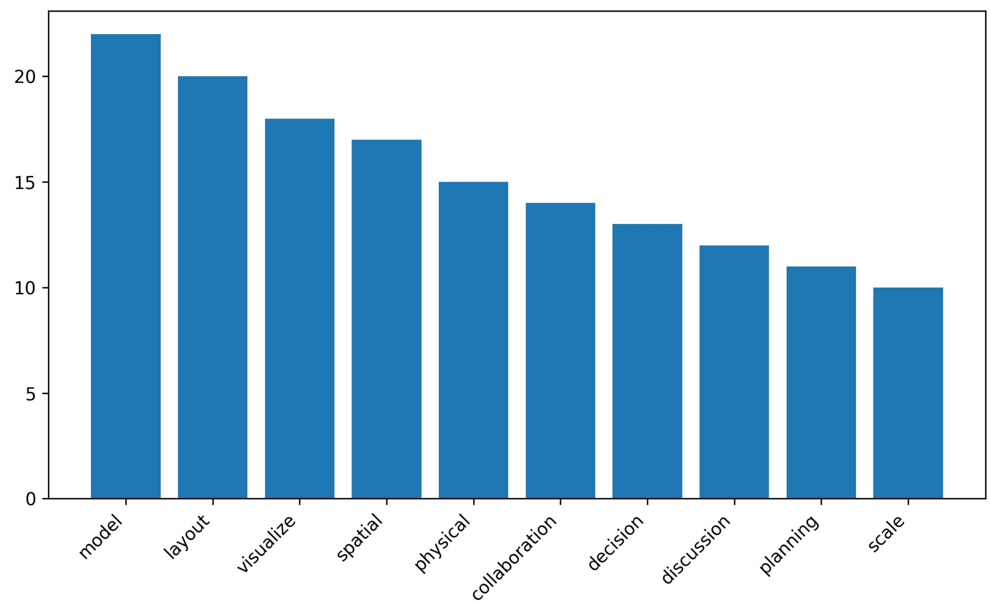

Figure 4. Frequency visualization of key terms extracted from student reflections

While the study demonstrates measurable differences in early projection-based laboratory performance and strong perceptual and qualitative evidence following the intervention, it does not include a post-intervention graded assessment designed specifically to isolate quantitative performance gains attributable solely to the 3D printing activity. Accordingly, the present findings should be interpreted as evidence of enhanced learning processes and collaborative spatial reasoning rather than definitive proof of measurable downstream performance improvement.

Conclusion

This study explored the integration of 3D-printed physical models as a supplemental instructional tool within a projection-based CAD and BIM learning sequence in construction education. Using performance-based comparisons, student perception surveys, and qualitative reflections, the study examined how physical models may support spatial reasoning and collaborative decision-making without replacing traditional digital tools.

Findings indicate that students entered the course with comparable baseline spatial reasoning ability and that subsequent performance differences on projection-based CAD laboratories reflect cohort-level variation rather than instructional effects. Survey results revealed positive student perceptions across Bloom's Taxonomy–aligned cognitive learning constructs and UTAUT-based technology acceptance dimensions, while qualitative reflections highlighted the role of physical models as external representations that supported spatial comprehension, shared understanding, and iterative evaluation during the capstone activity.

Limitations and Future work

This work represents a pilot investigation with a relatively small sample size and a cross-year design spanning a single academic term; accordingly, findings should be interpreted as exploratory. Although baseline projection-based assessments indicated comparable initial spatial reasoning ability between the control and test cohorts, subtle variations inherent to cross-year offerings, including classroom dynamics and cohort composition, cannot be fully eliminated and may have influenced learning experiences.

Because both cohorts were taught by the same instructor using identical materials and assessment rubrics, instructor-related variability was minimized; however, incremental pedagogical refinement across years cannot be entirely excluded.

The quasi-experimental cross-year design does not allow full control over unmeasured confounding variables such as prior informal CAD exposure, concurrent coursework, or cohort-specific academic culture. Therefore, findings are interpreted as exploratory associations rather than causal effects.

Performance comparisons were conducted on projection-based laboratories earlier in the semester; however, these assessments preceded the implementation of the 3D printing–supported capstone activity. Consequently, the study does not include a direct quantitative comparison of post-intervention graded performance that would isolate potential transfer effects of the 3D printing activity on subsequent coursework. Consequently, the study does not establish a direct causal linkage between the intervention and subsequent graded performance outcomes. Future studies may incorporate longitudinal or post-intervention performance measures to evaluate sustained or downstream impacts more rigorously.

Although learning-curve effects may influence student performance over time, the use of a control–test cohort comparison helps mitigate, but does not fully eliminate, such effects, as both groups progressed through the same projection-based curriculum sequence. Future research may extend this work through larger, multi-semester or multi-institutional studies to reduce cohort- and term-specific effects and strengthen the generalizability of findings.

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Appendix

Appendix Table A1. UTAUT-Based Student Perception Survey Items

Construct	Survey Item
Performance Expectancy	Q1. Using this method allows me to accomplish tasks efficiently and accurately.
	Q2. Using this method increases my productivity.
Effort Expectancy	Q3. I would find this method easy to use.
	Q4. It would be easy for me to become skillful using this method.
Social Influence	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	Q7. My program has the resources and knowledge necessary to use this method.
	Q8. Resources are available for assistance with method difficulties.
Technology Anxiety	Q9. I hesitate to use the method for fear of making mistakes I cannot correct.
Engagement	Q10. The method makes learning more interesting.
Behavioral Intention	Q11. I predict I would use the method in my future career.

Note: 7-point Likert scale (1 = Strongly disagree, 4 = Neutral, 7 = Strongly agree)

Appendix Table A2. Bloom's Taxonomy–Aligned Cognitive Learning Outcome Survey Items

Bloom's Category	Survey Item
Understanding & Application	Q1. I believe the proposed tasks improved my ability to remember important concepts relevant to the course.
	Q2. I believe the proposed tasks improved my ability to explain core ideas in my own words.
	Q3. I believe the proposed tasks improved my ability to apply learned methods to typical problems.
Analysis	Q4. I believe the proposed tasks improved my ability to distinguish components of a complex problem.
Synthesis & Evaluation	Q5. I believe the proposed tasks improved my ability to integrate ideas from multiple sources.
	Q6. I believe the proposed tasks improved my ability to justify my reasoning in ambiguous situations.
Collaboration & Motivation	Q7. I believe the proposed tasks improved my teamwork and communication skills.
	Q8. I believe the proposed tasks increased my motivation to learn through hands-on applications.
Higher-Order Thinking	Q9. I believe the proposed activities improved my critical and reflective thinking skills.

Note: 7-point Likert scale (1 = Strongly disagree, 4 = Neutral, 7 = Strongly agree)