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# From Showcase to Verification: Augmented Reality as a Catalyst for Spatial Thinking in Architectural Education

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**Abstract**

Over the last decade, augmented reality (AR) has been widely adopted in architectural education, yet it is still often treated as a visualization add-on rather than as an operative design medium. This paper argues that AR becomes pedagogically meaningful when it is anchored to physical or graphic artefacts so that overlays function not as final images, but as reversible instruments for testing, adjustment, and spatial verification. Building on reflection-in-action as a model of situated design learning, the study examines two teaching experiences: one focused on the AR-based translation of complex two-dimensional graphic fields into three-dimensional hypotheses, and another centred on kinematic reasoning through equilibrium and iterative adjustment. The article proposes that error within AR-based workflows has a double pedagogical role: first, as corrective feedback, when mismatch reveals imprecision, insufficient legibility, or unstable alignment in the target; and second, as generative design feedback, when recalibration and reconfiguration trigger new spatial hypotheses or bidirectional transfers between physical and digital models. Evidence is based primarily on analytic observation of documented episodes and on visual documentation of process transformations, complemented by a background evaluative scaffold and supplementary student feedback where available. Results indicate that AR can (a) increase the material and graphic precision of the supporting artefact; (b) strengthen spatial and kinematic understanding by making intermediate states and inconsistencies visible; and (c) turn mismatch and recalibration into operative parts of the design process itself. The paper therefore reframes AR in architectural education not as a representational endpoint, but as a medium of verification, adjustment, and projective transformation.

**Keywords:** augmented reality; model targets; reflection-in-action; spatial thinking; architectural education

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## 1. Introduction

### 1.1. Context: AR and Architectural Education Today

Augmented reality (AR) has become one of the most frequently cited spatial technologies in higher education and, increasingly, in architecture schools, due to its capacity to superimpose digital information onto physical environments. Within architectural training, AR has been adopted primarily in two directions: (i) heritage and museum-oriented visualization, where reconstructions are overlaid onto built remains or physical models; and (ii) the communication of already-defined proposals, where a virtual model is anchored to drawings, photographs, or printed triggers to support understanding and dissemination [1–4].

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However, in many of these implementations AR still functions primarily as an exhibition device. It adds information to an essentially passive support, often through two-dimensional markers, while the digital model is treated as closed geometry and the student's role remains limited to viewing or, at most, preparing input material for a final visualization stage. In that configuration, AR extends rendering and animation practices, but it rarely intervenes in the core of design learning: spatial judgement, iterative decision-making, and the active reformulation of proposals during the design process.

The methodological shift proposed in this paper moves from that representational use of AR toward a more operative understanding. Rather than being treated as a final display layer, AR is approached here as a medium through which physical and digital models enter into a reversible relationship of testing, mismatch, and adjustment. The teaching workflow underlying this shift is summarized in Figure 1.

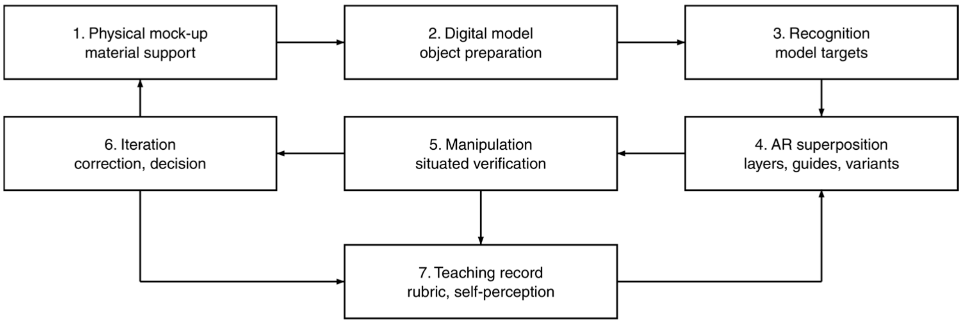


**Figure 1.** Augmented reality (AR) on physical mock-ups as an iterative verification loop in the design studio (teaching workflow). The diagram summarizes the shift from AR as end-stage visualization to AR as iterative verification: (1) physical mock-up as material support; (2) digital model preparation; (3) geometric recognition via model targets; (4) AR superposition of layers, guides, and variants; (5) manipulation and situated verification; (6) iteration through correction and decision-making; and (7) teaching record and assessment (rubric and student self-perception).

### *1.2. Problem and Approach: From Showcase to Verification*

This paper starts from the hypothesis that AR can occupy a different position in architectural learning: not as a final display, but as "technological sketching paper" layered onto a physical or graphic support and used during design activity itself. In this role, AR ceases to be a mere container of information and becomes a dialogic instrument through which students can test, correct, compare, and reformulate spatial decisions through immediate feedback.

While AR in architecture has been widely documented as a visualization medium, fewer studies examine AR as an active mediator between artefact and virtual model, particularly when anchoring depends not only on fixed markers but also on the recognizability, legibility, and stability of the target itself [5]. Under these conditions, the relation between physical support and augmented layer becomes operative: alterations in geometry, contrast, articulation, or position can stabilize the overlay, destabilize it, or force its recalibration. What might appear at first as technical failure therefore becomes pedagogically meaningful.

The argument advanced here is that such mismatch must be understood in two complementary ways. On the one hand, error can function as corrective feedback: it reveals imprecision, insufficient legibility, or unstable alignment in the support, compelling students to refine the physical model, the drawing, or the relation between them. On the other hand, error can also function as generative design feedback: when mismatch, recalibration, or target modification trigger new spatial hypotheses, new graphic configurations or bidirectional transfers between physical and digital models occur. In this sense, failure is not treated merely as technical noise, but as a possible driver of learning and design transformation.

More broadly, the approach reframes AR as a hinge between two epistemic conditions that are central to studio learning. The tangible artefact concentrates geometric certainty—dimension, proportion, weight, support, continuity, contrast—while the augmented layer introduces a controlled field of projective uncertainty, where alternatives can be tested, adjusted, rejected, or reformulated without destroying the physical base. AR is therefore positioned here not as a substitute for the model or drawing, but as an operative interface through which design decisions become visible, discussable, and revisable in real time.

### *1.3. Objectives, Research Questions, and Structure*

This study examines AR in architectural education not as an end-stage visualization device, but as an operative medium embedded in design activity. More specifically, it investigates how AR becomes pedagogically effective when it is anchored to physical or graphic artefacts and when recognition, mismatch, and recalibration enter the design process as actionable forms of feedback.

The paper has two main objectives. First, it describes a teaching methodology in which AR is coupled with physical or graphic targets so that overlays function as reversible instruments for testing, adjustment, and spatial verification. Second, it analyses how error operates within this environment in two complementary ways: as corrective feedback, when it reveals imprecision, insufficient legibility, or misalignment in the target; and as generative design feedback, when failure and recalibration trigger new spatial hypotheses, target reconfiguration, or bidirectional transfers between physical and digital models.

These objectives lead to two research questions. RQ1: How does AR, when anchored to physical or graphic artefacts, support corrective learning processes related to geometric precision, representational clarity, and spatial verification? RQ2: How can error, mismatch, and recalibration become productive elements within design learning, enabling students not only to correct but also to transform and extend their proposals?

To address these questions, the paper focuses on two teaching experiences developed in different but comparable pedagogical contexts: one centred on the AR-based translation of complex two-dimensional graphic fields into volumetric hypotheses, and another focused on kinematic reasoning through equilibrium and iterative adjustment. Rather than seeking broad statistical generalization, the study aims to identify transferable pedagogical mechanisms through a mixed-method, process-oriented analysis supported by visual documentation, analytic observation, selected evaluative criteria and complementary student feedback.

The article is organized as follows. Section 2 establishes the theoretical framework and expands the state of the art on AR in architectural education, with particular attention to reflection-in-action, representational mediation, and the pedagogical role of error. Section 3 presents the two case studies and introduces four documented process episodes—A1, A2, B1, and B2—used to make the role of corrective and generative feedback more explicit. Section 4 explains the research design, evidence base, and analytic instruments. Section 5 presents the results, distinguishing between corrective and generative forms of feedback. Finally, Section 6 discusses the contribution of the study and outlines future directions for more comparable and systematically documented implementations.

## 2. Theoretical Framework and State of the Art

### *2.1. Augmented Reality in Higher Education: From Definition to Pedagogical Claims*

Augmented reality (AR) is commonly defined as a system that merges real and virtual content in the same perceptual scene, registers information in three dimensions, and updates it in real time [6]. In higher education, AR has evolved from an experimental add-on into a mature instructional technology with a substantial evidence base. Recent systematic reviews and meta-analyses report positive effects on engagement, comprehension, and selected learning outcomes, while also emphasizing strong variance across implementations depending on task design, pedagogical framing, and the degree of active manipulation available to learners [7–10]. This variance matters for architectural education. Architecture relies not only on the communication of information, but on spatial judgement, representational translation, iterative decision-making, and the testing of alternatives under uncertainty. Yet a large part of AR-related work in architecture still foregrounds visualization-driven applications, particularly in heritage mediation, exhibition settings, and the communication of already-defined proposals [1–4]. These uses are valuable, but they often position AR as an output layer added after the main design process has already been resolved.

In response, recent studies have called for a shift from technologically driven novelty toward more discipline-specific pedagogical questions: how AR may contribute to spatial understanding, 2D–3D translation, studio ideation, and the development of transferable spatial reasoning skills [2,4,7]. A parallel issue is methodological. AR studies in education are often difficult to compare because they involve heterogeneous tasks, inconsistent assessment tools, and different operational definitions of what is being measured—usability, motivation, immersion, spatial ability, or design quality [4,7–10]. This paper takes that critique as a starting point and proposes a more focused framework: AR anchored to physical or graphic artefacts, examined not mainly as visualization, but as a medium of iterative verification, recalibration, and design transformation.

### *2.2. Mediation Across the Real–Virtual Continuum: Why Physical and Graphic Supports Still Matter*

A useful conceptual frame for positioning AR is the real–virtual continuum, which distinguishes AR from immersive virtual reality by its retention of the physical environment as an operative component of the experience [11]. In architectural pedagogy, this distinction is not merely technical. It preserves the model, the drawing, and the physical support as working media, rather than replacing them with a fully synthetic environment.

This retention is crucial because architecture has historically depended on intermediate artefacts—drawings, study models, diagrams, and mock-ups—that make spatial hypotheses discussable before construction. Physical and graphic supports do not simply display ideas; they structure the very conditions through which ideas are tested, revised, and compared. When AR is coupled to such supports, it does not abolish their disciplinary value. On the contrary, it can intensify it by making the relation between support and projection more dynamic.

This paper therefore treats the mock-up or graphic target not as a neutral display surface, but as an active component of design learning. A physical model offers volumetric legibility, material resistance, and geometric constraints. A graphic field, such as a printed or engraved plan, offers another kind of operative support: a dense representational substrate whose visual structure can trigger volumetric consequences when coupled with AR. In both cases, the support remains materially present while the augmented layer introduces reversible hypotheses, alternative readings, or kinematic cues that can be activated without destroying the base.

### *2.3. "Technological Sketching Paper": Reflection-in-Action as a Studio Model*

Within studio pedagogy, Schön's account of reflection-in-action remains one of the clearest descriptions of how design knowledge emerges through situated practice [12,13]. Design, in this view, is not a linear sequence in which a finished idea is merely executed. It is a process in which each action produces a response, and that response reorients the next move. The sketch is emblematic here: tracing paper allows architects to transform, overlay, test, and reformulate without erasing the base condition entirely.

AR can occupy an analogous role when it is configured as a reversible layer on top of a stable physical or graphic support. In that condition, it acts as technological sketching paper: a medium that allows hypotheses to be projected, inspected, compared, and revised while the underlying artefact remains accessible. The point is not that AR makes design more spectacular, but that it can make design more iterative by turning superposition into a working condition rather than a final image.

This reframing is essential for the present study because it shifts attention away from questions such as realism, novelty, or immersion, and toward a more specific pedagogical issue: whether AR increases the frequency, clarity, and productivity of design episodes in which students act, receive feedback, reinterpret what they see, and adjust their proposal accordingly. In this paper, that loop is not understood only as correction. It also includes moments in which mismatch generates new alternatives rather than simply repairing previous ones.

### 2.4. *Targets, Recognizability, and Geometric Feedback*

A technical hinge that enables AR to participate in studio reasoning is the issue of recognizability. In some workflows, the system depends on predesigned markers; in others, recognition is based on the geometry, contrast, articulation, or graphic density of the target itself. In both situations, AR does not float independently of the artefact. It depends on the legibility of a support that must be read by the system in order to stabilize the overlay [5].

