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Development and Implementation of a Digital Twin-Enabled Teaching Model for Introductory Spatial Cognition Education in Urban and Rural Planning

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Abstract: ***Spatial cognition is fundamental to site analysis and design practice in urban and rural planning education. To address challenges commonly encountered in first-year education—including fragmented on-site observation, difficulties in translating between two-dimensional drawings and three-dimensional space, a disconnect between site analysis and design development, and insufficient process-oriented assessment—this study uses a comprehensive campus teahouse design project completed by first-year urban and rural planning students as an exploratory teaching case. It introduces a lightweight, teaching-oriented digital twin to develop a virtual–physical integrated teaching model comprising six stages: on-site perception, digital mapping, virtual–physical comparison, spatial analysis, design exploration, and integrated representation. Developed in Unity, the environment supports site mapping, viewpoint switching, measurement, object visibility control, annotation, and the import and comparison of design schemes. The study further proposes a teaching assessment framework covering six dimensions: identification of environmental elements, judgment of spatial scale, understanding of spatial relationships, analysis of behavior and function, decision-making in design exploration, and integrated spatial representation. The study aims to explore how digital twins can connect on-site experience, design drawings, digital environments, and physical models, thereby providing a reference for introductory spatial cognition education in the first-year curriculum of urban and rural planning programs.***

Keywords: Digital twin, Urban and rural planning education, Spatial cognition, Virtual–physical integration, Unity

1. Introduction

The digital transformation of education is shifting from the online delivery of educational resources toward the systematic restructuring of teaching processes, learning environments, and assessment methods. The Outline for Building a Leading Country in Education (2024–2035) calls for the establishment of a digital education system and the development of new forms of digital educational resources [1]. For urban and rural planning, a discipline characterized by spatiality, comprehensiveness, and practice orientation, the value of digital technologies should extend beyond software operation and visual presentation. More importantly, it should be reflected in how students perceive sites, understand spatial relationships, and develop design judgments.

Spatial cognition is fundamental to the study of urban and rural planning. Lower-year students need to complete the transition from everyday users of space to professional observers and designers of space. This requires them not only to identify elements such as buildings, roads, green spaces, facilities, and human activities, but also to understand the relationships among scale, sightlines, function, and place. They must further translate on-site experience into, floor plans, elevations, sections, and physical models. Previous studies have shown that spatial ability can be improved through targeted spatial experience and representational training [2]. However, conventional courses still rely heavily on short-term site visits, photographic documentation, two-dimensional drafting, and periodic design critiques. As a result, there is often no intermediary environment through which real space, abstract drawings, and design proposals can be repeatedly observed, compared, and verified.

In recent years, virtual–physical integrated teaching has been applied in courses related to transportation engineering, architectural design, and landscape architecture. Hu et al. organized the teaching of transportation facilities through real, virtual, and blended virtual–physical scenarios [3]. Zhao employed digital twin technology and virtual simulation experiments to support planting design, enabling a continuous process of design, analysis, and evaluation [4]. Zhang et al. proposed strengthening spatial perception and technological application in architectural design through virtual–physical integrated environments [5]. Zhang and Hong addressed difficulties in three-dimensional spatial cognition in introductory architectural design courses by organizing virtual simulation activities involving independent learning, immersion, interaction, verification, discussion, and reflection [6]. Existing studies, however, have focused mainly on knowledge presentation, immersive experience, or software skills, while paying insufficient attention to the competency framework, teaching process, and assessment methods required for introductory spatial cognition education in lower-year urban and rural planning programs. Against this background, this study takes the teaching unit entitled Making, Integration, and Spatial Practice in the course Introduction to Architecture II as its application context. It develops a digital twin–enabled virtual–physical integrated teaching model and proposes corresponding pathways for course implementation and assessment.

