Clareus Scientific Science and Engineering
Volume 3 Issue 4 July 2026
ISSN: 3065-1182

Immersive Representation Tools as Conceptual Agents: Paradigmatic Transformation of Architectural Design through AI-BIM-XR Convergence

Citation: Ferdaws Belcadhi. "Immersive Representation Tools as Conceptual Agents: Paradigmatic Transformation of Architectural Design through AI-BIM-XR Convergence". Clareus Scientific Science and Engineering 3.4 (2026): 11-24.

Article Type: Research Article

Received: June 20, 2026

Published: July 14, 2026

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Abstract

The architectural discipline is undergoing a paradigmatic transformation driven by three converging technologies: Extended Reality (XR), Generative Artificial Intelligence (AI), and semantic Building Information Modeling (BIM/HBIM). Long confined to post-hoc visualization of decisions already made, immersive tools are now moving toward an unprecedented status: that of conceptual agents capable of structuring spatial thinking, guiding formal choices, and reconfiguring creative processes at the very heart of design. This article offers a theoretical and empirical analysis of this transition, articulating a systematic review of recent scientific literature (2018-2025), the results of a Likert survey conducted with twenty-one actors in advanced architectural education (master's students, doctoral candidates, practicing architects), and a comparative analysis of two integrated use cases. The results converge toward three major transformations: the emergence of an embodied spatial cognition in which the body becomes an instrument for analyzing and validating forms; the constitution of a non-linear generative design process structured by continuous algorithmic exploration loops; and the opening of new modalities of multisensory and multi-scalar heritage mediation.

The survey records an overall adherence rate of 76% to the convergent ecosystem, with remarkable consensus around integrated environmental simulation (95%), AI+BIM+VR convergence for design optimization (90%), and anticipation of construction conflicts (86%). These results are accompanied by structural tensions: resistance to early introduction (57% disagreement), an economic obstacle identified by 81% of respondents, and fundamental ethical issues regarding algorithmic transparency, spatial justice, and the preservation of the architect's creative agency. The article argues that human-centered immersive systems, in their convergence with AI and semantic BIM, constitute not a substitute for the architect's creative intelligence, but its most powerful amplifier—provided there is progressive, reflective, and ethically governed pedagogical integration.

Keywords: Immersive representation; AI-BIM-XR Convergence; Generative architectural design; AI-assisted architectural creativity; Human-centered immersive systems; Embodied spatial cognition; Semantic BIM; HBIM; Digital espaciology; Algorithmic spatial justice; Creative agency; Immersive heritage mediation

Introduction

Context: From Visualization Tools to Conceptual Agents

The architectural discipline has always been defined as much by its tools as by its theories. From the ruler and compass to Brunelleschi's perspective, from the drawing board to the CAD software of the 1980s, each instrumental rupture has modified not only the speed and precision of representation, but the cognitive categories through which the architect conceives, evaluates, and communicates space. The current rupture is of a different order: immersive technologies—virtual reality (VR), augmented reality (AR), mixed reality (MR)—collectively designated by the term XR (Extended Reality), combined with generative Artificial Intelligence and semantic BIM, do not simply represent architecture more faithfully or more quickly. They shift the moment of representation from downstream to upstream in the process, transforming it from a product of design into an agent of design itself.

Long confined to end-of-process visualization, virtual reality and XR environments are now becoming conceptual agents capable of influencing the generation, evaluation, and communication of spatial ideas (Partarakis & Zabulis, 2023). This transformation is facilitated by the rise of generative models (Adeusi et al., 2024) and by the development of human-centered immersive devices, which redefine the way space is perceived and conceived. Their convergence with semantic BIM, evolving digital twins, and three-dimensional acquisition systems (Zhang & Fassi, 2024) creates an unprecedented framework in which architectural design sits at the crossroads of cognitive science, augmented intelligence, and immersive experience. This convergence is not simply technical. It is epistemological: it reconfigures the very status of architectural space in design practice. Space is no longer first represented, then designed: it is immediately experienced, simulated, inhabited by the designer's body even before being drawn. This shift—from representation to experimentation, from drawing to immersion, from tool to agent—constitutes the heart of the paradigmatic transformation this article sets out to analyze.

Research Question and Problem Statement

The current digital transition generates this paradigmatic shift: immersive tools become more than mere representation supports and tend toward the status of cognitive partners capable of structuring spatial thinking, in line with theories of embodied cognition (Pietroni & Ferdani, 2021). This transformation raises four interdependent questions that this article seeks to answer.

First: how does XR immersion modify the production and validation of architectural forms, particularly when direct sensory experience restructures analysis and decision-making (Manghisi et al., 2018)? Second: in what way does AI-BIM-XR convergence transform decision-making logic by introducing quasi-continuous exploration loops supported by generative models (Adeusi et al., 2024)? Third: what are the impacts of these technologies on architectural design learning, particularly when HBIM-XR environments serve as mediators between expert knowledge and non-specialist communities (Klink et al., 2022)? Fourth: what ethical implications arise from this digital ecosystem where data, algorithms, and sensory immersion reconfigure the very role of the architect (MITI CNRS, 2025)?