This dependency has important pedagogical consequences. It means that precision is no longer only a matter of good craftsmanship or graphic discipline in a conventional sense; it becomes directly tied to whether the digital layer can appear, remain stable, or respond meaningfully. Edges, contrasts, hatch patterns, silhouette, articulation, and joint definition become operative conditions for the functioning of the augmented environment. Under these conditions, mismatch can initially appear as technical failure: drift, instability, loss of recognition, or incomplete deployment. Yet in studio terms, these events are not merely interruptions. They can reveal that the target is underdefined, too saturated, insufficiently differentiated, or geometrically ambiguous. This is the first meaning of error in the present paper: error as corrective feedback. In this sense, failure sharpens material and graphic precision because it discloses where the support no longer sustains the projected relation between physical and digital model.

### 2.5. *Representation as Productive Distance: Evans and the Pedagogical Value of Mismatch*

Evans' argument that architectural representation introduces a productive distance between object and image helps clarify why AR-on-artefact should not be understood as seamless fusion [14,15]. Representation does not merely transmit a building; it transforms it, opening a field in which geometric, spatial, and conceptual decisions can be tested through media that are neither the final building nor pure abstraction.

This is particularly relevant here because AR adds another layer to an already mediated condition. The physical model or graphic field is itself a representational construct; the augmented layer does not eliminate that condition but intensifies it. What becomes visible is not perfect identity between support and projection, but a relationship of partial fit, tension, correction, and reinterpretation.

This is where the second meaning of error becomes important. Mismatch is not only evidence of insufficient accuracy. It can also act as generative design feedback when it prompts students to redraw, recalibrate, reconfigure, retrain, or otherwise transform the target–overlay relationship in order to explore new spatial consequences. In that case, error is not simply the moment at which the system says “no”; it is the moment at which a new design possibility emerges. This productive role of mismatch is one of the central arguments of the present paper and helps distinguish the proposed approach from more conventional uses of AR as final representation.

### *2.6. From Diagnostic Error to Generative Error*

Educational technologies are often designed under the assumption that friction should be minimized and that seamless interaction is always preferable. In design education, however, friction can have a different value. A system that fails to recognize a target, loses stability, or forces recalibration can expose relationships that would otherwise remain hidden: the dependence of digital projection on material precision, the dependence of volumetric interpretation on graphic legibility, or the dependence of equilibrium on exact positioning.

For that reason, this paper distinguishes between two pedagogical roles of error. The first is diagnostic or corrective. Here error reveals imprecision, misalignment, instability, or insufficient legibility and therefore prompts refinement of the artefact or target. The second is generative or projective. Here error does not simply lead back toward correction, but outward toward variation: a modified drawing, a recalibrated target, a new spatial reading, or a bidirectional transfer between a physical configuration and a digital alternative.

This distinction is especially relevant to architectural learning because design rarely advances only by confirming what is already known. It also advances by making productive use of deviation, inconsistency, and reinterpretation. AR becomes pedagogically operative, in this sense, not simply when it stabilizes a correct answer, but when it makes the relation between support, projection, and variation available as a field of inquiry.

### *2.7. Evaluation Frameworks and the Need for Architectural Adaptation*

The literature increasingly emphasizes that AR studies require explicit evaluation strategies that connect technical performance with pedagogical aims. Frameworks such as EVAR have proposed structured ways of embedding AR evaluation into educational planning by relating learning activities, implementation quality, and assessment criteria [16]. Other work has similarly stressed the importance of clarifying what exactly AR is supposed to improve and how such effects should be documented in discipline-specific settings [17].

Architectural education, however, poses particular demands. It involves not only usability or engagement, but also graphic competence, spatial interpretation, iterative judgement, and the capacity to work across material and representational domains. For this reason, the present study uses a reduced, architecture-oriented analytic framework combining: (i) documented process episodes, (ii) complementary student feedback, and (iii) a background evaluative scaffold adapted from educational AR assessment literature.

The goal is therefore not to claim a single statistically generalizable effect. Rather, it is to identify and describe pedagogical mechanisms that can be made visible through process documentation: how AR sharpens precision, how it supports 2D–3D and kinematic understanding, and how error functions both as corrective feedback and as a generative design trigger.

Bridge to the cases. The two teaching experiences presented next operationalize this framework under different but comparable conditions. One focuses on the translation of a dense graphic field into volumetric hypotheses; the other on kinematic reasoning through equilibrium and iterative adjustment. In both, AR is studied not as a final representational layer, but as a working medium in which recognition, mismatch, and recalibration become part of design learning.

## 3. Context and Case Descriptions

### 3.1. Case Selection, Scope, and Comparability

The teaching experiences discussed in this paper are not presented as a broad survey of all AR applications developed by the authors, but as a deliberately narrowed empirical corpus selected to support a more coherent methodological comparison. In response to the need for greater comparability across contexts, the revised study focuses on two teaching experiences that share the same pedagogical and technical premise: AR is anchored to a physical or graphic artefact and used not as a final representational layer, but as an operative medium for testing, adjustment, and design verification.

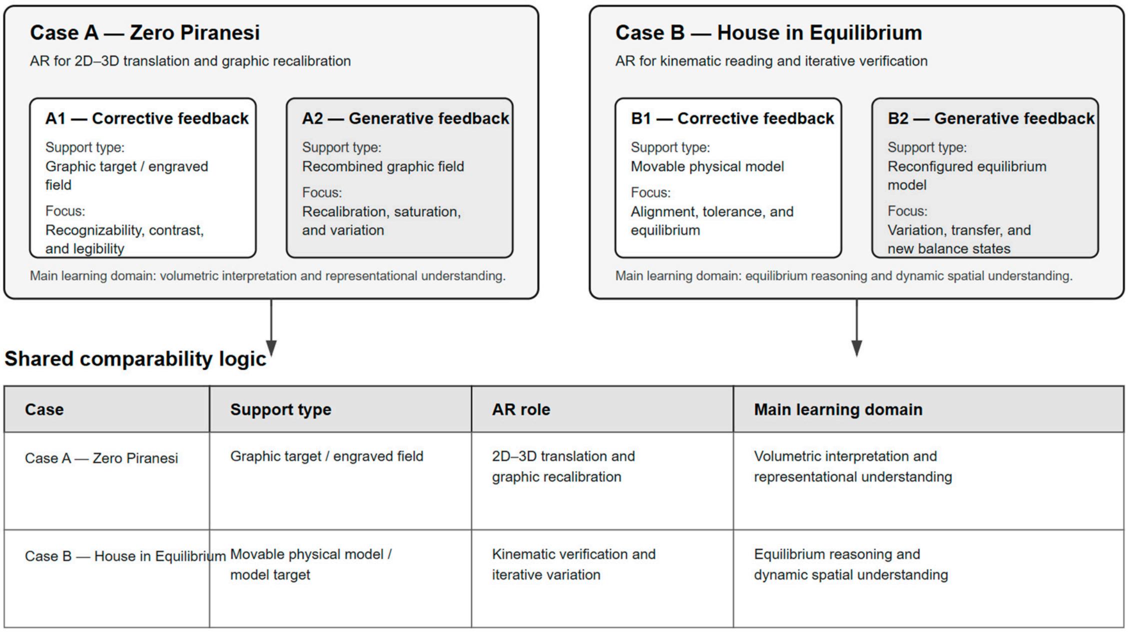
Both cases belong to the field of architectural graphic expression and involve a reversible interaction between a stable support and an augmented layer. In both, AR is introduced within ordinary teaching activity rather than as an isolated technological demonstration. More importantly, both cases make it possible to observe how recognizability, mismatch, recalibration, and variation become part of the design process itself. This shared interaction logic is the main reason for their joint reading.

At the same time, the two cases differ in the type of support and in the kind of spatial reasoning they activate. The first case is based on a dense two-dimensional graphic field whose interpretation is translated into volumetric hypotheses through AR. The second is based on a movable physical model in which AR supports the kinematic reading of equilibrium, instability, and iterative adjustment. This difference is analytically useful, because it allows the study to compare how the same operative principle—AR as technological sketching paper—behaves in two distinct but still comparable representational conditions: graphic translation and kinematic verification.

Within each case, two process episodes are documented in greater detail. These episodes do not function as anecdotal illustrations, but as focused units of evidence through which the role of error can be made explicit. In each case, one episode is primarily associated with corrective feedback, where mismatch reveals insufficient legibility, unstable alignment, or material imprecision; the other is associated with generative design feedback, where recalibration or target transformation opens a new design possibility. This subdivision allows the argument of the paper to be presented more systematically and reduces the need for the reader to infer the consequences of AR only retrospectively from the final discussion.

The study therefore does not claim broad statistical generalization. Instead, it adopts a process-oriented comparative logic: two cases, each examined through two documented episodes, are used to identify transferable pedagogical mechanisms related to precision, spatial interpretation, iterative adjustment, and the projective use of mismatch.

The revised study structure and comparability logic, including the conceptual focus of each case and the main learning domains addressed through the documented process episodes, are summarized in Figure 2.



**Case A — Zero Piranesi**
AR for 2D–3D translation and graphic recalibration

**A1 — Corrective feedback**
Support type:
Graphic target / engraved field
Focus:
Recognizability, contrast, and legibility

**A2 — Generative feedback**
Support type:
Recombined graphic field
Focus:
Recalibration, saturation, and variation

Main learning domain: volumetric interpretation and representational understanding.

**Case B — House in Equilibrium**
AR for kinematic reading and iterative verification

**B1 — Corrective feedback**
Support type:
Movable physical model
Focus:
Alignment, tolerance, and equilibrium

**B2 — Generative feedback**
Support type:
Reconfigured equilibrium model
Focus:
Variation, transfer, and new balance states

Main learning domain: equilibrium reasoning and dynamic spatial understanding.

**Shared comparability logic**

| Case | Support type | AR role | Main learning domain |
|---|---|---|---|
| Case A — Zero Piranesi | Graphic target / engraved field | 2D–3D translation and graphic recalibration | Volumetric interpretation and representational understanding |
| Case B — House in Equilibrium | Movable physical model / model target | Kinematic verification and iterative variation | Equilibrium reasoning and dynamic spatial understanding |

Each case includes one episode analysed as corrective feedback and one analysed as generative design feedback.
The figure summarizes the conceptual structure and expected learning outcomes of the revised study rather than a temporal sequence.

**Figure 2.** Comparative structure of the revised study. The paper examines two teaching experiences through four documented process episodes. In each case, one episode is analysed as corrective feedback, where mismatch reveals imprecision or insufficient legibility in the target, and one as generative design feedback, where recalibration or transformation of the target–overlay relation opens a new design possibility. The two cases remain comparable because both use AR as an operative layer anchored to a physical or graphic artefact, while differing in the kind of spatial reasoning they activate: 2D–3D translation in Case A and kinematic verification in Case B. Arrows indicate the analytical progression from case framework to documented episodes and from those episodes to their dominant feedback mod.

### *3.2. Case A: Zero Piranesi: AR for 2D–3D Translation and Graphic Recalibration*

#### 3.2.1. Pedagogical Context and Graphic–Spatial Premise

The first case examined in the revised study was developed in 2020 within the design studio Zero Piranesi at the University of Innsbruck. Its pedagogical relevance lies in the fact that AR was introduced not over a neutral marker or a completed architectural model, but over a graphic field whose spatial meaning was itself unresolved. The starting point was Giovanni Battista Piranesi's Campo Marzio dell'Antica Roma [18], understood not as a stable historical document, but as a projective construct assembled through the composition, distortion, and superposition of heterogeneous planimetric fragments.

This condition was central to the studio. On the one hand, the Campo Marzio offers an extraordinarily dense and precise two-dimensional field. On the other, it does not provide a complete or unambiguous three-dimensional account of the architectural world it depicts. For this reason, the exercise was not conceived as a literal reconstruction of ancient Rome, but as an investigation into how a complex planimetric field could become the basis for new spatial hypotheses. As a first step, the students redrew the overall field as a common operative ground [19]. This redrawing was not understood as a neutral act of copying, but as a disciplinary reconstruction that transformed the historical engraving into a shared support for analysis, fragment selection, graphic manipulation, and later AR registration. The resulting field is shown in Figure 3.