2. Problems and Reform Objectives in Introductory Spatial Cognition Education for Lower-Year Students

2.1 Discontinuities in Spatial Cognition Development in

Traditional Teaching

1) Fragmented on-site observation. First-year students tend to understand site investigation merely as taking photographs, making measurements, and listing individual elements. Although they may be able to identify roads, trees, building interfaces, and facilities, they often struggle to explain how these elements collectively influence entrance selection, spatial enclosure, activity organization, and the use of landscape resources. After leaving the site, students mainly rely on scattered photographs to recall its spatial conditions, making it difficult for the investigation findings to provide sustained support throughout the design process.

2) Difficulty translating between two-dimensional drawings and three-dimensional space. Lower-year students have not yet developed a stable understanding of scale and the representational conventions of architectural drawings. They therefore lack bodily references for interpreting distances on site plans, elevation differences in sections, and openings in floor plans. Likewise, spatial qualities experienced on site—such as openness, enclosure, compression, transition, and sequence—are difficult to translate accurately into drawings. This frequently results in problems such as disproportionate building volumes and poorly resolved transitions between interior and exterior spaces.

3) Disconnection between site analysis and design exploration. Students often determine the architectural form first and subsequently use analytical diagrams to justify an existing proposal. Because redrawing schemes and producing physical models require considerable time and effort, comparisons among alternative proposals often remain at the sketch stage. Consequently, students lack opportunities to systematically examine entrances, circulation routes, orientation, tree preservation, and outdoor spaces under consistent site conditions, and their design decisions tend to rely heavily on formal preferences.

4) Greater emphasis on outcome assessment than process assessment. Course assessment generally focuses on final drawings and physical models, making it difficult for instructors to trace how students identify problems, compare alternatives, and arrive at design decisions. In the absence of evidence documenting the design process, software proficiency and graphic presentation may obscure students' actual level of spatial cognition. Design critiques may consequently become one-way evaluations in which instructors judge only the final outcomes.

2.2 Six Reform Objectives Oriented toward Spatial Cognition

In response to the problems identified above, the course reform defines six objectives for spatial cognition development. The first is the identification of environmental elements, which requires students to accurately locate buildings, roads, trees, facilities, spatial interfaces, and activity nodes, and to assess their implications for design. The second is the judgment of spatial scale, which requires students to relate distance, elevation differences, building spacing, and degrees of enclosure to bodily experience. The third is the understanding of spatial relationships, which involves analyzing the connections between buildings and their sites, built form and open space, and interior and exterior environments. The fourth is the analysis of behavior and function, which requires students to derive functional arrangements, circulation patterns, and spatial requirements from users' activities. The fifth is decision-making in design exploration, which requires students to propose substantially differentiated design alternatives and to compare and revise them on the basis of site evidence. The sixth is integrated spatial representation, which requires students to accurately communicate design logic through drawings, physical models, digital environments, and written explanations. These six competencies develop progressively through the sequence of "identification–judgment–understanding–analysis–decision-making–representation" and collectively constitute a framework for introductory spatial cognition education for lower-year students.

3. Construction of a Digital Twin–Enabled Virtual–Physical Integrated Teaching Model

3.1 Definition of a Lightweight Digital Twin for Teaching

Digital twins emphasize the continuous connection among physical objects, digital models, associated data, and application tasks. Their core value lies in virtual–physical mapping, state awareness, and feedback-based decision-making [7–9]. The digital twin practice in Gulangyu further demonstrates that urban spatial digital twins generally consist of multiple layers, including spatial modeling, information database development, platform integration, and functional application [10]. Considering the learning objectives of first-year courses and students' technical backgrounds, this study defines its research object as a "lightweight digital twin environment for teaching." It takes an actual campus site as the physical object and establishes its digital representation through field measurements, imagery, base maps, and behavioral records. The environment maintains correspondences between major site elements and their digital model objects, while supporting measurement, annotation, layer control, design-scheme importation, and process feedback. Its purpose is not to construct a complex real-time operation and maintenance system, but to support spatial cognition and design exploration.