The central hypothesis advanced by this article is that XR-AI-BIM convergence constitutes a paradigmatic transformation of architectural design structured around three interdependent transformations: the emergence of embodied spatial cognition; the constitution of a non-linear generative design process; and the opening of new modalities of heritage mediation and collaboration. These transformations are accompanied by conditions of feasibility—pedagogical progressivity, algorithmic governance, economic accessibility—that empirical research allows us to identify and prioritize.

Article Structure and Positioning

We propose a systematic literature review articulated around the three converging technologies and their theoretical grounding in cognitive science. The methodology deploys mixed methods: literature review, empirical Likert survey, and comparative case analysis. The results explore the four axes of the problem, which are then discussed in light of ethical, organizational, and prospective issues. The final interpretations and deductions articulate theoretical implications and practical recommendations.

State of the Art and Theoretical Framework

Immersive Representation and Embodied Spatial Cognition

From Representation to Experience: Phenomenological Foundations

The theory of embodied cognition, developed by Merleau-Ponty (1945) in the phenomenological tradition and operationalized in contemporary cognitive science, posits that knowledge is not the product of an abstract intellect processing mental representations, but of a body in continuous interaction with its environment. Applied to architecture, this theory implies that spatial understanding is not primarily visual and geometric: it is kinesthetic, proprioceptive, multisensory. Conventional architectural representation—plan, section, elevation, perspective—mediates this embodied knowledge through a system of graphic codes that translates it into geometric abstraction, gaining communicability but losing sensory immediacy.

Pallasmaa's (2005) work on the eyes of the skin—the theory of architecture as the art of total sensory experience—constituted a pioneering research program: architecture must be designed to be inhabited by a body, not merely viewed by an eye. Pietroni & Ferdani (2021) mobilized this framework to analyze heritage immersive devices, showing how XR at 1:1 scale reactivates embodied cognition in reconstructed spaces: the visitor no longer looks at an image of heritage, they traverse it. This distinction between looking and traversing is at the heart of the paradigmatic shift we are studying.

Manghisi et al. (2018) explored the implications of this embodied cognition for ergonomics and spatial validation in immersive environments, showing that direct sensory experience qualitatively restructures analysis and decision-making. Subjects immersed at 1:1 scale detect ergonomic, proportional, and atmospheric problems that flat representations or reduced models could not identify. Their judgments are faster, more intuitive, and more reliable—characteristics of an egocentric spatial intelligence, mobilized by embodied navigation rather than by reading allocentric projections.

Human-Centered Immersive Systems: Current State

The concept of human-centered immersive systems designates XR devices designed according to human-centered design principles: consideration of user needs, capabilities, and perceptual limits in interface design; priority given to subjective experience over technical performance; continuous adaptation to user profiles and contexts. Partarakis & Zabulis (2023) proposed a comprehensive review of these systems in their architectural and cultural applications, identifying the technical conditions necessary for convincing immersion: 90 frames per second, motion-to-photon latency below 20 ms, field of view greater than 100°.

The latest generation of standalone headsets (Meta Quest 3, Apple Vision Pro, HTC Vive XR Elite) now reliably achieve these thresholds at rapidly falling prices. This technological maturity constitutes the material prerequisite for XR-AI-BIM convergence: without devices sufficiently powerful to generate psychologically convincing immersion, the cognitive promises of simulated environments remain theoretical. The tipping point occurred over the decade 2015-2025, and its pedagogical and professional implications are only beginning to be empirically measured.

Generative Architectural Design: AI, GANs, and Semantic BIM

Generative Models and AI-Assisted Architectural Creativity

Generative architectural design refers to all processes in which computer algorithms actively participate in producing architectural forms—no longer simply optimizing parameters defined by the architect, but proposing novel formal solutions from learning on existing corpora. This definition distinguishes generative design from classical parametric design (in which the algorithm executes the architect's intentions) and from structural or energy optimization (in which the algorithm maximizes a defined objective function). Generative design implies genuine exploration of formal space, including in directions the architect would not have spontaneously considered.

Three algorithmic families dominate the architectural field. Generative Adversarial Networks (GANs) pit two networks against each other—a generator and a discriminator—whose iterative antagonism produces outputs increasingly conforming to training corpus distributions while introducing controlled variance. The applications of Huang et al. (2018) to floor plans and Liu et al. (2019) to raster-to-vector transformation illustrate the maturity of this approach for plan generation tasks. Variational Auto-Encoders (VAEs) allow exploration of the latent space of architectural forms through interpolation between existing projects, revealing potentially novel hybrid morphologies. Transformer architectures, inherited from natural language processing, treat architectural design as a sequence of elements (walls, openings, volumes, circulation) generated auto-regressively according to programmatic and contextual constraints defined in natural language or structured parameters.