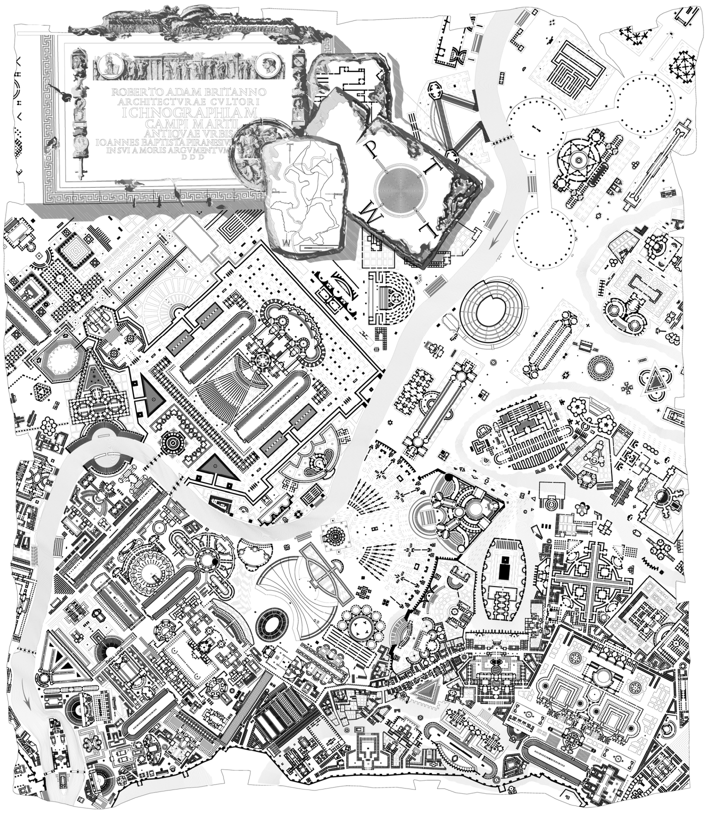


**Figure 3.** Redrawn Campo Marzio field used as the operative graphic basis of Case A. Student-produced redrawing of Piranesi's Campo Marzio dell'Antica Roma, used in the Zero Piranesi studio as the common support for analysis, graphic manipulation, fragment selection, and later AR-based spatial translation.

At the same time, the studio recognized that Piranesi's project was not reducible to a purely planar logic. Although the Campo Marzio is primarily known as a plan, Piranesi also produced engraved views in which some of its architectural fragments appear in oblique or perspectival form. These images do not provide a complete three-dimensional explanation of the Campo Marzio, but they show that the project already implied a reciprocal relation between planimetric construction and spatial imagination. This relationship is illustrated in Figure 4, which juxtaposes one engraved three-dimensional view with the corresponding plan fragment. Read together, these two images make clear that the movement between 2D and 3D was already latent in Piranesi's own representational practice.

The juxtaposition shows that the project can be read through a close dialogue between planimetric composition and spatial reconstruction, making explicit the transition from two-dimensional graphic order to three-dimensional architectural imagination.

For the students, this became a decisive conceptual trigger. If Piranesi himself operated between plan and spatial image, then the pedagogical task was not to remain at the level of graphic analysis alone, but to continue that movement through contemporary means. AR entered precisely at this point, not as a supplementary visualization device, but as a medium through which selected parts of the plan could become spatially interrogable. The exercise therefore shifted from reading the drawing as a closed artefact to activating it as a support, a target, and a generator of three-dimensional propositions.

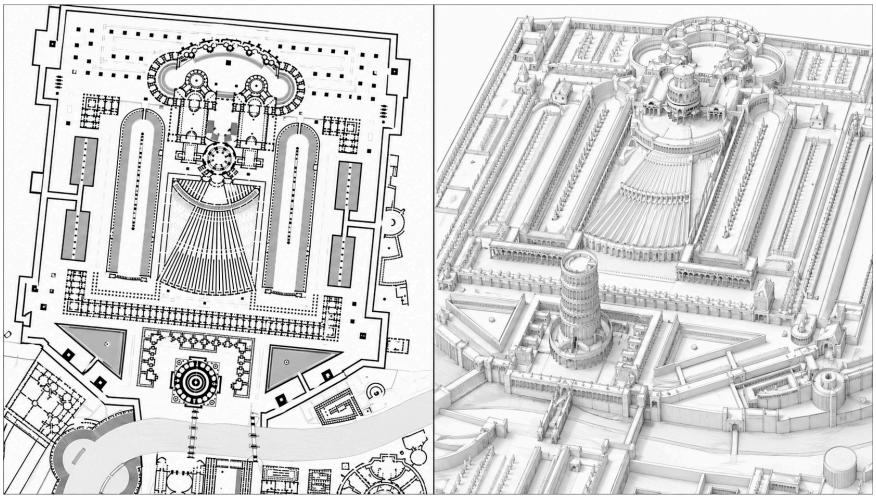

(**a**) (**b**)

**Figure 4.** Relation between 2D plan and 3D spatial reconstruction in Piranesi's Campo Marzio. (**a**) Corresponding plan fragment from the Ichnographia Campi Martii. (**b**) Monochrome occlusion-style spatial reconstruction produced by the authors from that fragment.

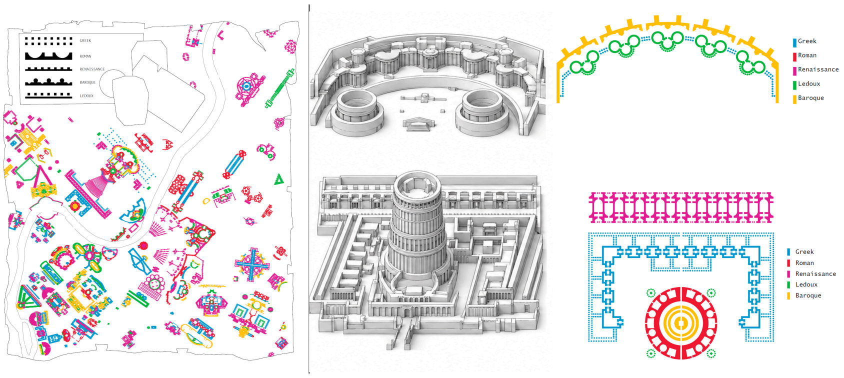
Under these conditions, the value of AR in Case A did not lie primarily in realism or immersive effect. Its role was methodological. By forcing a correspondence between a two-dimensional graphic field and a three-dimensional output, AR made students confront issues of abstraction, interpretation, registration, and formal consistency. In this sense, the case is especially relevant to the present article because it shows AR functioning not as an end-stage representational layer, but as a catalyst for spatial thinking grounded in the disciplinary problem of moving from 2D evidence toward 3D architectural reasoning.

### 3.2.2. Analytical Decomposition and Compositional Recognition

Before AR could be introduced as an operative medium, the students first had to understand the internal logic of the Campo Marzio as a composed graphic system. This analytical phase became essential to the pedagogical structure of the studio, because it shifted the work from passive historical reading toward an active recognition of how Piranesi's field had been assembled.

The students observed that the Campo Marzio did not behave as a homogeneous planimetric language. Instead, it appeared as a stratified and composite field in which distinct formal vocabularies, historical resonances, and typological families coexisted. Through redrawing, comparison, and abstraction, they identified recurrent compositional patterns that could be associated with different architectural genealogies and design attitudes. In this sense, the plan began to be understood less as a single image and more as a disciplinary collage built through the selective combination and transformation of heterogeneous plan elements.

This analytical discovery is summarized in Figure 5. On the left, the redrawn field is reorganized through the identification of recurring formal families and their distribution across the plan. On the right, selected engraved fragments by Piranesi are compared with their student-produced abstract reconstructions, showing that the historical material could be reduced to transferable compositional rules. What emerged from this process was not only a clearer reading of Piranesi's method, but also a projective insight: the Campo Marzio could be approached as a system of operations rather than as a fixed iconographic whole.



(**a**) (**b**) (**c**)

**Figure 5.** Student identification of Piranesi's compositional grammar in Case A. (**a**) Diagrammatic classification of recurrent formal families and their distribution across the redrawn Campo Marzio field. (**b**,**c**) Comparative analysis between selected reconstructed spatial views and their corresponding abstracted graphic reinterpretations, showing how students identified a transferable compositional vocabulary underlying the plan. All analytical drawings and reconstructed views were produced by the authors based on Piranesi's Campo Marzio.

This was a decisive pedagogical step. Once the students recognized that Piranesi's graphic world was constructed through compositional logic, they could begin to work with it using a similar method of transformation. The historical field thus became a precedent for their own design operations. Rather than simply translating an already-closed plan into three-dimensional form, the students learned to identify, isolate, and reactivate formal rules that could later be intensified, recombined, and spatially tested through AR. In that sense, the analytical decomposition shown in Figure 5 did not remain an interpretive exercise; it became the conceptual bridge between historical reading and generative design work.

### 3.2.3. Episode A1: Corrective Feedback: Target Calibration, Contrast, and Recognizability

The first documented episode within Case A (A1) concerns the corrective dimension of the process. Once the Campo Marzio field had been redrawn and analytically decomposed, a second problem emerged: the graphic material still had to become readable to the AR system. This introduced a new layer of learning. The issue was no longer only how to interpret the plan spatially, but how to transform selected fragments of that plan into recognizable targets capable of sustaining stable augmented registration.

This phase produced what the present paper describes as corrective feedback. In contrast to a conventional representational exercise, where the drawing may remain valid even if its material support is visually weak or technically imprecise, AR exposed the dependency of the digital layer on the physical legibility of the target. Recognition was not guaranteed by the historical value or graphic richness of the drawing alone. It depended on factors such as depth of engraving, contrast, sharpness of edges, graphic density, and the degree to which the selected fragment could be read by the software as a coherent visual field.

For that reason, the students developed and tested multiple engraved targets before arriving at workable solutions. Small-scale trials were first produced to compare different configurations of line depth, figure density, and contrast. These initial tests made it clear that not every fragment behaved equally well as a target, and that subtle graphic differences could determine whether AR deployment remained unstable, weak, or impossible. As shown in Figure 6a, the process began with a series of material experiments in which the engraved support was treated as a variable to be calibrated rather than as a neutral container of information.

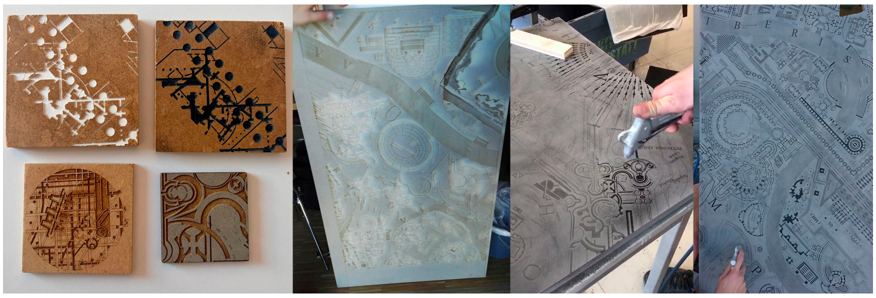

(**a**) (**b**) (**c**) (**d**)

**Figure 6.** Corrective feedback through target calibration in Case A. (**a**) Small-scale engraved target tests used to compare different graphic and material configurations. (**b**) Early full-size engraved board with insufficient contrast for stable target recognition. (**c**) Corrective darkening and calibration of the engraved field to increase legibility. (**d**) Finalized board after sanding and contrast adjustment, producing a sharper and more operative support for AR registration.

The same logic then scaled up to the full-size board. Early engraved versions of the larger support did not provide sufficient contrast to operate reliably as AR targets. As a result, the students and instructors introduced additional corrective operations: deeper engraving, darkening of the engraved field, and subsequent sanding of the upper surface in order to recover a sharper black graphic against the wooden ground. Figure 6b–d document this progression from low-contrast support to a more precise and legible target. What is pedagogically important here is that the "failure" of the system did not remain external to the design process. It was interpreted as information. The AR setup effectively taught the students that graphic representation had to be materially and optically calibrated if it was to function as an operative support for spatial translation.

In this sense, the corrective role of error in Case A was not merely technical. It sharpened the students' understanding of the relation between drawing and recognition, between representational intent and machine readability. The target had to be designed, fabricated, and adjusted as carefully as any other architectural artefact. AR therefore introduced a new form of disciplinary precision: one in which graphic clarity, material execution, and digital stability became inseparable parts of the same learning process.