The digital environment performs three functions in teaching. First, it extends on-site experience by transforming a short-term site visit into a shared object that can be repeatedly observed, measured, and annotated. Second, it connects eye-level views, bird's-eye views, drawings, and models, thereby helping students calibrate spatial scale and understand spatial relationships. Third, it reduces the cost of design verification, allowing different building volumes, entrances, circulation routes, and outdoor spaces to be compared under the same site conditions. To avoid placing excessive emphasis on technology at the expense of cognition, the basic site model is jointly developed by instructors and graduate teaching assistants, while students mainly undertake site verification, spatial analysis, design-scheme importation, and comparative evaluation.

3.2 The "Six-Stage, Three-Cycle" Teaching Model

Drawing on experiential learning and reflective practice [11-12], the course establishes a six-stage process comprising on-site perception, digital mapping, virtual–physical comparison, spatial analysis, design exploration, and integrated representation. These stages form three interconnected learning cycles. On-site perception and digital mapping constitute an “experience–representation cycle,” through which students verify and calibrate site information. Virtual–physical comparison and spatial analysis form an “analysis–interpretation cycle,” which enables students to establish relationships among spatial elements. Design exploration and integrated representation constitute an “exploration–reflection cycle,” through which students develop evidence-based and defensible design decisions. Rather than being introduced as an additional and isolated software-based component, the digital twin is integrated throughout site investigation, analysis, design development, and design critique, enabling students to move iteratively among the physical site, digital environment, drawings, and physical models.

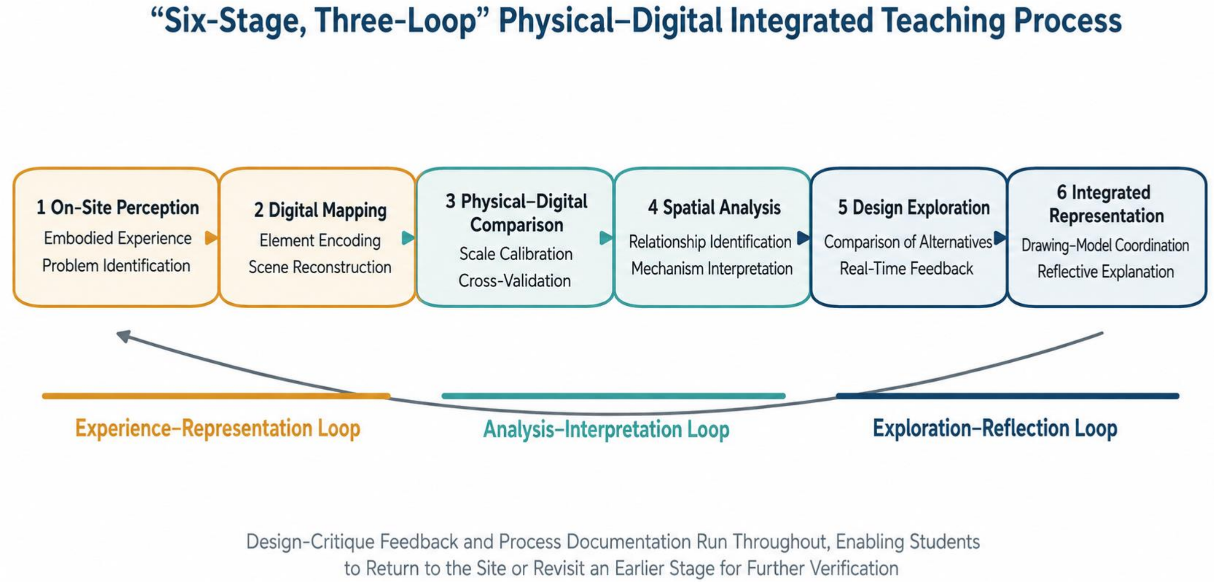

Figure 1: Digital Twin–Supported “Six-Stage, Three-Cycle” Virtual–Physical Integrated Teaching Model

4. Application Design for the Teaching Unit Making, Integration, and Spatial Practice

4.1 Course Assignment and Teaching Organization

Making, Integration, and Spatial Practice is a culminating comprehensive design assignment offered in the spring semester of the first year as part of the course Introduction to Architecture II for students majoring in urban and rural planning. The teaching case examined in this study was implemented during the spring semester of 2025 with 26 students from Urban and Rural Planning Class 24-1. The assignment lasted five weeks and comprised a total of 40 contact hours. Using the design of a small campus teahouse as its vehicle, the teaching unit required students to integrate the skills previously developed in site observation, spatial composition, physical model making, and architectural drawing into the design of an actual site.