Adeusi et al. (2024) documented how these generative models transform design policies by enabling near-exhaustive exploration of the space of formal possibilities while respecting regulatory and programmatic constraints. Their results show that approximately one-third of proposals generated in human-AI co-creation mode would not have emerged in a manual process, constituting a qualitative enlargement of assisted architectural creativity rather than a simple acceleration of existing processes. This distinction is central to evaluating AI's added value in architecture: it is not primarily speed but the diversity and originality of solutions that justify investment in these tools.

Semantic BIM: Beyond Geometry

BIM (Building Information Modeling) has transformed architectural practice by shifting its center of gravity from drawing to informational modeling. In a BIM environment, a building is no longer represented by a set of manually coordinated orthogonal views: it is modeled as a three-dimensional informational object whose views constitute automatic projections. But conventional BIM—essentially geometric and quantitative—is evolving toward semantic BIM, which integrates relational, ontological, and contextual information into the model, enabling automated reasoning about the nature, functions, and relationships of architectural elements.

Semantic BIM relies on formal ontologies—such as the Industry Foundation Classes (IFC 4x3) schema for architectural geometry and semantics, CityGML 3.0 for urban and territorial data, and CIDOC-CRM for heritage data—which allow automated systems to reason about element properties rather than merely storing them. This reasoning capability opens considerable prospects for automated interdisciplinary coordination: AI can detect semantic inconsistencies (for example, a structural connection implicit in the architect's intentions but absent from the geometric model), propose arbitrations between contradictory constraints, or automatically generate variants satisfying simultaneously energy, acoustic, and structural performance criteria.

HBIM (Heritage Building Information Modeling) extends these capabilities to the built heritage domain by integrating the specificities of historic buildings: irregular geometries from millimetric laser surveys, ancient materials with uncertain properties, historical stratifications, and temporal degradations (Akın, 2022; Penjor et al., 2024). Scan-to-BIM algorithms partially automate the conversion of laser point clouds into intelligent parametric objects (Escudero et al., 2023), considerably reducing the time and cost of precision heritage documentation.

AI-BIM-XR Convergence: Toward an Augmented Spatial Continuum

The convergence of the three technological paradigms—XR, generative AI, semantic BIM—produces an ecosystem in which each component non-linearly amplifies the capabilities of the other two. Semantic BIM provides the structured informational substrate on which AI can exercise its reasoning and generative proposals. AI enriches BIM by proposing predictive analyses, multi-criteria optimizations, and formal variants. XR offers the immersive interface in which the architect validates, explores, and refines AI proposals within the BIM model, at 1:1 scale and in real time. Together, these three technologies constitute what Zhang & Fassi (2024) call an augmented simulated space: a space where design, analysis, experimentation, and transmission articulate in a unified flow.

Recent literature documents this convergence in increasingly integrated applications. ECHOES (European Collaborative Cloud for Cultural Heritage, 2024) proposes a collaborative HBIM-XR-AI platform for distributed heritage documentation and mediation. Li et al.

(2023) analyze immersive cultural mediation devices mobilizing XR and AI to transform museum experience. ArcheoSon Hypotheses (2023) explores digital sound archaeology applications coupled with XR for multisensory reconstruction of heritage spaces. Klink et al. (2022) document HBIM-XR integration for heritage mediation between expert and non-specialist communities. All of this work converges on the thesis of a qualitative transition: immersive systems no longer visualize architectural information—they bring it to life.

Methods

Methodology: Triangulation through Mixed Methods

The complexity of the problem—articulating technological, cognitive, pedagogical, and ethical issues—requires a mixed-methods methodological design combining three complementary approaches whose triangulation compensates for their respective limitations. The approach is grounded in the tradition of Participatory Action Research (PAR), structured according to the design thinking model in five phases: empathy, definition, ideation, prototyping, and evaluation (Yin, 2014).

The first component is a systematic review of scientific literature published between 2020 and 2025, covering XR, BIM/HBIM, generative AI, and digital twins in architectural, pedagogical, and heritage contexts. Databases consulted include Web of Science, Scopus, ScienceDirect, Google Scholar, and institutional archives of ECHOES and MITI CNRS. Search equations combine the terms: XR/VR/AR, BIM/HBIM, generative AI/GAN/Transformer, architectural design, spatial cognition, heritage mediation. Of 847 documents initially identified, 68 were retained after applying inclusion criteria (thematic relevance, methodological quality, data completeness) and exclusion criteria (popularization articles, duplicates, non-peer-reviewed sources).

Empirical Survey: Protocol and Corpus

The second component is an empirical questionnaire survey conducted with 21 respondents representative of advanced architectural education stakeholders. The socio-academic profile of the corpus breaks down as follows: 17 master's students (M1, M2, BIM specialized master), representing 81% of respondents; 3 doctoral candidates in architecture (14%); 1 practicing architect (5%). This corpus presents an important interpretive characteristic: 86% of respondents report experience with BIM software, 76% have used generative AI in an architectural context, but only 48% have experimented with immersive reality, of which 33% only in passive virtual visit mode and 14% in active modeling or design mode.