### 3.2.4. Episode A2: Generative Feedback: Fragment Transformation and New Volumetric Hypotheses

The second documented episode within Case A (A2) concerns the generative dimension of the process. Once the students had identified the compositional logic of the Campo Marzio and understood the material conditions required for AR recognizability, the work could move beyond correction and toward transformation. At this stage, the graphic field was no longer treated only as something to be read more precisely, but as something that could be actively reconfigured in order to produce new spatial propositions.

This shift was consistent with the students' analytical discovery that Piranesi's method was itself compositional and synthetic. Because the Campo Marzio had been understood as a field assembled from heterogeneous formal vocabularies and typological fragments, the students were able to adopt a similar logic in their own work. Selected plan fragments were isolated, intensified, recombined, and supplemented with new graphic material, including references to canonical twentieth-century plans. In this way, the historical field did not function as a closed source to be reproduced, but as a generative matrix through which new formal relations could emerge.

Figure 7 documents this transition from graphic transformation to spatial hypothesis. In Figure 7a, a selected fragment is reworked into a denser and more articulated graphic construct. In Figure 7b, that transformed fragment is translated into a three-dimensional

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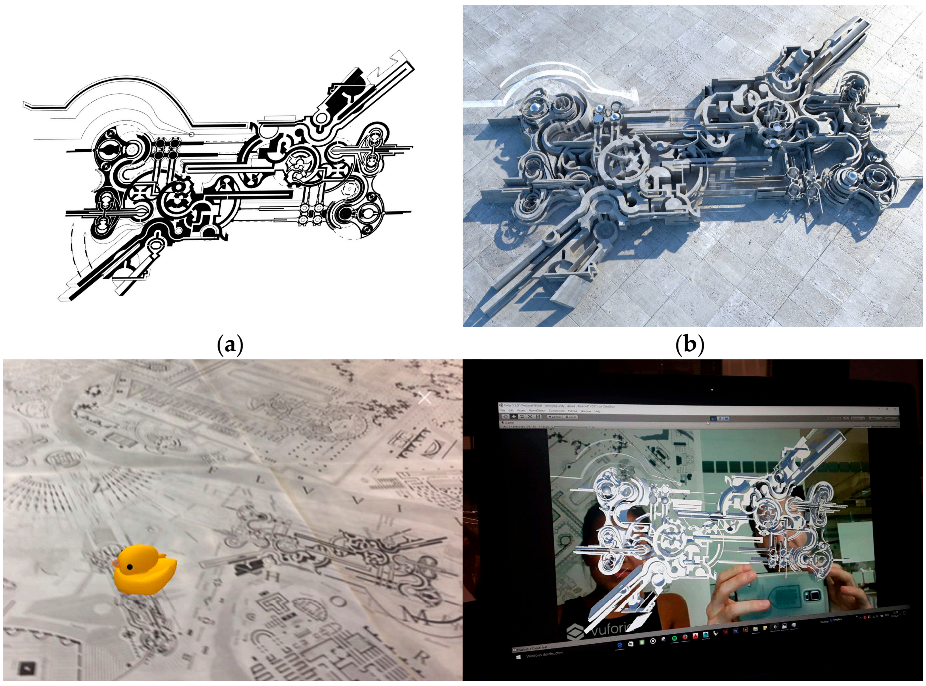
model that no longer simply illustrates the original plan, but proposes a new spatial reading derived from it. The relation between the two is not one of direct reconstruction, but of projective inference: the two-dimensional figure acts as a structured trigger for a new volumetric configuration.



(**a**) (**b**)

(**c**) (**d**)

**Figure 7.** Generative feedback through fragment transformation and AR-based spatial translation in Case A. (**a**) Student-transformed plan fragment derived from the Campo Marzio field. (**b**) Corresponding three-dimensional spatial hypothesis generated from that fragment. (**c**) Initial dummy volumetric test used to verify AR deployment over the target. (**d**) AR visualization of the student-developed three-dimensional proposal registered over the graphic support.

Within this process, AR did not function merely as a means of display. It became a testing environment in which the transformed fragment, the target, and the three-dimensional proposition could be checked against one another. Before the final student-generated models were fully deployed, preliminary volumetric tests were used to verify whether the selected target behaved reliably under AR conditions. This is illustrated in Figure 7c, where a simple dummy object was used as an initial registration test. Once this target–overlay relation had been confirmed, the student-developed three-dimensional proposal could be superimposed and evaluated through AR, as shown in Figure 7d.

The pedagogical importance of this episode lies in the fact that mismatch and recalibration no longer operated only as corrective mechanisms. They became part of a genuinely projective workflow. The students were not simply adjusting an imperfect target so that the system would function; they were learning how to transform a graphic field into a design instrument whose spatial consequences could be iteratively explored. In this sense, mismatch and recalibration acquired a generative role: it opened the possibility of variation, prompted the reformulation of fragments, and made the relation between 2D support and 3D hypothesis available as a field of experimentation.

Case A therefore shows that AR can support a mode of architectural learning in which historical analysis, graphic abstraction, material calibration, and spatial invention are not separate stages, but interconnected operations. The transformed fragment becomes at once a target, a design device, and a spatial proposition. AR, in turn, allows that proposition to be tested not as an end-stage image, but as an operative hypothesis derived from and projected back onto the graphic field from which it emerged.

### 3.2.5. Final Deployment and Pedagogical Synthesis

The final phase of Case A consisted in the public deployment of the work as an exhibition environment in which the redrawn field, the engraved support, the analytical panels, and the AR models were presented as a single pedagogical artifact. At this stage, the project no longer functioned only as a studio exercise, but as a coherent representational system that combined graphic analysis, material fabrication, and spatial augmentation.

Figure 8 documents this final configuration. In Figure 8a, the exhibition is shown as a complete installation in which the engraved Campo Marzio board occupies the center of the room and is surrounded by analytical material displayed on the walls. In Figure 8b, the installation is seen in operation, making clear that the project did not conclude with the fabrication of the physical support itself, but depended on the activation of AR as part of its final pedagogical and representational logic.


(**a**) (**b**)

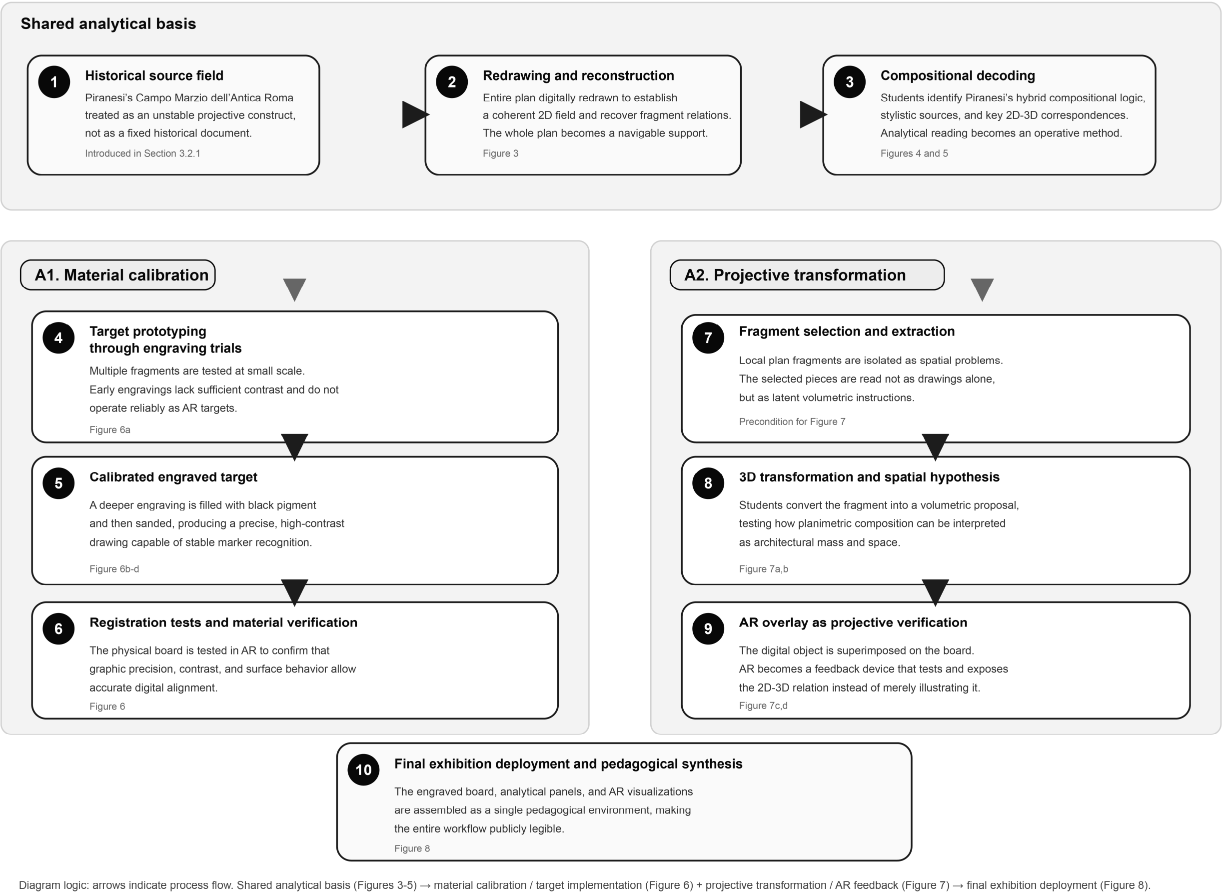
**Figure 8.** Final exhibition deployment of Case A. (**a**) General view of the exhibition, showing the engraved Campo Marzio board as the central support of the installation, surrounded by analytical panels. (**b**) Exhibition in operation, combining the physical board, wall-based analytical material, and AR-based spatial visualization.

What is important in this final stage is that the installation preserved the same tensions that structured the entire exercise: between plan and volume, historical source and contemporary intervention, graphic precision and projective transformation. Rather than resolving these tensions into a single stable object, the exhibition staged them as a field of relations through which viewers could move between the engraved surface, the superimposed digital models, and the analytical arguments that framed the work.

From a pedagogical point of view, this final deployment confirmed that AR was not used merely as a visualization layer added at the end of the process. In Zero Piranesi, AR acted as a catalyst for spatial thinking precisely because it required students to move back and forth between historical analysis, graphic abstraction, target calibration, and volumetric projection. The final exhibition made this chain of operations legible. Instead of displaying only finished forms, it revealed how a historical plan could become a target, how a target could become a testing ground for three-dimensional inference, and how that inference could in turn become part of a public representational environment.

Case A can therefore be understood not as a linear sequence from drawing to model, but as an iterative pedagogical system structured by feedback between analysis, fabrication, and projection. The exhibition phase consolidated these operations into a legible whole and, for that reason, functions as the closing synthesis of the case.

To clarify the sequence of operations involved in Case A, Figure 9 provides a synthetic analytical diagram of the workflow, from the redrawing of the Campo Marzio to the fabrication of calibrated targets, AR testing, fragment transformation, and final exhibition deployment.



**Shared analytical basis**

1 **Historical source field**
Piranesi's Campo Marzio dell'Antica Roma treated as an unstable projective construct, not as a fixed historical document.
Introduced in Section 3.2.1

2 **Redrawing and reconstruction**
Entire plan digitally redrawn to establish a coherent 2D field and recover fragment relations. The whole plan becomes a navigable support.
Figure 3

3 **Compositional decoding**
Students identify Piranesi's hybrid compositional logic, stylistic sources, and key 2D-3D correspondences. Analytical reading becomes an operative method.
Figures 4 and 5

**A1. Material calibration**

4 **Target prototyping through engraving trials**
Multiple fragments are tested at small scale. Early engravings lack sufficient contrast and do not operate reliably as AR targets.
Figure 6a

5 **Calibrated engraved target**
A deeper engraving is filled with black pigment and then sanded, producing a precise, high-contrast drawing capable of stable marker recognition.
Figure 6b-d

6 **Registration tests and material verification**
The physical board is tested in AR to confirm that graphic precision, contrast, and surface behavior allow accurate digital alignment.
Figure 6

**A2. Projective transformation**

7 **Fragment selection and extraction**
Local plan fragments are isolated as spatial problems. The selected pieces are read not as drawings alone, but as latent volumetric instructions.
Precondition for Figure 7

8 **3D transformation and spatial hypothesis**
Students convert the fragment into a volumetric proposal, testing how planimetric composition can be interpreted as architectural mass and space.
Figure 7a,b

9 **AR overlay as projective verification**
The digital object is superimposed on the board. AR becomes a feedback device that tests and exposes the 2D-3D relation instead of merely illustrating it.
Figure 7c,d

10 **Final exhibition deployment and pedagogical synthesis**
The engraved board, analytical panels, and AR visualizations are assembled as a single pedagogical environment, making the entire workflow publicly legible.
Figure 8

Diagram logic: arrows indicate process flow. Shared analytical basis (Figures 3-5) → material calibration / target implementation (Figure 6) + projective transformation / AR feedback (Figure 7) → final exhibition deployment (Figure 8).