The site is located between the campus supermarket and Hongye Apartments at North China University of Technology, with a designated construction area of approximately 17 m × 52 m. The proposed teahouse was required to have a total floor area of 150–200 m² and to be primarily arranged on a single story. Its principal functions included 100 m² for tea drinking and reading, 30 m² for tea sales and service, 15 m² for management, and 15 m² for storage. Students determined the supplementary floor area required for the entrance hall, corridors, and other ancillary spaces according to their respective design proposals. The design was expected not only to address relationships with surrounding buildings, roads, and everyday pedestrian flows, but also to carefully assess the value of retaining the existing pergola, sculpture, and trees. Outdoor spaces for reading, exhibitions, and rest were also to be incorporated into the site design. Final submissions included an A1 presentation board, a site plan, floor plans, elevations, sections, perspective drawings, analytical diagrams, photographs of the physical model, and a design statement. The physical model was required to be produced at a scale of no smaller than 1:100.

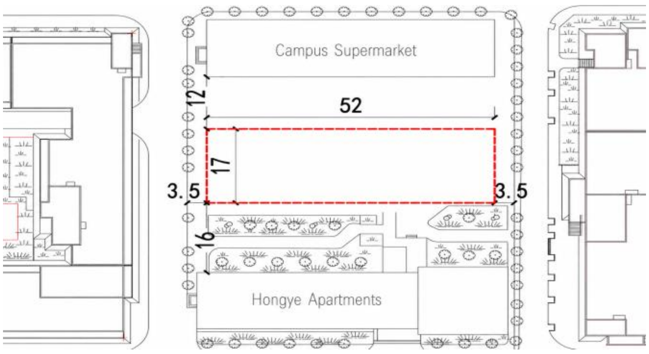

Figure 2: Site and Construction Scope for the Campus Teahouse Design Task (Source: Course Design Brief)

The teaching unit was organized around a shared site, group-based investigation, individual design work, and multiple rounds of design critique. Instructors were responsible for formulating spatial cognition questions, organizing comparisons among design alternatives, and controlling the level of technical difficulty. Graduate teaching assistants maintained the base model, checked the formatting of imported design proposals, and provided support for platform operation. Students were responsible for verifying site information, producing analytical annotations, importing and comparing design proposals, and preparing reflective explanations. The platform was introduced only after students had completed their on-site experience and preliminary hand-drawn sketches, thereby preventing the digital model from prematurely constraining their observation and design conception.

4.2 Construction of the Unity-Based Teaching Environment

The platform was developed according to the principles of functional sufficiency, ease of use, and support for spatial cognition. Based on the site plan provided in the design brief, field measurements, photographs, and videos, the instructors and graduate teaching assistants constructed base models of the site and its surrounding elements, including the campus supermarket, Hongye Apartments, roads, trees, and site facilities. These models were then imported into Unity, where their scales and coordinate systems were standardized. The platform included only the core functions that first-year students could use directly, including switching between eye-level navigation and bird's-eye views, distance measurement, visibility control for major objects, annotation of key locations, and the importation and switching of student design proposals. Students were not required to undertake complex environmental programming or detailed modeling. Instead, they primarily used the platform to observe the site, calibrate spatial scale, and compare design alternatives.