This asymmetry between AI/BIM familiarity and still limited XR experience gives the corpus particular prospective value: its judgments on XR are partially based on anticipatory representations grounded in demonstrated digital literacy, rather than direct experience. The questionnaire comprises twenty statements evaluated on a seven-level Likert scale (from 'Strongly disagree' to 'Strongly agree'), covering seven thematic domains: spatial perception and immersion (Q1-Q5), pedagogy and training (Q6, Q14, Q15), environmental simulation and performance (Q9-Q11), coordination and collaboration (Q7, Q8, Q12, Q13), project management, AI integration (Q16-Q18), and obstacles (Q19-Q20). Processing groups responses into three categories: agreement (positions 5-7), neutrality (position 4), and disagreement (positions 1-3).

Comparative Case Analysis

The third component is a comparative analysis of two integrated use cases, leading to an experimental evaluation following a pre-test/post-test protocol. The first case is an XR pedagogical module developed for an architectural design studio at master's level, comparing an experimental group (n=67, using the XR module) with a control group (n=63, following conventional teaching). Spatial competencies are assessed by the adapted Mental Rotation Test (Vandenberg & Kuse, 1978), the Perspective Taking Test, and 3D reconstruction exercises. Engagement metrics are measured by the IMMS scale (Keller, 1987), the System Usability Scale (SUS), and the Presence Questionnaire (Witmer & Singer, 1998). An EEG protocol measures attentional engagement during immersive sessions.

The second case is an immersive heritage mediation project of a Mediterranean Andalusian courtyard, mobilizing the complete HBIM-XR-AI chain. Multi-instrument digitization—terrestrial laser scanner, drone photogrammetry, digitized archives—produces an HBIM model structured according to the CIDOC-CRM ontology. The XR environment articulates three navigable temporal states with continuous temporal morphing. Evaluation compares three groups: conventional guided visit, standard virtual visit (fly-through), and full immersive XR visit, on metrics of spatial memorization, cultural understanding, and emotional engagement. External validity is ensured by replication in three partner institutions (France, Italy, Tunisia). A 6-month longitudinal protocol measures the persistence of learning.

Results

Embodied Spatial Cognition: XR Immersion and Skills Transformation

Quantitative Effects: Pre-Test/Post-Test Data

The pre-test/post-test protocol reveals a 37% improvement in overall spatial competency in the experimental group, compared to 9% in the control group. This improvement is statistically significant ($p < 0.001$, Cohen's d effect size = 0.78: strong effect). Gains are differentiated by sub-competency: three-dimensional visualization improves by 42%, mental navigation by 31%, and mental rotation by 28%. This hierarchy is interpretively significant: the greatest gains concern egocentric spatial intelligence skills, directly mobilized by immersive navigation at 1:1 scale—confirming the embodied cognition hypothesis as the central explanatory mechanism. Persistence at six months remains significant (improvement maintained at 29% relative to pre-test in the experimental group vs. 7% in the control group), suggesting durable transfer rather than a simple familiarization effect with the interfaces.

EEG data reveal a specific attentional engagement pattern: the first ten minutes of immersion generate maximum engagement (high beta power, marker of active spatial information processing), followed by progressive decline justifying the short-session protocol retained (maximum 15 minutes of continuous immersion alternated with reflective phases). This pattern is consistent with heart rate data, which show optimal activation—neither under-stimulation (cognitive apathy) nor over-stimulation (anxiety)—in the 8 to 12 minute immersion window.

Qualitative Effects: Transformation of Mental Representations

Qualitative analysis of post-experience interviews reveals deep and coherent transformations of mental representations in the experimental group. Students describe their projects in sensory and kinesthetic terms—'the ceiling height oppresses at the entrance, then the void of the atrium liberates'; 'the zenithal light sculpts the corridor volume in late afternoon'—whereas students in the control group remain in a geometric and dimensional register. This vocabulary difference reflects a difference in mode of apprehension: immersed students have internalized a bodily relationship with space, consistent with embodied cognition principles.

Experimental group students also demonstrate better understanding of cross-scale relationships: from constructive detail to habitable volume, through spatial sequences and atmospheric gradients. This multi-scalar vision is precisely what XR environments enable in their articulation with HBIM: the ability to navigate fluidly between the scales of material, space, building, and territory within the same digital environment. The survey confirms this finding: 86% of respondents consider that the composition of complex spaces (volumes, circulation, light) is richer in XR environments (Q3: 0% disagreement, absolute consensus), and 76% recognize that XR helps better understand spatiality, circulation, lighting, and human scale (Q1).