**Figure 9.** Analytical summary diagram of Case A. Synthetic diagram of the pedagogical workflow developed in Zero Piranesi, showing the sequence from source selection and redrawing to compositional decoding, target prototyping, calibrated AR deployment, fragment transformation, volumetric generation, and final exhibition installation. Solid arrows indicate workflow progression, while dashed arrows indicate the branching from the shared analytical basis toward the two operative sequences (A1 and A2).

## *3.3. Case B: House in Equilibrium: AR for Kinematic Reading and Iterative Verification*

### 3.3.1. Pedagogical Context and Equilibrium-Based Premise

Case B was developed at the School of Architecture of the University of Granada (ETSA Granada) within the second-year course EGA3 in 2024. The exercise focused on the project known as House in Equilibrium, composed of two concrete volumes that rest on paired supports and mutually stabilize one another. The singularity of the project lies in the fact that equilibrium is only achieved within a narrow range of relative positions: small geometric variations displace the system from stability toward tipping or collapse. This made the house especially suitable for a pedagogical experiment centered on AR-assisted kinematic reading, positional verification, and iterative adjustment.

The exercise was introduced first through digital reconstruction. Students modeled the house in three dimensions in order to understand its overall geometry and to reconstruct the formal relation between its two main parts. At this stage, the digital model did not function merely as a representational artifact, but as the geometric basis for the subsequent AR workflow. The same model was later introduced into Vuforia and configured as a 3D model target, which required defining its correct orientation, assigning the appropriate upward axis, and calibrating the physical dimensions so that the trained target corresponded to the material mock-up used in class. The digital reconstruction and the preparation of the model target are shown in Figure 10.

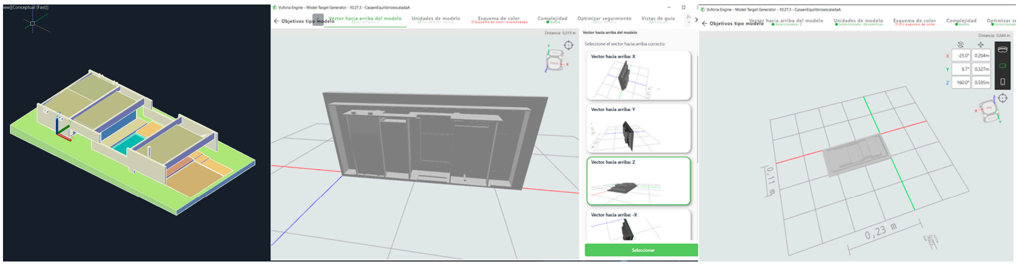

(**a**) (**b**) (**c**)

**Figure 10.** Case B—digital reconstruction of House in Equilibrium and preparation of the model target. (**a**) Digital model of the house produced by the students as the geometric basis for the exercise. (**b**) Configuration of the 3D model in Vuforia as a model target, including the definition of the correct upward axis. (**c**) Calibration of guide views and physical dimensions so that the trained target corresponds to the physical mock-up.

At the same time, the project was analysed as a kinematic problem rather than only as a static composition. What made the house pedagogically valuable was not simply its form, but the fact that its architectural logic depended on a highly specific state of balance between two parts. The digital study therefore focused on understanding the narrow interval in which the elements could mutually stabilize one another and on visualizing the difference between stable and unstable configurations. This study is shown in Figure 11.

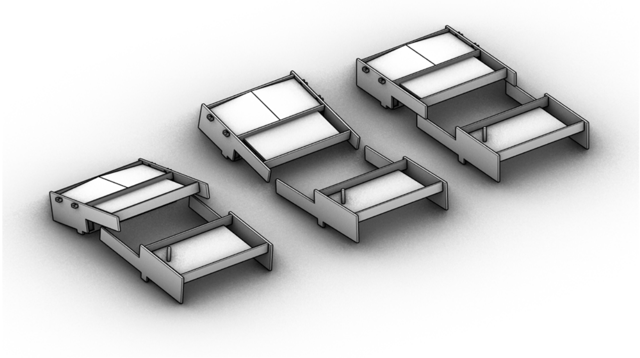


**Figure 11.** Case B—digital study of the equilibrium condition. Diagrammatic study of the two-part system used to analyse the narrow positional range in which the concrete elements mutually stabilize one another. The figure illustrates the kinematic logic of the project and the relation between stable and unstable configurations.

The pedagogical objective of the exercise was twofold. First, it introduced the notion of unstable equilibrium and trained a kinematic reading of a simple but demanding structural system. Second, it tested how AR could make visible intermediate states between stability and fall—states that are difficult to communicate through orthographic media alone. Rather than treating equilibrium as a binary condition, the studio sought to reveal it as a sequence of positional adjustments, tolerances, and thresholds.

In order to move from digital analysis to material verification, the students worked with a dismountable physical mock-up whose two parts could be manually separated, displaced, and reassembled. Within this setting, AR functioned simultaneously as technological sketching paper and as an immediate feedback mechanism. As the students moved the physical pieces, the system responded visually by confirming, destabilizing, or refusing the augmented overlay depending on the degree of correspondence between the physical model and the trained 3D target. In Schön's terms, this feedback operated as back talk: a situated response that activated reflection-in-action because it forced students to reconsider their decisions while manipulating the system, rather than only afterwards.

Case B is thus particularly relevant to the present article because it shifts AR from the domain of spatial translation toward that of kinematic verification. The issue here is not only whether a form can be recognized in space, but whether a physical object can reach and maintain a precise condition of equilibrium while also remaining recognizable to a trained digital system. For this reason, the case is examined through two episodes. Episode B1 addresses the corrective dimension of the workflow, focusing on equilibrium, recognizability, and positional tolerance. Episode B2 addresses the generative dimension, examining how new balance states and physical-digital transfers could become drivers of design variation rather than mere corrections.

### 3.3.2. Episode B1: Corrective Feedback: Equilibrium, Recognizability, and Positional Tolerance

The first documented episode within Case B (B1) concerns the corrective dimension of the process. Once the digital model had been trained as a model target and the physical prototype had been fabricated, AR could be used not only to visualize the house but also to verify whether the material system had reached the correct condition of equilibrium. In this episode, augmented reality became a diagnostic device for evaluating the relation between digital reference, physical assembly, and positional precision.

The physical mock-up was essential to this process because it made the equilibrium problem materially explicit. The two parts could be separated, displaced, and reassembled by hand, allowing students to test how small positional changes affected the capacity of the system to stabilize itself. This manual exploration of the narrow balance range is shown in Figure 12, where the physical model is progressively disassembled and reassembled. In pedagogical terms, the model made it possible to move from abstract geometric understanding toward embodied verification: equilibrium had to be found materially, not only inferred digitally.

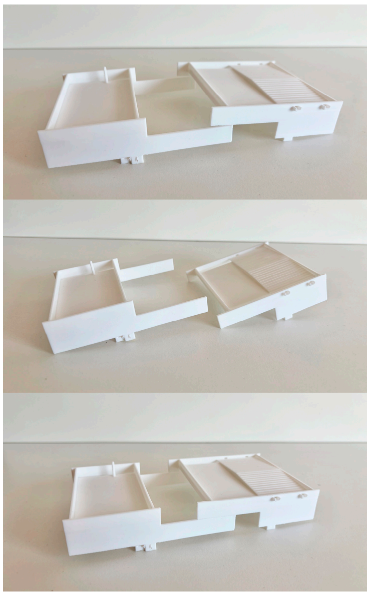
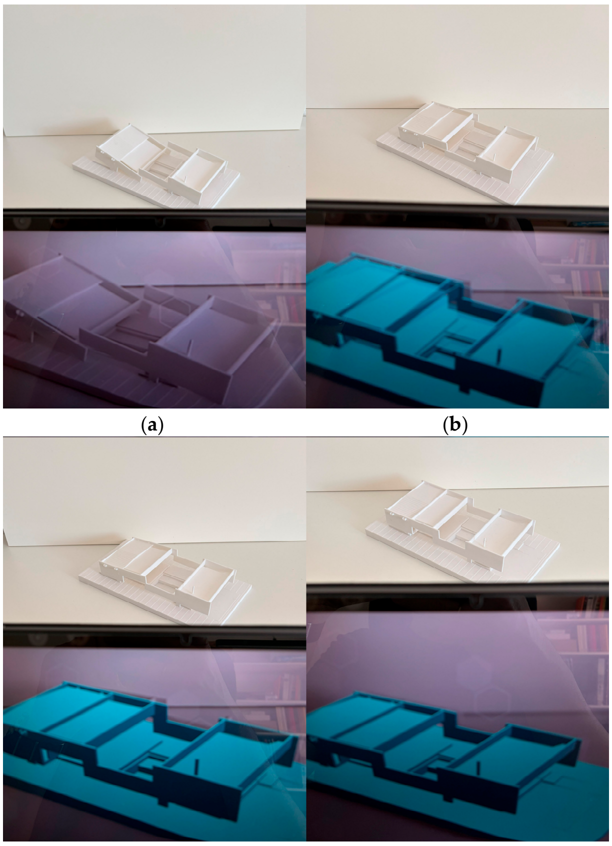


**Figure 12.** Case B, Episode B1—physical mock-up used to test the equilibrium condition. Sequence showing the two movable parts of the physical model during assembly, separation, and reassembly. The mock-up allowed students to verify materially the narrow positional range in which the two elements reach equilibrium.

What AR added to this process was a second layer of verification. Because the system had been trained on a specific three-dimensional configuration, it did not respond equally to any approximate arrangement of the pieces. Its behavior depended on how closely the physical mock-up matched the trained model target. This made it possible to test two related conditions at once. First, students could observe the tolerance margin of model-target recognition, that is, the extent to which the system could still identify and track the prototype despite slight deviations in the assembly. Second, AR could act as an indicator of equilibrium, since the augmented overlay only stabilized when the two movable parts approached the correct relative position.

The verification sequence shown in Figure 13 makes this especially clear. In the first state, the two pieces are not yet correctly assembled, and the AR model does not deploy (Figure 13a). In the second, the parts come into contact, but their relative position is still incorrect; the AR appears only intermittently and produces visible flickering, indicating unstable recognition (Figure 13b). In the third, the physical model reaches a better state of equilibrium and the AR becomes more stable, yet a slight displacement remains visible between the digital overlay and the material mock-up, revealing incomplete alignment (Figure 13c). Finally, in the fourth state, the physical components are placed in the correct relative position, and the AR overlay becomes stable and properly registered (Figure 13d).


(**a**) (**b**)

(**c**) (**d**)

**Figure 13.** Case B, Episode B1—AR verification sequence showing equilibrium, recognition tolerance, and registration accuracy. (**a**) When the physical model is not correctly assembled, AR does not deploy. (**b**) When the parts are in contact but not yet correctly positioned, the augmented model appears with unstable flickering. (**c**) When the physical model reaches a better state of equilibrium, AR becomes stable but still shows a slight displacement relative to the mock-up. (**d**) When the parts are correctly placed, the AR overlay is stably deployed and properly aligned. The augmented overlay is shown in blue to distinguish the digital AR model from the white physical mock-up and to make visible the degree of deployment, stability, and registration accuracy.

What is pedagogically significant in this episode is that the system did not only reward the final correct position. It also exposed intermediate states and degrees of imprecision. Students could therefore understand that equilibrium was not a binary yes-or-no condition, but a narrow interval of positional accuracy within which mechanical stability and digital recognizability converged. AR made these thresholds legible in real time and transformed them into part of the learning process.

Episode B1 therefore shows AR operating as a corrective feedback medium rather than as a final representational effect. The overlay became a visible indicator of whether the physical model had achieved the required configuration of balance and correspondence. In this case, equilibrium was verified not only by the material stability of the prototype, but also by the capacity of the digital system to recognize, register, and remain stable upon it. AR thus linked physical precision and digital verification into a single pedagogical operation.