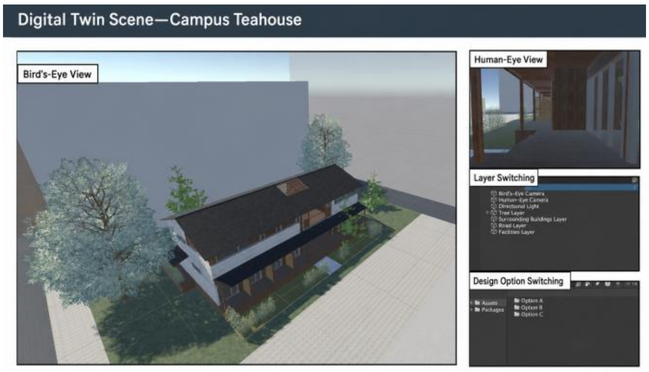

Figure 3: Schematic Interface for Site Cognition and Design Exploration Supported by the Unity Environment

4.3 Application of the Six-Stage Teaching Process

During the on-site perception stage, emphasis was placed on bodily engagement and problem identification. Students documented changes in visual openness and enclosure, light and shadow, materials, sounds, and the atmosphere of activities, while also completing the necessary field measurements. During the digital mapping stage, the collected information was repositioned within the digital coordinate system. Through element classification and model verification, students examined whether their understanding of the site was sufficiently complete. During the virtual–physical comparison stage, students moved iteratively among on-site photographs, existing-condition drawings, and the digital environment, using eye-level views, bird's-eye views, and measurement tools to correct errors in their perception of scale.

During the spatial analysis stage, students were required to establish causal relationships among roads and entrances, trees and shading, spatial interfaces and publicness, and activity nodes and functional requirements, thereby preventing analytical diagrams from becoming mere collages of isolated elements. During the design exploration stage, each student was required to propose at least three alternatives that differed substantially in building massing and site organization. These alternatives were compared within the same digital environment in terms of pedestrian accessibility, spatial openness, landscape views, degree of enclosure, tree preservation, and the transition between interior and exterior spaces. During the integrated representation stage, the final outcome was presented through a site plan, floor plans, elevations, sections, a physical model, digital screenshots, and a design statement. The digital environment was used to demonstrate spatial relationships and the logic underlying design revisions, rather than to replace conventional architectural drawings and physical models. The stages, tasks, and outputs of the virtual–physical integrated teaching process are summarized in Table 1.

Table 1: Stages, Tasks, and Outcomes of Virtual–Physical Integrated Teaching

Stage	Core Tasks	Digital Twin Support	Process Outcomes
On-site Perception	Conduct walking experiences, observations, and measurements, and identify site-related problems	Physical site and field investigation worksheets	Perception maps, photographs, and problem lists
Digital Mapping	Locate buildings, roads, trees, facilities, and activity nodes	Base models, semantic annotations, and layers	Element layers and model verification records
Virtual–Physical Comparison	Compare the physical site, digital scene, and existing-condition drawings to calibrate spatial scales	Switching between eye-level and bird's-eye views, measurement tools, and path walkthroughs	Virtual–physical comparison tables and supplementary measurement records
Spatial Analysis	Analyze spatial relationships	Layer overlays, node annotations, and visual-field observation	Spatial relationship diagrams and design evidence
Design Exploration	Develop at least three differentiated schemes and conduct comparative optimization	Scheme import, switching, overlay, and screenshots	Scheme comparison matrices and version records
Integrated Presentation	Coordinate drawings, physical models, digital scenes, and written descriptions	Key-viewpoint verification and process review	Final outcomes and reflective summaries

5. Evaluation of Teaching Effectiveness

5.1 Spatial Cognition Competency Indicators

The effectiveness of digital twin–supported teaching should not be assessed solely on the basis of graphic presentation quality or the frequency of platform use; rather, it should be evaluated in relation to students' spatial cognition competencies. Drawing on the six reform objectives outlined above, this study establishes an evaluation framework comprising six dimensions: identification of environmental elements, judgment of spatial scale, understanding of spatial relationships, analysis of behavior and function, decision-making in design exploration, and integrated spatial representation. The evaluation considers not only whether the final design proposal is reasonable, but also whether students can explain how problems were identified, what evidence informed their comparisons, and how their revisions were developed. In this way, outcome assessment is integrated with process assessment. The principal observation criteria, sources of evidence, and recommended weights for each dimension are presented in Table 2.