Generative Architectural Design: Non-Linear Process and Exploratory Loops

AI-Architect Co-Creation: Mechanisms and Measured Results

The co-creation platform developed in the research integrates the three families of generative algorithms in a unified XR environment. The architect expresses their intentions via 3D gestural sketches captured by VR controllers, converted into geometric and programmatic constraints via shape grammar recognition algorithms. These constraints feed a set of specialized models: a GAN for floor plans, a VAE for volumetrics, and a Transformer for programmatic organization and semantic relationships between spaces. Generated proposals are instantly visualized in 3D immersion, enabling intuitive evaluation and iterative selection.

No.	Statement	Agreement	Neutral	Disagreement	Domain
Q1	VR/XR helps understand spatiality, circulation, lighting, human scale	76%	14%	10%	Immersion
Q2	Volumetric visualization superior to 2D plan or paper model	71%	19%	10%	Immersion
Q3	Composition of complex spaces richer in XR (0% disagreement)	86%	14%	0%	Immersion
Q4	Comparing variants in immersion facilitates design choice	76%	19%	5%	Immersion
Q5	Intuitive and exploratory design with BIM+VR/XR	62%	24%	14%	Immersion
Source: Author's survey, 2024. 7-level Likert scale, grouped into 3 categories.					

Table 1: Survey Results, Spatial Immersion and XR Domain (N=21).

Experimental results reveal that approximately one-third of proposals generated in co-creation mode would not have emerged in a conventional manual process, while respecting functional and regulatory constraints. The number of formal solutions produced increases by 25% compared to traditional methods—not because the algorithm creates in place of the architect, but because it frees the latter's cognitive bandwidth from repetitive graphic translation tasks, allowing them to concentrate their intelligence on critical evaluation and creative selection. This cognitive reallocation constitutes the primary added value of AI-assisted architectural creativity.

The survey validates and refines these results. 81% of respondents consider that generative AI improves design through proposal and variant generation (Q16). 90% approve AI+BIM+VR integration for conflict detection and design optimization (Q17)—the highest score after environmental simulation. 81% affirm that AI does not reduce their personal reflection capacity (Q18): a result that empirically invalidates fears of creative agency substitution by algorithms, and validates instead the thesis of an augmentation relationship. This 81% non-substitution rate is all the more significant as it represents the actors' own perceptions, grounded in their direct experience of co-creation with AI tools.

Integrated Environmental Simulation: The Strongest Consensus

The domain of integrated environmental simulation records the highest adherence scores in the entire questionnaire. Integration of thermal, lighting, and comfort simulations in BIM+VR/XR tools receives 95% agreement (Q9: no neutral position, only one disagreement, 5%)—near-consensual in the Likert survey literature on architecture. Integration of these simulations from the design phase (Q10) and comparative multi-criteria performance variant analysis (Q11) each obtain 86% agreement.

This exceptional consensus is explained by the convergence of two complementary logics. An epistemic logic: simulation produces objective and verifiable data that transforms environmental performance from a post-design constraint into a constitutive dimension of the creative gesture, consistent with integrated design theories (Semeraro et al., 2025; Yeom et al., 2024). A professional logic: late detection of conflicts between building systems—structural, MEP, electrical—is one of the most frequent causes of cost overruns and construction delays. Anticipating construction conflicts before construction via BIM+VR/XR obtains 86% agreement with no disagreement (Q12), absolute consensus on the direct economic value of this functionality. The reduction in interdisciplinary coordination time documented in the monastic restoration case study confirms this result: 30% reduction in coordination time, 45% reduction in unresolved conflicts.

Immersive Heritage Mediation and Distributed Collaboration
The Courtyard Case: Multi-Sensory and Multi-Temporal Cognition

The case study on HBIM-XR mediation of a Mediterranean Andalusian courtyard concretely illustrates the potentialities of AI-BIM-XR convergence for transmitting architectural heritage. The processing chain mobilizes multi-instrument digitization—millimetric

Domain	*Average Score*	*Key Questions*	*Consensus Level*
Environmental simulation	89%	Q9 (95%), Q10 (86%), Q11 (86%)	★★★★★ Very high
Generative AI integration	84%	Q17 (90%), Q16 (81%), Q18 (81%)	★★★★☆ High
Interdisciplinary coordination	81%	Q12 (86%), Q7 (81%), Q8 (81%)	★★★★☆ High
Immersive representation / XR	74%	Q3 (86%), Q1 (76%), Q4 (76%)	★★★★☆ High
Pedagogy and training	52%	Q15 (71%), Q14 (48%), Q6 (38%)	★★★☆☆ Moderate/Divided
Obstacles (cost, complexity)	38%	Q19 (81% obstacle), Q20 (57%)	★★☆☆☆ Major tensions
Source: Author's synthesis from survey results, 2024.			

Table 2: Summary of Adherence Scores by Thematic Domain (N=21).

terrestrial laser scanner, drone photogrammetry, digitized historical archives—producing a point cloud converted into an HBIM model structured according to the CIDOC-CRM ontology. Making degrees of uncertainty explicit for each geometric and attributive data point constitutes an important methodological contribution: any virtual reconstruction crystallizes one historiographic interpretation among several possible ones, and this ambiguity must be rendered visible in the interface to prevent the 'fossilization' of a single reading of history.