### 3.3.3. Episode B2: AI-Assisted Projective Variation and Generative Feedback

Beyond the corrective logic of Episode B1, a second stage of the exercise explored whether the same workflow could be used projectively, that is, not only to verify a predefined equilibrium, but also to generate and test alternative equilibrium hypotheses. In this phase, students used an AI-assisted digital workflow to speculate on new spatial arrangements derived from the original House in Equilibrium system, asking whether different configurations could still produce a coherent condition of balance and whether such digitally generated proposals could be transferred back into physical form.

This shift marked an important pedagogical transition. In Episode B1, AR had functioned primarily as a corrective device, confirming whether the physical mock-up matched the trained model and whether the equilibrium condition had been reached with sufficient positional precision. In Episode B2, by contrast, the workflow became generative: the original system was treated as a formal and tectonic seed from which new equilibrium scenarios could be imagined, simulated, materialized, and tested. The question was no longer only whether the known model was correctly assembled, but whether the same logic of mutual stabilization could be reinterpreted into new architectural organizations.

Two examples illustrate this generative use of AR. The first, shown in Figure 14, develops a horizontal variation in the original system. Starting from the logic of two interdependent elements, the students proposed a new layered arrangement in which the original balance condition was extended into a more distributed spatial composition. The sequence shows the digitally generated hypothesis (Figure 14a), the physical mock-up assembled to test that transformed configuration (Figure 14b), and the AR overlay used to compare the projected model with its material reconstruction (Figure 14c). In this case, AR allowed the students to evaluate whether the expanded horizontal configuration could be coherently transferred from digital speculation to physical prototype.

The second example, shown in Figure 15, explores a vertical variation in the same system. Here the transformation is more radical: the relation between the two balancing elements is reinterpreted as a stacked and upright arrangement, producing a new tectonic and gravitational reading of the project. Again, the figure presents the digital hypothesis (Figure 15a), the corresponding physical test model (Figure 15b), and the AR overlay used to verify the degree of correspondence between both (Figure 15c). Through this process, students could assess not only whether the new configuration was visually plausible, but whether its physical assembly and digital projection could still converge within a stable and legible relation.

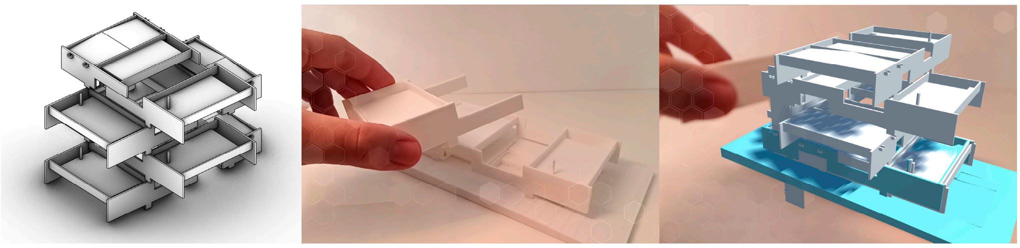

(**a**) (**b**) (**c**)

**Figure 14.** Case B, Episode B2—AI-assisted horizontal variation and AR verification of a new equilibrium hypothesis. (**a**) Digital model proposing a new horizontal equilibrium configuration derived from the original House in Equilibrium system. (**b**) Physical mock-up assembled to test the transformed horizontal configuration. (**c**) Augmented reality overlay superimposed on the mock-up, allowing comparison between the digitally generated hypothesis and its material reconstruction. In this example, AR was used as a generative feedback device linking speculative transformation, physical prototyping, and spatial validation.

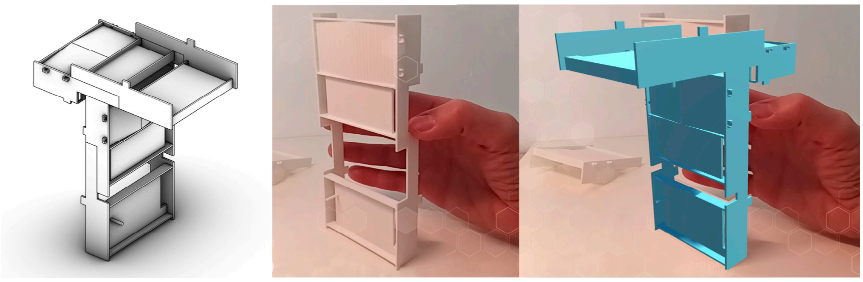

(**a**) (**b**) (**c**)

**Figure 15.** Case B, Episode B2—AI-assisted vertical variation and AR verification of a new equilibrium hypothesis. (**a**) Digital model proposing a new vertical equilibrium configuration derived from the original House in Equilibrium system. (**b**) Physical mock-up assembled to test the transformed vertical configuration. (**c**) Augmented reality overlay superimposed on the mock-up, allowing comparison between the digitally generated hypothesis and its material reconstruction. This example shows how AR can support the testing of more radical reorganizations of the original balancing logic.

In both cases, AR functioned as a generative feedback device. It did not simply validate a fixed solution, but mediated between invention and verification. The digital proposal suggested a new spatial possibility; the physical model tested its material feasibility; and the augmented overlay revealed the degree of alignment or mismatch between both. This feedback loop allowed students to move iteratively between speculative design and embodied testing, turning AR into a tool for design development rather than a final representational supplement.

Pedagogically, Episode B2 extends the role of AR from kinematic control to projective experimentation. Students no longer used the system only to locate the correct equilibrium of the original object, but to investigate whether new equilibrium conditions could be designed, simulated, and assessed through the same physical-digital interface. AR thus became a medium through which alternative architectural hypotheses could be both imagined and critically tested, linking AI-assisted variation, model making, and spatial validation in a single iterative workflow.

### 3.3.4. Final Synthesis of Case B

Case B shows that AR can operate across two complementary pedagogical registers. In the first, developed in Episode B1, it functions as a corrective medium that makes visible whether a physical system has reached the narrow positional condition required for equilibrium and stable recognition. In the second, developed in Episode B2, it becomes a generative medium through which alternative balance hypotheses can be proposed, prototyped, and tested across digital and material domains.

What makes this case especially relevant is that AR does not remain external to the architectural problem. It does not simply illustrate a finished form, but becomes entangled with the very condition being studied: balance. The overlay is meaningful only insofar as the physical model, the trained digital target, and the projected hypothesis converge with sufficient geometric precision. For that reason, the system teaches not only how to see a form, but how to understand the thresholds through which form, position, and stability become mutually legible.

From a pedagogical point of view, this produces a particularly rich loop of reflection-in-action. Students begin by reconstructing and understanding a known equilibrium condition, they then test it materially, they observe how AR confirms, destabilizes, or refuses recognition depending on positional accuracy, and finally, they use the same workflow to speculate on new equilibrium scenarios. The exercise therefore moves from verification to invention without abandoning precision. Instead, precision becomes the condition through which speculation can be meaningfully assessed.

Case B can thus be understood as an iterative learning system in which digital modelling, physical prototyping, AR recognition, and projective transformation continuously inform one another. Rather than separating analysis, validation, and design development into distinct phases, the case integrates them within a single workflow. In that sense, AR acts not only as a visualization technology, but as a catalyst for kinematic reasoning, material control, and architectural experimentation.

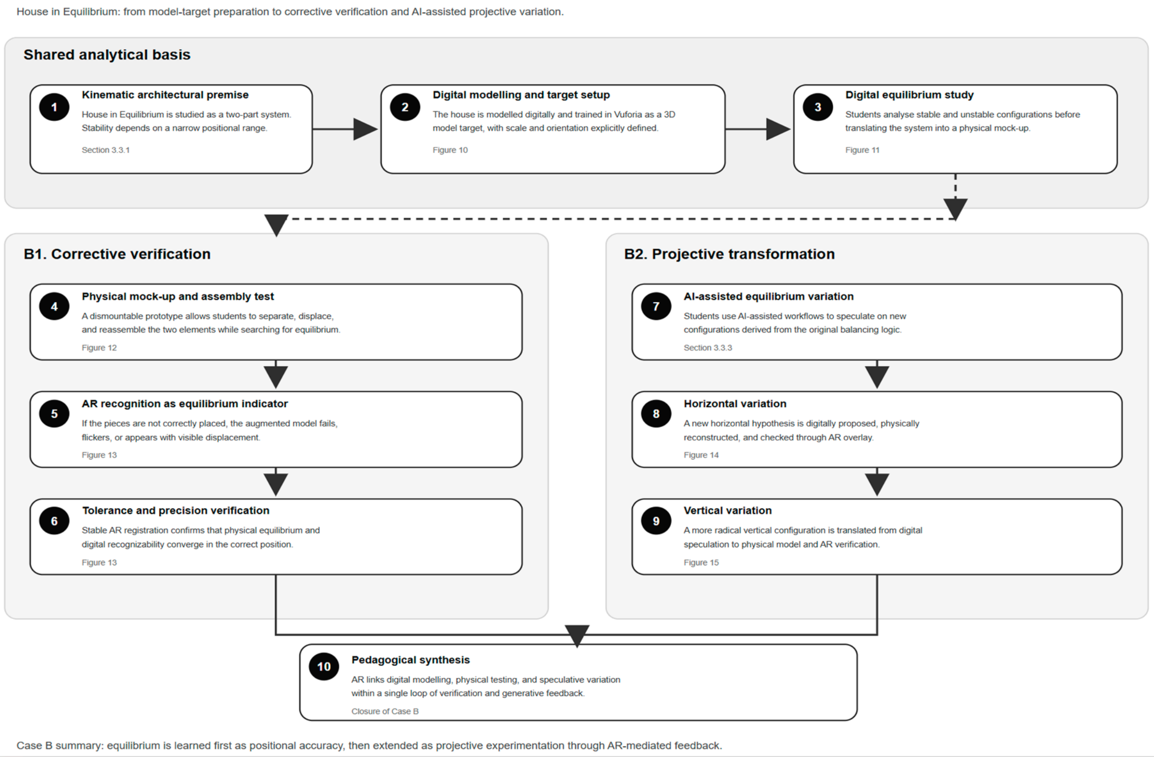
### *3.4. Comparability Across Cases and Rationale for Cross-Case Reading*

Although the two cases differ in task type and disciplinary emphasis—Case A addressing speculative 2D–3D translation through the Campo Marzio, and Case B addressing kinematic reasoning through unstable equilibrium—they remain comparable through a shared pedagogical structure. In both, a stable physical artefact operates as the reference support for judgement, while AR functions as a reversible superposed layer through which hypotheses can be tested, corrected, or reformulated without destroying the material base.

This shared configuration supports the paper’s central claim: AR becomes pedagogically operative when it shifts from end-stage visualization to iterative verification embedded in studio learning. In Case A, verification is oriented toward the relation between graphic fragment, target recognizability, and spatial translation. In Case B, it is oriented toward positional precision, equilibrium, and the testing of alternative balance states. Across both cases, AR is therefore not used to increase realism or immersion for their own sake, but to make architectural decisions testable against an artefact through repeated episodes of trial, consequence, and adjustment.

The revised study is organized not only by cases, but also by episodes within each case. In both A and B, a first episode examines the corrective use of AR, where the system exposes mismatch, instability, or insufficient precision. A second episode examines its generative use, where the same workflow is extended into projective variation and the testing of alternative configurations. This episode-based comparability is crucial because it allows the paper to move beyond a generic account of AR in education and toward a more precise description of how AR participates in design learning under different disciplinary conditions.

The rationale for cross-case reading is therefore not that both exercises produce the same outputs, but that they share the same interactional logic: a material support remains stable enough to anchor judgement, while the augmented layer re-enters the design process as feedback. This common logic allows the analysis to compare how AR sharpens material precision, mediates between physical and digital states, and intensifies reflection-in-action, even though the architectural content of the two cases differs substantially. This shared interactional logic is summarized diagrammatically in Figure 16.



House in Equilibrium: from model-target preparation to corrective verification and AI-assisted projective variation.