5.2 Teaching Evaluation Methods

Teaching effectiveness was evaluated primarily through three methods: comparative analysis of student work, criterion-based instructor assessment, and student feedback. Based on the six spatial cognition competency indicators presented in Table 2, instructors assessed students' site analysis, design exploration, and final submissions. The comparative analysis of student work drew mainly on site investigation drawings, sketches, study models, interim proposals, and final outcomes. Particular attention was paid to changes in students' identification of site elements, control of spatial scale, treatment of relationships between buildings and their surroundings, and the logic underlying design revisions. Student feedback was collected through questionnaires, interviews, or reflective records to examine how the digital environment contributed to site understanding, scale judgment, and comparison among design alternatives, as well as the difficulties students encountered when using the platform. These three methods respectively addressed the learning process, design outcomes, and learning experience, thereby generating complementary evidence of teaching effectiveness.

5.3 Comparative Analysis of Student Work

The comparative analysis of student work followed the sequence of "initial conception–digital environment verification–problem identification–design adjustment–integrated presentation" (Figure 4). From the 26 course submissions, proposals with representative revision processes were selected. For each case, the initial sketch or study model, key viewpoints after the proposal was placed in the digital environment, the spatial problems identified, the revised site plan or massing relationships, and the final outcome were presented in a consistent format. This approach avoided displaying only highly polished final submissions. All student work was anonymized and assigned identification codes, while drawing size, viewpoint, and scale were kept consistent to ensure the readability of before-and-after comparisons.

Table 2: Spatial Cognition Assessment Indicators and Sources of Evidence

Evaluation Dimension	Main Observation Criteria	Evidence Source	Recommended Weight
Identification of environmental elements	Accurately locates and classifies elements and explains their implications for design	Perceptual maps, semantic annotations, and site analysis	15%
Judgment of spatial scale	Makes reasonable judgments regarding distance, elevation differences, spacing, and degree of enclosure	Pre- and post-tests, sections, and digital measurement records	15%
Understanding of spatial relationships	Explains the relationships between buildings and the site, built form and open space, and interior and exterior spaces	Spatial relationship diagrams, site plans, and oral presentations	20%
Analysis of behavior and function	Derives functional arrangements and circulation patterns from user activities	Behavioral observations, functional diagrams, and floor-plan design	15%
Decision-making in design exploration	Develops differentiated alternatives, applies clear comparison criteria, and provides evidence for revisions	Comparison matrices and version records	20%
Integrated spatial representation	Maintains consistency among drawings, models, the digital environment, and written explanations	Final drawings, physical models, and screenshots of the digital environment	15%