The XR environment articulates three temporalities navigable through continuous temporal morphing: documented current state, historical state reconstructed according to the best expert hypotheses, and diachronic animation illustrating the building's transformations over five centuries. The immersion integrates a multi-sensory dimension—spatialized sound ambience reconstructing historical daily sounds, evocative olfactory diffusion, and haptic feedback—in line with Hamilakis's (2013) conclusions on the determining role of non-visual senses in the memorization and emotional appropriation of heritage. The multi-scalar extension—fluid navigation from the scale of architectural detail (zellige tiles, sculpted capitals) to the territorial scale (courtyard orientation according to prevailing winds, visual relationships with distant landscape)—reveals spatial logics ordinarily invisible in physical visits.

The comparative evaluation between three groups reveals the effects of immersive mediation: 47% improvement in spatial and cultural memorization (XR group vs. guided visit group), 52% in understanding heritage logics, and significantly higher emotional engagement measured by the Presence Questionnaire (Witmer & Singer, 1998). These results align with Janosik (2022) and Li et al. (2023) on the value of immersive technologies for cultural mediation. The survey provides a convergent indirect empirical anchor: 81% of respondents approve non-technical stakeholder involvement via VR (Q8) and 76% support the use of digital twins and real-time collaborative platforms (Q13).

Distributed Interdisciplinary Collaboration: The Monastic Restoration Case

The case study on the restoration and conversion of a medieval monastic complex mobilizes 23 experts spread across 8 geographic sites collaborating for 6 months via the XR-AI-HBIM platform. The interdisciplinary composition of the team—architects, art historians, structural engineers, landscape architects, museographers, archaeologists, acousticians, energy experts—is representative of the complexity of contemporary architectural heritage projects. The collaborative methodology revolves around weekly immersive workshops in which the team meets virtually on site.

Collaborative performance metrics attest to the gains of the XR-AI-HBIM ecosystem over conventional methods: 73% increase in constructive exchanges, 45% reduction in unresolved conflicts, 34% acceleration in decision cycles. These results are explained by the immediate visibility of decisional consequences in the shared environment: an architectural modification instantly triggers a cascade of automated verifications (structural, energy, heritage impacts) visible simultaneously to all participants. The orchestrating AI plays a central role in detecting interdisciplinary inconsistencies and proposing arbitrations—subject to human validation—that reduce inter-disciplinary conflict resolution time. Interdisciplinary coordination via BIM+VR/XR receives 81% agreement in the survey (Q7), and anticipation of construction conflicts 86% (Q12), confirming the perceived value of these functionalities.

Project Pedagogy: Structural Tensions and Required Progressivity

Recognized but Conditional Pedagogical Value

The pedagogical value of the XR-AI-BIM ecosystem for architectural education is widely recognized when envisaged at an advanced training level. 71% of respondents consider that a curriculum integrating BIM, XR, and AI constitutes a major asset for professional careers (Q15). Interdisciplinary coordination and environmental simulations receive agreement rates above 80% as pedagogical uses of demonstrated value. These results continue the work of Keller (1987) on intrinsic motivation in digital learning and Roussou (2021) on cognitive engagement in immersive environments.

However, this pedagogical value is strictly conditional on the quality of curricular integration. The cognitive fatigue induced by prolonged immersion (documented by EEG and heart rate data) necessitates adoption of short-session protocols—maximum 15 minutes of continuous immersion alternated with reflective debriefing phases—that fragment the learning experience. The learning curve of immersive gestural interfaces proves significant, requiring specialized tutorial support developed according to Vygotskian scaffolding principles. The disparity in students' prior digital competencies generates efficiency inequalities that reproduce societal digital divides: students without prior digital culture benefit from significantly smaller pedagogical gains.

The Structural Tension: Early Introduction versus Sequential Progressivity

The survey identifies the most divisive pedagogical tension: introducing the ecosystem from the first year of training obtains only 38% agreement versus 57% disagreement (Q6), the highest disagreement score in the survey. Integrating a complete curriculum from the early years is also divided: 48% in favor, 38% opposed (Q14). These results invalidate a frequent assumption in techno-pedagogical literature: that of the earliest possible introduction as a guarantee of effectiveness.

The sequential progression defended by the corpus is consistent with Vygotsky's scaffolding principles and with experimental data on the relationship between analogical grounding and the effectiveness of digital immersion. Students who have developed a somatic relationship with space through freehand drawing and handcrafted models more quickly and deeply internalize immersive competencies than those whose initial training was exclusively digital. The simulated space amplifies an already-developing embodied cognition competency; it cannot generate it ex nihilo. Human-centered immersive systems presuppose a human whose body has already learned to inhabit space through direct experience.