**Shared analytical basis**

1 **Kinematic architectural premise**
House in Equilibrium is studied as a two-part system. Stability depends on a narrow positional range.
Section 3.3.1

2 **Digital modelling and target setup**
The house is modelled digitally and trained in Vuforia as a 3D model target, with scale and orientation explicitly defined.
Figure 10

3 **Digital equilibrium study**
Students analyse stable and unstable configurations before translating the system into a physical mock-up.
Figure 11

**B1. Corrective verification**

4 **Physical mock-up and assembly test**
A dismountable prototype allows students to separate, displace, and reassemble the two elements while searching for equilibrium.
Figure 12

5 **AR recognition as equilibrium indicator**
If the pieces are not correctly placed, the augmented model fails, flickers, or appears with visible displacement.
Figure 13

6 **Tolerance and precision verification**
Stable AR registration confirms that physical equilibrium and digital recognizability converge in the correct position.
Figure 13

**B2. Projective transformation**

7 **AI-assisted equilibrium variation**
Students use AI-assisted workflows to speculate on new configurations derived from the original balancing logic.
Section 3.3.3

8 **Horizontal variation**
A new horizontal hypothesis is digitally proposed, physically reconstructed, and checked through AR overlay.
Figure 14

9 **Vertical variation**
A more radical vertical configuration is translated from digital speculation to physical model and AR verification.
Figure 15

10 **Pedagogical synthesis**
AR links digital modelling, physical testing, and speculative variation within a single loop of verification and generative feedback.
Closure of Case B

Case B summary: equilibrium is learned first as positional accuracy, then extended as projective experimentation through AR-mediated feedback.

**Figure 16.** Analytical summary diagram of Case B. Synthetic diagram of the pedagogical workflow developed in House in Equilibrium, showing the shared analytical basis of digital modelling and target preparation, the corrective branch of equilibrium verification and recognition tolerance, the generative branch of AI-assisted horizontal and vertical transformations, and their convergence in a final pedagogical synthesis.

## 4. Research Design and Methods

### *4.1. Overall Research Design*

This study is designed as a multiple-case investigation embedded in real teaching settings. Rather than constructing a laboratory experiment isolated from architectural pedagogy, it examines how augmented reality (AR), configured through target-based workflows, reconfigures tasks that already exist within architectural representation and studio learning. The empirical corpus is composed of two teaching experiences developed in different academic contexts: Case A, Zero Piranesi at the University of Innsbruck 2020, and Case B, House in Equilibrium at the University of Granada 2024. These cases differ in disciplinary emphasis and task structure, yet they remain comparable because both are organized around the same operational principle: a stable physical artefact supports a reversible augmented layer through which architectural hypotheses are tested, corrected, or reformulated.

The study does not seek to estimate a single generalizable average effect of AR in architectural education. Instead, it aims to identify recurrent pedagogical mechanisms and to describe how these become visible through concrete episodes of interaction. The emphasis therefore lies on observable design consequences: the sharpening of material precision, the emergence of recognition thresholds, the role of mismatch in triggering correction, and the extension of AR from corrective verification toward generative projective variation.

Accordingly, the methodological approach privileges mechanism description over broad attitudinal reporting. The principal evidentiary basis of the article is the documented interaction between physical artefact, digital model, and AR response. This allows the paper to address AR not simply as a medium of visualization, but as an operative device that affects the way architectural problems are analysed, tested, and reformulated in real time.

### *4.2. Episode-Based Analytical Protocol*

To make the two cases comparable without erasing their specificity, the study adopts an episode-based analytical protocol [20]. Each case is examined through two distinct but related episodes:

- A corrective episode, in which AR reveals mismatch, instability, insufficient target recognizability, or incomplete positional correspondence;
- A generative episode, in which the same physical-digital setup is extended into projective variation and the testing of transformed architectural hypotheses.

This protocol makes it possible to analyse AR not as a single homogeneous tool, but as a medium that operates under two pedagogically different regimes. In the corrective regime, AR functions as an indicator of whether a required condition has been reached with sufficient accuracy—graphic recognizability in Case A, positional equilibrium in Case B. In the generative regime, AR functions as a mediator between speculative transformation and embodied testing, allowing new design proposals to be projected, materialized, and checked iteratively.

Within this structure, the main analytical categories were the following:

1. Physical action on the artefact: calibration, assembly, disassembly, modification, or transformation of the support;
2. System response: stable recognition, flickering, misalignment, non-recognition, or stable deployment of a transformed overlay;
3. Design consequence: correction, recalibration, acceptance, reformulation, or development of a new spatial hypothesis;
4. Direction of transfer: physical-to-digital, digital-to-physical, or bidirectional adjustment.

These categories allow the study to describe how AR participates in the loop of action, observation, and revision, while also distinguishing between moments in which the system confirms a known condition and moments in which it enables design development.

### *4.3. Sources of Evidence and Documentary Material*

The analysis is grounded primarily in documentary evidence produced during the exercises themselves. These materials include digital models, diagrammatic studies, target-preparation records, photographs of physical mock-ups, captures of AR deployment, and sequential images showing instability, misalignment, correction, or transformed configurations. Rather than relying mainly on retrospective reporting, the article reads these materials as direct traces of design action and pedagogical response.

A second layer of evidence is provided by teaching observation and classroom documentation, including photographs, brief screen captures, and records of intermediate testing situations in which students manipulated physical artefacts while monitoring the immediate response of the augmented layer. These materials are not treated as exhaustive ethnographic records, but as carefully selected evidence of the moments in which AR became pedagogically consequential. They make it possible to identify where precision became necessary, where recognition thresholds became visible, and where a technical disturbance turned into a disciplinary insight.

Student self-assessment materials, where available, are treated as supplementary rather than central evidence. The main evidentiary basis of the study rests on the documented interaction between artefact and overlay, since this makes it possible to ground the argument directly in observable design mechanisms.

For the same reason, evaluative criteria concerning physical artefact quality, coherence between material and augmented layers, spatial or kinematic understanding, and usability under course conditions are retained as a background analytical scaffold, rather than as a separate scoring system. These dimensions remain useful for structuring attention, but they are embedded within the episode-based reading rather than functioning as the main demonstrative framework of the article.

Accordingly, the strongest form of triangulation in this study is established between (i) the physical artefact, (ii) the digital/AR response, and (iii) the documented transformation of the exercise over time. This triangulation is crucial to the paper's central thesis, because it allows non-recognition, flickering, misalignment, and corrected deployment to be interpreted not as incidental technical problems, but as pedagogically meaningful events.

### *4.4. Limitations and Scope*

The study has several limitations. First, the two cases are heterogeneous: they differ in academic level, institution, task structure, and representational problem. The goal of the paper is therefore not to compare equivalent cohorts under tightly controlled experimental conditions, but to analyse how a comparable AR logic becomes operative within different architectural exercises.

Second, the workflow depends on a specific technical stack, including Vuforia, Unity, and mobile devices, as well as on environmental factors such as light, shadow, contrast, occlusion, and surface quality. These conditions affect recognition stability and preparation time and may therefore amplify or suppress the pedagogical effects described in the paper. The argument advanced here should thus be understood as applying to target-based AR workflows under real studio conditions, not to all educational uses of AR in general.

Third, the article foregrounds selected and well-documented episodes rather than exhaustive dataset-wide quantification. This is a deliberate methodological choice. The purpose is to isolate the moments in which AR becomes pedagogically meaningful and to describe the mechanisms through which this occurs. As such, the value of the study lies in the identification of reproducible feedback dynamics, not in the estimation of a single statistically generalisable effect size.

Finally, although the two cases are read comparatively, the paper does not claim simple universal transferability. Some aspects are likely to travel well across contexts—especially the logic of stable artefact plus reversible overlay—whereas others remain dependent on teacher mediation, student modelling competence, and available infrastructure. These distinctions are revisited in the Section 5, where the paper differentiates between broadly transferable mechanisms and context-dependent conditions.

## 5. Results and Discussion

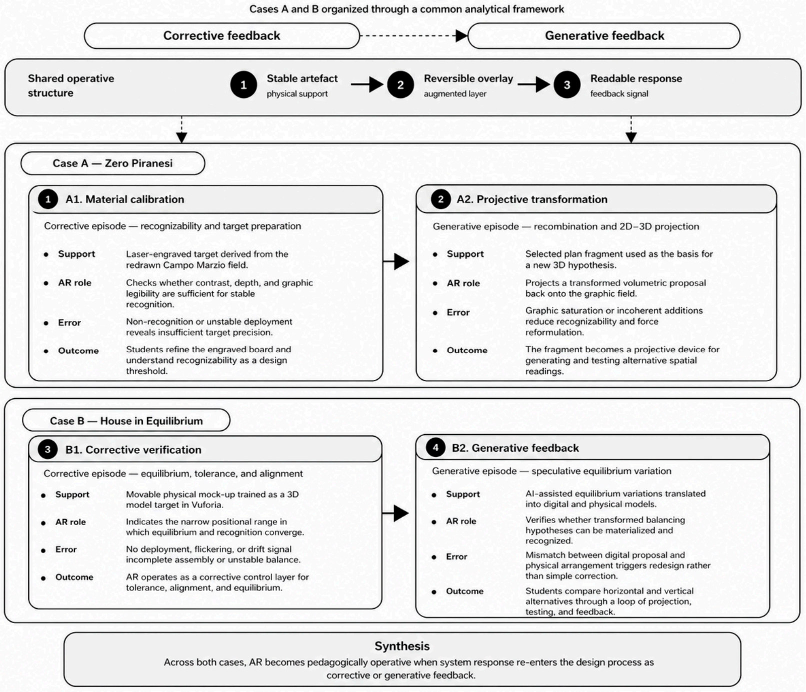
### *5.1. AR as Corrective Feedback: Precision, Recognition, and Thresholds*

Across both cases, one of the clearest results is that AR increases the importance of the precision of the physical artefact. Once students understand that the mock-up, engraved support, or movable prototype will function as the anchor for augmentation, material imprecision ceases to be secondary. Inaccurate joints, insufficient contrast, ambiguous contours, or misplaced parts are amplified by superposition: the virtual layer flickers, drifts, misaligns, or disappears. In this sense, AR does not simply sit on top of the artefact; it makes the artefact's degree of geometric clarity immediately consequential.

The specific mechanism differs by case. In Case A, corrective feedback emerged through the calibration of engraved targets and the recognizability of graphic fragments. Not every fragment behaved equally well as a target, and not every engraving was sufficient to sustain stable deployment. Recognition therefore depended on a chain of adjustments involving contrast, depth, line density, and graphic legibility. In Case B, corrective feedback emerged through the relation between positional equilibrium and model-target recognition. Here the system was trained on a three-dimensional object rather than a graphic field, and AR became sensitive to the relative placement of movable parts. As a result, physical equilibrium and digital recognizability converged in a narrow threshold condition.

What is important in both cases is that failure became informative. Non-recognition, flickering, or misalignment were not treated merely as technical inconveniences; they became readable as diagnostic signals. These signals revealed where the physical support was insufficiently precise, where the system's tolerance was being exceeded, or where an intended state had not yet been reached. AR thus functioned as a corrective medium that made thresholds visible and actionable.

The comparative structure of these corrective dynamics is summarized in Figure 17, which shows how the two cases differ in support type and task, but converge in their use of AR as a mechanism for exposing threshold states. In Case A, the threshold is primarily graphic and material; in Case B, it is primarily geometric and positional. In both, however, the pedagogical effect is similar: students learn that architectural precision is not only representational or constructive, but also relational, because it determines whether the augmented layer can operate coherently.



A1. Material calibration

Corrective episode — recognizability and target preparation

- **Support** Laser-engraved target derived from the redrawn Campo Marzio field.
- **AR role** Checks whether contrast, depth, and graphic legibility are sufficient for stable recognition.
- **Error** Non-recognition or unstable deployment reveals insufficient target precision.
- **Outcome** Students refine the engraved board and understand recognizability as a design threshold.

A2. Projective transformation

Generative episode — recombination and 2D–3D projection

- **Support** Selected plan fragment used as the basis for a new 3D hypothesis.
- **AR role** Projects a transformed volumetric proposal back onto the graphic field.
- **Error** Graphic saturation or incoherent additions reduce recognizability and force reformulation.
- **Outcome** The fragment becomes a projective device for generating and testing alternative spatial readings.

B1. Corrective verification

Corrective episode — equilibrium, tolerance, and alignment

- **Support** Movable physical mock-up trained as a 3D model target in Vuforia.
- **AR role** Indicates the narrow positional range in which equilibrium and recognition converge.
- **Error** No deployment, flickering, or drift signal incomplete assembly or unstable balance.
- **Outcome** AR operates as a corrective control layer for tolerance, alignment, and equilibrium.

B2. Generative feedback

Generative episode — speculative equilibrium variation

- **Support** AI-assisted equilibrium variations translated into digital and physical models.
- **AR role** Verifies whether transformed balancing hypotheses can be materialized and recognized.
- **Error** Mismatch between digital proposal and physical arrangement triggers redesign rather than simple correction.
- **Outcome** Students compare horizontal and vertical alternatives through a loop of projection, testing, and feedback.

Synthesis

Across both cases, AR becomes pedagogically operative when system response re-enters the design process as corrective or generative feedback.