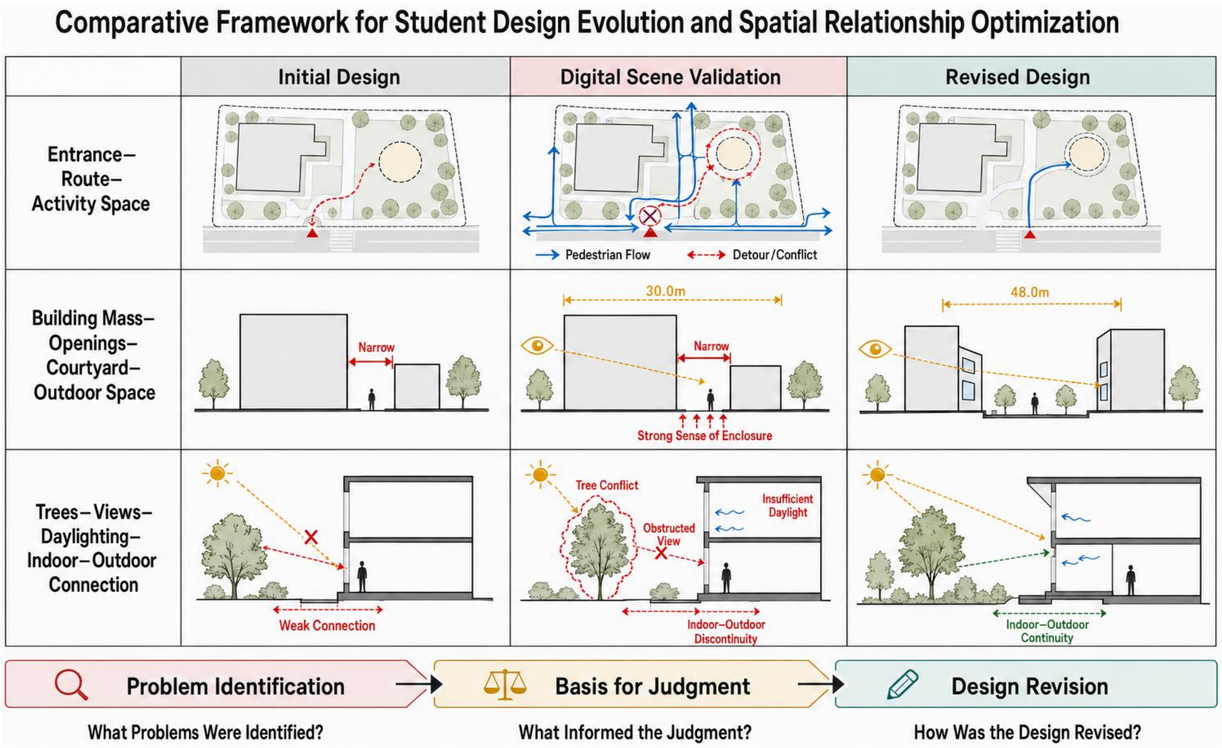

Figure 4: Comparative Framework for the Evolution of Student Design Proposals and the Optimization of Spatial Relationships

The comparative analysis focused on three aspects. First, it examined whether the organization of entrances, circulation routes, and principal activity spaces developed from simple arrangement into a response to campus pedestrian flows and site interfaces. Second, it considered whether building massing, openings, courtyards, and outdoor spaces were adjusted following scale measurement and eye-level observation. Third, it assessed whether tree preservation, landscape orientation, natural lighting, and indoor–outdoor connections shifted from supplementary treatment toward an integrated organization of building and site. A design revision was regarded as valid evidence of digitally supported spatial cognition only when the student could explain what problem had been identified, what evidence informed the judgment, and how the proposal was subsequently adjusted.

Comparative analysis of student work can reveal cognitive changes that may have been triggered by the digital environment. However, improvements in individual proposals cannot be directly interpreted as a general enhancement in the abilities of all students. Formal evaluation must therefore triangulate the findings with the six-dimensional rubric and student feedback. The criteria for selecting student work should also be clearly defined to avoid bias resulting from the exclusive use of successful cases.

6. Conclusion

This study addresses the difficulties encountered by lower-year students in urban and rural planning in site observation, scale judgment, translation between drawings and spatial environments, design exploration, and process-based representation. Taking the comprehensive campus teahouse design assignment in the course Introduction to Architecture II as its application context, the study proposes a virtual–physical integrated teaching model comprising six stages: on-site perception, digital mapping, virtual–physical comparison, spatial analysis, design exploration, and integrated representation.

Grounded in direct experience of the physical site, the model employs a lightweight digital twin environment for teaching as a tool for spatial cognition and design exploration. By providing a digital environment that can be observed, measured, and compared, it connects the physical site, drawings, digital models, and physical models. In doing so, it supports students' transition from recording isolated elements to analyzing spatial relationships, and from making form-driven choices to developing evidence-based design decisions. The present study remains at the stage of teaching-model construction and exploratory application. Future research should further reduce the operational barriers associated with the platform and examine the transferability of the proposed model to architectural design and other related courses.

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