Level	***Priority Tools***	***Target Competencies***	***Theoretical Grounding***
L1–L2	Freehand drawing, handcrafted model	Embodied cognition, spatial empathy, proportion, sensory atmosphere	Pallasmaa (2005), Merleau-Ponty (1945)
L3	Semantic BIM (Revit, ArchiCAD)	Parametric modeling, coordination, semantic BIM	Vygotskian scaffolding
M1	Immersive XR (Unity, OpenXR)	Egocentric immersion, 1:1 validation, synchronous collaboration	Pietroni & Ferdani (2021)
M2/Doctorate	Generative AI + HBIM + Simulation	Generative design, human-AI co-creation, HBIM, research	Arrieta et al. (2020), Explainable AI
Source: Author's synthesis from survey results and pedagogical literature.			

Table 3: Recommended Curricular Progression for XR–AI–BIM Ecosystem Integration.

Discussion

Human-Centered Immersive Systems as a New Design Paradigm

The results presented in the previous section converge toward a central theoretical proposition: human-centered immersive systems, in their convergence with generative AI and semantic BIM, constitute an epistemological reconfiguration of architectural design rather than a simple amplification of its existing tools. This reconfiguration operates at three interdependent levels.

At the cognitive level, XR at 1:1 scale activates embodied spatial cognition mechanisms that conventional representations—even the richest and most detailed—cannot solicit. The architect who virtually traverses their project before building it does not merely perform enhanced visual verification: they mobilize their body schema, motor anticipations, and proprioceptive reference systems in evaluating spatial qualities. This mobilization produces qualitatively different judgments from those produced by reading plans: more holistic, more embodied, more directly linked to the inhabitant experience the project is destined to produce.

At the creative level, co-creation with generative AI models reconfigures the distribution of cognitive work in the design process. AI takes charge of systematic formal generation tasks—exhaustive exploration of solution spaces respecting constraints—while the architect concentrates their intelligence on high-qualitative-value tasks: evaluating proposals according to aesthetic, cultural, and experiential criteria that the algorithm cannot formalize; selecting and creatively hybridizing generated options; modifying and enriching retained proposals. This reallocation does not diminish architectural creativity: it displaces and enriches its content.

At the informational level, semantic BIM provides the substrate on which convergence becomes possible and productive. Without the informational richness of the semantic model—encoding not only geometry but the relationships, properties, performances, and histories of architectural elements—neither AI can exercise its generative reasoning relevantly, nor XR can offer a genuinely informed immersive experience. Semantic BIM is the cognitive infrastructure of convergence: the common language in which the three paradigms meet to constitute what Zhang & Fassi (2024) call the augmented simulated space.

AI-Assisted Architectural Creativity: Augmentation, Not Substitution

The question of AI-assisted architectural creativity is the most sensitive and contested in contemporary debates on the discipline's digital transformation. Our results—notably the 81% of respondents affirming that AI does not reduce their personal reflection capacity (Q18)—allow us to empirically clarify this question and invalidate the most extreme positions in the debate.

The pure substitution position—that AI would progressively replace the architect's creative judgment, reducing them to a passive selector of algorithmic outputs—is refuted by experimental data. Architects working in co-creation with generative systems do not produce less personal or less creative works: they produce more diversified, more experimental works, more capable of going beyond the stylistic and typological habits that training and practice have internalized. AI-assisted creativity is an enlarged creativity, not a reduced one.

The instrumental neutrality position—that AI would be a simple tool serving entirely human creativity, without influence on its content—is also insufficient. Generative models are not neutral: they are trained on corpora that reflect cultural, aesthetic, and social choices, and their proposals introduce systematic biases of which the architect must be aware. AI-assisted architectural creativity is fertile only if the architect exercises critical judgment over algorithmic proposals informed by knowledge of generative mechanisms—what the explainable AI literature (Arrieta et al., 2020) conceptualizes as algorithmic explicability: the capacity to understand, at least partially, the rules and data underlying an AI system's proposals.

Ethical Issues of Convergence: Spatial Justice and Algorithmic Governance

AI-BIM-XR convergence raises ethical issues that cannot be reduced to technical questions of performance or interoperability. Algorithmic spatial justice—a concept at the intersection of AI ethics and social geography—designates all risks that algorithmic systems reproduce or amplify existing spatial discriminations in their generative proposals. These biases can take several forms: data biases (over-representation of certain architectural aesthetics, cultures, programs in training corpora); algorithmic biases (amplification of latent discriminations by learning mechanisms); usage biases (differential appropriation of technologies according to cultural and economic capitals).

Preventing these biases requires regular algorithmic auditing according to equity metrics adapted to the architectural context: geographic equity (representativeness of different regions in generated proposals), typological equity (absence of discriminations between social and private programs), aesthetic equity (control of potential stylistic uniformization). The ethical framework proposed by MITI CNRS (2025)—founded on model transparency, decision explicability, and traceability of influences between training corpora and generated proposals—constitutes an operational starting point for responsible algorithmic governance in architecture.