**Figure 17.** Comparative matrix of corrective and generative feedback across the four documented episodes.

The diagram synthesizes the two cases through four episodes: A1 and B1 as corrective feedback, where AR exposes instability, insufficient recognizability, or incomplete positional correspondence; and A2 and B2 as generative feedback, where the same workflow is extended into projective variation and the testing of transformed hypotheses. The matrix highlights both the comparability of the feedback structure and the disciplinary specificity of each case.

### *5.2. AR as Generative Feedback: Variation, Transfer, and Design Development*

A second major result is that the same physical-digital setup can support not only correction, but also projective variation. Once AR has been stabilized enough to operate as a verification device, it can be extended into a generative medium through which alternative configurations are imagined, tested, and revised.

In Case A, this generative role appeared when students moved from identifying Piranesi's compositional logic to reworking selected fragments into new spatial hypotheses. The field ceased to be only a historical object of analysis and became a generator of new volumetric propositions. AR mediated this passage by allowing the transformed fragment to be checked against the target and projected back onto the graphic support. In Case B, the generative role became explicit when students used AI-assisted workflows to speculate on new horizontal and vertical equilibrium scenarios. The original balancing logic was not simply repeated; it was reinterpreted into new tectonic organizations that then had to be tested through physical mock-ups and AR overlay.

In both cases, the key dynamic is transfer. A graphic or digital hypothesis is translated into a material artefact; a material artefact is compared against a projected model; and discrepancy between the two prompts further revision. AR therefore supports a bidirectional movement between digital speculation and physical testing. This is what justifies speaking not only of feedback, but of generative feedback: the response of the system does not merely confirm or deny a fixed idea, but helps shape the next iteration of the design.

This shift is important because it shows that AR does not only stabilize a correct answer. It also provides a controlled environment in which alternative answers can be explored without abandoning the discipline-specific demands of geometry, recognizability, and material coherence. In that sense, AR extends the physical artefact into a projective interface rather than reducing it to a static trigger.

### *5.3. Reflection-in-Action and the Productive Role of Error*

From the perspective of reflection-in-action, the most significant result of the study is that AR intensifies a loop of action–response–adjustment in which error becomes pedagogically productive. Students manipulate a physical artefact, observe the immediate system response, interpret that response, and modify the artefact or the digital hypothesis accordingly. In this cycle, the augmented layer acts as a form of technological sketching paper: a reversible trace that does not replace the material base, but comments on it.

The revised analysis makes a distinction between two roles of error. In the first, error acts as a corrective indicator. This is the case when AR reveals insufficient contrast, unstable target recognition, or incorrect positional assembly. In the second, error acts as a projective trigger. This is the case when mismatch or instability leads students not merely to correct a known solution, but to explore whether a different configuration might be more coherent, more stable, or more spatially productive. The shift from corrective to generative use is one of the central findings of the study.

This distinction also helps explain why AR is pedagogically meaningful here in a way that goes beyond display. The system does not simply show what the project is supposed to look like. It responds to what the student has done and thereby re-enters the design process as situated back talk. That back talk may be graphic, positional, visual, or kinematic, but in all cases, it becomes part of the studio conversation. Error is therefore not external to the method; it is one of the main means through which the method becomes operative.

The loop through which this occurs is synthesized in Figure 18. The diagram shows how physical action, system response, interpretation, and revision are linked in a recursive sequence. Crucially, the sequence does not always return to the same point. Under corrective conditions, it tends toward improved alignment or recognizability; under generative conditions, it may instead open a new path of transformation. This is why AR can be understood not only as a verification tool, but as a medium that modulates the relation between discipline-specific control and design exploration.

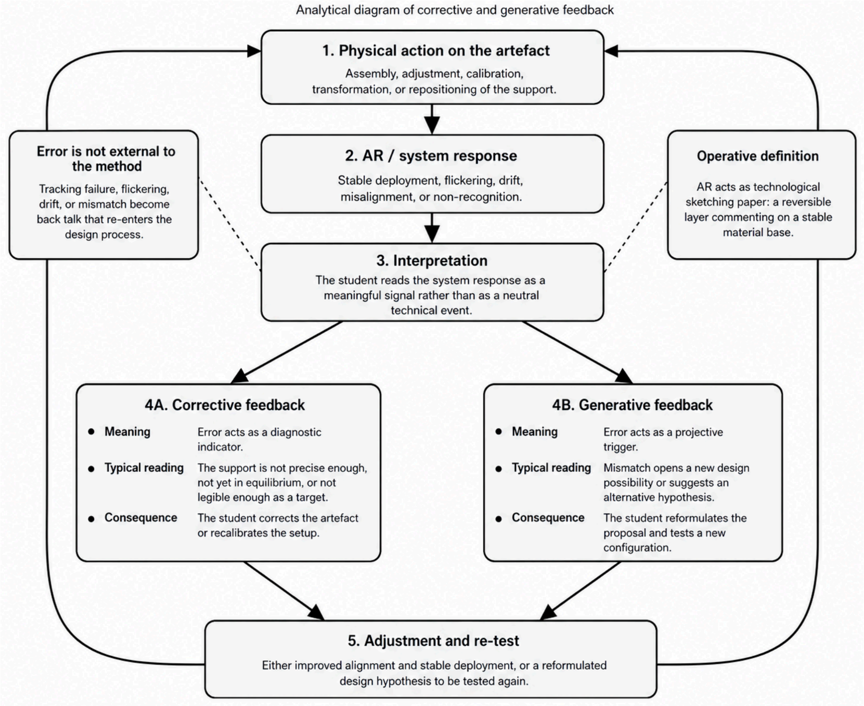


**Figure 18.** Reflection-in-action loop and the productive role of error in target-based AR workflows.

The diagram shows how physical action on the artefact produces a system response—stable deployment, flickering, misalignment, or non-recognition—which is then interpreted by the student as either corrective feedback or generative feedback. The resulting adjustment may improve alignment or open a new design variation, thus integrating AR into a recursive cycle of action, observation, interpretation, and revision.

### *5.4. Comparability, Constraints, and Pedagogical Transferability*

The two cases suggest that target-based AR has a transferable pedagogical structure, but not a universally uniform effect. What appears transferable is the mediating logic itself: a stable artefact anchors judgement; a reversible overlay makes consequences visible; and the student works within a loop of trial, response, and revision. What varies across cases is the specific architectural content of that loop—graphic recognizability in Case A, equilibrium and kinematic precision in Case B.

The cases also show that AR's pedagogical value does not derive from recognition alone, but from the feedback regime that the exercise activates. If the system is introduced without sufficient mediation, it risks remaining a novelty or a fragile visual effect. Its value emerges when technical response is interpreted in disciplinary terms: when instability means insufficient target precision, when misalignment means incomplete positional accuracy, or when a transformed overlay invites further design development.

At the same time, the findings remain dependent on conditions that can constrain transferability: infrastructure, preparation time, modelling competence, light conditions, device performance, and teacher mediation. These factors affect not only ease of use, but the quality of the feedback loop itself. The contribution of the present study is therefore not to claim that AR will automatically improve any architectural course, but to identify the conditions under which AR becomes pedagogically operative as verification and generative feedback.

For architectural education, this is perhaps the most useful level of transferability. What can travel from one context to another is not a fixed software recipe, but a methodological relation: stable artefact + reversible overlay + interpretable system response. When this relation is carefully staged, AR can intensify material precision, support spatial and kinematic understanding, and transform error into a productive component of design learning.

## 6. Conclusions

The teaching experiences presented in this paper suggest that augmented reality (AR), when configured through target-based workflows anchored to physical artefacts, can move from a representational add-on toward a catalyst for spatial and projective thinking in architectural education. Across the two cases examined here—Case A, centred on the speculative 2D–3D translation of Piranesi's Campo Marzio, and Case B, centred on the kinematic reading of unstable equilibrium—AR was embedded in the core of graphic work, physical testing, and design decision-making rather than confined to end-stage presentation.

The main contribution of the study is both conceptual and methodological. Conceptually, AR-on-artefact is framed as technological sketching paper: a reversible, situated layer that mediates between the relative certainty of the physical support and the uncertainty of evolving design hypotheses. Methodologically, this framing is clarified through an episode-based structure that distinguishes between corrective feedback and generative feedback. In the corrective mode, AR reveals thresholds of precision, recognizability, and positional stability. In the generative mode, the same workflow supports the testing of transformed hypotheses and the iterative transfer between digital speculation and physical prototyping.

One of the central findings of the paper is that error is not external to the method, but one of its main pedagogical engines. Recognition failure, flickering, drift, misalignment, or incomplete correspondence do not simply interrupt the workflow. Instead, they act as a form of situated back talk that re-enters the design process and makes architectural decisions testable in real time. In some situations, this back talk functions correctively, indicating that the artefact is not yet precise enough or that a required condition has not been reached. In other situations, it functions generatively, opening a new design possibility and triggering reformulation. This distinction between error as indicator and error as projective trigger is one of the principal contributions of the revised study.

From a pedagogical standpoint, the results converge around three major effects. First, AR tends to increase the material and graphic precision of the physical support, because stable deployment depends on legible geometry, calibrated targets, and coherent assembly. Second, AR supports spatial and kinematic understanding by enabling 2D–3D verification, exposing threshold states, and making intermediate or unstable conditions visible through superposition. Third, AR intensifies reflection-in-action loops: manual intervention on the artefact coupled with immediate system response produces rapid sequences of action, observation, interpretation, and revision, consistent with Schön's model of situated reflective practice [11,13]. In this sense, AR does not merely display outcomes; it reorganizes the conditions under which design decisions are taken.

The study also suggests that the pedagogical value of AR does not lie in immersion alone, but in the feedback regime that the exercise activates. What can be transferred across contexts is not a fixed technical recipe, but a methodological relation: a stable artefact, a reversible overlay, and an interpretable system response. When this relation is carefully staged, AR becomes operative as a medium of verification and variation. Under such conditions, the physical artefact is no longer just a support for display, but an interface through which the project is negotiated, corrected, and transformed.

At the same time, the study has limitations. The cases are heterogeneous in academic level, institutional context, and task structure; no strictly parallel control group was employed; and the workflow depends on a specific technical stack and on environmental conditions that affect recognition stability. For these reasons, the paper does not claim a universally generalizable statistical effect. Its value lies instead in the identification of reproducible pedagogical mechanisms: the coupling of physical support and augmented layer, the visibility of recognition thresholds, the conversion of mismatch into feedback, and the extension of verification into projective transformation.

Future research should expand the empirical base, further document how feedback episodes unfold across different cohorts and task types, and refine ways of recording the passage from corrective to generative use. It would also be valuable to distinguish more explicitly between broadly transferable mechanisms—such as mock-up/overlay mediation logic and iterative verification—and those that remain more dependent on infrastructure, environmental conditions, and students' prior modelling skills.

With these cautions, the two cases indicate that target-based AR can renew architectural representation pedagogy by turning the mock-up, the target, or the physical prototype into an active site of inquiry. Under these conditions, the project is not simply shown, but continuously tested, reformulated, and negotiated. AR therefore becomes pedagogically meaningful not because it produces more spectacular images, but because it sharpens precision, supports reflection-in-action, and allows error itself to become part of the design method.

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**Institutional Review Board Statement:** Ethical review and approval were not required for this study. The manuscript is framed as a teaching methodology and educational innovation contribution. It reflects on the pedagogical value of using augmented reality tools in architectural education and discusses the teaching outcomes derived from this academic activity. It does not present a clinical, biomedical, or health-related study. Nor does it involve patients, clinical data, biological samples, biomedical intervention, medical procedures, sensitive personal data, or identifiable personal data. The educational observations and outcomes referred to in the manuscript are presented in anonymised and/or aggregated form, and the manuscript does not disclose individual student identities or personal information. In the Spanish and Andalusian regulatory context, the formal framework for mandatory ethics review is mainly articulated around biomedical and health-related research. On the basis of the documentation reviewed, the teaching activity described in the manuscript corresponds to an ordinary teaching and educational innovation activity in architecture, carried out within the academic duties of the authors as university teachers. It does not fall within the scope of biomedical, clinical, or health-related ethics review as described in the applicable local regulatory framework.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** The materials supporting the findings of this study are largely included within the article in the form of figures, diagrams, sequential process documentation, and AR deployment records. Additional visual documentation, selected digital models, and complementary teaching records are available from the corresponding author upon reasonable request. All figures are by the authors unless otherwise stated. Student-produced material included in the article is reproduced with permission.

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