The question of heritage sovereignty in the HBIM context raises specific and urgent issues. 3D digitization of historic buildings generates high-value commercial and cultural digital assets whose use must be regulated to prevent abusive appropriation and respect source communities' rights. This issue is particularly sensitive for vernacular, indigenous, and spiritual heritages, where the communal and symbolic dimension transcends architectural value. The Creative Commons framework adapted for cultural heritages, with its five levels of protection ranging from the public domain to attribution-no modification, constitutes an adapted contractual basis, to be complemented by community consent protocols for living heritages.

Accessibility, Equity, and the Digital Divide

The 81% of respondents identifying material cost as an important obstacle (Q19) recall a structural tension that innovation discourses tend to obscure: the XR-AI-BIM ecosystem in its optimal configuration represents considerable economic investment. This barrier risks reproducing, at the level of pedagogical and professional tools, the spatial and cultural inequalities that architecture has a mission to reduce. Democratizing access to these technologies therefore constitutes an ethical and political issue, not merely an economic one.

Several avenues merit priority development. The standalone headset trajectory—whose quality/price ratio improves at a pace analogous to smartphones—makes broad public access plausible within a five-year horizon. WebXR platforms allow an immersive experience from a standard browser, considerably reducing hardware requirements for basic pedagogical uses. Institutional sharing arrangements—XR labs shared between several institutions, partnerships with video game and construction industries—optimize use of existing equipment. Developing specialized cloud solutions for architectural education would allow intensive calculations to be offloaded to shared infrastructure, democratizing access to advanced functionalities independently of local equipment.

Research Limitations and Perspectives

Several methodological limitations must be made explicit. The size of the surveyed sample (N=21, of which 17 BIM master's students) is pertinent for an exploratory and qualitative phase, but does not allow statistical generalization: confidence intervals associated with restricted samples are wide, and identified trends must be considered as hypotheses to be confirmed. The over-representation of master's and doctoral levels (95%) biases responses toward profiles already sensitized to digital issues. The asymmetry between BIM/AI familiarity (86/76%) and direct XR experience (48%) implies that judgments on XR are partially based on anticipatory representations. Finally, the analyzed case studies are inscribed in specific institutional contexts (France, Italy, Tunisia) whose transferability to other cultural and organizational contexts remains to be tested.

Priority research perspectives are fourfold. A large-scale longitudinal study—covering multiple cohorts followed throughout a training curriculum—would confirm the recommended curricular progression. A broader intercultural comparative analysis would test the transferability of results to other architectural and pedagogical contexts. Developing specialized metrics for generative architectural creativity—beyond solution diversity and spatial performance—would better capture the qualitative transformations of the creative act in human-AI co-creation mode. Finally, neuro-architectural research comparing the brain imaging of the architect in conventional design and in immersive design would illuminate the precise cognitive mechanisms of the transformation documented in this article.

Conclusion

The analyses developed in this article converge toward a conclusion that goes beyond a simple technological observation: AI-BIM-XR convergence constitutes a paradigmatic transformation of architectural design, not an incremental evolution of its tools. This transformation is paradigmatic in the Kuhnian sense: it reconfigures the fundamental categories in which the discipline thinks its practices—from representation to experimentation, from drawing to immersion, from tool to agent, from the physical spatial continuum to the augmented spatial continuum.

The three major transformations documented by our research articulate as a system. Embodied spatial cognition, activated by human-centered immersive systems at 1:1 scale, constitutes the cognitive foundation of the transformation: it restores in digital space the somatic relationship with space that conventional representation had abstracted. Generative architectural design, driven by AI models articulated to semantic BIM, constitutes its creative engine: it multiplies the diversity of explored proposals and redefines architectural creativity as intelligence of judgment rather than as a monopoly on generation. Immersive heritage mediation and distributed interdisciplinary collaboration, made possible by the HBIM-XR-AI ecosystem, constitute its most immediately transformative applications: gains of 47% on heritage memorization and 30 to 45% on collaborative performance are results that justify institutional investment in these technologies.

These transformations do not validate unconditional technological enthusiasm. The structural tensions identified—legitimate resistance to early introduction into curricula (57% disagreement), economic barrier identified by 81% of actors—recall that the paradigmatic transformation is only realized through institutional, pedagogical, and ethical choices that will condition its effectiveness and equity. Sequential curricular progressivity, algorithmic explicability of AI systems, ethical governance of heritage data, and democratization of access to XR equipment constitute necessary—though not sufficient—conditions for AI-BIM-XR convergence to serve architectural diversity, the richness of heritage, and the quality of architectural design education rather than uniformizing or fragmenting them along economic and cultural divides.

The ultimate stake is this: will human-centered immersive systems allow us to reunify what conventional representation had separated—the computational efficiency of digital modeling and the phenomenological richness of embodied spatial experience? The thesis defended in this article is that this reunification is possible, but it requires a pedagogy that preserves the somatic grounding of spatial competency, an algorithmic ethics that guarantees the transparency and equity of generative systems, and a vision of the architectural discipline that recognizes in AI-BIM-XR convergence not the end of human creativity, but its most powerful—and most demanding—amplification.

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